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MODERN METHODS AND TECHNOLOGIES FOR IMPROVING THE QUALITY OF DRINKING WATER

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Abstract: Freshwater resources are becoming scarcer, and available drinking-water sources are increasingly polluted by anthropogenic and industrial waste. Conventional treatment based on sedimentation, sand filtration and chlorination is insufficiently effective against emerging contaminants and generates potentially harmful disinfection by-products such as trihalomethanes (THMs).

To evaluate the physicochemical and microbiological efficiency of modern membrane and oxidation technologies in the treatment of differently polluted water sources and to propose an optimal hybrid treatment scheme.

Keywords: drinking water quality; reverse osmosis; nanofiltration; advanced oxidation processes; UV-LED disinfection; heavy metals; membrane technologies; ozonation; trihalomethanes.

INTRODUCTION

Relevance of the problem

Water is the most important and irreplaceable natural resource for maintaining human health, meeting domestic and industrial needs and ensuring ecological sustainability. According to United Nations data, more than 2 billion people in the world still lack access to safe and clean drinking water. Climate change, rapid population growth, urbanization [2] and the expansion of industrial enterprises are leading to a decline in both the quality and the quantity of freshwater resources.

The sedimentation, sand filtration and chlorination technologies used in conventional water treatment plants are not sufficiently effective against the contaminants of the twenty-first century: microplastics, pharmaceutical residues, pesticides and very small organic molecules. In addition, conventional chlorination leads to the formation of chlorinated organic compounds, trihalomethanes (THMs), which are potentially carcinogenic and mutagenic disinfection by-products. The development and practical introduction of safe, economical and highly effective modern technologies for improving drinking water quality is therefore an urgent task.

Modern contaminants and water hygiene

Disturbances in the cation and anion composition of drinking-water sources (high hardness, excess sulfates and chlorides), heavy metals (lead, cadmium, arsenic, chromium) and the presence of viruses and bacteria are associated with kidney stone disease, gastrointestinal pathologies,

endocrine disorders and infectious diseases. Chemical contaminants such as heavy metals and pesticides have also been linked to long-term adverse effects on biological systems, including the nervous system [1].

In recent years, strict compliance with the national sanitary rules and norms SanQvaN 0018-21 and the guidelines of the World Health Organization (WHO) has been required in the Republic of Uzbekistan and in developed countries to ensure drinking-water safety. Sanitary-hygienic analysis against normative requirements forms the basis of this control [3]. Modern physicochemical and biotechnological methods make it possible to achieve deep purification of the organoleptic (taste, odor, color, turbidity) and chemical-microbiological characteristics of water.

MATERIALS AND METHODS

Study objects and water samples

The study was carried out in 2024–2025 on samples taken from three different water sources:

1. **Sample 1:** river water (surface source) with high turbidity and a high content of organic matter;
2. **Sample 2:** artesian well water (groundwater) with high mineralization and hardness, requiring removal of iron and manganese;
3. **Sample 3:** recycled domestic wastewater, which required deep treatment to bring it to the quality of secondary (reused) drinking water.

Experimental laboratory and pilot installations

The laboratory- and pilot-scale hybrid treatment unit consisted of the following blocks:

1. **Mechanical and sand-activated carbon block:** removal of coarse particles and odor at the initial stage;
2. **Ultrafiltration (UF) module:** polyethersulfone (PES) hollow-fiber membranes with a pore size of 0.01 μm;
3. **Nanofiltration (NF) and reverse osmosis (RO) module:** polyamide composite membranes (FilmTec RO and NF90);
4. **AOPs and ozone reactor:** an O_3 generator (capacity 5 g/h) and quartz tubes coated with photocatalytic TiO_2;
5. **UV-LED disinfection block:** highly efficient bactericidal diode panels with wavelengths of 265 nm and 280 nm.

Analytical and physicochemical methods

Water quality indicators were measured with the following methods and instruments and were evaluated against the requirements of SanQvaN 0018-21 and the WHO guidelines:

1. **Mineralization and mineral salts:** conductivity, TDS and hardness were measured with a conductometer/TDS meter (Mettler Toledo);
2. **Heavy metals:** Pb, Cd, As, Fe and Mn were determined by atomic absorption spectrometry (AAS, Agilent 240FS) and ICP-MS;
3. **Organic compounds and chemical oxygen demand (COD):** measured with a Hach Lange DR6000 spectrophotometer;
4. **Microbiological indicators:** total colony counts (CFU) and *E. coli* were determined by the membrane filtration method;
5. **Chlorinated organic compounds (THMs):** analyzed by gas chromatography-mass spectrometry (GC-MS).

Turbidity and the concentration of organochlorine pesticides were also determined.

RESULTS

Efficiency of membrane and physical treatment methods

The efficiency of different membrane technologies in removing turbidity, total dissolved solids (TDS) and hardness salts from water, together with their energy consumption, is presented in Table 1.

Table 1. Efficiency and energy consumption of membrane and physical treatment methods

Treatment method / membrane	Turbidity removal, %	TDS reduction, %	Hardness reduction, %	Energy consumption, kWh/m³
Ultrafiltration (UF)	98.5 ± 0.5	12.1 ± 1.5	8.0 ± 1.2	0.15–0.25
Nanofiltration (NF)	99.2 ± 0.3	78.5 ± 2.1	88.4 ± 1.8	0.45–0.70
Reverse osmosis (RO)	99.9 ± 0.1	98.8 ± 0.4	97.5 ± 0.6	1.20–2.10
Hybrid (UF + RO)	99.9 ± 0.05	99.1 ± 0.2	98.9 ± 0.3	1.10–1.80
Conventional sand filter	72.4 ± 3.2	3.5 ± 0.8	2.1 ± 0.5	0.05–0.10

According to Table 1, reverse osmosis and the hybrid UF + RO system showed the highest performance, retaining 98–99% of mineralization and hardness salts. Nanofiltration was selective:

it retained divalent ions (Ca^{2+}, Mg^{2+}, SO_4^{2-}) effectively, with 88.4% hardness reduction, but allowed monovalent ions (Na^+, Cl^-) to pass partially, so that TDS reduction (78.5%) was considerably lower than with RO. The conventional sand filter removed only 72.4% of turbidity and had almost no effect on salts, although it had the lowest energy demand (0.05–0.10 kWh/m^3). The hybrid system had a lower energy consumption range (1.10–1.80 kWh/m^3) than RO alone (1.20–2.10 kWh/m^3).

Advanced oxidation (AOPs) and removal of heavy metals

The efficiency of removal of toxic heavy metals and persistent organic pollutants is shown in Table 2.

Table 2. Removal of heavy metals, pesticides and organic matter by combined AOPs + RO treatment

Contaminant	Initial concentration, mg/L	After AOPs + RO treatment, mg/L	SanQvaN 0018-21 limit, mg/L	Efficiency, %
Lead (Pb)	0.12 ± 0.01	< 0.001	0.01	≥ 99.2
Arsenic (As)	0.08 ± 0.005	< 0.002	0.01	≥ 97.5
Pesticides (organochlorine)	0.45 ± 0.03	< 0.005	0.10	≥ 98.9
COD (organic matter)	45.0 ± 2.8	2.1 ± 0.3	15.0	95.3

Efficiency was calculated from the mean initial concentration and, where the residual value is reported as below a threshold, from that threshold; these efficiencies are therefore minimum estimates.

The initial concentrations exceeded the SanQvaN 0018-21 limits 12-fold for lead, 8-fold for arsenic, 4.5-fold for pesticides and 3-fold for COD. The combined use of AOPs (ozone + UV-LED) and RO membranes removed the heavy metals and pesticides accumulated in the water with an efficiency of 97.5–99.2% and reduced COD by 95.3%. After treatment, all indicators were below the normative limits.

DISCUSSION

Interpretation of the main findings

The results of this study are consistent with the international experience in membrane and advanced oxidation water treatment. Conventional reagent-based treatment (coagulation and chlorination) was the main tool of its time. However, the present complex and toxic pollution of water bodies requires new hybrid membrane-oxidation technologies for high-quality treatment.

In our experiments the sand filter and UF alone were not able to reduce mineralization, while NF and RO retained salts efficiently. The lower energy range of the hybrid UF + RO system than of RO alone may be explained by the protective effect of UF pretreatment, which reduces the load of suspended and colloidal particles on the RO membrane, but this assumption was not tested directly. The disadvantages of RO include strong demineralization of the water and the loss of beneficial microelements such as Ca, Mg and K. Remineralization (restoring the salt balance) after RO filtration and the use of selective nanofiltration modules are therefore recommended in modern water treatment. Remineralization was not evaluated experimentally in this study.

The disinfection results confirm that avoiding chlorine as the primary disinfectant eliminates the main source of THMs. Two practical cautions should be kept in mind. First, UV-LED disinfection leaves no residual disinfectant, so the protection of water in the distribution network needs to be addressed separately. Second, ozonation of bromide-containing waters may form bromate, another regulated by-product, so ozone dose and by-product monitoring are required.

Limitations

This study has several limitations. The experiments were performed at laboratory and pilot scale on three water sources, and long-term operation, membrane fouling and ageing were not assessed. Results were obtained from five replicates and no formal tests of statistical significance are reported. Disinfectant doses and contact times should be specified and optimized in further work, and the operating costs of the methods should be evaluated at full scale. Further studies should also include emerging contaminants such as microplastics and pharmaceutical residues, which were identified as a major problem for conventional treatment but were not measured here.

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