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# Recent developments in water purification

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## Abstract
Day by day problem of water scarcity and water contamination is rising due to the rapid population growth, climatic change and urbanization. The greater use of fresh water in agricultural, industrial and domestic use has led to its depletion. Further, alteration in rainfall and melting of glaciers by the climate change further enhance fresh water depletion. Water contamination is continuously increasing from textile, paper industries agriculture runoff, and irrigation practices that leads to discharge of dyes, chemicals, heavy metals, pesticides, fertilizer, pharmaceutical, microplastic and perfluoroalkyl sunstance into the water. To tackle with these problems, advanced water purification technology have been evolved that are much better than the traditional methods in terms of cost, design of equipment less use of toxic materials and greater removal efficiency. This review discussed the most recent and advanced techniques used in water purification Advanced Hybrid oxidation system, Advanced filtration techniques by using novel materials Advanced Membrane technology, Plasma-Based Water Purification, AI-Driven Smart Water Purification Systems and Microbial Fuel Cells (MFCs) for water purification.


**Keywords:** Advanced water purification, membrane filtration, nanotechnology, Oxidation method, Al-driven water purification, Microbial Fuel Cells

## Introduction
Ensuring access to safe water is crucial for multiple aspects of living things survival, as it is vital for fostering economic development, promoting environmental sustainability. Additionally it preserve biodiversity, support ecosystem and regulate rainfall. However, this fundamental resource is rapidly declining day by day due to various factors. These include increasing population, climatic change, industrial waste, and rising global demands that lead to water scarcity and contamination. Both these issues stem from natural as well human human-induced factors. Rapid population growth, poor irrigation practices, excessive agriculture, and industrial and domestic use put immense pressure on the underground reservoirs. Alterations in rainfall, prolonged droughts, and accelerating melting glaciers due to climatic change further worsen the crisis of water scarcity. Water contamination results from industrial waste releasing toxic chemicals, dyes, and heavy metals, agricultural runoff introducing pesticides, herbicides, and fertilizers, and untreated wastewater carrying viruses, bacteria, and pathogens. Many of these pollutants like heavy metals, pharmaceuticals, microplastics, and perfluoroalkyl substances (PFAS) are difficult to detect and raise significant environmental and health risk issues. Consequently, strict control of pollution and recent advancements in water-based technologies have been crucial to meet the growing demand for preserving water. Recent modern water purification technologies have been developed that are far better than traditional chemical and filtration methods. These innovative solutions offer enhanced pollutant removal efficiency, low cost, and greater environmental sustainability. Consuming less energy can be used for both large and small scale application, these advanced techniques reduce pollution to many folds by utilizing non-toxic hazardous materials, some of the most advanced techniques are:

**Advanced Hybrid oxidation system**

This water purification technology combines different advance oxidation process for the greater degradation of pollutants. The integration of these multiple processes results in greater pollutant removal efficiency, less toxic by-products production and reduces energy consumption rate. Barazeh and others discussed an advanced oxidation process that used H2O2 and UV light together to treat organic contaminants [Barazeh *et al*., 2015] [1]. A study published in *environmental science and pollution research international* discussed the degradation of stubborn pollutants like micropollutants and pathogens using advanced oxidation processes. Ozonation when integrated with additional technologies like UV, hydrogen peroxide, catalysts, and biological treatments provides a sustainable approach for greater degradation of pollutants [Mahmoodi & Pishbin., 2025] [3]. Additionally, kim and group introduces an innovative oxidation process of electro-chemical de-salination system integration. The efficiency of water treatment process is enhanced much more, using this synergistic effect of innovative system. This hybrid system combines an oxidant-generating anode that facilitates cation removal and pollutant oxidation with cation-selective battery material and a desalination component. [Kim *et al*., 2018] [4].

**Advanced filtration techniques by using novel materials**

Advanced filtration techniques using novel materials have been developed to enhance water purification. Minimizing microplastic pollution seems to be very difficult and challenging especially those smaller than 3 µm [Sun *et al*., 2021] [7]. They pose adverse impact on aquatic life and thus disrupt the ecosystem. To tackle this problem, advance filtration techniques using bioinspired materials has emerged as an innovative solution that mimics the natural bioinspired filtration systems. These systems have high adsorption capacity and selective permeability that effectively remove microplastics from water resources. Furthermore, these utilize natural materials, minimizing the use of chemicals and offering an ecofriendly and effective solution for reducing microplastic pollution. Wu and others developed a adsorbent supra-molecular self-assembly of cellulose and very known chitin. Due to multiple intermolecular interactions between different microplastic and Ct-Cel, this functional biomass framework effectively removes various microplastics like polystyrene, polymethyl methacrylate, polypropylene, and polyethylene terephthalate, and thus proves a promising material for microplastic removal [Wu *et al*., 2024] [6].

The Journal of Hazardous Materials published a study that created novel chitin-based sponges made of graphene oxide (GO) and oxygen-doped carbon nitride (O-C3N4) that efficiently eliminate various functionalised microplastics, such as polystyrene (PS), carboxylate-modified polystyrene (PS-COOH), and amine-modified polystyrene (PS-NH2). The adsorption process is driven by electrostatic forces, hydrogen bonding, and π-π interactions. This biodegradable materials prove a sustainable approach for microplastic removal and can be reuse up to 3 cycles [Sun *et al*., 2021] [7]. Metal organic frameworks are class of solid crystalline materials that are formed when metal ions coordinated with organic ligands [Li *et al*., 2023] [8]. Their unique properties like porous structure, functionally active sites, tunable pore channels and good thermal stability and high surface area make them an ideal candidate not for the effective pollutants removal but also a versatile material in other applications. MOFs effectively remove these pollutants like organic and inorganic compounds, heavy metals, and biological organisms by the processes like adsorption, photocatalysis and filtration [Rasheed *et al*., 2020; Wibowo *et al*., 2021] [9, 10]. Sanchez-Cano, and others developed an iron based metal-organic frameworks (MOFs) MIL-88B-$NH_2$ that effectively eliminates chlorite and chlorate from fresh water [Sanchez-Cano, *et al*., 2024] [11].

**Advanced Membrane technologies**

Advancement in membrane technology has emerged as an innovative solutions to address the potential challenges faced in desalination and water purification. Different type of membrane has developed like covalent organic framework membrane, polymeric membranes with integrated nanoparticles, aqua based biomimetic membranes nano-composites, bio-mimetic, composites of thin-film, hybrids, and forward osmosis membranes, that can be used in various industries [Yuan *et al*., 2019; Khadryy *et al*., 2023; Li *et al*., 2019; Foorginezhad *et al*., 2025] [13, 14, 19, 16] Among these the most recent and advanced techniques is Aquaporin-Based Biomimetic Membranes that has the efficiency for enhancing water purification processes. Aquaprotein are the membrane proteins that acts as a channel for the rapid and selective transport of water molecules across the cell membranes [Takata *et al*., 2004] [17]. These Aquaproteins are integrated into polymeric membrane through various fabrication techniques that enhance water purification and are presumed to increase sea-water de-salination by salt rejection. [Habel *et al*., 2015 and Li *et al*., 2019] [18, 19].

**Plasma-Based Water Purification**

Plasma methods are used to degrade the most recalcitrant class of compounds polyfluoroalkyl substances (PFAS) in water. These are difficult to degrade by traditional methods but eco-friendly plasma based method proven to be very helpful. The plasma based process generates reactive oxygen species like hydroxyl radicals, ozone, and UV photons, used for breaking of organic pollutants, and for killing of pathogens. Lewis and others explores a novel plasma based method for degrading Poly- and per-fluoro-alkyl substances also abbreviated as PFAS in water. The non-thermal plasma technology utilizes a reversal vortex gliding arc plasma (GAP) system with air, $N_2$ and $O_2$ gases, for degradation of long chain PFAS. About 90% degradation was achieved in one hour of treatment [Lewis *et al*., 2020] [20]. Palma and other study the breaking of the three namely, perfluorooctanoic acid (PFOA), perfluorohexanoic acid (PFHxA) and pefluorooctanesulfonic acid (PFOS) in different water matrices by non-thermal plasma generator. In this study a high-energy plasma discharges leads to the production of reactive species in the liquid phase (hydroxyl radical, hydrogen peroxide) and in the gas phase (ozone, $NO_x$) that are used for degradation [Palma *et al*., 2021] [20].

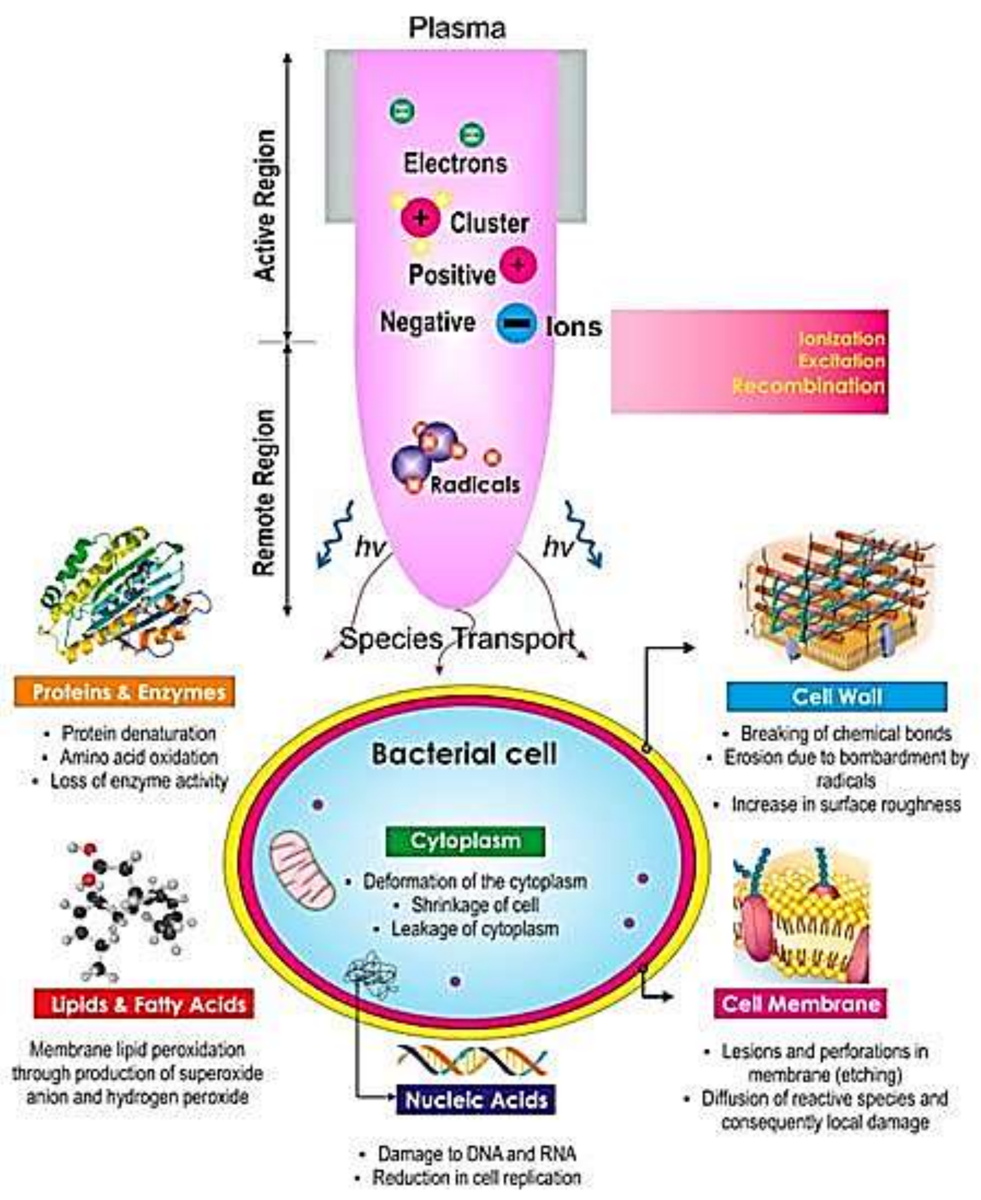


**Fig 1:** Plasma technology water purification. Barjasteh *et al* 2021 [2]

**AI-Driven Smart Water Purification Systems**

The discovery of various Al technologies help in waste water treatment for water quality determination, coagulation/flocculation, disinfection, membrane filtration, desalination, modeling wastewater treatment plants, prediction of membrane fouling, heavy metals removal, and monitoring of biological oxygen demand (BOD) and chemical oxygen demand (COD) levels [Safeer *et al*., 2022] [23]. A review published in *environmental chemistry letters* study the optimisation of pharmaceutical wastewater treatment systems through the application of AI and machine learning. It focusses on biological treatment, disinfection, renewable energy, block chain technology, big data, machine learning algorithms, cyber-physical systems, automated smart grid power distribution networks, and water quality. [Ganthavee & Trzcinski., 2024] [24]. A new process for assessing quality of water using latest artificial intelligence (AI) technologies with integrated sensor system. This whole system has the ability to distinguish among clean-unclean, contaminated-non contaminated, and UV-disinfected-affected water samples, hence detect variations in the quality of $H_2O$. It employs spectroscopic analysis for real-time monitoring applying machine learning algorithms like Random Forest, SVM, and Neural Networks for accurately classify spectral data [Durgun., 2024] [12].

**Microbial Fuel Cells (MFCs) for Water Purification**

Microbial fuels emerged as an innovative solution for the purification of water. In this technology electricity is generated by the metabolic of chemically active bacteria that is used for purifying waste water [Obileke *et al*., 2021]. Recent advancement has taken place to enhance the efficiency of this technology. A study by Bhowmick and others explored the integration of MFC with activated carbon/$TiO_2$ cathodes and membrane bioreactors that enhance pollutant degradation efficiency, and bioelectricity generation [Bhowmick *et al*., 2019] [22].

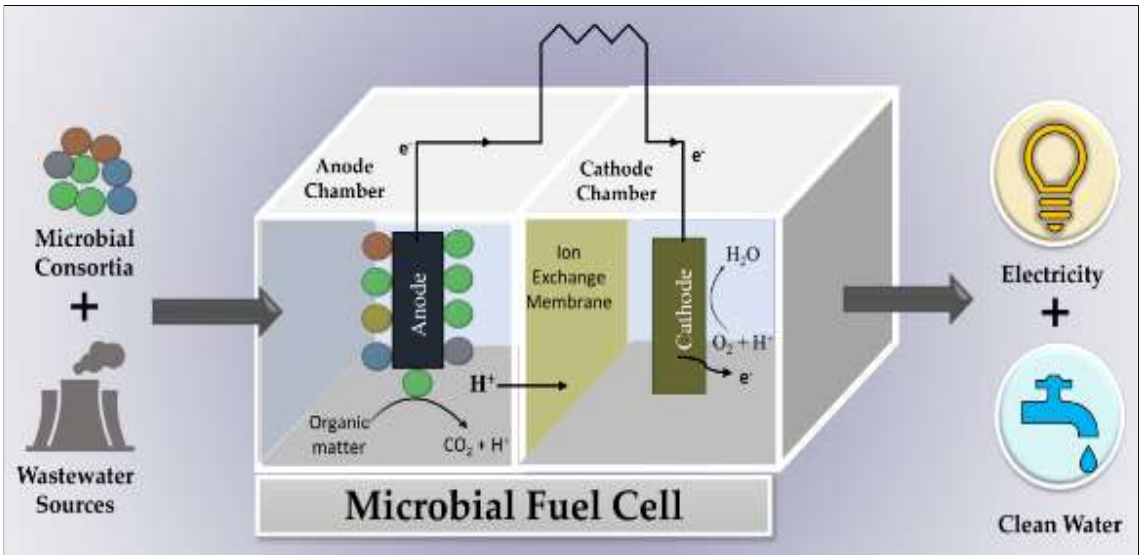


**Fig 2:** Microbial Fuel Cells in Treatment and Product Recovery from Wastewater, Malik, S *et al.* 2023

## Conclusion

Water scarcity and water contamination, are the escalating global crisis caused by rapid population growth, urbanization, and climatic change. Water contamination occurs by releasing heavy metals, dyes, and toxic chemicals from Industrial Waste, Agricultural Runoff, and untreated wastewater. Meanwhile, water scarcity is also continuously alarming due to the depletion of freshwater resources by excessive water use for agricultural, industrial, and domestic purposes. Climatic change further exacerbated this, by altering rainfall and melting of glaciers. Cutting-edge water purification technologies have been developed to mitigate the water crisis problem. These include advanced hybrid oxidation systems that break down the pollutants, Novel filtration and membrane technology, both are promising solutions in microplastic and heavy metal removal, Stubborn pollutants that are difficult to degrade are neutralized by the plasma-based purification technology. Additionally, the most innovative research the Aldriven smart systems found very effective in monitoring the quality of water. Furthermore, Microbial Fuel calls offer a sustainable approach for degradation of pollutants and electricity generation by the chemically active bacteria. The integration, implementation and continuous research in these advanced technologies can be extended further in the future for meeting the requirement of secure water supply.

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