

# Writing Assignment

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Nature-inspired methods of water purification – a literary review

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## **Abstract**

Water is an indispensable component of any form of life on Earth. It is an abundant resource, but due to its potent solvent properties, it often contains contaminants that make it unsuitable for human consumption or even agricultural or industrial use. The most common pollutants include insoluble suspended particles, dissolved organic compounds, toxic metal ions, excess salts, and pathogenic organisms. The expected growth of the human population is associated with increased production of wastewaters and increased demand for clean water. To address the issue of water purification, this literary review provides examples of various water treatment methods. For each method are explained the general operation mechanisms with its' benefits and drawbacks. These methods can be combined in a modular fashion to generate designs of water purification systems. Such designs can be attuned to local environments' specific needs and opportunities, reducing economic and environmental costs and generating additional value in the form of biogas, biomass, fertilizers, or recovering metals.

## **Layman's summary**

Water is essential for all life forms, and it is an abundant resource on Earth's surface, but it can easily get contaminated by dissolving other substances. This contamination can result in water that is unusable for consumption or even technical applications. With more humans living on our planet, the production of wastewater and the demand for clean water will both increase. To address the issue of purifying water, this literary review provides examples of various water treatment methods. For each method are explained the basic working principles, the method's benefits, and its costs. These methods can be combined like modules to help generate designs of water purification systems. Such designs can be specifically attuned to the needs and opportunities of local environments, reducing economic and environmental costs and generating additional value in the form of fuel, fertilizers, or recovered metals.

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# 1 Introduction to water

From a chemical point of view, water is a non-toxic substance composed of two partially positively charged hydrogen atoms bound to a single partially negatively charged oxygen atom, making for a polar molecule. Under normal pressure and room temperature, water occurs as a transparent liquid with a taint of blue color <sup>[1]</sup>. It is abundant in Earth's biosphere and can be found either in its gaseous phase (e.g., clouds, air humidity), liquid phase (e.g., rivers, lakes, oceans), or solid phase (e.g., ice sheets, snow). Due to water's strong polar character, it acts as an excellent solvent for both polar and ionic compounds (e.g., carbon dioxide, sugars, salts). Its unique chemical properties and abundance made it an indispensable part of all known forms of life. Living organisms use water to transport dissolved substances, facilitate chemical reactions, transfer heat, as a structural component, or as a component of their metabolism.

## 1.1 Water as a solvent

Due to water's potent solvent properties, it does not occur in nature in its pure form but instead is mixed with various contaminants at various concentrations. The resulting water mixture may contain too many contaminants for human consumption or even agriculture or industrial applications. Common water contaminants include insoluble particles suspended in it (e.g., clay, oils, biomass), dissolved inorganic compounds (e.g., nitrates, metal ions), dissolved organic compounds (e.g., pharmaceuticals, dyes, pesticides), pathogenic microorganisms (bacteria, fungi, protozoa, viruses) <sup>[2]</sup>.

Apart from the character of contaminants present in water, their concentration plays a pivotal role in determining the usability of a water source. The most abundant contaminant is dissolved salts, with 97.5% of the total global water being saline (e.g., oceans, seas, saline lakes) and only 2.5% comprising freshwater. From this 2.5% of total global water, 30.1% represents groundwater, and 68.7% is stored in glaciers and ice caps. Rivers and lakes, which are among the most used freshwater sources, comprise less than 1/15 000<sup>th</sup> of total global water volume <sup>[3]</sup>.

## 1.2 Common uses of water

According to the Centre for Disease Control and Prevention [CDC], the most common uses of the world's water resources include drinking and household needs, recreation, industry, agriculture, and energy production <sup>[4]</sup>. The major portion (69%) of freshwater used by humans is used for agriculture and food production, and from the year 2012 to 2050, the demand for freshwater by these sectors is expected to rise by 50% due to population growth. The use of freshwater sources by agriculture and food production is often associated with environmental issues such as pollution, depletion of aquifers and rivers, and degradation of natural habitats. Industry and energy production together account for around 19% of the total freshwater used <sup>[5]</sup>. The remaining freshwater is primarily utilized for direct consumption or recreational activities. In the industrial sector, water can be used for fabricating, processing, washing, diluting, cooling, or product transportation <sup>[6]</sup>. Each of these uses requires different purity criteria of the water used. For example, a purity criterion required in hydroelectric powerplants to spin turbines is for the water to be free of solid particles or larger aquatic organisms that might damage the turbines' blades. In the case of agriculture, the water used for irrigation purposes must pass criteria addressing the concentration of salts and their toxicity (e.g., water salinity, sodium adsorption ratio, residual sodium carbonates, and ion toxicity) <sup>[7]</sup>. The strictest purity criteria are applied in the case of water used for consumption and sanitation, where inside the whole European Union (Directive 2020/2184), such water must be regularly tested for at least 48 specific parameters, including microbial

(E. coli, legionella), chemical pollutants (lead, arsenic) and other indicators of water quality (e.g., pH, turbidity, salinity) <sup>[8]</sup>.

### **1.3 Nature-inspired design**

Conventional sustainable-design practices aim to boost the efficiency of specific parameters of existing products and services (eco-efficiency). Still, such adjustments fail to improve the overall environmental impact of the design. Nature-inspired design strategies such as Biomimicry, Cradle-to-Cradle, and Natural Capitalism introduce a more systemic view on product or service design <sup>[9]</sup>. The nature-inspired design handbook proposes six basic principles for creating a product or service with a positive environmental impact. These include treating waste as a resource, using renewable energy sources, being locally attuned and responsive, adapting to changing conditions, integrating development with growth, and being resource-efficient <sup>[10]</sup>. These six principles summarize how nature generates its designs and thus provide inspiration to human designing efforts.

### **1.4 Scope of this report**

The United Nations has addressed 17 Sustainable Development Goals, stating clean water and sanitation (Goal 6) as one of the primary goals towards global sustainability. Namely, by 2030, the global water quality must be improved by reducing pollution, eliminating dumping, minimizing the release of hazardous chemicals and materials, halving the proportion of untreated wastewater, and substantially increasing recycling and safe re-use globally <sup>[11]</sup>.

This literary review aims to provide the reader with essential information for understanding water purity and summarizes water purification methods with potential for integration into nature-inspired water purification systems.

## 2 Methods of water purification

From the earliest days of human civilization, humanity required a steady supply of water, which was not always available in a clean-enough state. For this reason, humans developed numerous methods to treat water by removing or neutralizing different types of contaminants. The improvement in water quality will depend on the character of the purification methods applied. These methods are often used in combination with each other, and they rely on physical, chemical, or biological mechanisms to achieve an optimal water purity improvement. Water purification methods can be divided into primary, secondary, and tertiary methods. Primary water treatments, also known as pre-treatments, include processes to remove bulk matter from the treated water and reduce its turbidity. Secondary water treatment methods aim to removing fine particles suspended in the water and dissolved organic compounds and toxic metals. In general, secondary treatments produce water suitable for industrial or agricultural applications but not for direct consumption as it may still contain harmful microorganisms. Once the turbidity, organic pollutants, and toxic metals are sufficiently reduced, the treated water needs to be disinfected before being used for consumption or recreation.

### 2.1 Primary water purification methods

#### 2.1.1 Screening

A standard water purification pre-treatment step includes the removal of larger debris (e.g., plant matter, aquatic organisms, plastic waste) with the help of simple sieves or woven fabric filters. The purpose of this step is to protect the more delicate components of the purification system from mechanical damage or clogging, reducing both operation and maintenance costs<sup>[12]</sup>. Screening does not remove small particulate matter, pathogens, or soluble contaminants, so the effluent water often requires further purification steps.

#### 2.1.2 Sedimentation

Another pre-treatment method designed to reduce the number of contaminants suspended in water is called sedimentation. In slow-flowing waters, gravity concentrates settable particles (e.g., sand, silt, or clay) on the bottom of the sedimentation tank due to the difference in densities between the particles and water. The effluent water is collected on the outer rim of the tank by overflowing.

The low flow velocity required for the proper functioning of sedimentation tanks may deem them unsuitable for operations where larger volumes of water need to be processed, and the available space is limited. Sedimentation does not remove all suspended particles and pathogens and does not affect water-soluble pollutants<sup>[13]</sup>.

#### 2.1.3 Coagulation and flocculation

Materials in water that are smaller than 100  $\mu\text{m}$  (e.g., colloids and simple ions) have relatively large surface areas compared to their mass, making them more affected by surface phenomena (e.g., adsorption, solvation) rather than gravity (e.g., sedimentation). This means that colloidal and smaller particles can stay suspended in water practically indefinitely. Coagulation refers to the destabilization of the otherwise stably dispersed state of the matter, resulting in precipitation and subsequent aggregation of the precipitate, also known as flocculation<sup>[14, 15]</sup>. Coagulation and flocculation are suitable pre-treatment methods for combination with sedimentation. For the initiation of coagulation is required a coagulating agent, also known as a coagulant. The most common coagulants include

compounds of aluminum or iron, which are either added (e.g., chemical coagulation) or generated inside the treated water from raw metal (e.g., electrocoagulation) <sup>[16]</sup>.

Chemical coagulation in comparison to electrocoagulation produces more sludge that needs to be processed and operates at a narrower range of pH, possibly requiring its adjustment in the treated water. Nonetheless, chemical coagulation is generally more straightforward and requires less energy to use.

Despite being effective at reducing all types of water pollutants, coagulation processes utilizing metal-based coagulants may negatively affect human health and aquatic ecosystems while producing non-biodegradable sludge <sup>[17]</sup>. A prospective solution is using natural substances for coagulation and flocculation <sup>[17, 18]</sup>. It was observed that dried ground seeds of *Moringa oleifera* and mucilage obtained from *Opuntia ficus-indica* or *Aloe vera* effectively reduced treated wastewater's turbidity and chemical oxygen demand. These bio coagulants could remove 30-60% of the treated water's turbidity and chemical oxygen demand. These results indicate that bio coagulants cannot yet fully replace conventional metal-based coagulants, achieving around 90% reduction in the treated water's turbidity and chemical oxygen demand. However, they still may have potential in treating freshwater with low turbidity or as a supplement to conventional coagulants, reducing their required dosage <sup>[18]</sup>.

## 2.2 Secondary water purification methods

### 2.2.1 Rapid sand filtration

A typical rapid sand filter [RSF] is composed of a 1.5 to 2.5 meters tall container filled with sand particles through which is vertically down-wards flown the treated water. The top of the sand filter captures particles larger than the pore size between the sand grains, while the remaining depth of the filter captures smaller particles by adsorption to the sand grains and capture in the grain interspace <sup>[19]</sup>. The filters must be cleaned periodically every 24 – 72 hours by simply reversing the water flow (backwashing) and then disposing of the contaminated water <sup>[20]</sup>. RSF were observed to be effective at removing fecal bacteria and significantly reducing the turbidity of the treated water but were not effective in eliminating excess dissolved salts. RSFs are commonly used as a pre-treatment step in desalination plants <sup>[21, 22]</sup>. If combined with proper pre-treatment and disinfection methods, RSF can provide safe drinking water <sup>[20]</sup>.

Rapid sand filters are generally referred to as physical filters, but research has revealed that microbial communities often develop within the filter and provide additional purification benefits. A study from 2012 has shown that during an 85-day long maturation period, a newly operating rapid sand filtration system has developed a diverse microbial community that improved the removal of organic pollutants (e.g., chlorophyll a, transparent exopolymer particles, and total organic carbon) from the treated water <sup>[22]</sup>. Another study has investigated the effects of adding manganese-oxidizing bacteria into a quartz-sand filter on removing iron, manganese, arsenic, and antimony from the treated water. Results have shown that the manganese-oxidizing bacteria could decrease the levels of the four metal ions in the effluent water while developing stable microbial communities in the filtration system <sup>[23]</sup>. In 2014 a study showed that ammonium-oxidizing bacteria that naturally colonize the filters could remove ammonium and nitrites to safe levels by converting them to less toxic nitrate. The study has not indicated that the overall nitrogen present in the water was reduced <sup>[24]</sup>. In 2014, researchers observed in Danish waterworks that the microbial communities present in the rapid sand filters could reduce the concentration of commonly used pesticides (e.g., methylchlorophenoxypropionate, bentazone, glyphosate, and p-nitrophenol). The degree of the observed microbial degradation was strongly dependent on the oxygen levels present in the filtered water <sup>[25]</sup>. Lastly, a study from 2003 observed that a moving bed sand filter inoculated with heavy metal absorbing/precipitating bacteria could remove



metals from the filtered water with high efficiency. Specifically, it was observed that zinc and copper were removed with the efficiency of 95 – 100%, cobalt with 80 – 90%, iron with 60 – 80 %, and other metals like aluminum, silver, chromium, arsenic, and selenium with above 80% efficiencies. The generated microbial biomass was periodically removed, and over 10% of its dried mass constituted the retained metals, making it a prospective source for metallurgic industries <sup>[26]</sup>.

Research into RSF shows to be suitable for large-scale applications due to high filtration flow rates, the robustness of the system, and relatively compact size. Colonization of the large surface area of the filter sand grains with specific bacteria, also known as bioaugmentation, can provide additional remediation benefits (e.g., removal of organic carbon, pesticides, heavy metals, or neutralization of ammonia and nitrite) for the system with low added costs and potential to generate resources for other industries.

### **2.2.2 Membrane filtration**

Membrane filtration is a relatively new process that can potentially remove multiple pollutants in a single step with relatively low energy requirements. An ideal membrane is a physical porous barrier that only allows particles smaller than the diameter of the pores to pass through, resulting in the separation of purified effluent from the source water. Membrane filtration can be divided into four categories based on the size of particles that can be retained, namely microfiltration, ultrafiltration, nanofiltration, and reverse osmosis <sup>[27]</sup>.

Microfiltration membranes are designed to retain particles larger than 100 nm, such as bacteria or larger polymers. They require low operating pressures between 0.5 and 1 bar. Ultrafiltration membranes can capture particles larger than 10 nm, such as viruses or proteins, and the operation pressures are also relatively low, between 1 to 10 bar. Nanofiltration membranes can filter out particles larger than 1 nm, such as pesticides and larger ions, but this process requires much higher pressures, up to 70 bar. Reverse osmosis is used to remove particles larger than 0.1 nm, making it effective in removing fluoride ions <sup>[28]</sup>. Reverse osmosis filters operate at pressures up to 100 bar.

The membranes used for filtration may be expensive, made from non-renewable materials, and require regular chemical cleaning to prevent irreversible membrane fouling, rendering the membrane permanently damaged. Micro- and ultrafiltration systems can operate at low pressures, but nanofiltration and reverse osmosis are highly energy demanding. A significant benefit of this system is that it allows for simple collection of the concentrated sludge, which holds potential for nutrient, energy, or chemical recovery <sup>[11]</sup>.

### **2.2.3 Biological treatments**

Biological treatment commonly refers to using living organisms, such as bacteria, fungi, or plants, for pollutant reduction in the treated water. The most widely used biological methods include microbial digestion, mycoremediation, and phytoremediation <sup>[29]</sup>. Biological treatments provide a relatively cheap way of eliminating a wide range of organic compounds or toxic metals in large quantities. However, the main drawbacks of these treatments are their rather long treatment times ranging from days to months, the inability to remove excess salts, and the necessity to culture the organisms used for the treatment <sup>[29]</sup>.

### 2.2.3.1 Microbiological digestion

The use of microorganisms has found great application in wastewater purification. Still, their use was also observed in the treatment of freshwater using slow sand filters (see section 2.3.1) <sup>[30]</sup> or bio augmented rapid sand filters (see section 2.2.1) <sup>[23, 26]</sup>. Microbial cultures are often used as a secondary treatment, specified for eliminating organic pollutants <sup>[22, 24, 25, 31]</sup> and toxic metal ions <sup>[23, 26]</sup>.

Microbiological systems are sensitive to extreme variations in operating conditions, and achieving optimal performance in water purification requires proper maintenance of temperature, water pH, nutrient content, oxygen levels, and low levels of toxic substances <sup>[29]</sup>. Microbial treatments are often categorized according to the microorganism's oxygen demand into aerobic and anaerobic processes.

Anaerobic treatments operate in the absence of added oxygen and thus are characterized by biogas production <sup>[32]</sup>. Biogas is generally composed of around 50% methane (CH<sub>4</sub>), 40% carbon dioxide (CO<sub>2</sub>), and trace amounts of hydrogen sulfide (H<sub>2</sub>S), nitrogen (N<sub>2</sub>), hydrogen (H<sub>2</sub>), carbon monoxide (CO), and oxygen (O<sub>2</sub>) <sup>[33]</sup>. This means that biogas is flammable (CH<sub>4</sub> and H<sub>2</sub>), and potentially poisonous (CO<sub>2</sub>, CO, and H<sub>2</sub>S), and corrosive (H<sub>2</sub>S), and it has a potent greenhouse effect if released into the atmosphere because the main two constituents include CH<sub>4</sub> and CO<sub>2</sub>. Compared to CO<sub>2</sub>, CH<sub>4</sub> has about 28-times more potent greenhouse effect on a 100-year timescale <sup>[34]</sup>. Fortunately, biogas from anaerobic digestors is often captured and used as a renewable energy resource to generate heat and electricity <sup>[35]</sup>, resulting in the conversion of CH<sub>4</sub> into the much less harmful CO<sub>2</sub>. Apart from the equipment for biogas processing, anaerobic systems are generally smaller, simpler, and have lower operating costs but require greater initial investment than aerobic treatments. Anaerobic systems can treat highly polluted waters, with chemical oxygen demand over 1g of O<sub>2</sub> per one liter of treated water. They respond quickly to adding new substrate after a long shut-down period, allowing for seasonal operation. A possible drawback of anaerobic treatments is the lower level of biological degradation achieved and the different profile of substances that can be degraded compared to aerobic treatment <sup>[32, 36]</sup>.

Aerobic treatments are performed by adding oxygen into the treated water (e.g., algae or aeration), allowing for a greater degree of biological degradation resulting in the metabolic production of CO<sub>2</sub> and water. These systems require more energy and space to operate while generating 6-8 times more sludge, which must be periodically removed and treated <sup>[29, 36]</sup>. Since aerobic treatments produce more biomass in sludge, nutrient levels need to be monitored, possibly requiring supplementation. Additionally, aerobic systems are not good at processing wastewaters with chemical oxygen demand over 1 g of O<sub>2</sub> per liter, and dilution may be necessary <sup>[32]</sup>. To achieve maximal degradation of the broadest range of organic compounds, aerobic followed by anaerobic treatment is often applied <sup>[31, 32, 37]</sup>.

### 2.2.3.2 Mycoremediation

Mycoremediation refers to using fungi, or specifically the mycelia, for degradation or sequestering of contaminants. Mycelia are fiber-like, vegetative parts of fungi that secrete lytic enzymes and acids to decompose surrounding organic matter <sup>[29]</sup>. Fungi are natural decomposers of organic compounds. They evolved enzymes and methods to degrade a wide range of substances, providing a comparatively cost-effective and environmentally friendly way for removing pollutants. One of the issues with using mycelia is to select an appropriate fungus for the contaminant that needs to be removed. Different fungal species have been observed to degrade or neutralize polycyclic aromatic hydrocarbons, heavy metals, dyes, pesticides, antibiotics, pharmaceuticals, phthalates, cyanotoxins, algal blooms, and detergents. Still, all the pollutants cannot be treated with a single fungal species <sup>[38, 39]</sup>. It was observed that fungi specialized in the degradation of wood are often well suited for the degradation of complex aromatic hydrocarbons and chlorinated organic molecules <sup>[29]</sup>. Compared to bacterial treatments, fungi can process a broader range of pollutants and are more resistant to varying operating conditions, making

mycoremediation systems more robust and better suited for working under natural conditions [38]. In some fungi, the treated pollutant could not be completely degraded by the fungus alone, and complete degradation required the presence of indigenous soil bacteria [40], or other fungal species [41], suggesting possible inter-species synergic effects in pollutant processing. Apart from being used in bioreactors, fungi and specifically mycorrhizal fungi, can be inoculated directly into the soil. Such bioaugmentation was observed to improve physio-chemical properties and enzyme activities in contaminated soils or soils irrigated with contaminated water, resulting in greater crop yields [42, 43]. The main drawback of using mycoremediation in water purification is the long operation times, ranging from days to months.

### 2.2.3.3 Phytoremediation

Phytoremediation is a process that utilizes plants to remove or neutralize pollutants, as they can absorb metal ions even at low concentrations. The main advantages of plant-based purification systems are their economic feasibility, simple installation, and management, making phytoremediation ideal for application in fields for purification of soil and groundwater [43]. As plants grow, they extend their root systems through soil or another substrate in search of nutrients. During their development, plant roots establish a microbially dense zone called the rhizosphere, composed of diverse microorganisms, such as bacteria, protozoa, or fungi [44]. In collaboration with these microbes, the plants stabilize soil and improve its physio-chemical properties, resulting in greater field fertility and groundwater quality [45].

Certain plants have found application in treating soils contaminated with heavy metals. They can accumulate these elements in their body parts (e.g., hyperaccumulators), allowing for simple and affordable removal of toxic metals from the soil and groundwater [43]. By harvesting such plants, metals can be effectively removed from the environment with the possibility of using the harvested biomass in energy production and metal recovery [46].

Aquatic plants (e.g., *Salvinia molesta* or *Pistia stratiotes*) have found wide application in the treatment of agricultural, domestic, and industrial wastewaters for their ability to accumulate both inorganic and organic pollutants (e.g., heavy metals or pharmaceuticals). The main drawback of using aquatic plants for bioremediation is that they can only treat relatively shallow waters but readily use ammonium and nitrate ions, effectively removing excess nitrogen compounds from the treated water [47].

### 2.2.4 Adsorption using porous materials

Porous materials have unique properties due to the large surface-to-volume ratio, resulting in light-weight materials, small in volume, and a large surface where contaminants can be neutralized. It was observed that an adsorbent mixture composed of porous ceramics made from recycled glass bottles (80 mass percent) and charcoal bamboo (20 mass percent) could be used as a microbe-carrying substrate. Such bio augmented porous material could remove around 97% of biodegradable contaminants in 5 days of re-circulation in a tank [48].

Adsorption using powdered activated carbon has shown greater effectiveness at removing small molecular weight organic compounds, which is complementary to the coagulation treatment, which delivers greater effectiveness on higher molecular weight compounds [49].

A study from 2014 observed that activated carbon was effective at removing heavy metals from treated water in 24 hours. The results indicate that at a concentration of 30 ppm, cadmium, lead, chromium, nickel, and zinc were removed with efficiencies of 86%, 83%, 51%, 90%, 84%, respectively. The study showed that activated carbon exhibits significantly better efficiencies at removing heavy metals from more diluted samples, indicating that this treatment is better suited for water that has already been pre-treated. Additionally, the study concluded that a composite made from activated carbon and silica nanoparticles (3:2) showed the greatest removal efficiencies for treating nickel,

followed by activated carbon and silica nanoparticles <sup>[50]</sup>. This conclusion is in line with another study, which observed improved adsorption properties of activated carbon treated with oxidizing agents (e.g., hydrogen peroxide, nitric acid, or hypochlorous acid). This treatment increased the number of negatively charged functional groups (e.g., carboxyl-, alcohol-, nitro-, or keto- groups) in the porous structure, giving more opportunities for the positively charged metal ion to interact with the adsorbent via electrostatic interactions and Van der Waals forces. It was also suggested that the unique structure of activated carbon, which is mainly composed of distorted graphene sheets, may contribute to the formation of metal complexes by interactions with the delocalized  $\pi$ -electrons present in the graphene structures <sup>[51]</sup>. An added benefit of using activated carbon with additional negatively charged functional groups is the presence of both hydrophobic and hydrophilic sites, allowing for the removal of both types of pollutants.

### **2.2.5 Electrochemical treatments**

Electrochemical treatment involves the application of electricity to induce chemical reactions on electrodes immersed in the treated solution. These processes effectively neutralize certain metals (e.g., chromium) at low operation costs <sup>[52]</sup>. A recent article from 2018 presented an innovative method that can remove mercury from water solutions in a wide range of pH and both at high and low concentrations of the metal. This method uses thin platinum plate cathodes (100 nm) and electric potential, which causes mercury to form a stable alloy (PtHg<sub>4</sub>) with the platinum. The layer of platinum-mercury alloy (PtHg<sub>4</sub>) can grow in thickness up to 750 nm, and the overall removal capacity of the cathodes is over 88g of mercury per cm<sup>3</sup> of platinum. This method was able to remove over 90% of mercury present in 6 days. The study also investigated cathode regeneration, as the cathodes were made from precious metal. The results showed that over 95% of the captured mercury was released from the platinum plates in 10 hours, and the cathodes were successfully re-used in further water treatment. This process allows for sustainable removal of mercury from water across a broad range of operating conditions and provides for retrieving mercury and safe storage or re-use <sup>[53]</sup>.

Electrochemical reactions can also fully mineralize any organic compounds, in operation times ranging from minutes to hours. This process generally requires little energy and no added chemical oxidants, as only electricity is consumed during the reaction <sup>[54, 55]</sup>. The main drawbacks of this technology are the potentially very expensive equipment, need for skilled operators.

## **2.3 Tertiary water purification methods**

### **2.3.1 Slow sand filters**

Slow sand filters primarily produce potable water from surface water with low turbidity levels and other pollutants (e.g., organic matter, pesticides, fertilizers, heavy metals). These filters are composed of a 1 to 2 meters tall vertical bed filled with sand on the top and gravel on the bottom. During the first 30 days of usage, the sand surface of the filter develops a 5-10 cm thick, transparent biolayer composed of aerobic microorganisms and biofilms. This newly created layer increases the pathogen filtration efficiency of the filter from an initial 30-70%, attributed to mechanical trapping and adsorption, to a maximum of 99% <sup>[30]</sup>. Once the biolayer becomes too thick and excessively blocks water flow, the top few centimeters of this layer are scraped off to re-establish proper water flow.

The main advantages of this water purification system are the ability to produce potable water with low requirements for construction, maintenance, and scaling up, which makes them prospective for domestic use or use in remote areas <sup>[56]</sup>.

To produce potable water, slow sand filters require relatively clean source water, with low turbidity and low levels of pollutants. These filters are also incapable of removing excess salts from the treated

water, and therefore they are not applicable for the purification of saline water. Slow sand filters have limited filtration rates that depend directly on the width area of the filter, which means larger systems require larger land areas for their operation <sup>[57]</sup>.

### **2.3.2 Boiling**

The use of heat for disinfection is one of the oldest water treatment methods. According to the CDC, bringing clear water to a rolling boil for one minute under normal pressure is sufficient to neutralize pathogens that might be present in it <sup>[58]</sup>. The excess heat causes denaturation of proteins and DNA, resulting in the inactivation of any pathogen (e.g., viruses, bacteria, fungi). This method can be applied in any climate and at any time, making its use extremely versatile. The main drawback of boiling water for disinfection is the high energy demand for this process since water has a very high specific heat capacity. This drawback can be solved by using solar energy for heat generation through solar kettles. Solar kettles are composed of a water-containing vessel placed in the focal point of a large parabolic mirror, which concentrates solar radiation onto the kettle, effectively bringing it to boil <sup>[59]</sup>.

### **2.3.3 Solar disinfection**

Solar disinfection is a method developed in 1980 for inexpensive disinfection of low turbidity water. This process uses sealed, transparent containers filled with treated water placed in direct sunlight for 6 to 48 hours <sup>[60]</sup>. This method effectively kills pathogenic microorganisms through the combined action of ultraviolet [UV] light and elevated temperatures of the treated water. The UV light can penetrate pathogenic organisms, directly damaging their DNA and structural components while generating reactive oxygen species that further damage the microbes <sup>[61]</sup>. For solar disinfection, poly ethyl terephthalate [PET] plastic bottles are often used as they are transparent to the UV radiation required for this process. The use of plastic bottles may introduce secondary contamination caused by the degradation of the plastic and leaching of additives. The leaching of secondary contaminants from the plastic into the treated water does not occur at very high rates, but it may be problematic for long-term usage <sup>[62]</sup>. An alternative to the use of PET bottles is the use of glass bottles. Research has shown that ordinary glass bottles used for beverages provide similar levels of transmittance of UV light under operating conditions as PET bottles. The use of window glass should be avoided as this type of glass is generally opaque to UV light <sup>[63]</sup>. The main drawback of this method is the high requirements for surfaces exposed to sunlight and potentially long operating times <sup>[60]</sup>. Still, if appropriately used, the treated water will remain disinfected as long as the bottles are sealed. The reliance on direct sunlight makes this method unsuitable for areas with limited or low-intensity sunlight.

### **2.3.4 Electroporation**

Electroporation is a phenomenon that occurs when microorganisms are exposed to static electricity, which makes their membranes leaky <sup>[64]</sup>. The increased membrane permeability results in the inactivation of the pathogen even without the use of chemical disinfectants that generate toxic disinfection byproducts. A study from 2014 has proposed using a copper oxide nanowire mesh as an electrode creating the static charge. The nanowire structure significantly amplifies the strength of the electric field, resulting in minimal energy consumption that can be supplied by conventional batteries or powered by mechanical motion. The nanowire structure was created through a simple one-step process, where copper mesh was oxidized on air at 500 C°. The system could completely inactivate the tested bacteria and viruses with an extremely high flow rate of almost 1 liter per second per meter squared of the copper oxide nanowire mesh. The copper leaching from the mesh was observed to be minimal <sup>[65]</sup>.

### 2.3.5 Ultraviolet irradiation

Ultraviolet germicidal irradiation is a commonly used method for inactivating pathogens causing water-borne diseases, including (oo)cysts of *Cryptosporidium* and *Giardia* [66]. The process involves exposing the treated water to intense UV light of the right wavelength, which degrades the molecular structures of the pathogens, resulting in their inactivation. The main benefits of this method are the low cost per liter of treated water, short operation times ranging from seconds to minutes, and much lower amounts of disinfection byproducts commonly associated with chemical treatments [67, 68]. The ultraviolet light used for disinfection is also harmful to humans, so exposure to it should be avoided [69]. UV light can only inactivate pathogens directly exposed to it. Thus, it is not suitable for turbid waters or containers that include shaded parts.

### 2.3.6 Ozonation

Ozone is a highly reactive and unstable gas produced from oxygen. Ozone has more potent oxidizing properties than conventionally used chlorine. This property of ozone accounts for its potent microbial activity, making it suitable even against protozoic pathogens, which may be resistant to conventional disinfectants. Since ozone is highly unstable, it has to be produced on-site using electricity. The high reactivity of ozone is also responsible for creating disinfection byproducts, namely bromate, which is known as a mutagen and carcinogen [70, 71]. Ozonation is also a relatively expensive and energy-demanding process. On the other hand, research has suggested it may hold potential at mineralizing organic micropollutants, especially when combined with hydrogen peroxide, UV irradiation, or metal catalysts (e.g.,  $\text{MnO}_2$ ,  $\text{Al}_2\text{O}_3$ ,  $\text{Fe}_2\text{O}_3$ ) [72, 73].

### 3 Summary of the findings

The general process of purifying water starts with the removal of insoluble matter suspended in the treated water. Next are removed or neutralized dissolved organic pollutants (e.g., detergents, dyes, pharmaceuticals) and metal ions (e.g., aluminum, arsenic, iron, manganese). The final step in purifying water is the neutralization of any active or dormant pathogenic organisms.

#### 3.1 Removal of insoluble suspended matter

Larger debris can be easily removed by screening, using sieves or woven fabrics. The process of screening decreases the load on downstream operations and protects sensitive equipment from damage and clogging.

Sedimentation allows for a low-cost and straightforward reduction in the concentration of insoluble particles suspended in water. This process has minimal energy requirements, but it does not work on particles smaller than 100  $\mu\text{m}$ , as they are more affected by surface phenomena than gravity. Sedimentation can be performed either continuously or in batches.

Coagulation and flocculation are effective in reducing the turbidity of the treated water and some dissolved contaminants. These processes can be performed in batches or continuously. Conventional metal-based coagulants introduce secondary contamination in the treated water as well as contaminating the sludge. The issue of metal contamination can be mitigated by using natural substances as coagulating and flocculating agents. Examples of such substances include processed seeds of *Moringa olifera*, dried mucilage from *Opuntia ficus-indica*, or fresh mucilage from *Aloe vera*. These three bio coagulants are less effective than metal-based coagulants, but they may be combined with lower doses of conventional coagulants for an optimal result.

Rapid sand filters are highly efficient at removing suspended particles and microorganisms from water, and these filters operate continuously and can be easily cleaned by reversing the flow of water. An added benefit of RSFs is that they can be inoculated with microbial cultures that help eliminate organic pollutants or metal ions.

Membrane filtration systems using microfiltration membranes can remove bacteria or larger pathogens at operating pressures of up to 1 bar, while ultrafiltration membranes can remove viruses and proteins at operating pressures of up to 10 bar. Membrane filtration provides a simple way for the collection of concentrated sludge and its utilization in chemical, energy, or nutrient recovery. Membrane filters are often expensive, made from non-renewable materials, and they require periodic chemical cleaning to prevent permanent damage to the filter.

#### 3.2 Removal of dissolved pollutants

Biological treatments, such as bacterial digestion, mycoremediation, and phytoremediation, can remove bio-degradable pollutants and specific metal ions from the treated water. Biological systems generally have low energy requirements and generate resources such as biogas, biomass, or sludge, which can be used for chemical, energy, or nutrient recovery. Biological treatments tend to be effective only on a narrow range of pollutants, so they need to be tailored to specific local needs. Synergic interactions in pollutant removal were observed between various bacterial, fungal, and plant species, indicating that complex consortia of organisms may remove a broader range of pollutants with lower costs.

Membrane filtration systems using nanofiltration membranes can remove substances such as micropollutants and larger ions. Using reverse osmosis membranes can effectively remove any ions, including fluoride, from the treated water. Both nanofiltration and reverse osmosis require high

operating pressures of up to 70 and 100 bar, respectively and use expensive membranes made from non-renewable materials. The water treated by nanofiltration or reverse osmosis needs to be sufficiently purified to prevent excessive membrane fouling.

Highly porous materials such as activated carbon and silica nanoparticles have effectively reduced the concentration of toxic metal ions in treated water. Such treatments often require little energy and use natural materials that can be locally produced. Activated carbon was also shown to be effective in removing low molecular weight organic compounds. A highly porous material made from recycled glass bottles and charcoal is well suited as a supporting medium for microbial cultures degrading organic pollutants.

Electrochemical treatments are very effective at removing metal ions and mineralizing organic pollutants. Still, they need to be tailored for a specific pollutant or mixture of pollutants that are to be treated. These processes have relatively low operating costs but often use expensive or exotic materials in the equipment components. In the case of removing metal ions from the treated water, electrochemical reactions enable recovery of the extracted metals from the treated water at low operating costs and the possibility of metal recovery. Operating times in electrochemical treatments can range from minutes to days.

### **3.3 Neutralization of pathogenic microorganisms**

Slow sand filtration is a low-cost system for the preparation of drinking water from low-turbidity freshwater. The system has relatively low filtration rates but can be operated continuously and easily scalable from domestic to municipal use.

Boiling is a fast, simple, and versatile method for effective neutralization of all pathogens without creating toxic disinfection byproducts. Still, it is an energy-intensive process performed in batches. A possible alternative is the use of freely available heat sources, such as in the case of solar kettles.

Solar disinfection utilizes the microbicidal effects of solar radiation and heat to disinfect water in closed transparent containers. This method is straightforward and requires minimal investments, but it has relatively long operation times (6-48 hours), requires water of low turbidity, and is performed in batches. Solar disinfection is not suitable for climates with limited sunlight, and the use of window glass should be avoided as it is opaque to UV radiation.

A more versatile alternative to solar disinfection of water is the use of microbicidal UV lamps. This technology has minimal investment and operation costs but needs a careful operation as the emitted light is harmful to humans. Treatment with UV light does not require any chemical additives and produces much lower levels of disinfection byproducts when compared to chemical disinfection. It is performed in batches but only requires seconds to minutes for pathogen neutralization. This method is only suitable for low-turbidity waters.

Electroporation using static electricity and copper oxide nanowire mesh is a relatively inexpensive experimental method for continuous water disinfection with minimal energy requirements and high flow rates. It does not require any chemical additives and produces no disinfection byproducts.

Ozone treatment of water effectively destroys all types of pathogens, and it uses a renewable resource for disinfection. On the other hand, ozone treatment is a relatively expensive and energy-demanding method that can produce harmful disinfection byproducts, such as bromate.



## **4 Conclusion**

This review presented numerous processes used during water purification, including pre-treatments and disinfection procedures. In proper combination, the given processes can purify even heavily polluted waters (e.g., industrial or domestic wastewaters) and achieve satisfactory water purity levels for human consumption. The highly diverse methods of water purification are presented in a modular fashion that allows for constructing water purification systems tailored to the specific needs and opportunities of local environments. As the technological means for proper water treatment are already available, the next step in attaining a globally sustainable clean water supply is to apply these technologies in systemic designs that tackle more than just the problem of water purity alone. Such designs should rely on renewable energy sources, process resources in closed loops.

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