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Water pollution and advanced water treatment technologies

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Definitions:

- Water treatment – Treating wastewater to make it suitable for reuse, using chemical, physical, or biological methods.
- Advanced oxidation processes (AOPs) – Processes that involve generation of oxidising species to chemically destroy pollutants.
- Micropollutants – Water pollutants with concentrations of several ng/L to µg/L, usually pharmaceuticals, personal care products, pesticides and herbicides.
- Microplastics – Pieces of plastics with length less than 5 mm, these are emerging water pollutants in urban settings.

Keywords

Water treatment, Advanced oxidation processes (AOPs), Membrane based methods, Photocatalysis, SDG6

Synonyms

Wastewater processing, wastewater recycling

Introduction

The demand for safe potable water is growing exponentially due to the rapid growth of the global population. The United Nations sustainable development goal (SDG) 6 has set the target to provide clean water access to everyone by 2030. (UN, 2018) However, supplying clean water to the population that is currently deprived of access to safe potable water remains a global challenge. Moreover, existing freshwater resources are under increasing threat of pollution caused by industrialisation and intensive agriculture, which have expanded to satisfy the needs of the growing population.(UN, 2018) Additional issues are emerging as a result of climate change, e.g. climate change has triggered severe and intense drought conditions in some parts of the world. (Huber, 2018; WWF, 2019) The rise in atmospheric temperatures caused by climate change is also resulting in accelerated demand for drinking water in urban settlements, even within the population that already has access to clean and safe drinking water. (Brears, 2020a) Simultaneously, frequent floods are occurring in some parts of the world, which disturb freshwater ecosystems. (Talbot et al., 2018)

Water demand is mainly influenced by five key factors: population growth and migration, industrialisation, agriculture, changing lifestyle, and climate change, as shown in Figure 1. These factors are inter-related. In urban areas, high population density and industrial pollution present major challenges. In rural areas, the key driver of water demand is agriculture, but access to safe drinking water also remains a challenge. (MacAllister et al., 2020) According to the United Nations Department of Economic and Social Affairs (UN-DESA), 55% of the world's population was urban in 2018, and the urban population is anticipated to grow to 68% by 2050, with almost 90% of this increase predicted to be in Asia and Africa. (UN-DESA, 2018) Urbanisation accelerates water demand and contributes more to water pollution compared to rural regions. (McGrane, 2016)

The overall demand for clean water is already higher than usable clean water reserves across the globe. (FAO, 2021) This is compounded by the increase in drought conditions, which is causing the natural water sources to dry faster.(MacAllister et al., 2020) This means that there is a situation of increased water stress at the global level. (FAO, 2021) Thus, to address the world water problem, it is crucial to develop the water infrastructure and to establish sustainable water management.

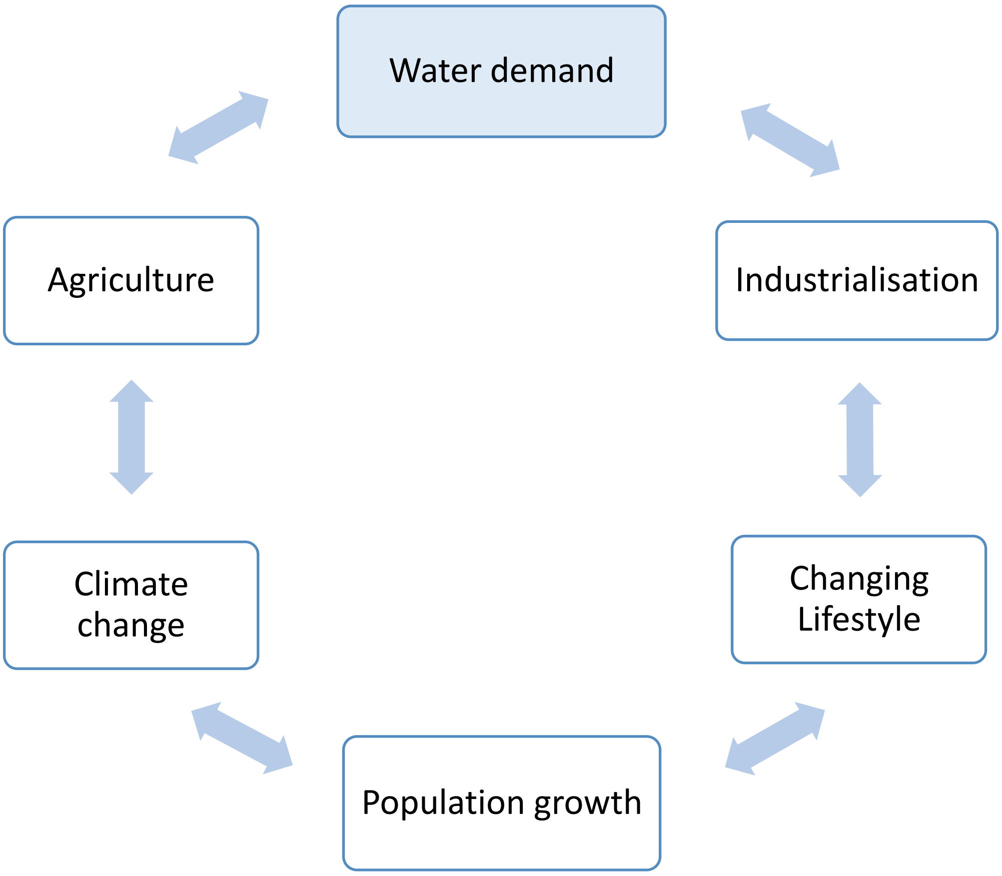

Figure 1 Factors that affect water demand

There are two approaches to water management: the first is to increase water supply, while the second is to improve the effectiveness of existing water supply channels. Conventionally, the first approach is followed, by building new infrastructure to deliver water to consumers, but now the focus is moving towards the second approach in the framework of developing water-smart cities.(Brears, 2020b) Responsible use of available water resources, e.g. by reducing water consumption, is one of the routes towards achieving water security. In addition, sustainable reuse of water is an essential step to lower the water stress. This means, for example, that “grey” water (domestic wastewater from all channels in households, except sewage) can be re-used for the irrigation. (UN-Water, 2015) Moreover, after suitable treatment to achieve high purity, recycled water can be used for drinking purposes. Thus, water recycling and wastewater treatment become the inevitable solution to achieve the circular water economy.(Brears, 2020a)

Water pollution

80% of the wastewater across the globe is discharged untreated into natural water resources, resulting in water pollution.(UNESCO, 2020) The water pollution is affecting both humans and the environment. The pollutants reach humans either via direct intake of polluted water or via consumption of food grown using the polluted water, e.g. vegetables grown with contaminated water supply were found to have the content of metal pollutants higher than the natural levels.(Gebre & Van Rooijen, 2009) The hazards associated with water pollution include but are not limited to diarrhoea, typhoid and cholera. Some of these adverse effects are immediate and may result in death. For example, diarrhoea caused by water pollution due to the presence of bacteria, parasites and viruses in drinking water kills almost half a million people every year. (WHO, 2019) Moreover, acute and chronic toxicity associated with water micropollutants can result in hormonal disruptions, antimicrobial resistance, cancer, and difficult pregnancies. (Stasinakis & Gatidou, 2010) Thus, it is crucial to understand what pollutants are present in water, where they come from and how they can be treated.

Water pollutants are released into the environment through various channels, such as agriculture, industry, and domestic wastewater, and then enter different water matrices such as rivers, lakes, surface water and groundwater. Rapidly growing industrialisation, agricultural practices, direct discharge of wastewater and waste from household and fuel stations are some of the main sources of water pollution. Notably, some of the factors creating water demand are also the factors or key sources of water pollution.(UN, 2018)

The World Health Organisation (WHO) has provided guidelines for monitoring the quality of drinking water, which include three main aspects of water pollution – microbial, chemical, and radiological.(WHO, 2017) Wastewater quality is described by two important parameters: biochemical oxygen demand (BOD), which indicates the amount of biologically degradable matter, and chemical oxygen demand (COD), which shows the amount of chemically oxidisable matter. (Drinan et al., 2000) Water contaminants can be broadly categorised into biological or chemical. Figure 2 lists some of the key persistent water pollutants: natural organic matter, silts, clays, pathogens, dyes, heavy metals, microplastics, pharmaceuticals, pesticides, and herbicides. (Parsons & Jefferson, 2006)

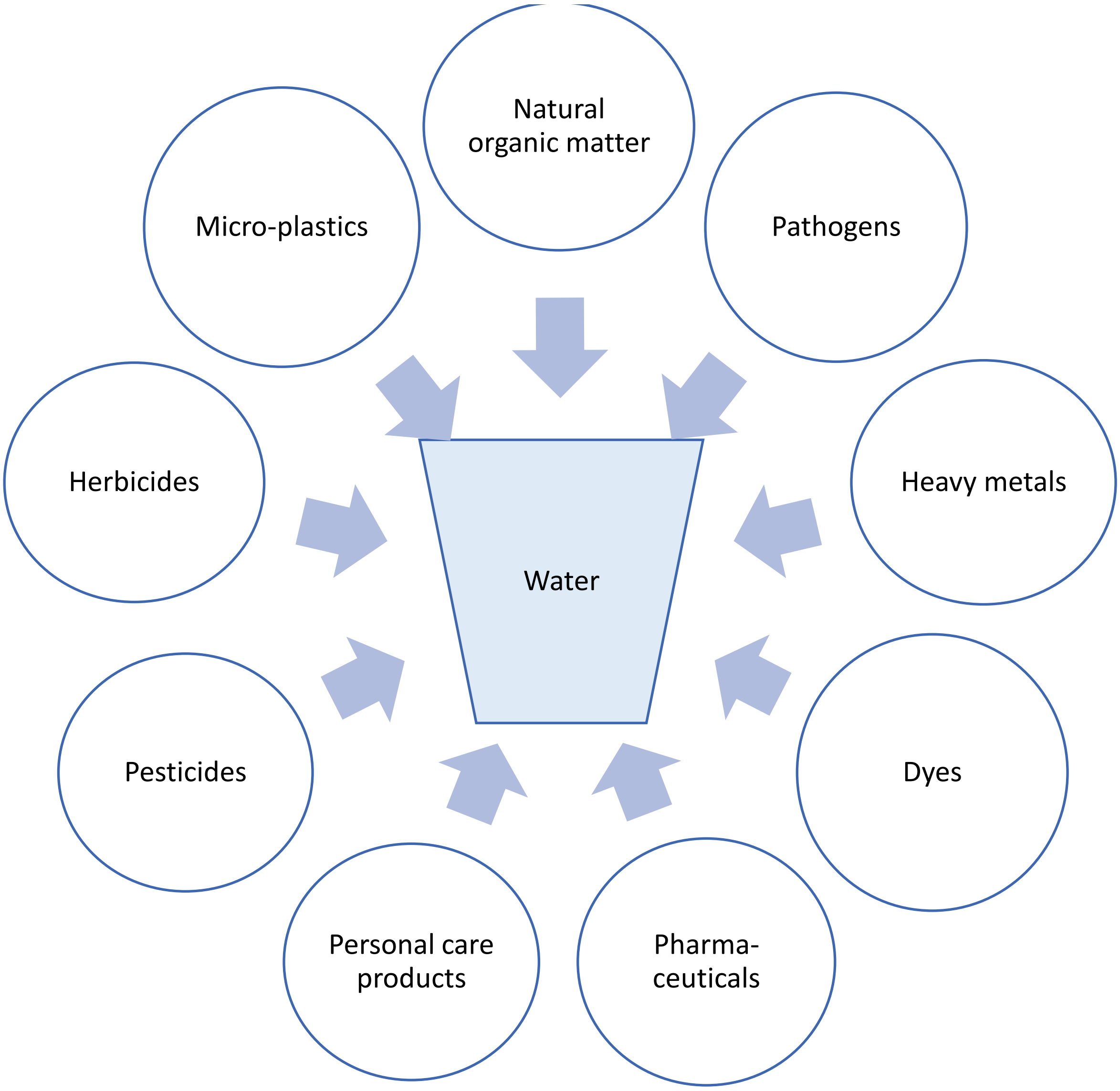

Figure 2 Key water pollutants

Biological pollutants or pathogens include bacteria such as *E. coli*, which is mainly responsible for spread of infectious diseases through water, protozoa, e.g. cryptosporidium that causes gastroenteritis, as well as viruses and parasites (Parsons & Jefferson, 2006). WHO has developed guidelines for drinking water quality regarding the concentration levels of pathogens in a variety of matrices.(WHO, 2017)

Heavy metal pollution includes metals such as arsenic, lead, nickel, tin, molybdenum, antimony, copper, selenium, which are recognised as some of the high toxicity materials, and are released into the environment by metallurgical industry effluents. (Václavíková et al., 2009) Presence of metals in wastewater has a beneficial side-effect of killing pathogens.

However, if metal impurities are present in excess, they cause a problem for sludge disposal, resulting in higher process cost and environmental impact. (Drinan et al., 2000)

Another emerging type of pollutants are microplastics. (Di & Wang, 2018) Microplastics are plastic pollutants or plastic fragments with length less than 5 mm. These microplastics in the ocean are consumed by fish and thus may end up in human bodies, but they can also be consumed by humans with drinking water and breathing air.(Gasperi et al., 2018; Lim, 2021)

Perfluoroalkyl substances (PFAS), commonly known as deadly 'forever chemicals', are another type of critical water pollutants, which have strong resistance to degradation. (Franke et al., 2019; Meegoda et al., 2020) PFAS can be polymeric or non-polymeric and originate from chemical industries or consumer products.(Meegoda et al., 2020) The high electronegativity of fluorine results in a strong bond between carbon and fluorine, thus making degradation of these pollutants difficult even by some of the advanced oxidation processes. (Franke et al., 2019)

Pollutants coming from the textile industry largely constitute of dye molecules which colourise water if they are discharged untreated. (Vandevivere et al., 1998) Water contaminated with high concentrations of colourful dyes from textile industrial wastewater has received attention due the immediate hazards associated with them. (Lellis et al., 2019) Water contaminated with dyes cannot be used for bathing, household or for irrigation applications due to the acute toxicity associated with it. (Lellis et al., 2019)

Water polluted by colourless pollutants, including pharmaceuticals, hormones, personal care products and pesticides, also has long-term hazards, such as bioaccumulation and endocrine disruption. (Stasinakis & Gatidou, 2010) Pharmaceutical pollutants are often released to the environment from hospitals, households, veterinary clinics, and farms.(Pérez & Barceló, 2008) These colourless pollutants occur in concentrations of several picograms per litre to micrograms per litre range and thus are known as micropollutants. (Schröder et al., 2016) The concentration of colourless micropollutants in river surface waters as well as sediments is reported to be proportional to the density of population and livestock units.(Osorio et al., 2016)

The concentrations of pollutants vary at different collection points over the water course due to natural degradation methods such as biodegradation, sorption and sunlight driven transformation along the path, dependent on the season.(Meierjohann et al., 2016) Degradation rates were found to vary for different compounds depending on their degradation mechanisms, e.g. carbamazepine was not degraded during any season, but for a photosensitive drug such as ketoprofen its sunlight- and temperature-dependent degradation results in significantly lower concentrations in summer than in winter. (Meierjohann et al.)

The presence of pharmaceutically active compounds can have varying adverse effects on humans as well as the environment, e.g. a case study performed at the river Yamuna, downstream of Wazirabad in India, found that the concentrations of pharmaceutically active pollutants were too small to cause acute toxicity to the flora and fauna of the river Yamuna; however, they could potentially result in chronic toxicity to the aquatic and human life. (Mutiyar et al., 2018) The case study at the Iberian region of Spain indicated relatively small toxicity effect on the aquatic life, but potentially significant ecotoxicological impact on algae in the most polluted basins of the rivers Llobregat and Ebro. (Osorio et al.) These case studies showed that although water pollution is a global issue, occurrence and concentrations of pharmaceutically active compounds as micropollutants are site-specific. (Meierjohann et al.; Mutiyar et al., 2018; Osorio et al., 2016)

Information on all pollutants posing potential hazards to human health, ecology and environment is necessary, to be used as a guideline for monitoring water quality. The UN SDG 6 report recommended monitoring water quality as one of the measures to provide sustainable water for all. (UN, 2018) The SDG 6 update report in 2021 further highlighted the importance of water quality monitoring, noting that more than 3 billion people are at risk due to lack of data about their water quality, as these data are not collected on a regular basis in a majority of countries across the globe.(UN-Water, 2021) Furthermore, guidelines on water quality are needed for control of wastewater discharge and for design of water treatment facilities.

Water treatment technologies

Water treatment can classified into wastewater treatment and drinking water treatment, depending on the extent of treatment. (Parsons & Jefferson, 2006) Water treatment has three stages: primary, where the large portion of pollutants or solid biomass is separated from wastewater using processes such as sedimentation and filtration; secondary, where biological and organic matter is removed using biological processes; and tertiary for further purification before the water can be used for purposes such as drinking, pharmaceutical and food industry. (Gupta et al., 2012) In particular, treatments for odour and taste are essential for drinking water supply. (Montiel, 1983; Zoschke et al., 2012) A separate type of water treatment is desalination water treatment, where minerals from sea water can be removed to make the sea water usable for industrial, agricultural, or domestic applications.(Lattemann & Höpner, 2008) Oil-water separation is another type of water treatment, which is required for oil-spills, and much research is being carried out on developing these techniques. (Bayat et al., 2005; Xue et al., 2014) Figure 3 summarises the key water treatment techniques, which are discussed in the following sections.

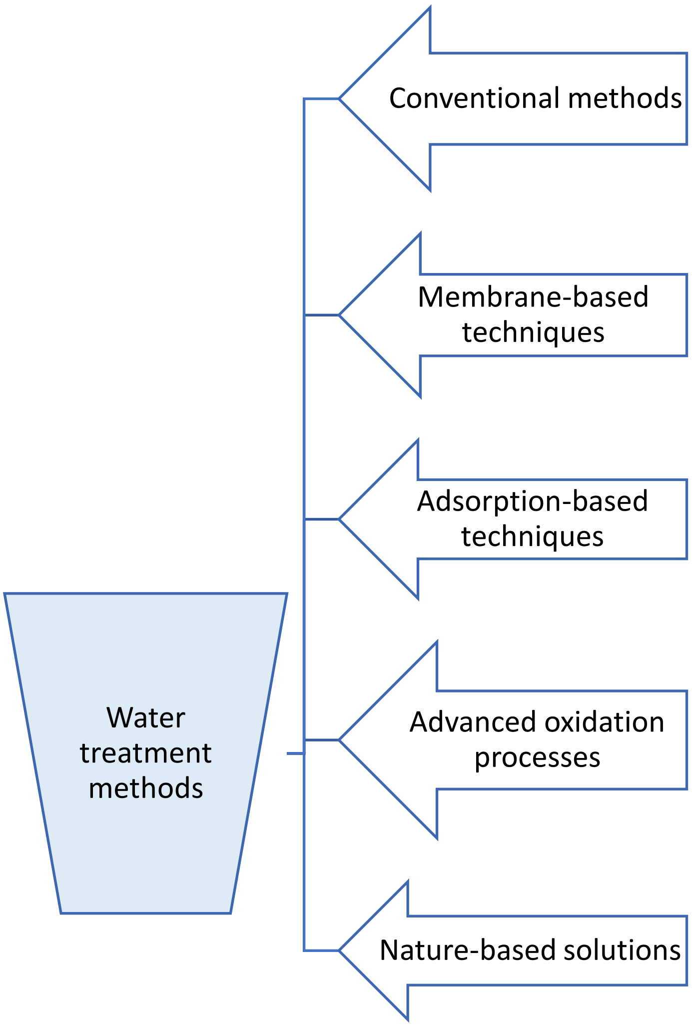

Figure 3 Key water treatment methods

1. Conventional water treatment techniques

Conventional water treatment techniques involve physical methods for pollutant removal, such as clarification, filtration, sedimentation; chemical methods, such as flocculation/coagulation, chemical disinfection, and distillation; and biological methods, such as microbial treatment. Some of the conventional treatments are effectively applied in primary treatment of wastewater, for separation of solid sludge from the wastewater, and for separation of natural organic matter and soil contamination. For example, clarification, also known as sedimentation, is a method of purification which involves settling the impurities with the help of gravity.(Parsons & Jefferson, 2006) Filtration is a method that involves slowly passing contaminated water through porous media where the impurities remain on the mesh and clean water passes through it. The efficiency of filtration or sedimentation is greatly dependent on the particle size, dimensions and solubility of the pollutants. (Jefferson & Jarvis, 2006)

Primary treatment using coagulation involves precipitating the impurities by adding metal salts, such as ferric chloride or potassium aluminium sulphate (alum). (Parsons & Jefferson, 2006) Coagulation is usually followed by a process of agglomerating the precipitated impurities, which is known as flocculation. (Chong, 2012) Treatment and disposal of coagulated sludges is a challenge in this process, as it involves highly concentrated waste. (Bratby, 2016) Water disinfection to kill pathogens is carried out by applying chemicals, such as chlorination and ozonation, or physical processes such as UV disinfection. (Parsons & Jefferson, 2006) Although chlorination has been in wide use, the by-products of chlorine disinfection are known to be carcinogenic; therefore requiring stricter regulations and development of alternative methods (Boorman, 1999; Drinan et al., 2000). Ozonation and UV disinfection emerged as the two most common alternative disinfection methods.(Drinan et al., 2000; Parsons & Jefferson, 2006)

Pollutants that cannot be separated by conventional methods during the primary stage of treatment require advanced methods of treatment. These methods include adsorption technologies, membrane-based methods, advanced oxidation processes and nature-based solutions.

2. Adsorption-based methods

Adsorption of water pollutants on sorbent materials can occur via two mechanisms: physisorption or chemisorption. A variety or carbon materials are commonly used as sorbents. For example, carbon nanotubes are excellent in sorption processes.(Sharma et al., 2012) Granular activated carbons (GAC) have been widely researched and are effective for PFAS removal, except for short chain PFAS. (Khaydarov & Gapurova, 2009; Meegoda et al., 2020) The cheaper alternative to activated carbon is agro-industrial waste products, such as banana stalk waste, jackfruit peel, and pomelo peel, which have been used as treatment for water decolourisation. (Teng & Low, 2012) The natural compounds that are mainly responsible for earthy taste and odour of drinking water, geosmin and methylisoborneol (MIB), can also be removed from water by sorption on activated carbon. (Ridal et al., 2001) Other advanced materials are being researched for adsorption of pollutants, such as graphene, zeolites, and metal-organic frameworks.(Cao & Li, 2014; Joseph et al., 2019; Wang & Peng, 2010) In addition to chemical adsorption, biosorption is a technique that is suitable for removing heavy metals and organic pollutants. (Sun et al., 2012)

3. Membrane based technologies

The conventional method of filtration has been in use since ancient times. Membrane-based techniques have been developed as an advanced type of filtration techniques for removal of key persistent pollutants. (Parsons & Jefferson, 2006) These methods are of particular interest due to the chemical-free nature of treatment, and they are very effective. Membrane-based methods are further classified based on the type and size of membrane (Singh & Hankins, 2016) Membranes can be polymeric, glass, sintered metals, ceramic, charged or ion exchange. Some of the commercially popular membrane-based techniques are reverse osmosis (pressure-based technique) and forward osmosis, nanofiltration (NF), microfiltration (MF) and ultrafiltration (UF). The effectiveness of membrane-based methods is dependent on the size of the membrane pores and the size of the pollutants, chemical and thermal stability of membranes and pollutants, reusability of membranes, and their selectivity towards pollutant removal.(Singh & Hankins, 2016)

Figure 4 presents an overview of membrane-based techniques effective for the removal of pollutants of different sizes. For example, reverse osmosis (RO) is suitable for removal of metal ions or salts and is useful in desalination treatment. Nanofiltration can remove some salts effectively; it has also been used for removal of colour from the textile wastewater, whereas ultrafiltration is effective for removal of viruses and natural organic matter (NOM). Microfiltration can be useful for removal of microplastics, clay particles, hydrophobic NOMs, and some bacteria. (Parsons & Jefferson, 2006) Membrane-based techniques are also effective for removal of all types of PFAS, but membrane-methods such as but RO and NF are more expensive than GAC-based adsorption. (Meegoda et al., 2020) Membrane-based techniques have their limitations: one of the main challenges associated with these techniques is the fouling of membrane over the period of several reuses.(Singh & Hankins, 2016)

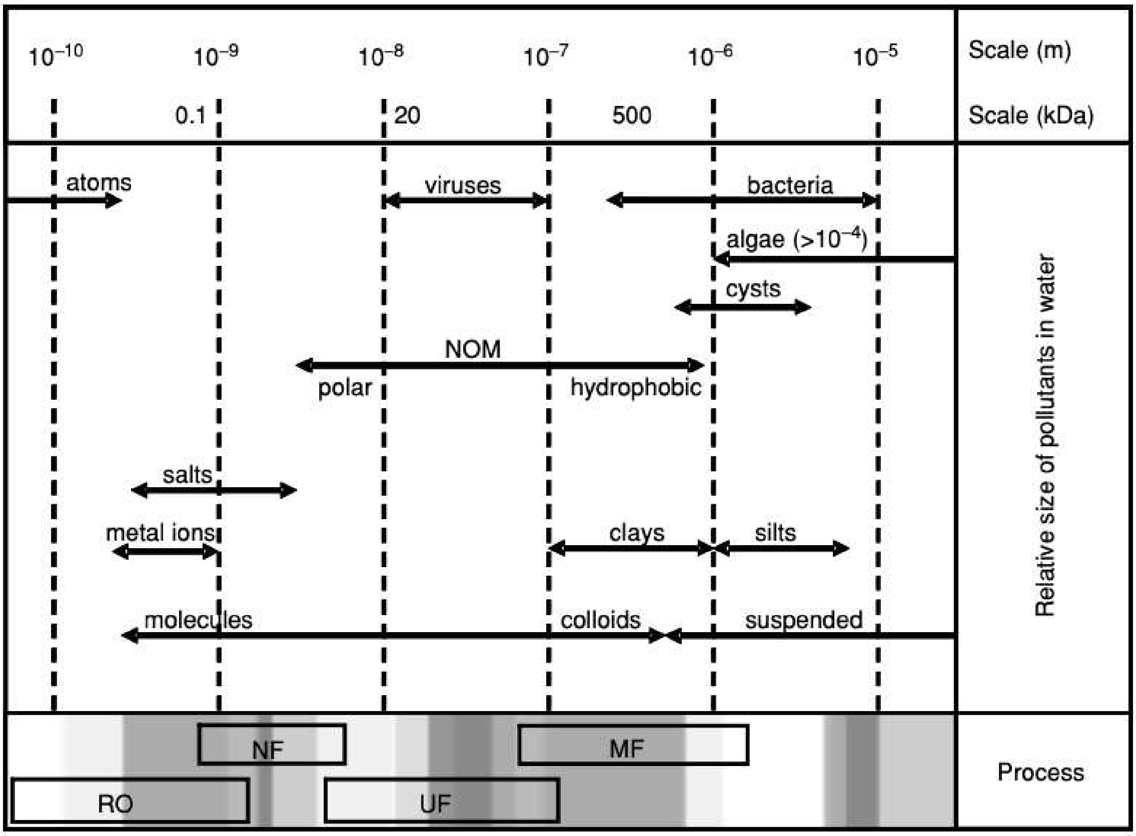

Figure 4 Membrane-based separation techniques after Parsons et al. (Parsons & Jefferson, 2006)

There are two main problems associated with the techniques discussed so far. The first problem is that the conventional techniques are still not able to completely remove all pollutants and ensure safe drinking water. The second problem is that when the pollutants are separated from water, they still need to be disposed of, which can be hazardous to the environment. So, there is a need for methods that can destroy pollutants instead of just separating them from water. Therefore, new techniques are being researched. The most important of them are advanced oxidation processes, which instead of separating or removing the pollutants attempt to destroy those pollutants and convert them into chemically simpler, relatively less toxic or non-toxic form.

4. Advanced oxidation processes

Advanced oxidation processes (AOPs) use strong oxidising species to destroy pollutants.(Deng & Zhao, 2015) Pollutants that have high resistance to degradation processes and are relatively stable can be destroyed to less complex and relatively less toxic or non-toxic molecular forms by interacting with reactive oxygen species.(Deng & Zhao, 2015) AOPs are further classified based on the method of generation of the oxidising species into photochemical and non-photochemical methods, as shown in Figure 5.

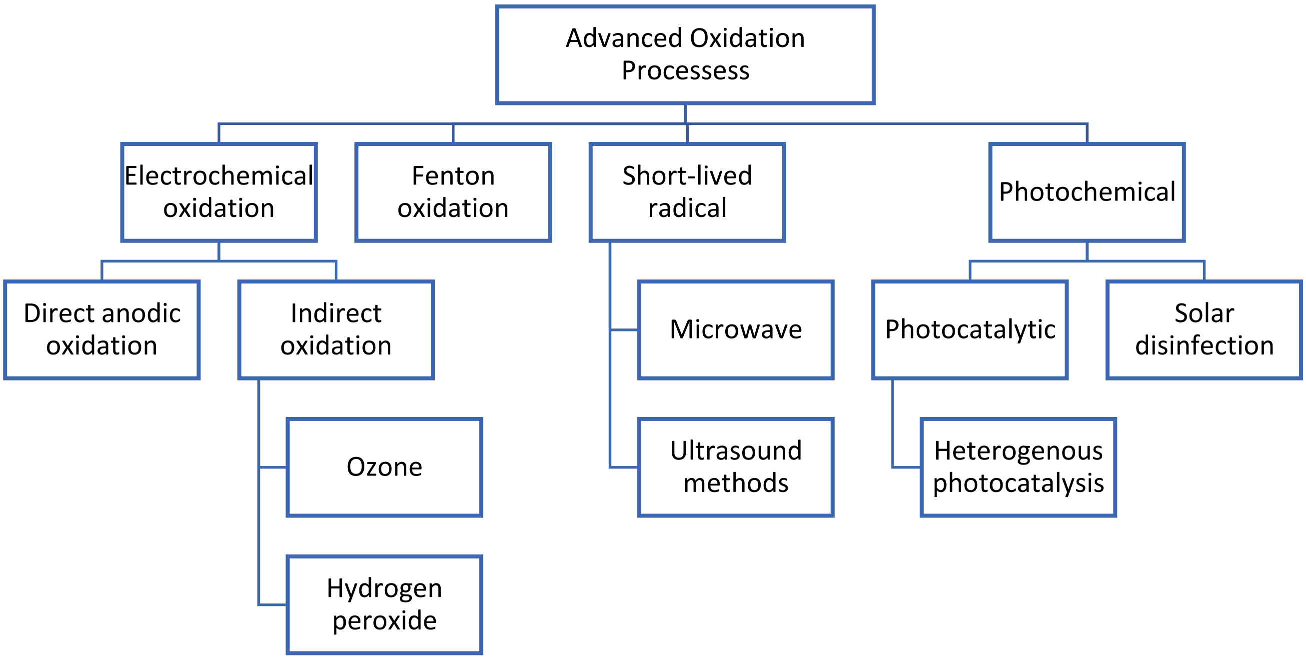

Figure 5 Types of advanced oxidation processes

Photochemical processes are light-driven chemical treatment processes, such as photocatalysis where light-activated photocatalyst materials in the presence of light (either solar light or lamp) generate the oxidising species to destroy the pollutants. (Chong et al., 2010; Malato et al., 2009; Mulay & Martsinovich, 2021) Photochemical techniques include solar disinfection - use of sunlight for water disinfection. (Marugán et al., 2020)

Non-photochemical methods include electrochemical oxidation, Fenton oxidation and short-lived radical-based methods. Electrochemical oxidation uses an electrochemical cell, where voltage applied to electrodes results in the formation of reactive chemicals such as hydrogen peroxide, ozone and hydroxyl radicals, which chemically react with pollutants and destroy them.(Martínez-Huitle & Panizza, 2018) Fenton oxidation process uses ferrous salts together with hydrogen peroxide to produce reactive species that destroy water pollutants. (Deng & Zhao, 2015) Microwave radiation and ultrasound energies are also used for generation of oxidising species. (Mudhoo, 2012) Advanced oxidation processes are suitable for destroying organic pollutants and micropollutants, such as pharmaceuticals, personal care products, industrial pollutants such as dyes, as well as pesticides and herbicides.(Garcia-Segura et al., 2018; Mulay & Martsinovich, 2021; Vandevivere et al., 1998) The drawback is that AOPs are not suitable for treatment of PFAS pollution as PFAS contain strong carbon-fluorine bonds which are difficult to break by AOPs. As an alternative, high temperature and pressure methods have been used to decompose PFAS, but their cost is prohibitive. (Meegoda et al., 2020)

5. Nature inspired methods

Nature-based methods have been used since distant past by indigenous communities and can be categorised as a sub-group of conventional methods. However, these methods have recently found increased attention due their effectiveness and sustainability aspects and their relatively fewer or no side-effects. Nature-based methods involve removal of pollutants with the help of entities found in nature. For example, phytoremediation is one of the nature-based methods. “Phyto” means “plant” in Greek, therefore phytoremediation literally means plant-based remediation. (Sharma et al., 2013) Phytoextraction processes involve interaction with plant roots to remove heavy metal pollutants from the soil. A similar process used for wastewater treatment is known as rhizofiltration, where plants are used in either hydroponic settings (grown in wastewater) or in constructed wetland settings for heavy metal removal. (Dushenkov et al., 1995) This method needs harvesting of plants over time, as the plants get saturated with the contaminants. (Sharma et al., 2013) In another approach, living or dead microorganisms can interact with metal pollutants and absorb them in the process known as bio-sorption or bioaccumulation.(Sun et al., 2012) Dye pollutants can be removed with algal treatment using species such as spirogyra. This treatment method is performed at relatively low energy, therefore it not only saves costs but also reduces greenhouse gas emissions. (Dwivedi & Vats, 2013)

Plant biomass, such as dried leaves, flowers and bark have been extensively researched for heavy metal removal and found to be effective.(Srinivasan, 2013) For example, Moringa oleifera is a tree, which is also known as drumstick vegetable; its leaves and seed pods are often used in Asian cuisine. Extracts of Moringa oleifera seeds have been found to have properties of a coagulant that can remove dyes by adsorption. (Sánchez-Martín & Beltrán-Heredia, 2012) It was found to be effective for anionic dyes, such as azo, anthraquinone and indigoid dyes, but not effective for cationic dyes such as methylene blue (Sánchez-Martín & Beltrán-Heredia, 2012) Some tannin-based compounds have also been found effective as coagulants in removal of commonly used surfactants such as sodium laurel sulphate. (Sánchez-Martín & Beltrán-Heredia, 2012)

Thus, nature-based and nature-inspired methods promise cost-effective, low-energy, low environmental impact processes for water remediation. Besides the process benefits, nature-based methods offer wider environmental and community benefits. (Boano et al., 2020)

6. Hybrid methods of water treatment

Efficiency and cost-effectiveness are important consideration in the choice of suitable techniques for water treatment facilities. Combinations of techniques were often found to be more effective than standalone techniques. Table 1 after Torres et al. (Torres et al., 2007) compares some of the AOPs for decomposition of Bisphenol-A (BPA) when used standalone and when used in combination with other AOP, using electric energy per order of pollutant removal (EE/O) as the figure of merit. For example, combination of the ultrasound (US) method with the Fenton oxidation method has yielded 64% removal of total organic carbon (TOC) from water in 600 min, whereas only the ultrasonic method has removed <60% TOC under the same conditions. Furthermore, this performance of the ultrasound/Fenton method is outperformed by a combination of ultraviolet (UV) light with US (UV/US) in just 300 mins, although with higher power. The values of EE/O in the table clearly show that when three methods – UV, ultrasonic and Fenton – are combined, this combination results in a drastic reduction in the energy cost. In another example, intermediates of photocatalytic degradation accumulated at the photocatalyst surface and degraded the performance, but a combination of photocatalysis with sonolysis improved the mass transfer by preventing adsorption of the intermediates at the surface, resulting in better performance.(Neppolian et al., 2012) Other studies showed that combinations of biological treatments with advanced oxidation processes can deliver the advantages of advanced oxidation process at relatively lower costs. (Oller et al., 2011)

Table 1 Electric energy cost estimates for Bisphenol A (BPA, 300 ml, initial concentration of 118 µmol L^{-1}) degradation by various AOPs, after Torres et al.(Torres et al., 2007) with permission from ACS

Process	Power (W)	Time (min)	% TOC removed	EE/O (kWh/m^{-3})
UV	25	600	Less than 60 %	-
US	80	600	Less than 60 %	-
US/Fe(II)	80	600	64	6010
UV/US	105	300	66	3735
UV/US/Fe(II)	105	120	79	1033

7. Analysis and comparison of water treatment techniques

Table 2 presents a summary of persistent pollutants and the key treatment techniques that can be suitable for treating the water pollution, based on compilation of data from references. (Meegoda et al., 2020; Mulay & Martsinovich, 2021; Parsons & Jefferson, 2006; Salimi et al., 2017; Singh & Hankins, 2016; Sánchez-Martín & Beltrán-Heredia, 2012) It is clear that there is no single method that works for all types of pollutants. Effectiveness of the methods strongly depends on the chemistry of the pollutants. For example, removal or separation methods are effective for chemically stable pollutants such as PFAS. For microplastics, the commonly used methods are microfiltration, coagulation, and magnetic separation. However, coagulation-based methods may require high amounts of salts for removal of microplastics, which is a drawback. In contrast, advanced oxidation methods are able to destroy a variety of pollutants but are not very effective for microplastics. (Shen et al., 2020) Although individual methods cannot achieve complete elimination or degradation of all pollutants, combinations of several methods are often more effective and can be used to eliminate multiple types of pollutants.

Table 2 Water treatment methods used at primary, secondary and tertiary stages, and commonly found pollutants which can be removed using these methods. A single tick indicates that the method is effective for removing this pollutant; a double tick indicates that the method is highly effective, while a cross indicates that this method is ineffective for this pollutant.

Pollutants (row)/ Methods (Column)	**Requirements**	**NOM**	**Pathogens**	**Heavy metals**	**Dyes**	**Micropollutants**	**PFAS**	**Microplastics**	**Taste and odour compounds**
Origin	->	Animal and plant litter	Faecal waste, animal manure	Industrial effluents	Textile industrial wastewater	Pharmaceutical industry, domestic industrial wastewater, agricultural run-off	Consumer products, foams, chemical industry products	Consumer products, plastic waste	Metabolism of algae
Sedimentation/ clarification, chemical precipitation		✓							
Disinfection:	Chlorine, ozone, UV, solar etc.		✓						
Coagulation	Coagulating agent - salts	✓		✓	✓			✓	
Nature-based coagulation	Natural products with coagulating		✓	✓	✓				

Pollutants (row)/ Methods (Column)	**Requirements**	**NOM**	**Pathogens**	**Heavy metals**	**Dyes**	**Micropollutants**	**PFAS**	**Microplastics**	**Taste and odour compounds**
	properties								
Flocculation	Flocculating agent	✓		✓					
Magnetic separation				✓				✓	
Reverse osmosis	Membrane						✓		
Nanofiltration	Membrane	✓		✓			✓✓		
Ultrafiltration	Membrane		✓						
Microfiltration	Membrane	✓	✓					✓✓	
Adsorption	Carbonaceous materials, nanomaterials, zeolites, metal-organic frameworks			✓	✓		✓		✓
Biosorption, Bioremediation	Microorganisms, fungi, algae,			✓	✓				

Pollutants (row)/ Methods (Column)	**Requirements**	**NOM**	**Pathogens**	**Heavy metals**	**Dyes**	**Micropollutants**	**PFAS**	**Microplastics**	**Taste and odour compounds**
	yeast								
Phytoremediation/ Rhizofiltration	Plants			✓					
Advanced oxidation processes	Source to generate oxidising species	✓	✓		✓	✓✓	X		✓

Based on the capabilities of these water treatment techniques discussed so far, analysis of strengths, weaknesses, opportunities, and threats (SWOT) of the key water treatment methods can be carried out as presented in Table 3. The weaknesses of the methods can be turned into opportunities with more investment into the research & development.

Table 3 Strength, weakness, opportunity, threat (SWOT) analysis of common water treatment methods

Methods	**Strengths**	**Weaknesses**	**Opportunity** **(Scope to improve)**	**Threat** **(Hazards or alarming side-effects)**
Primary separation methods	Easy to use, require little investment	Not effective to remove all pollutants	Can be used in combination with the advanced methods to have higher efficiency	Not all pollutants are removed
Adsorption based methods	Good for removal of pollutants that cannot be chemically destroyed	Scaling up is a challenge; high cost of manufacturing of nanomaterials	Scope for selectivity – selective removal of hazardous chemicals, persistent pollutants	Possibility of chemical contamination from the treatment materials
Membrane based techniques	Chemical-free treatment	Membrane fouling, high operational cost	Research to improve the recyclability and reusability of the membrane	Disposal of the separated pollutants is a problem
Advanced oxidation processes	Pollutants can be destroyed to less toxic form	Process cost and higher environmental impact	Complete destruction of pollutants	Secondary pollution by intermediates
Nature based solutions	Potentially sustainable alternative with low environmental impact, wider community benefits	Scaling up can be challenging	More research is needed for improving the range of applicability and scale-up	It should not result in excess burden on land, forest or nature when scale up.

Challenges and Future scope

The efficiency of water treatment depends on the type of the technique, operational conditions of treatment, as well as the properties of the pollutants. Figure 6 represents the challenges associated with existing water treatment technologies. One of the key challenges associated with the advanced techniques for water treatment is their high costs. Another challenge associated with some of the advanced oxidation processes, such as photocatalysis, is secondary pollution, i.e. the possibility of formation of equally or more toxic intermediates by destruction of organic micropollutants. Thus, sustainability of advanced oxidation processes requires further investigation. Some of the methods have proven to be efficient in destroying pollutants on the laboratory scale; however, their efficacy at the pilot level or larger commercial scale needs further investment into research and development.

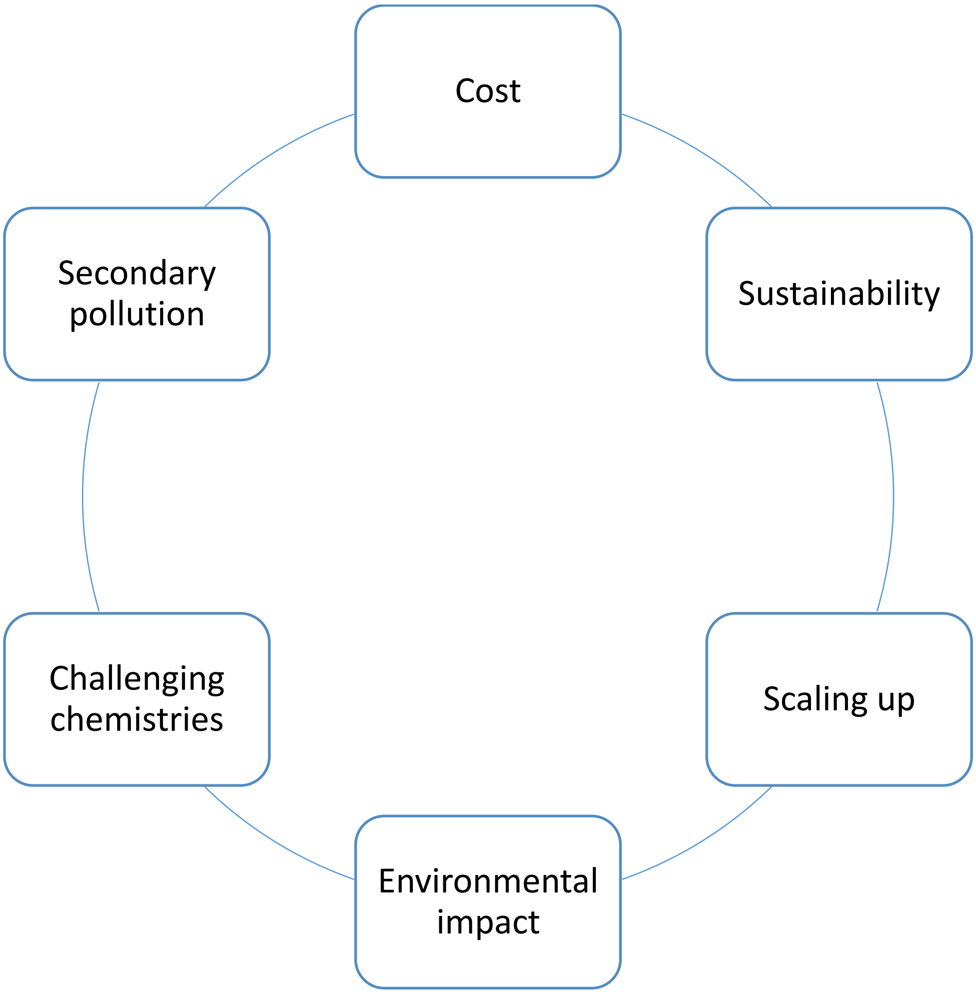

Figure 6 Open challenges associated with advanced water treatment techniques

Currently available water treatment technologies are excellent for carbon, heavy metal, nitrogen, and microbial elimination. However, complete elimination of some of the emerging pollutants, such as PFAS and critical PhAcs, is challenging with most of the existing technologies. This is because even if they are removed from water, they still need to be disposed of, so their complete elimination from the environment is yet not achieved. Existing methods are also very energy intensive. (Schröder et al.) Thus, existing methods are not sufficiently effective and more advanced methods are needed. Moreover, policy guidelines are needed for reducing water pollution and maximising effectiveness of water treatment technologies. WHO has provided guidelines for drinking water quality; however, some of the emerging persistent organic pollutants need more attention and further study. (WHO, 2017)

Recommendations

Improving the effectiveness of treatment of polluted water is one of the key strategies for water-resilient future. Strategic planning and management of water resources and research in treatment technologies promise to provide clean water resources for sustainable and healthier life. At the same time, sustainable lifestyle and sustainable agriculture, such as reduction in the use of pesticides and pharmaceuticals, can result in decreased pollution. The following necessary steps for achieving clean water resources can be recommended:

- Investing in research and development for advanced water treatment technologies in academia and industry. This includes research and development of new methods and materials, as well as development of modelling techniques to model pollutant removal.
- Cross-sector collaboration and partnerships between research laboratories, industries, and policymakers.

Treatment of polluted water for re-use is essential for sustainable water supply. However, minimising water pollution in the first place is equally important to protect the environment from irreversible damage. Minimising water pollution can be achieved with collective efforts through public-private partnerships. The following steps can be recommended to minimise water pollution:

- Make the environmental impact assessment mandatory before approval of new industrial projects
- Conduct regular environmental audits, including water audits
- Set effluent discharge permits
- Sustainable use of pesticides and herbicides
- At domestic level: responsible disposal of pharmaceuticals
- Policymaking for industrial wastewater disposal
- Documentation and monitoring of potential health hazards associated with emerging pollutants

Additionally, treatments such as desalination offer vast potential to tap into sea and ocean-based water. (Laffoley et al., 2021) 97% of all water on Earth is in the ocean. However, existing desalination treatments have very high environmental and marine impact, which may be reduced by using renewable energy sources. (Lee & Jepson, 2021) More research and development is needed to make desalination processes more sustainable to alleviate the stress on the freshwater resources.

Water, food, and energy are entangled with community lives. An integrated approach at the water-food-energy nexus is needed. Only with clean water resources can food production be truly sustainable, and only with sustainable use of water in agriculture and industry can water stress be reduced and eliminated. At the same time, policies on renewable energy generation affect water resources, and usage of clean energy can ensure lower environmental impact of water treatment techniques. (Beck & Walker, 2013; Endo et al., 2017)

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Cross references

- Circular Water Economy - Robert C. Brears
- Water Security, Sustainability, and SDG 6 - Alan Shapiro
- Meeting SDG6: Ensuring Safe Drinking Water for All in Rural India - Aviram Sharma

Palgrave

- Water-Smart Cities - Robert C. Brears
- Water Security and the Green Economy - Robert C. Brears

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