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Wastewater Treatment in Central Asia: Treatment Alternatives for Safe Water Reuse

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Review

Wastewater Treatment in Central Asia: Treatment Alternatives for Safe Water Reuse

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Abstract: Due to water scarcity and ready availability, treated wastewater in Central Asia is increasingly reused and seen as a valuable resource, requiring effective management with particular care for human health, environmental protection, and water security. Due to limited technical and economic support and poorly developed regulatory systems, many cities have inadequate wastewater treatment infrastructure. Improved wastewater effluent management is paramount due to its relationship with surface and groundwater quality used for drinking and agricultural irrigation. This paper presents a brief review of the published literature reporting on current wastewater treatment technologies and effluent composition, with particular attention paid to reuse needs. The impact of these practices on water quality is further assessed from information and reports gathered from various sources on the quantity and quality of surface waters and groundwaters. Finally, alternatives to current wastewater treatment practices in Central Asia will be explored with a particular emphasis on the removal of contaminants of emerging concern, including biological treatment systems, adsorption, advanced oxidation processes, and managed/unmanaged aquifer recharge techniques based on permeable reactive barriers, aiming to increase the availability and quality of surface waters and groundwaters for safe water reuse.

Keywords: adsorption; advanced oxidation process; contaminants of emerging concern; wastewater treatment; Central Asia

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1. Introduction

Vindication and rational use of municipal and industrial wastewater is one of the most serious problems of ecology. Currently, tens of thousands of substances pollute municipal and industrial wastewaters, whereas methods of removing them from polluted water are only confirmed for several compounds [1]. Purifying polluting water environments in industrial areas remains one of the urgent tasks facing chemists, engineers, and ecologists. Several works have reported contaminants in many aquatic systems of Central Asia, including heavy metals and polychlorinated biphenyls (PCBs, anthropogenic persistent non-biodegradable organochlorine compounds resulting from several industrial activities being among the most prevalent and notorious pollutants found in environmental media) [2–5]. Contaminants of emerging concern (CECs), persistent chemicals, microorganisms and other substances pose a potential, perceived, or real risk to the environment and/or human health. Traces of pharmaceuticals and personal care products, hormones, metals, perfluorinated compounds, antibiotic-resistant bacteria, and antibiotic resistance genes [6–8], pesticide residues [4], may occur in effluents of urban wastewater treatment facilities thus affecting reuse of this water.. Wastewater effluent is the primary source of CECs in the environment. While conventional biological processes in wastewater treatment facilities existing in metropolitan areas of Central Asia do not efficiently remove these emerging pollutants [9,10], less developed cities and rural settlements often lack proper infrastructure for wastewater treatment. Inefficient removal of pollutants and lack of treatment leads to discharge and accumulation of CECs in water reservoirs used for drinking and irrigation purposes, posing grave risks to human health [11,12] and to Central Asia in particular, where climate change is expected to exacerbate water stress and reuse needs. Food-borne illness outbreaks can occur in fruits and vegetables irrigated with partially or untreated wastewater [12,13]. This public health concern is aggravated due to the lack of societal, governmental, and regulatory bodies' awareness of the seriousness of this problem, urging studies on identifying and quantifying wastewater inputs in Central Asia, water scarcity, and the health impact of water reuse in this region. There is thus a critical need to improve wastewater treatment and infrastructure in Central Asia to reduce human and ecosystem health risks.

This paper provides an overview of the published literature reporting on current wastewater treatment technologies in Central Asia. It articulates current use of waste stabilization ponds and wastewater reuse practices, enabling a critical discussion on how these practices impact surface waters and groundwater quality. The literature evaluated here is based on the search criteria consisting of the keywords: "wastewater treatment, Central Asia, Kazakhstan, Uzbekistan, Kyrgyzstan, Tajikistan, Turkmenistan", privileging publications of the last five years to keep the content concise and timely. Data sources included the Web of Science citation index, Scopus, and published reports by national/international authorities regulating/managing wastewater treatment in Central Asia to complement the published peer-reviewed scientific information. The search was refined to include the identified most-practiced wastewater treatment technologies and their possible relation with water quality issues, namely on identifying persistent CECs. Because few studies include pharmaceuticals and their metabolites in wastewater facilities, we will focus on these contaminants and propose alternatives to current wastewater treatment practices in Central Asia, aiming to increase the availability and quality of surface waters and groundwaters for safe water reuse. The assessment of the impact of current wastewater treatment technologies in Central Asia on water quality used for drinking and irrigation purposes, and the need to provide more efficient and cheaper alternatives for the removal of CECs, will drive future research. Investments carried out in the region, in alignment with the sustainable development goals of the United Nations, are aimed to ensure access to water and sanitation for all until 2030. Some attractive alternatives to current wastewater treatment practices in Central Asia are technologies such as adsorption, advanced oxidation processes, membrane technologies, and permeable reactive barriers. This review also provides an overview of the published literature reporting the application of those technologies for removing CECs. From this review paper, readers from the scientific community will better understand the critical situation of properly responding to water scarcity and availability that arid regions such as Central Asia face, mimicking many other regions around the globe, and provides possible solutions available to use treated wastewater for safe reuse for drinking and irrigation purposes.

2. Wastewater Treatment in Central Asia

Wastewater treatment in Central Asia is a critical issue that has been gaining increasing attention in recent years. As a large, arid region with a rapidly growing population, Central Asia faces significant challenges in managing its water resources, including adequate wastewater treatment and disposal. Water purification and safety in Central Asia is a critically important and ongoing problem throughout the region [14]. One of the main challenges is the lack of funding and investment in the sector, which has limited the capacity of Central Asian countries to build and maintain wastewater treatment facilities. Another challenge is the lack of public awareness about the importance of wastewater treatment and the need for sustainable water management practices. The scarcity of funds and lack of public awareness has led to a shortage of political will and support for investing in this infrastructure sector. Existing Soviet-era wastewater treatment plants are typically designed only with mechanical and biological treatment. It is well known that wastewater treatment technologies can play a crucial role in improving the quality of water resources in the region, especially in urban areas where access to safe drinking water is limited. There are a number of wastewater treatment technologies currently being used in Central Asia, including activated sludge treatment [15], trickling filter treatment [16], membrane filtration [17], reverse osmosis, and UV disinfection [18]. Central Asia is an area that includes five former Soviet republics: Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan. This region faces significant challenges in managing its wastewater due to population growth, industrialization, and urbanization.

The most common wastewater treatment technologies in Central Asia are conventional activated sludge treatment (CAST), evaporation, and stabilization ponds. CAST is a system confidently and widely used for biological treatment plants of municipal wastewater, effective in removing organic matter and nutrients but suffering from operational problems that affect its efficiencies and effluent qualities, especially when treating low-strength wastewater with increasing incoming flow, requiring significant infrastructure and energy inputs [19]. On the other hand, less advanced evaporation and stabilization ponds are also very common wastewater treatment technologies used in Central Asia due to their low cost and simplicity.

In recent years, several newer technologies have slowly been introduced in Central Asia, including membrane bioreactors, sequencing batch reactors, and moving bed biofilm reactors. These technologies offer higher treatment efficiencies and smaller footprints than CAST but require higher capital and operating costs. In addition to these conventional and newer technologies, there has been growing interest in decentralized wastewater treatment systems in Central Asia. These systems can be installed at the household or neighborhood level and treat wastewater to a level suitable for reuse in agriculture or other non-potable applications. Decentralized systems can potentially improve wastewater treatment in areas without centralized infrastructure, but they require careful management and monitoring to ensure effective operation.

2.1. Conventional Activated Sludge Treatment (CAST)

Conventional activated sludge treatment (CAST) is a typical wastewater treatment technology used in Central Asia, particularly installed to treat large wastewater volumes for entire large communities, as in large cities such as Almaty, Kazakhstan [20]. CAST is a biological treatment process that utilizes microorganisms to remove organic matter, nitrogen, and phosphorus from wastewater. The CAST process consists of four main stages, as depicted in Figure 1 and described below:

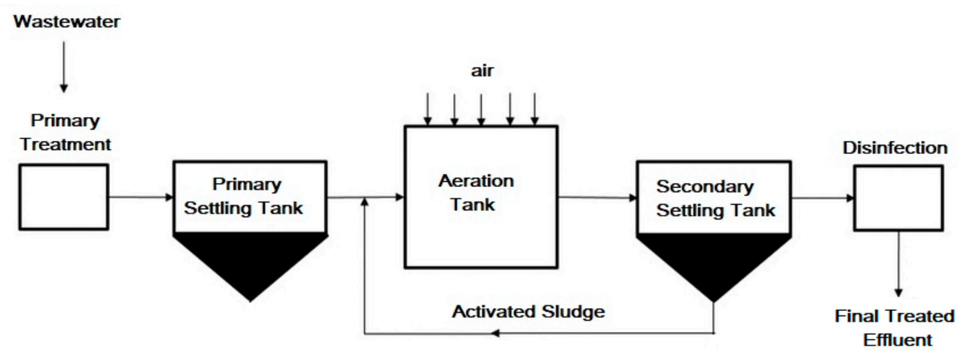

Figure 1. Schematic diagram of the main stages of a conventional activated sludge wastewater treatment system (CAST). Reprinted/adapted with permission from Ref. [21].

Primary treatment: During this stage, the wastewater is screened to remove large particles and sent to a primary settling tank where heavier solids can settle to the bottom.

Aeration: In this stage, the wastewater is mixed with activated sludge, a mixture of microorganisms that consume the organic matter in the wastewater. The mixture is aerated to provide oxygen to the microorganisms, facilitating their growth and metabolism.

Secondary settling: After the aeration stage, the mixture is sent to a secondary settling tank where the activated sludge and remaining solids are allowed to settle to the bottom.

Disinfection: Finally, the effluent from the secondary settling tank is disinfected to remove any remaining pathogens before being discharged into the environment.

Although CAST is used to treat urban wastewater due to its effectiveness in removing organic matter and nutrients, this technology requires significant infrastructure and energy inputs, which can be a challenge in the region. Most of the sewage treatment plants were designed and built in the 1960s and 1980s, and the installation's capacity is related to the development of the city's industry. Additionally, CAST is sensitive to fluctuations in influent quality and can be impacted by operational issues such as sludge bulking or foaming.

To address these challenges, some efforts have been made to optimize CAST performance in Central Asia. For example, a few plants have implemented advanced nutrient removal systems to improve nitrogen and phosphorus removal. Additionally, newer variations of the technology, such as modified Ludzack-Ettinger (MLE) and oxidation ditch processes, have been introduced to achieve higher treatment efficiencies and reduce energy requirements. Despite these improvements, CAST remains a relatively high-cost wastewater treatment technology compared to other options, such as stabilization ponds or constructed wetlands. Nevertheless, it remains a critical treatment technology in Central Asia, particularly in urban areas with stringent effluent quality standards and limited land availability. Another problem with CAST in urban wastewater treatment is that the technology was not designed to remove CECs, allowing them to enter the aquatic environment via discharge of wastewater effluents in surface waters, ultimately ending up in aquifers [22].

A recent study to assess the sewage treatment facilities of Almaty, Kazakhstan [20] measured several water quality indicators at five locations adjacent to the sludge beds. The results showed high levels of contamination of the groundwaters, with the water from the sludge beds to some extent polluting the waters of the adjacent Bolshaya Almatinka River with various chemical elements, not meeting the maximum allowed concentration standards for fishery water bodies [23]. After complete biological treatment, the final purified waters were sent to the Sorbulak storage lake. Analysis of samples from this location revealed an alkaline environment of the wastewater storage, with chemical indicators exceeding the standards, justified by historical contamination of the lake that has been in operation for 49 years. Thus, even waters arriving from CAST treatment plants in Central Asia typically may discharge above the established concentrations of maximum permissible discharge, contaminating groundwater near sludge beds and making them unsuitable for irrigation purposes and discharge in adjacent rivers.

2.2. Evaporation and Stabilization Ponds

Central Asia has a continental climate characterized by cold winters, hot summers, and very low precipitation, making fresh water a scarce resource. Despite this, evaporation ponds are widely used for wastewater disposal for both industrial and domestic effluents. In Kazakhstan, more than 500 such pond systems were reported to be in operation [24]. In comparison with evaporation ponds, waste stabilization ponds offer major advantages, such as providing treated water for a variety of uses, including irrigation in summer and high-quality water to replenish rivers or aquifers in autumn, providing a valuable contribution to river flows in arid or sharply continental climates, such as those found in Central Asia. Under certain conditions, they may also retain water, which would otherwise be lost during winter. These ponds are essentially large, shallow basins that allow for the natural degradation of organic matter and other pollutants in the wastewater through biological, physical, and chemical processes.

Stabilization ponds can be anaerobic, facultative, or aerobic maturation ponds, as shown in Figure 2. Facultative ponds are designed to operate under either aerobic and anaerobic conditions, and they are typically the most common type of stabilization pond used in Central Asia. Aerobic ponds are designed to maintain aerobic conditions, while anaerobic ponds support anaerobic conditions. Each type of pond is used to treat wastewater based on the specific conditions required to degrade pollutants [24]. Various factors influence stabilization ponds' performance in Central Asia, including temperature, hydraulic retention time, and hydraulic loading rate. Typically, these ponds are designed to achieve removal efficiencies of 50–70% for organic matter, 30–50% for nitrogen, and 20–30% for phosphorus. However, the effectiveness of stabilization ponds in removing pollutants is also influenced by other factors such as the influent characteristics, loading rates, and pond design and operation.

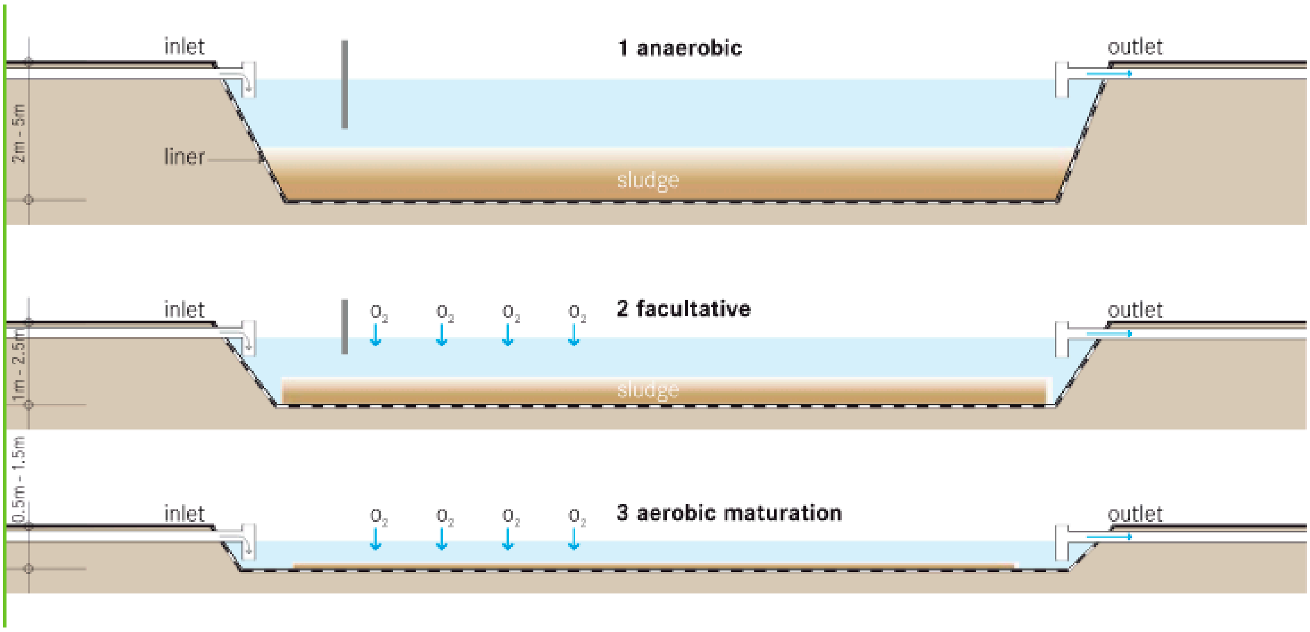

Figure 2. Schematic diagram of the three main types of waste stabilization ponds used for wastewater treatment: (1) anaerobic, (2) facultative, and (3) aerobic (maturation), each with different treatment and design characteristics. Reprinted/adapted with permission from Ref. [25].

Despite their low cost and simplicity, stabilization ponds do have some limitations. They require large areas of land, which can be a challenge to use in densely populated areas, and the wastewater volumes treated with this methodology are much lower than CAST (400–1500 times lower). Additionally, they are less effective in removing nutrients compared to other treatment technologies, such as activated sludge (CAST) or membrane bioreactors. There are reported instances where untreated water from pond and canals is used for livestock and local irrigation. Finally, these structures are sensitive to weather conditions such as temperature and sunlight, impacting their performance. Overall, stabilization ponds remain a common wastewater treatment technology in Central Asia due to their low cost, simplicity, and lack of dependence on power supplies, mechanical equipment, or imported components. Stabilization systems may be combined with other treatment technologies to achieve higher levels of pollutant removal. Additionally, efforts are ongoing to improve the performance of stabilization ponds by optimizing their design and operation and by integrating them with other treatment technologies to achieve more efficient and sustainable wastewater treatment, following trends in northern Europe [26].

Previous work [27] has examined the potential of waste stabilization ponds to provide water for reuse in extreme continental climates, such as those of Central Asia, where precipitation is low and summer evaporation rates are high. Their results have shown that a significant proportion of flows could be saved for irrigation or aquifer and river replenishment, requiring the modification of standard designs to suit these climates, changing the system to be both more robust and more flexible in terms of types of reuses. The analysis of three case studies of evaporation pond systems in Kazakhstan supported their conclusions for system conversion to complete biological treatment systems for water conservation and reuse.

2.3. Membrane Bioreactors (MBRs), Sequencing Batch Reactors (SBRs), and Moving Bed Biofilm Reactors (MBBRs)

MBRs, SBRs, and MBBRs are three wastewater treatment technologies that are gaining popularity in Central Asia due to their high treatment efficiencies, compact design, and large volumes of treated wastewater in the order of those treated with CAST [28,29]. MBRs use a combination of biological treatment and membrane filtration (microfiltration or ultrafiltration) to treat wastewater (Figure 3). The process involves the same biological and aeration process as CAST, but instead of settling tanks, the mixed liquor is filtered through a membrane, which removes suspended solids, pathogens, and other pollutants. MBRs are highly effective in removing contaminants from wastewater and producing high-quality effluent, making them suitable for reuse applications. However, they are relatively expensive to operate and require significant maintenance. A new wastewater treatment plant (WWTP) incorporating an MBR was recently installed in Atyrau, Kazakhstan, on the bank of the Ural River [30].

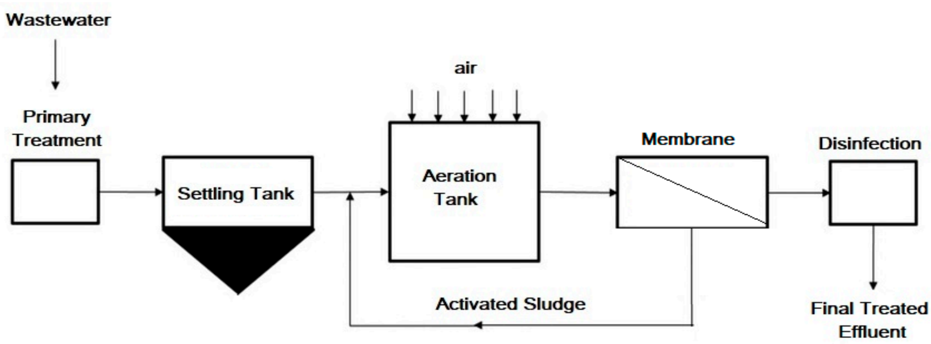

Figure 3. Schematic diagram of a membrane bioreactor (MBR).

SBRs are a treatment technology that involves treating wastewater in batch cycles. The process consists of four main stages: filling, aeration, settling, and decanting. During the filling stage, the reactor is filled with wastewater, and then the aeration stage begins, where air is introduced to provide oxygen to the microorganisms. During the settling phase, the microorganisms settle to the bottom of the reactor, and eventually clear water is decanted. SBRs are flexible and compact technology that can be used for various applications, including industrial and decentralized municipal wastewater treatment. SBR has been considered a technical option for constructing a new wastewater treatment plant in Zhezkazgan, Kazakhstan [28].

MBBRs are another biological wastewater treatment technology involving microorganisms' growth on moving media within the reactor. The moving media provide a large surface area for the microorganisms to grow and form a biofilm, which can effectively treat wastewater. MBBRs are compact and highly efficient, making them suitable for decentralized wastewater treatment applications. They can also be used as a post-treatment option for effluent polishing. MBBR has been considered in the evaluation of treatment processes and technologies for the rehabilitation and upgrading of wastewater treatment plants and collection systems in the cities of Akhangaran, Almalyk, Angren, Bekabod, Chirchik and Yangiyul, and in the Chinaz district's urban center in Uzbekistan [29].

Overall, these three technologies are effective in treating wastewater in Central Asia. However, their success depends on factors such as influent quality, system design, and operation. Efforts are ongoing to optimize these technologies for the specific conditions in the region and to develop more sustainable and cost-effective solutions for wastewater treatment.

2.4. Decentralized Wastewater Treatment Systems (DEWATSs)

Decentralized wastewater treatment systems, or DEWATSs, have gained popularity in Central Asia due to their ability to provide cost-effective and sustainable wastewater treatment solutions, especially in rural and remote areas where centralized wastewater treatment systems are not feasible [31]. DEWATSs are small-scale wastewater treatment systems that treat domestic and industrial wastewater at the source or near the source of generation. They are usually designed to treat low wastewater volumes, from 10 to 1000 population equivalent (PE), in the same fashion as stabilization ponds. These systems use natural processes such as biological treatment, sedimentation, and filtration to treat wastewater. They can be constructed using various technologies, including constructed wetlands, biogas digesters, and anaerobic baffled reactors [31]. A schematic diagram of a DEWATS for physical and biological wastewater treatment, with constructed wetlands that use natural processes to treat wastewater, is presented in Figure 4. These systems involve using aquatic plants to remove pollutants from wastewater through a combination of physical, chemical, and biological processes. Constructed wetlands are low-maintenance and have low operating costs, making them an attractive option for rural areas in Central Asia. A report from 2018 updated the information on the status of natural wetlands in Kazakhstan, Kyrgyzstan, and Turkmenistan by collection and dissemination of good practices for conservation and sustainable use of wetlands by local communities [32]. Human population growth and climate change contribute to the deterioration of natural wetlands worldwide including Central Asia [33]; thus, if managed properly, constructed wetlands could augment natural wetlands in remote areas of this region.

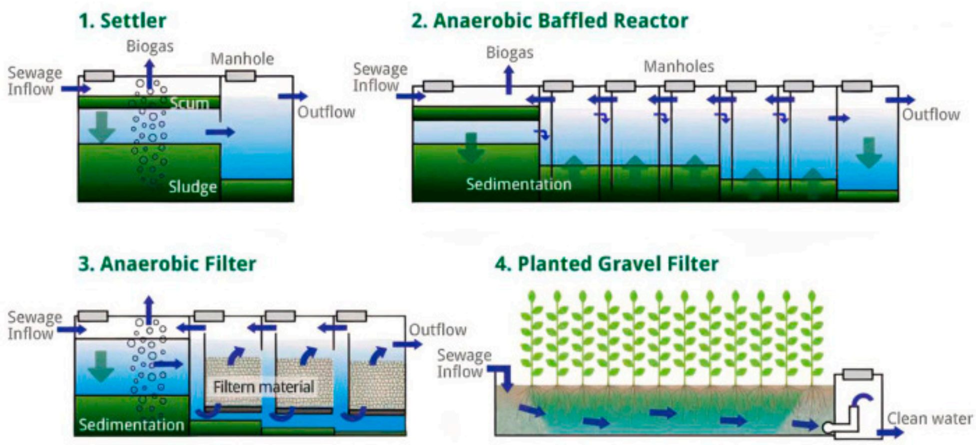

Figure 4. Schematic diagram of a decentralized wastewater treatment system (DEWATS) for physical and biological wastewater treatment. Reprinted with permission from Ref. [34].

Biogas digesters are another type of DEWATS that can be used to treat organic wastewater. These systems use anaerobic digestion to convert organic matter in wastewater into biogas, which can then be used for cooking or heating. Biogas digesters have been successfully used in Central Asia to treat wastewater from livestock farms and dairy processing plants. Numerous biogas plants have been installed in the Kyrgyz Republic, but many are neglected because they do not function properly in the harsh winter conditions that the country faces [35]. Improved biogas technology and system management can provide biogas even in the harshest winter conditions, with the added benefit of generating a byproduct that can be used as fertilizer [35].

Anaerobic baffled reactors (ABRs) are another type of DEWATS using anaerobic digestion to treat wastewater. These reactors consist of multiple compartments that are separated by baffles. Wastewater flows through each compartment, and the baffles create an anaerobic environment that promotes the growth of anaerobic bacteria. ABRs are an effective technology for treating high-strength wastewater, such as industrial wastewater. In Tajikistan, a DEWATS incorporating ABRs was constructed at the two hospitals in the town of Somoniyon, Tajikistan, to demonstrate alternative and hybrid sanitation practices and to enable authorities and sector players to operate it [31]. Overall, DEWATSs have the potential to provide cost-effective and sustainable wastewater treatment solutions in Central Asia, particularly in rural and remote areas where centralized wastewater treatment systems are not feasible. However, their success depends on several factors, including proper design, operation, and maintenance.

As a summary of the most common wastewater treatment technologies in Central Asia described in Section 2, Table 1 presents the advantages and disadvantages of each method to allow for their comparison, including typical volumes of wastewater treated.

Table 1. Comparison of the most used wastewater treatment technologies in Central Asia.

Technology	Advantages	Disadvantages	Volume of Water Treated per Day
Conventional activated sludge treatment (CAST)	- Effective in removing organic matter and nutrients	- Requires significant infrastructure and energy inputs - Suffers from operation problems that affect their efficiencies and effluent qualities, especially when treating low-strength wastewater with increasing incoming flow - Sensitive to fluctuations in influent quality and can be impacted by operational issues such as sludge bulking or foaming - Relatively high-cost wastewater treatment technology compared to other options, such as stabilization ponds or constructed wetlands - Technology not designed to remove CECs	640,000 m^3/day [20]

Table 1. *Cont.*

Technology	Advantages	Disadvantages	Volume of Water Treated per Day
Waste stabilization ponds	- Low cost and simplicity - Lack of dependence on power supplies, mechanical equipment, or imported components - Provides treated water for a variety of uses, including irrigation in summer and high-quality water to replenish rivers or aquifers in autumn - Under certain conditions, they retain water, which would otherwise be lost during winter	- Requires large areas of land - Less effective in removing nutrients compared to other treatment technologies, such as CAST or membrane bioreactors - Sensitive to weather conditions such as temperature and sunlight, impacting their performance	400–1400 m^3/day [24]
Membrane bioreactors, sequencing batch reactors, and moving bed biofilm reactors	- Higher treatment efficiencies and smaller footprints than CAST - Highly effective in removing contaminants from wastewater and producing high-quality effluent, making them suitable for reuse applications	- Higher capital and operating costs than CAST - Relatively expensive to operate and require significant maintenance	3000–780,000 m^3/day [36]
Decentralized wastewater treatment systems (DEWATSs)	- Cost-effective and sustainable wastewater treatment solution - Treat wastewater to a level suitable for reuse in agriculture or other non-potable applications	- Require careful management and monitoring to ensure effective operation	30–9960 m^3/day [37]

3. Pressing Need for Alternative Treatment

In Kazakhstan, variable-quality groundwater is unevenly distributed throughout the country and becoming a critically important freshwater source for drinking and irrigation. Exploration of groundwater is carried out with estimated reserves of about 16 km^3/year [38]. Due to the increasing importance of groundwater, it is critical to accurately assess its quality, identify and quantify the presence of CECs, and to maintain the quantity of the country's groundwater resources, proposing solutions to guarantee either their quality or their replenishment, assuring its sustainability. In these solutions, effluents of wastewater treatment plants can play a major role in the recharge of groundwaters, applying the technology of managed aquifer recharge (MAR), provided that they are properly treated to eliminate pathogens, nutrients, and CECs typically found in its composition. CECs in wastewater include pharmaceuticals, personal care products, antibiotics, and antibiotic resistance genes (ARG) [39]. Among these, the occurrence of antibiotics and their metabolites in water bodies has become more frequent due to their steady increase in consumption over the years. Since conventional wastewater treatment plants cannot remove these compounds, suitable treatment solutions should be used, such as advanced oxidation processes (AOPs), which have been shown to be efficient in treating various classes of antibiotics [40]. According to Ilurdoz et al. [41], the methods with the best elimination percentages (80–100%) are biological methods (biological aerated filter, anaerobic digestion, and biological activated carbon filter) and membrane technology (nanofiltration and reverse osmosis), while those with the worst results (under 80%) are chemical methods (coagulation-flocculation). The next sections describe advances in treatment chemistries that could be considered in redesigning municipal wastewater treatment in Central Asia while improving the removal of CECs.

3.1. Adsorption Processes

Adsorption techniques have been identified as a promising solution for removing CECs from water sources. Adsorption is a process in which contaminants adhere to the surface of a solid material or adsorbent, thereby removing them from the water. The elimination efficiency of adsorption techniques can reach up to 99.9% [42], making them highly effective methods for water treatment [43]. Adsorbents used in water remediation can be sourced from natural materials, locally manufactured and activated. The use of adsorption in removing a range of organic contaminants from various polluted water sources has gained popularity due to its simple operating procedure, cost-effectiveness, and regeneration capability [44]. The most widely used adsorbent in water remediation is activated carbon, which has a large surface area and high adsorption capacity.

Activated carbon is effective at removing a wide range of emerging contaminants, including dyes, heavy metals, pharmaceuticals, pesticides, and petroleum hydrocarbons [45]. The adsorption capacity of activated carbon is due to its high degree of surface reactivity, large surface area, and high microporosity. However, despite its effectiveness, activated carbon has limitations in terms of high regeneration cost and poor mechanical rigidity. To address these limitations, researchers have been exploring the use of other adsorbents such as natural zeolites, metal-organic frameworks, and carbon nanotubes for water treatment [46].

Biochar is a form of low-cost, variable quality activated carbon that may serve as adsorptive material for the removal of CECs. An economic analysis utilizing the rate of return (ROR) method indicated that biochar presents itself as a cost-effective, eco-friendly, versatile, and high-capacity adsorbent alternative to activated carbon for the removal of CECs [47]. The surface of biochar possesses unique qualities, which include large surface area, high cation exchange capacity, oxygen-containing functional groups, and high mineral content [48]. The primary mode of adsorption is via hydrogen bonding and π-π electron donor-acceptor interactions. Any functional group promoting π-π electron donor-acceptor interactions on biochar surfaces can improve adsorption efficiency [49]. Therefore, research on producing and modifying biochar surfaces with metal oxide, clay minerals, and introducing functional groups is receiving attention.

A high purity form of carbon adsorbent is graphene, which consists of a single layer of sp^2 hybridized carbon atoms in a two-dimensional (2D) honeycomb pattern. The sheet structure provides the high surface area needed for efficient adsorption. Graphene structure is highly porous, which enhances the diffusion of CECs, specifically antibiotics, rapidly making it an excellent choice for the removal of CECs [50]. Graphene utilizes van der Waals interaction or π-π electron coupling to adsorb aromatic organic compounds [51]. Surface modification of graphene sheets with functional groups can increase hydrogen bonding, electrostatic interactions, and π-π interactions, which can be beneficial in enhancing adsorption capabilities [52,53]. Reduced graphene oxide was also recently used in the development of absorption sponges, patented by researchers in Kazakhstan for the purification of oily wastewaters [54].

3.2. Advanced Oxidation Processes

Advanced oxidation processes (AOPs) are effective methods for the removal of CECs from water and wastewater. AOPs involve the generation of highly reactive hydroxyl radicals ($HO^{\bullet}$) or other powerful oxidizing species, which can degrade and mineralize a wide range of organic pollutants. Recent research has shown growing interest in developing advanced oxidation process (AOP) technologies to mitigate CECs by oxidative radicals [55,56]. AOPs have been highly efficient in eliminating multiple varieties of CECs from wastewater across different spectrums, making them a choice of remediation [57]. The advanced degradation process of AOPs can convert contaminants into biodegradable intermediates, and even eliminate CECs via mineralization of contaminants [58]. AOPs rely on in situ generation of highly reactive radicals. The efficiency of AOP processes largely depends on forming strong reactive oxygen species (ROS), which can be generated via multiple pathways, including catalysis, UV irradiation, electrochemical, and cavitation mechanisms [57]. Hydroxyl radicals are one of the main radicals commonly generated in AOP techniques and are highly reactive, which can oxidize organic contaminants through direct electron transfer, hydrogen abstraction, or addition reactions. This leads to the breakdown of complex organic molecules into smaller, less toxic compounds, carbon dioxide, and water.

Ozone is a powerful oxidant commonly used in AOPs. Ozone can be applied alone or in combination with hydrogen peroxide (known as ozone-based advanced oxidation processes) to generate hydroxyl radicals [59]. Ozone reacts with water to produce hydroxyl radicals through a process called ozone decomposition. Photocatalytic AOPs utilize semiconductor materials, typically titanium dioxide (TiO_2), which absorb UV light and generate electron-hole pairs [60]. The electron-hole pairs are highly reactive and instantly react with water to form hydroxyl radicals, while the electrons can participate in reduction reactions. This process is known as photocatalytic oxidation [61]. UV light can directly generate hydroxyl radicals in water by the photolysis of hydrogen peroxide or by the photolysis of other photosensitizers [62]. UV-based AOPs are particularly effective in degrading CECs that are sensitive to direct photolysis or susceptible to reaction with hydroxyl radicals.

The efficiency of AOPs for the removal of CECs depends on various factors, including the concentration and nature of the contaminants, pH, temperature, reaction time, oxidant dosage, and reactor design [63]. Optimization of these parameters is crucial to achieve desired treatment goals and maximize contaminant degradation [63]. AOPs can be combined with other treatment technologies, such as adsorption, membrane filtration, or biological processes, to achieve more comprehensive removal of CECs [64]. These hybrid approaches can capitalize on the strengths of each method to enhance overall treatment efficiency and can be cost-effective.

Despite AOPs being a promising technology for removing a plethora of CECs from wastewater, they can lead to the formation of intermediate byproducts during the oxidation process [65]. Identifying and monitoring byproducts are essential to assess the effectiveness and environmental impact of the treatment process. It is worth noting that selecting the appropriate AOP and process conditions depends on the specific CECs of concern, water quality parameters, and treatment objectives [66]. Pilot-scale studies and operational optimization are often necessary to determine the feasibility and efficiency of AOPs for the removal of CECs in real-world applications. It is also critical to ensure cost-effectiveness of these new technologies and identify their potential in developing countries [67].

3.3. Membrane Purification

Membranes have been utilized in gas and liquid separation processes for decades. This technology is relatively easy to fabricate, operate, provides high selectivity, and adsorbent regeneration is not required [68]. Membranes play an increasingly important role in desalination, food and pharmaceutical industry applications, and water treatment. Membrane purification of wastewater typically involves the separation of chemical species through a membrane interphase, and performance is measured by the difference in the rates of separation of specific constituents [69,70]. Separation is usually dependent on the driving forces, mobility, and concentration of the individual component within the interphase. The morphological structure of the membrane, solute molecular size, and chemical affinity are the key factors for the efficient separation of chemical components.

Membranes are usually classified as porous and nonporous (dense membranes), organic, inorganic (ceramic), and composite membranes; isotropic and anisotropic; and as cationic and anionic membranes according to the structure, composition, and surface charge [69]. Isotropic (also known as symmetric) membranes are uniform in composition and physical structure, whereas anisotropic membranes are non-uniform over the membrane area and are made up of different layers with different compositions and structures. Isotropic membranes can be either microporous and nonporous (dense) with high and low permeation fluxes, respectively. Anisotropic (asymmetric) membranes have a thicker and highly permeable layer, and they are particularly applied in reverse osmosis (RO) processes [71].

A membrane can be classified as organic (polymeric), inorganic (ceramic), composites, and liquid, according to its material make-up. Organic membranes are usually made from polymers such as polysulfone (PS), polyethersulfone (PES), polyvinylidene fluoride (PVDF), polyethylene (PE), polytetrafluorethylene (PTFE), polypropylene, and cellulose acetate, among others [68,72]. The typical fabrication methods for organic membranes are (1) interfacial polymerization and (2) phase separation methods. Inorganic membranes are made from such materials as clays, geopolymers, carbon molecular sieves, metals, zeolites, and silica, among others [68,70]. The advantages of inorganic membranes are their chemical and thermal stability, and the literature suggests that the hydraulic performance of inorganic membranes is better. Ceramic membranes utilized for water and wastewater treatment usually have anisotropic structures comprising a thin selective layer, intermediate layer(s), and a permeable supporting layer. The thin selective layer provides the separation objective, while the intermediate and support layers provide the desired selectivity as well as stability and strength [73].

The geometries and configuration of membranes used for purification are governed by the supports that allow them to be either in the form of flat geometry (i.e., flat sheet) with different packing densities or cylindrical configuration (namely hollow-fiber and multichannel tubular) [74]. Among the different geometries, tubular and hollow-fiber ceramic membranes are well suited for application in wastewater treatment [73], since hollow-fiber and multichannel tubular membrane modules have higher mechanical strength and better handling capability against high crossflow velocities as compared to a flat-sheet membrane [74]. In addition, ceramic membranes are resistant to chlorine, frequently used to clean membranes for flux recovery, and are less prone to organic fouling due to their hydrophilicity [73]. However, organic membranes are the most popular due to their high selectivity rates, relative ease of operation and surface feature modifications, and the vast extent of studies [75].

Membrane fouling is the most common maintenance issue in use for wastewater treatment. Hydrodynamic techniques used to reduce fouling rates include "Dean and Taylor" vortices, pulsatile flows, and dynamic filtration, which can generate high shear rates more efficiently than crossflow filtration. Conventional dead-end filtration (DEF), crossflow filtration (CF), and dynamic filtration (DF) are illustrated in Figure 5.

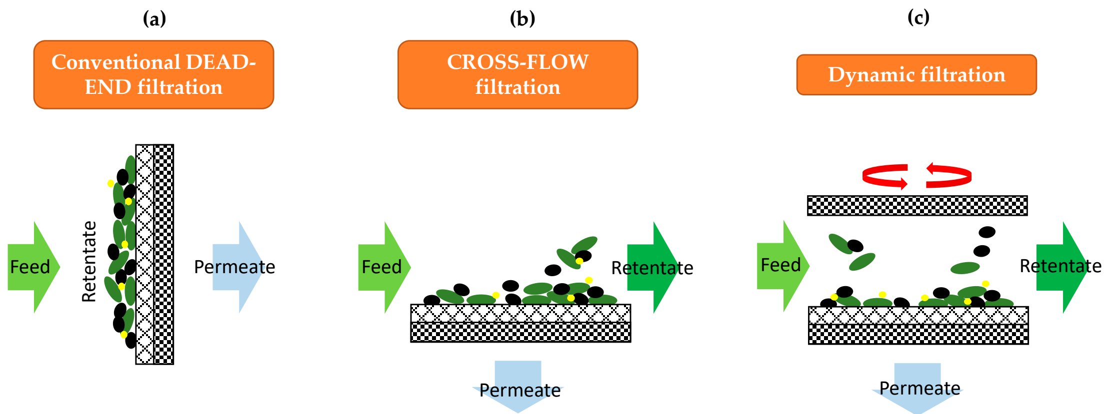

Figure 5. Direction flow in (**a**) dead-end (perpendicular feed), (**b**) crossflow (tangential feed), and (**c**) dynamic filtration.

A large number of hydrodynamic operation techniques, based on fluid instabilities, have been investigated in the application of membranes for wastewater treatment, including pulsating flow, periodic stop of the transmembrane pressure, generation of "Dean or Taylor" vortices, introduction of turbulence promoters (baffled channel, stamped membrane), periodic back-flush or a back-shock process, or the use of a two-phase flow (gas-liquid, liquid-solid) [76]. In dynamic filtration, a mechanical device is introduced to promote turbulence at the membrane surface independently of retentate flow rate. Dynamic filtration modules could use either a vibrating and rotating membrane or the motion of a mechanical device with a rotating and/or vibration disc or impeller [76]. These strategies are applied in pressure-driven-based technologies as microfiltration.

3.4. Adapting Membranes for Wastewater Treatment

Membrane technology may be classified by the different driving forces of the process. The separation phenomena through the membranes are based on different driving forces. Separation processes are equilibrium-based and non-equilibrium-based, and membrane processes may be further classified as pressure-driven and non-pressure-driven as represented in Figure 6.

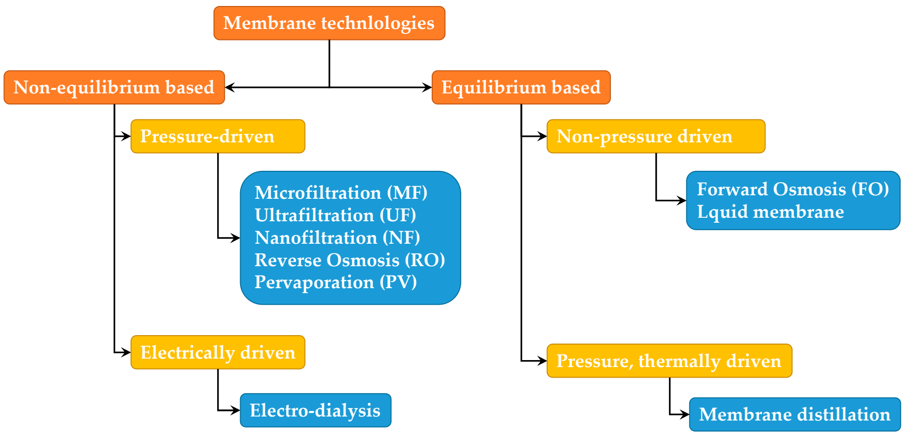

Figure 6. Schematic representation of some membrane processes. Reprinted/adapted with permission from Ref. [70].

Pressure-driven-based membranes, i.e., processes that rely on hydraulic pressure to achieve separation, are by far the most widely applied processes in wastewater treatment. The fourth main types of these processes are microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO). The main difference exhibited by these processes, apart from their pressure requirements, is their membrane pore sizes [70]. Table 2 provides a summary of the main features of these processes.

Table 2. Characteristic of pressure-driven-based membranes. Reprinted/adapted with permission from Ref. [70].

Membrane Process	Pressure Required (bar)	Average Permeability (L/m^2 h bar)	Nominal Pore Size (µm)	Solutes Retained
MF	1–3	500	0.1–10	Bacteria, fat, oil, grease, colloids, and particles
UF	2–5	150	0.01–0.1	Proteins, pigments
NF	5–15	10–20	0.001–0.01	Divalent ions and organics (Mw > 200 g/mol)
RO	15–75	5–10	0.0001–0.001	All contaminants, including monovalent ions

Table 3 summarizes the removal efficiencies of CECs by FO, RO, NF, and UF membranes from different aqueous media and under diverse experimental conditions. RO, FO, NF, and UF may remove CECs from wastewater effluents with good efficiency depending on the technology, membrane characteristics, and operating conditions. Because of the low molecular weight, CEC removal follows the declining order: RO $\geq$ FO > NF > UF. Although UF alone may not effectively remove CECs, it can be employed as a pretreatment step prior to FO and RO. In addition, it can be concluded that more polar (more hydrophilic) and less volatile organic CECs have less retention than less polar (higher hydrophobic character) and more organic CECs. Most studies of membrane purification focus on only one technology (FO, RO, NF, or UF), the use of commercial membranes (e.g., HTI-CTA), and the removal of a few compounds under selected conditions (pH and conductivity are not typically assessed, and scarce studies aim to study the differences among dead end, crossflow, or dynamic flow). Thus, future studies should aim to investigate the removal mechanisms of FO, RO, NF, and UF membranes in the presence of co- and counterions in natural source waters, efficiencies in the presence of different NOMs, and draw solutions for FO membranes, aiming to reduce the effect of fouling and evaluate larger-scale processes.

3.5. Permeable Reactive Barriers Coupled to Managed/Unmanaged Aquifer Recharge

Despite the removal efficiencies reported in membrane filtrate and oxidation processes for the removal of CECs, these treatment methods are mostly regarded as tertiary technologies to clean effluents of wastewater treatment facilities for use in drinking or discharge into highly regulated surface waters. Direct use of treated wastewater for drinking is quite expensive, and surface water effluent regulations in Central Asia are unlikely to regulate these contaminants. Recently, attention has been paid to the development and application of innovative and environmentally sustainable technologies for low-cost treatment and reuse of wastewater to solve global problems of water scarcity. One innovative idea is continuous purification of wastewaters by permeable reactive barriers (PRBs), which feed partially treated wastewaters to groundwater by managed aquifer recharge (MAR). MAR can be a viable alternative to the traditional pumping and purification typically used for the restoration of local groundwater quantity and quality [77]. Combining managed aquifer recharge and wastewater treatment with PRBs has progressed rapidly from laboratory bench studies to full-scale implementation [78]. PRBs originally were developed and used to treat groundwater contaminated with inorganic constituents, such as heavy metals. Traditional approaches to treat contaminated groundwater involve removal of the contaminant source through pumping, followed by treatment of the plumes of contaminated groundwater, or by isolation of the contaminant source, employing low-permeability barriers or covers. The use of PRBs has appeared as an alternative in situ approach to replace or supplement those existing techniques [79].

Table 3. Removal of Contaminants of Emerging Concern (CECs) by forward osmosis (FO), reverse osmosis (RO), nanofiltration (NF) and ultrafiltration (UF) membranes.

Membrane Technology	Membrane	Draw Solution	Flow Type	CEC	C_0	AM *	Key Removal (%)	Ref.
UF	Polyamide TFC (MWCOs ¥ = 2–20 kDa)		Crossflow	Pesticides (chlortoluron, isoproturon, diuron, linuron)	5–50 µM	SW	35–85 w/NOM; 40–90 w/o NOM	[80]
UF	Hollow fiber cellulose acetate (MWCO ¥ = 100 kDa)		Crossflow	Benzotriazole, *N*,*N*-diethyl-m-toluamide, 3-methylindole, chlorophene, nortriptyline	1 µM	WW	<5	[81]
UF	UF (MWCO ¥ = 100 kDa)		Crossflow	16 PhACs Φ	<10–2500 ng L^{-1}	SW	<5–95	[82]
UF	Powdered AC + UF (MWCO ¥ = 100 kDa)		Crossflow	16 PhACs Φ	<10–2500 ng L^{-1}	SW	20–95	[82]
UF	Hollow fiber (Pore size = 0.04)		Outside-in	16 EDCs † and PPCPs Γ	1000 ng L^{-1}	NW	<5–90	[83]
UF	Polyamide TFC (MWCOs ¥ = 2–20 kDa)		Crossflow	11 EDCs † and PPCPs Γ	500 µg L^{-1}	SW and WW	<60 excluding hydroxybiphenyl (>90)	[84]
UF	Sulfonated PES (MWCO ¥ = 8 kDa)		Dead-end	E2	0.1, 0.5 µM	SW	10–20 w/ NOM; 60–95 w/o NOM	[85]
UF	MWCOs ¥ = 1–100 kDa		Dead-end	E2, E2, progesterone, testosterone	100 ng L^{-1}	SW	20–50 (E2), 15–40 (E3), 35–65 (progesterone), 5–30 (testosterone)	[86]
UF	Hollow fiber			Amoxicillin, cefuroxime axetil	20 mg L^{-1}	WW	70–71 (hollow fiber)	[87]
UF	Spiral wound			Amoxicillin, cefuroxime axetil	20 mg L^{-1}	WW	90–91 (spiral wound)	[87]
UF	Hollow fiber, polyvinylidene fluoride			Atenolol, dilatin, carbamazepine, caffeine, diclofenac, sulfamethoxazole	54.1–206.6 ng L^{-1}	WW	<40 (DCF > SMX > caffeine > others)	[88]

Table 3. *Cont.*

Membrane Technology	Membrane	Draw Solution	Flow Type	CEC	C_0	AM *	Key Removal (%)	Ref.
UF	MWCO ¥ = 100 kDa		Dead-end	EDCs † and bisphenol A	100 µg L^{-1}	WW	10–90 (BPA > EE2 ≥ E2 ≥ E1 > E3)	[89]
UF	MWCO ¥ = 1 k, 10 kDa		Crossflow	10 PPCPs Γ	1–150 ng L^{-1}	WW	<1–99	[90]
UF	Powdered AC-UF Pore size = 20, 40 nm			Sulfamethoxazole, carbamazepine, mecoprop, diclofenac, benzotriazole	200–4300 µg L^{-1}	WW	35–95	[91]
NF	TFC or CA (MWCOs ¥ = 15–300 Da)		Crossflow	11 EDCs † and PPCPs Γ	500 µg L^{-1}	SW and WW	>70 excluding acetaminophen (<40)	[84]
NF	MWCO ¥ = 490, 560 Da		Crossflow	E1	100 ng L^{-1}	SW	10–40 after 10 hr filtration time	[92]
NF	TFC (thin-film composite)		Crossflow	Acetaminophen, amoxicillin, cephalexin, indomethacin, tetracycline	500 µg L^{-1}	SW	35–99	[93]
NF	Polypierazine (Pore radius = 0.128 nm)		Crossflow	Carbamazepine, acetaminophen, atenolol, diatrozate	750 µg L^{-1}	WW	90–95	[94]
NF	Polypierazine (Pore radius = 0.258 nm)		Crossflow	Carbamazepine, acetaminophen, atenolol, diatrozate	750 µg L^{-1}	WW	20–90	[94]
NF	TFC polyamide (MWCO ¥ = 200–300 Da)		Crossflow	Organic acids including ibuprofen, glutaric acid, acetic acid	1.5–13.2 mg L^{-1}	SW	10–95	[95]
NF	NF270-polyamide TF and NTR7450-TFC (MWCO ¥ = 300–550 Da)		Crossflow	Acetaminophen, sulfamethoxazole, triclosan	500 µg L^{-1}	SW	<10 (acetaminophen), 35–80 (SMX), 80–95 (TCS)	[96]
NF	Polyamide TFC		Crossflow	18 PPCPs Γ charged (positive, neutral, and negative)	2000 ng L^{-1}	SW	>60	[97]
NF	NF90 4040 NF membranes (spiral wound, MWCO ¥ = 200 Da)			12 PhACs Φ	<1–58.8 ng L^{-1}	NW	24–99	[98]

Table 3. *Cont.*

Membrane Technology	Membrane	Draw Solution	Flow Type	CEC	C_0	AM *	Key Removal (%)	Ref.
NF	Polyamide TFC		Crossflow	Carbamazepine, diatrizoate	800 μg L^{-1}	WW	>53	[99]
NF	Surface modified NF		Crossflow	Bisphenol A, ibuprofen	1000 μg L^{-1}	SW	75–95 (BPA), >95 (IBP)	[100]
NF	UTC-60 (MWCO ¥ = 150 Da)		Crossflow	Clofibric acid, diclofenac, ketoprofen, carbamazepine, primidone	100 ng L^{-1}	SW and WW	>70	[101]
NF	TFC		Crossflow	8 PhACs Φ	10 mg L^{-1}	SW	99–99.4	[102]
NF	Polyamide TFC (MWCO ¥ = 150–400 Da)		Crossflow	10 PPCPs Γ	1–150 ng L^{-1}	WW	13–99	[90]
NF	NF200 (MWCO ¥ = 200–300 Da)		Dead-end	17 PhACs Φ	10 μg L^{-1}	SW	35–99	[103]
MBR-NF	MBR-flat sheet, MBR-hollow fiber			10 EDCs † and PPCPs Γ	0.06–59.5 μg L^{-1}	WW	4.2–>99	[104]
MBR-NF	MWCO ¥ = 210 Da		Crossflow	11 EDCs † and PPCPs Γ	26.2–433.9 ng L^{-1}	WW	78–>99	[105]
RO	Dow Filmtec-BW-30		Crossflow	Phenol, 4-chlorophenol, atrazine, carbamazepine, sulfamethoxazole	2 μM	SW	ATZ (93.7), CBM (84.3), SMT (75.2), 4CP (60.9), PHN (47.3)	[106]
RO	Sahan-RE4040-FL, Spiral wound			26 EDCs † and PPCPs Γ	10–11,500 ng L^{-1}	WW	>90–99	[107]
RO	Polyamide		Crossflow	E1	100 ng L^{-1}	WW	>90	[108]
RO	Cellulose acetate		Crossflow	E1	100 ng L^{-1}	WW	30–90	[108]
RO	Eight commercial membranes		Crossflow, Dead-end	E2, E3	100 ng L^{-1}	SW	>80	[109]
RO	Four RO membranes		Dead-end	E1	100 ng L^{-1}	SW	>95	[110]
RO	Polyamide TFC			Atenolol, dilatin, carbamazepine, sulfamethoxazole, caffeine, diclofenac	54.1–206.6 ng L^{-1}	WW	>60	[88]

Table 3. *Cont.*

Membrane Technology	Membrane	Draw Solution	Flow Type	CEC	C_0	AM *	Key Removal (%)	Ref.
RO	ESPA4-Polyamide TFC		Crossflow	18 PPCPs ^{Γ}	2000 ng L^{-1}	SW	>95	[97]
RO	Polyamide			16 EDCs † and PPCPs ^{Γ}	0.55–610 µg L^{-1}	NW	>87	[111]
RO	Polyamide		Crossflow	11 EDCs † and PPCPs ^{Γ}	100 µg L^{-1}	SW	57–91 (polyamide)	[112]
RO	Cellulose acetate		Crossflow	11 EDCs † and PPCPs ^{Γ}	100 µg L^{-1}	SW	<1–85 (cellulose acetate)	[112]
RO	TFC on polyester		Crossflow	10 PPCPs ^{Γ}	1–150 ng L^{-1}	WW	<19–99	[90]
MBR + RO	flat-sheet membranes (Kubota, porous size of 0.4 m)		Crossflow	20 PhACs ^{Φ}	17–2020 ng L^{-1}	WW	>99	[113]
MBR + RO	CTA, Spiral wound		Crossflow	6 antibiotics, 3 pharmaceuticals, and bisphenol A	<1500 ng L^{-1}	WW	>93	[114]
MBR − RO	MBR-flat sheet, MBR-hollow fiber			10 EDCs † and PPCPs ^{Γ}	0.06–59.5 µg L^{-1}	WW	4.2–99	[104]
FO/RO mode	HTI-CTA	NaCl, $MgSO_4$		Bisphenol A, triclosan, diclofenac	500 µg L^{-1}	WW	>80 (BPA), >95 (TCS), >90 (DCF)	[115]
FO	HTI-CTA		Crossflow (58.8 cm s^{-1})	Phenol, 4-chlorophenol, atrazine, carbamazepine, sulfamethoxazole	2 Mm	SW	SMT (89.7), CBM (82.6), ATZ (48.7), 4CP (38.6), PHN (21.9)	[106]
FO	CTA	NaCl	Crossflow	E1, E2	1000 ng L^{-1}	SW	>95 (E1), 75–95 (E2)	[116]
FO	CTA	NaCl, $MgSO_4$, glucose	Crossflow (9 cm s^{-1})	12 EDCs † and PPCPs ^{Γ}	2000 ng L^{-1}	SW	30–90	[117]
FO	HTI-CTA	NaCl	Crossflow	18 PPCPs ^{Γ} charged	2000 ng L^{-1}	SW	> 50	[97]
FO	HTI-CTA	NaCl		23 EDCs † and PPCPs ^{Γ} (positive, negative, hydrophobic non-ionic, non-ionic)	0.63–388 ng L^{-1}	WW	>40	[118]

Table 3. *Cont.*

Membrane Technology	Membrane	Draw Solution	Flow Type	CEC	C_0	AM *	Key Removal (%)	Ref.
FO	TiO_2 modified FO	NaCl	Crossflow	MTP, sulfamethoxazole, triclosan,	500 µg L^{-1}	SW	>97	[119]
FO	CTA and TFC	NaCl	Crossflow	carbamazepine, diclofenac, ibuprofen, naproxen	250 µg L^{-1}	SW	65–>95 (CBM > DCF > IBP > NPX)	[120]
FO	HTI-CTA	NaCl	Crossflow (8 cm s^{-1})	sulfamethoxazole, trimethoprim, norfloxacin, roxithromycin	200 µg L^{-1}	WW	90–95	[121]
FO + electrochemical oxidation	HTI-CTA	NaCl	Crossflow (20.4 cm s^{-1})	24 PhACs [Φ]	100 µg L^{-1}	SW	>60 (retention increases with increasing water flux)	[122]

* AC = Activated Carbon; AM = aqueous media; SW = synthetic water; WW = wastewater; NW = natural surface water or groundwater. [¥] MWCO = molecular weight cutoff. [Φ] PhACs = pharmaceutically active compounds; [†] EDCs = endocrine-disrupting compounds; [Γ] PPCP = pharmaceutical and personal care products, TFC = thin film composite, CTA = cellulose tri-acetate.

Application of PRBs to eliminate CECs from wastewater prior to groundwater replenishment by MAR may provide a promising solution, particularly in water-scarce regions such as Central Asia. PRBs are barriers through which waters should flow, constituted by materials that passively capture a plume of contaminants and remove or break down the contaminants, releasing uncontaminated water by adsorption, precipitation, chemical reaction, or reactions involving biological mechanisms [123]. Using this technology, purified water can be used to replenish local groundwater by MAR. The selection of proper materials, as adsorbents and catalysts, is crucial in the development of PRBs for the removal of CECs, such as antibiotics, from effluents of wastewater treatment plants [124]. As previously discussed, several investigators have reported the suitability of synthetic carbon-based materials or natural clay-based materials as adsorbents for the removal of antibiotics from waters and wastewaters. For example, the removal of sulfamethoxazole and tetracycline was evaluated and validated with biochars (BCs), activated carbons (ACs), carbon nanotubes (CNTs), graphite, bentonite, and clay minerals [125]. Other studies have revealed high performance in complete mineralization of antibiotics and pharmaceutical compounds by chemical oxidation reactions. These reactive materials have yet to be incorporated into a PRB system for wastewater treatment and groundwater recharge. Magnetic graphitic nanocomposites were also prepared and employed as efficient heterogeneous catalysts in the activation of persulfate for the degradation of SMX [126]. Taking into consideration the previously demonstrated capacity of carbon-based materials and natural clay-based materials as adsorbents and catalysts, it is reasonable to conceive the development of PRBs with these fillers to remove CECs from the effluents of wastewater treatment plants for further recharge of groundwaters by MAR.

Locally produced carbon nanotubes (CNTs) may serve as an environmentally friendly, effective, and fast in situ remediation technology which may be easily derived from wastewater influent [127]. CNTs are a highly efficient adsorbent material, as hexagonal arrays of carbon atoms have a strong interaction with other molecules. Pollutant adsorption can be improved through surface modification with functional groups such as –COOH, –OH, and $–NH_2$ by chemical oxidation [128]. While conventional CNT production with vapor deposition using pure polymer feedstock is expensive, a recently developed process involves the synthesis of CNTs from plastic waste, providing a low-cost, valorization of co-occurring solid pollutants that is currently another global concern [127]. CNTs synthesized from plastic waste were activated using persulfate, impregnation, and co-precipitation (using Al_2O_3, Ni, Fe, and/or Al) and implemented to grow CNTs by CVD using low-density polyethylene as carbon feedstock [127]. These CNTs were also used to fabricate a composite polymeric membrane with poly(vinylidene fluoride) that was demonstrated to be effective for the removal of the CEC venlafaxine in continuous mode of operation [129].

Natural clays are also low-cost locally sourced adsorbents and permeable catalysts that can also be used in PRBs [130]. For example, column tests combined with reactive transport modeling have reported hydraulic conductivities of a mixture of pillared clays and wood of ~10^{-4} m/s, sufficient to ensure an adequate hydraulic performance of an eventual barrier excavated in most aquifers. Several column experiments confirmed Cs retention under different flow rates and inflow solutions [130]. The use of natural pillared clay-based materials in the removal of CECs from aqueous solutions was also reported [131], making the modification of natural clays promising for the development of PRBs for the treatment of effluents of wastewater treatment plants containing CECs.

4. Risk Assessment

Continued use of untreated and improperly treated wastewater for irrigation, livestock consumption, and similar purposes poses a serious risk to human health and must be addressed through better wastewater management practices. Treated wastewater in water-scarce Central Asia is increasingly reused and should be seen as a valuable resource, requiring effective management due to its relationship with surface and groundwater quality used for drinking and agricultural irrigation purposes [6]. Current wastewater treatment technologies are generally inadequate, relying on conventional activated sludge treatment (CAST), evaporation, and stabilization ponds [9]. Stabilization ponds remain a common wastewater treatment practice due to their low cost and simplicity; however, they are an inefficient use of a valuable resource and likely lead to contamination of local groundwater, thus reducing the availability of this valuable resource for human consumption, irrigation, and other purposes. For example, in Kazakhstan, it is noted that biological treatment stages for most municipal wastewater systems are not operating properly and are likely discharging poorly or even untreated wastewater, with human health consequences [132].

Alternatives to current wastewater treatment used in Central Asia are required to reduce health risks associated to the reuse of water in this region, especially if the wastewater is used for irrigation. Continued inefficient removal of pollutants and lack of treatment imply critical human health risks because exposure to an identified range of contaminants threatens food security, nutrition, and livelihoods. Reports from different locations globally have linked microbial outbreaks with agricultural reuse of wastewater, urging the need to raise the awareness of societal, governmental, and regulatory bodies in Central Asia. There is an urgent need for investments that target safe and quality wastewater reuse [133].

5. Future Perspective

This review provides a summary of the literature on wastewater treatment issues and potential solutions beyond traditional wastewater treatment. We show that the incorporation of system designs using membrane bioreactors, sequencing batch reactors, and moving bed biofilm reactors has been effective in treating wastewater in Central Asia. However, their success depends on various factors, and efforts are being made to optimize these technologies for the specific conditions in the region. Decentralized wastewater treatment systems may become more common, as they can provide cost-effective and sustainable wastewater treatment solutions, particularly in rural and remote areas where centralized wastewater treatment systems are not feasible. Alternatives which may further improve wastewater quality for safe reuse include adsorption, advanced oxidation processes, and membrane technologies. Permeable reactive barriers may be coupled with managed aquifer recharge using permeable reactive barriers, aiming to increase the availability and quality of local freshwater sources. Practical adsorption techniques using activated carbon seem particularly effective at removing a wide range of emerging contaminants, including dyes, heavy metals, pharmaceuticals, pesticides, and petroleum hydrocarbons. Biochar, graphene, and locally produced carbon nanotubes all may improve techniques for removing difficult-to-treat CECs. AOPs are effective in the complete destruction of CECs in wastewater. Membrane technologies can be employed in either pre- or post-treatment in any wastewater treatment scheme.

Depending on local hydrogeology, onsite purification using permeable reactive barriers (PRBs) and storage by recharging local groundwater using managed aquifer recharge (MAR) seems to be a particularly appealing means for addressing local groundwater depletion. The selection of proper adsorbents and catalysts will need to be tested on effluents from wastewater treatment plants to demonstrate their practicality. To make this technology a reality in Central Asia, more projects are needed. Research on low-cost synthesis and characterization of inexpensive carbon nanotubes from plastic solid waste and the modification of natural clay-based materials should also be considered. Proposed treatment processes must consider the removal of CECs identified in wastewater, and few studies have evaluated these contaminants in Central Asia. Finally, the synthesis and characterization of inexpensive carbon nanotubes from plastic solid waste and the modification of natural clay-based materials seem promising for PRBs and MAR for local wastewater treatment, storage, and reuse.

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References

1. Costa, S.I.G.; Ferreira, F.L.; Weschenfelder, S.E.; Fuck, J.V.R.; da Cunha, M.d.F.R.; Marinho, B.A.; Mazur, L.P.; da Silva, A.; de Souza, S.M.A.G.U.; de Souza, A.A.U. Towards the removal of soluble organic compounds present in oilfield produced water by advanced oxidation processes: Critical review and future directions. *Process Saf. Environ. Prot.* **2023**, *174*, 608–626. [CrossRef]
2. Ngoubeyou, P.S.K.; Wolkersdorfer, C.; Ndibewu, P.P.; Augustyn, W. Toxicity of polychlorinated biphenyls in aquatic environments—A review. *Aquat. Toxicol.* **2022**, *251*, 106284. [CrossRef] [PubMed]
3. Allen, D.S.; Kolok, A.S.; Snow, D.D.; Satybaldiyev, B.; Uralbekov, B.; Nystrom, G.S.; Thornton Hampton, L.M.; Bartelt-Hunt, S.L.; Sellin Jeffries, M.K. Predicted aquatic and human health risks associated with the presence of metals in the Syr Darya and Shardara Reservoir, Kazakhstan. *Sci. Total Environ.* **2023**, *859*, 159827. [CrossRef] [PubMed]
4. Snow, D.D.; Chakraborty, P.; Uralbekov, B.; Satybaldiev, B.; Sallach, J.B.; Thornton Hampton, L.M.; Jeffries, M.; Kolok, A.S.; Bartelt-Hunt, S.B. Legacy and current pesticide residues in Syr Darya, Kazakhstan: Contamination status, seasonal variation and preliminary ecological risk assessment. *Water Res.* **2020**, *184*, 116141. [CrossRef]
5. Crosa, G.; Froebrich, J.; Nikolayenko, V.; Stefani, F.; Galli, P.; Calamari, D. Spatial and seasonal variations in the water quality of the Amu Darya River (Central Asia). *Water Res.* **2006**, *40*, 2237–2245. [CrossRef]
6. Verlicchi, P.; Lacasa, E.; Grillini, V. Quantitative and qualitative approaches for CEC prioritization when reusing reclaimed water for irrigation needs—A critical review. *Sci. Total Environ.* **2023**, *900*, 165735. [CrossRef]
7. Singh, A.; Chaurasia, D.; Khan, N.; Singh, E.; Chaturvedi Bhargava, P. Efficient mitigation of emerging antibiotics residues from water matrix: Integrated approaches and sustainable technologies. *Environ. Pollut.* **2023**, *328*, 121552. [CrossRef]
8. Williams-Nguyen, J.; Sallach, J.B.; Bartelt-Hunt, S.; Boxall, A.B.; Durso, L.M.; McLain, J.E.; Singer, R.S.; Snow, D.D.; Zilles, J.L. Antibiotics and Antibiotic Resistance in Agroecosystems: State of the Science. *J. Environ. Qual.* **2016**, *45*, 394–406. [CrossRef]
9. Andraka, D.; Ospanov, K.; Myrzakhmetov, M. Current state of communal sewage treatment in the Republic of Kazakhstan. *J. Ecol. Eng.* **2015**, *16*, 101–109. [CrossRef]
10. Nguyen, P.Y.; Carvalho, G.; Reis, M.A.M.; Oehmen, A. A review of the biotransformations of priority pharmaceuticals in biological wastewater treatment processes. *Water Res.* **2021**, *188*, 116446. [CrossRef]
11. Adegoke, A.A.; Amoah, I.D.; Stenström, T.A.; Verbyla, M.E.; Mihelcic, J.R. Epidemiological evidence and health risks associated with agricultural reuse of partially treated and untreated wastewater: A review. *Front. Public Health* **2018**, *6*, 337. [CrossRef] [PubMed]
12. Kesari, K.K.; Soni, R.; Jamal, Q.M.S.; Tripathi, P.; Lal, J.A.; Jha, N.K.; Siddiqui, M.H.; Kumar, P.; Tripathi, V.; Ruokolainen, J. Wastewater treatment and reuse: A review of its applications and health implications. *Water Air Soil Pollut.* **2021**, *232*, 208. [CrossRef]
13. Dickin, S.K.; Schuster-Wallace, C.J.; Qadir, M.; Pizzacalla, K. A review of health risks and pathways for exposure to wastewater use in agriculture. *Environ. Health Perspect.* **2016**, *124*, 900–909. [CrossRef] [PubMed]
14. Severskiy, I.V. Water-related problems of Central Asia: Some results of the (GIWA) international water assessment program. *AMBIO J. Hum. Environ.* **2004**, *33*, 52–62. [CrossRef]
15. Bhargava, A. Activated Sludge Treatment Process—Concept and System Design. *Int. J. Eng. Dev. Res.* **2016**, *4*, 890–896.
16. Daigger, G.T.; Boltz, J.P. Trickling filter and trickling filter-suspended growth process design and operation: A state-of-the-art review. *Water Environ. Res.* **2011**, *83*, 388–404. [CrossRef]
17. Parveen, S.; Malviya, A. Analytical Review on Membrane Water Filter using Different Materials to Prevent Microbial Activities. *J. Pure Appl. Microbiol.* **2022**, *16*, 2352–2362. [CrossRef]
18. Wu, Y.-H.; Chen, Z.; Li, X.; Wang, Y.-H.; Liu, B.; Chen, G.-Q.; Luo, L.-W.; Wang, H.-B.; Tong, X.; Bai, Y. Effect of ultraviolet disinfection on the fouling of reverse osmosis membranes for municipal wastewater reclamation. *Water Res.* **2021**, *195*, 116995. [CrossRef]

19. Latif, E.F. Applying novel methods in conventional activated sludge plants to treat low-strength wastewater. *Environ. Monit. Assess.* **2022**, *194*, 323. [CrossRef]
20. Ospanov, K.; Kuldeyev, E.; Kenzhaliyev, B.; Korotunov, A. Wastewater treatment methods and sewage treatment facilities in Almaty, Kazakhstan. *J. Ecol. Eng.* **2022**, *23*, 240–251. [CrossRef]
21. Sanderson, H.; Fricker, C.; Brown, R.S.; Majury, A.; Liss, S.N. Antibiotic resistance genes as an emerging environmental contaminant. *Environ. Rev.* **2016**, *24*, 205–218. [CrossRef]
22. Michael, I.; Hapeshi, E.; Vasquez, M.I.; Toumazi, T.; Fatta-Kassinos, D. Urban wastewater treatment processes. In *Integrated Water Cycle Management in Kazakhstan*; Meyer, B.C., Lundy, L., Eds.; Al-Farabi Kazakh National University: Almaty, Kazakhstan, 2014; pp. 113–118.
23. *Rules of Surface Water Protection of the Republic of Kazakhstan, 21*; Guiding Normative Document 01.01.03-94; Ministry of Ecology and Bioresources: Astana, Kazakhstan, 1994.
24. Heaven, S.; Lock, A.; Pak, L.; Rspaev, M. Waste stabilisation ponds in extreme continental climates: A comparison of design methods from the USA, Canada, northern Europe and the former Soviet Union. *Water Sci. Technol.* **2003**, *48*, 25–33. [CrossRef] [PubMed]
25. Tilley, E.; Ulrich, L.; Lüthi, C.; Reymond, P.; Zurbrügg, C. *Compendium of Sanitation Systems and Technologies*, 2nd ed.; Swiss Federal Institute of Aquatic Science and Technology (Eawag): Duebendorf, Switzerland, 2014.
26. Ødegaard, H.; Balmer, P.; Hanaeus, J. Chemical precipitation in highly loaded stabilization ponds in cold climates: Scandinavian experiences. *Water Sci. Technol.* **1987**, *19*, 71–77. [CrossRef]
27. Heaven, S.; Banks, C.; Pak, L.; Rspaev, M. Wastewater reuse in central Asia: Implications for the design of pond systems. *Water Sci. Technol.* **2007**, *55*, 85–93. [CrossRef] [PubMed]
28. ZhKH, K. *Kazakhstan: Urban Infrastructure Modernization Program—Wastewater Treatment Project: Construction of Wastewater Treatment Plant in Zhezkazgan City*; Project Number: 51365–001; Asian Development Bank: Manila, Philippines, 2020.
29. ADB. *ADB TA 9715-UZB: Tashkent Province Sewerage Improvement Project Technical Due Diligence Report*; Project number: 52317–001; Asian Development Bank: Manila, Philippines, 2021; p. 669.
30. Penetron. Atyrau Wastewater Treatment Plant. Available online: https://www.penetron.com/projects/view/Atyrau-Wastewater-Treatment-Plant (accessed on 27 July 2023).
31. Ali, O. *Decentralised Sanitation Solutions in Tajikistan: Decentralised Wastewater Treatment Systems (DEWATS) in Peri-Urban and Urban Areas in Tajikistan*; Oxfam: Oxford, UK, 2022. [CrossRef]
32. Rustamov, E.A.; Karina, Z.; Davletbakov, A.T.; Kozybakov, A.M. *Update of the Information on the Status of the Wetlands in Kazakhstan, Kyrgyzstan and Turkmenistan by Collection and Dissemination of Good Practices for Conservation and Sustainable Use of Wetlands by Local Communities*; Ramsar Regional Initiative for Central Asia: Almaty, Kazakhstan, 2018; 110p.
33. Tesch, N.; Thevs, N. Wetland distribution trends in Central Asia. *Cent. Asian J. Water Res.* **2020**, *6*, 39–54. [CrossRef]
34. Geetha Varma, V.; Jha, S.; Himesh Karthik Raju, L.; Lalith Kishore, R.; Ranjith, V. A review on decentralized wastewater treatment systems in India. *Chemosphere* **2022**, *300*, 134462. [CrossRef]
35. JICA. *Central Asia and the Caucasus*; Japan International Cooperation Agency Annual Report; JICA: Tokyo, Japan, 2010; pp. 46–51.
36. Zhang, J.; Xiao, K.; Liu, Z.; Gao, T.; Liang, S.; Huang, X. Large-Scale Membrane Bioreactors for Industrial Wastewater Treatment in China: Technical and Economic Features, Driving Forces, and Perspectives. *Engineering* **2021**, *7*, 868–880. [CrossRef]
37. Zaharia, C. Decentralized wastewater treatment systems: Efficiency and its estimated impact against onsite natural water pollution status. A Romanian case study. *Process Saf. Environ. Prot.* **2017**, *108*, 74–88. [CrossRef]
38. Zhupankhan, A.; Tussupova, K.; Berndtsson, R. Water in Kazakhstan, a key in Central Asian water management. *Hydrol. Sci. J.* **2018**, *63*, 752–762. [CrossRef]
39. Salimi, M.; Esrafili, A.; Gholami, M.; Jonidi Jafari, A.; Rezaei Kalantary, R.; Farzadkia, M.; Kermani, M.; Sobhi, H.R. Contaminants of emerging concern: A review of new approach in AOP technologies. *Environ. Monit. Assess.* **2017**, *189*, 414. [CrossRef]
40. Phoon, B.L.; Ong, C.C.; Saheed, M.S.M.; Show, P.-L.; Chang, J.-S.; Ling, T.C.; Lam, S.S.; Juan, J.C. Conventional and emerging technologies for removal of antibiotics from wastewater. *J. Hazard. Mater.* **2020**, *400*, 122961. [CrossRef] [PubMed]
41. De Ilurdoz, M.S.; Sadhwani, J.J.; Reboso, J.V. Antibiotic removal processes from water & wastewater for the protection of the aquatic environment—A review. *J. Water Process Eng.* **2022**, *45*, 102474.
42. Wang, S.; Li, X.; Zhao, H.; Quan, X.; Chen, S.; Yu, H. Enhanced adsorption of ionizable antibiotics on activated carbon fiber under electrochemical assistance in continuous-flow modes. *Water Res.* **2018**, *134*, 162–169. [CrossRef] [PubMed]
43. Attia, A.A.M.; Abas, K.M.; Ahmed Nada, A.A.; Shouman, M.A.H.; Šišková, A.O.; Mosnáček, J. Fabrication, modification, and characterization of lignin-based electrospun fibers derived from distinctive biomass sources. *Polymers* **2021**, *13*, 2277. [CrossRef]
44. Wackett, L.P. Nothing lasts forever: Understanding microbial biodegradation of polyfluorinated compounds and perfluorinated alkyl substances. *Microb. Biotechnol.* **2022**, *15*, 773–792. [CrossRef]
45. Chali, W.; Yakub, I. The Performance of Coconut Shell-based Activated Carbon (CSAC) in Treating Drinking Water. *J. Civ. Eng. Sci. Technol.* **2013**, *4*, 11–16. [CrossRef]
46. Okoye, C.C.; Onukwuli, O.D.; Onyesolu, C.F.O.; Okafo, I.A.O. Remediation of crystal violet dye aqueous solution using agro waste based activated carbon: Equilibrium and kinetics studies. *J. Eng. Res. Rep.* **2020**, *15*, 1–11. [CrossRef]
47. Amiri, M.J.; Bahrami, M.; Beigzadeh, B.; Gil, A. A response surface methodology for optimization of 2,4-dichlorophenoxyacetic acid removal from synthetic and drainage water: A comparative study. *Environ. Sci. Pollut. Res.* **2018**, *25*, 34277–34293. [CrossRef]

48. Zhang, Y.; Cao, B.; Zhao, L.; Sun, L.; Gao, Y.; Li, J.; Yang, F. Biochar-supported reduced graphene oxide composite for adsorption and coadsorption of atrazine and lead ions. *Appl. Surf. Sci.* **2018**, *427*, 147–155. [CrossRef]
49. Zhang, A.; Li, X.; Xing, J.; Xu, G. Adsorption of potentially toxic elements in water by modified biochar: A review. *J. Environ. Chem. Eng.* **2020**, *8*, 104196. [CrossRef]
50. Ji, L.; Chen, W.; Xu, Z.; Zheng, S.; Zhu, D. Graphene nanosheets and graphite oxide as promising adsorbents for removal of organic contaminants from aqueous solution. *J. Environ. Qual.* **2013**, *42*, 191–198. [CrossRef]
51. Li, M.-F.; Liu, Y.-G.; Zeng, G.-M.; Liu, N.; Liu, S.-B. Graphene and graphene-based nanocomposites used for antibiotics removal in water treatment: A review. *Chemosphere* **2019**, *226*, 360–380. [CrossRef] [PubMed]
52. Yusuf, M.; Elfghi, F.; Zaidi, S.A.; Abdullah, E.; Khan, M.A. Applications of graphene and its derivatives as an adsorbent for heavy metal and dye removal: A systematic and comprehensive overview. *RSC Adv.* **2015**, *5*, 50392–50420. [CrossRef]
53. Cruz-Cruz, A.; Rivas-Sanchez, A.; Gallareta-Olivares, G.; González-González, R.B.; Cárdenas-Alcaide, M.F.; Iqbal, H.; Parra-Saldívar, R. Carbon-based materials: Adsorptive removal of antibiotics from water. *Water Emerg. Contam. Nanoplastics* **2023**, *2*, 2. [CrossRef]
54. Sugurbekova, G.K.; Kudaibergenova, R.M.; Ualibek, O.; Sugurbekov, Y.T.; Demeuova, G.K. Method of Producing an Oil-Absorbing Magnetic Sponge. Patent No. 8437 for Utility Model, 22 September 2023.
55. Macías-Quiroga, I.F.; Henao-Aguirre, P.A.; Marín-Flórez, A.; Arredondo-López, S.M.; Sanabria-González, N.R. Bibliometric analysis of advanced oxidation processes (AOPs) in wastewater treatment: Global and Ibero-American research trends. *Environ. Sci. Pollut. Res.* **2021**, *28*, 23791–23811. [CrossRef]
56. Garrido-Cardenas, J.A.; Esteban-García, B.; Agüera, A.; Sánchez-Pérez, J.A.; Manzano-Agugliaro, F. Wastewater treatment by advanced oxidation process and their worldwide research trends. *Int. J. Environ. Res. Public Health* **2020**, *17*, 170. [CrossRef]
57. Feijoo, S.; Yu, X.; Kamali, M.; Appels, L.; Dewil, R. Generation of oxidative radicals by advanced oxidation processes (AOPs) in wastewater treatment: A mechanistic, environmental and economic review. *Rev. Environ. Sci. Bio Technol.* **2023**, *22*, 205–248. [CrossRef]
58. Surenjan, A.; Pradeep, T.; Philip, L. Application and performance evaluation of a cost-effective vis-LED based fluidized bed reactor for the treatment of emerging contaminants. *Chemosphere* **2019**, *228*, 629–639. [CrossRef]
59. Ahangarnokolaei, M.; Ayati, B.; Ganjidoust, H. Simultaneous and sequential combination of electrocoagulation and ozonation by Al and Fe electrodes for DirectBlue71 treatment in a new reactor: Synergistic effect and kinetics study. *Chemosphere* **2021**, *285*, 131424. [CrossRef]
60. Nakata, K.; Fujishima, A. TiO_2 photocatalysis: Design and applications. *J. Photochem. Photobiol. C Photochem. Rev.* **2012**, *13*, 169–189. [CrossRef]
61. Rangel-Peraza, J.G.; Prado, M.A.R.; Amabilis-Sosa, L.E.; Bustos-Terrones, Y.A.; Ramírez-Pereda, B. Malathion removal through peroxi-electrocoagulation and photocatalytic treatments. optimization by statistical analysis. *Int. J. Electrochem. Sci.* **2020**, *15*, 8253–8264. [CrossRef]
62. Ryan, C.C.; Tan, D.T.; Arnold, W.A. Direct and indirect photolysis of sulfamethoxazole and trimethoprim in wastewater treatment plant effluent. *Water Res.* **2011**, *45*, 1280–1286. [CrossRef] [PubMed]
63. Hajalifard, Z.; Mousazadeh, M.; Khademi, S.; Khademi, N.; Jamadi, M.H.; Sillanpää, M. The efficacious of AOP-based processes in concert with electrocoagulation in abatement of CECs from water/wastewater. *NPJ Clean Water* **2023**, *6*, 30. [CrossRef]
64. Dadban Shahamat, Y.; Hamidi, F.; Mohammadi, H.; Ghahrchi, M. Optimisation of COD removal from the olive oil mill wastewater by combined electrocoagulation and peroxone process: Modelling and determination of kinetic coefficients. *Int. J. Environ. Anal. Chem.* **2021**, 1–14. [CrossRef]
65. Ferrag-Siagh, F.; Fourcade, F.; Soutrel, I.; Aït-Amar, H.; Djelal, H.; Amrane, A. Tetracycline degradation and mineralization by the coupling of an electro-Fenton pretreatment and a biological process. *J. Chem. Technol. Biotechnol.* **2013**, *88*, 1380–1386. [CrossRef]
66. Ramteke, L.P.; Gogate, P.R. Treatment of toluene, benzene, naphthalene and xylene (BTNXs) containing wastewater using improved biological oxidation with pretreatment using Fenton/ultrasound based processes. *J. Ind. Eng. Chem.* **2015**, *28*, 247–260. [CrossRef]
67. Mousset, E.; Loh, W.H.; Lim, W.S.; Jarry, L.; Wang, Z.; Lefebvre, O. Cost comparison of advanced oxidation processes for wastewater treatment using accumulated oxygen-equivalent criteria. *Water Res.* **2021**, *200*, 117234. [CrossRef]
68. Dong, X.; Lu, D.; Harris, T.A.L.; Escobar, I.C. Polymers and Solvents Used in Membrane Fabrication: A Review Focusing on Sustainable Membrane Development. *Membranes* **2021**, *11*, 309. [CrossRef]
69. Bera, S.P.; Godhaniya, M.; Kothari, C. Emerging and advanced membrane technology for wastewater treatment: A review. *J. Basic Microbiol.* **2022**, *62*, 245–259. [CrossRef]
70. Obotey Ezugbe, E.; Rathilal, S. Membrane Technologies in Wastewater Treatment: A Review. *Membranes* **2020**, *10*, 89. [CrossRef]
71. Sagle, A.; Freeman, B. Fundamentals of membranes for water treatment. *Future Desalination Tex.* **2004**, *2*, 137.
72. Aliyu, U.M.; Rathilal, S.; Isa, Y.M. Membrane desalination technologies in water treatment: A review. *Water Pract. Technol.* **2018**, *13*, 738–752. [CrossRef]
73. Asif, M.B.; Zhang, Z. Ceramic membrane technology for water and wastewater treatment: A critical review of performance, full-scale applications, membrane fouling and prospects. *Chem. Eng. J.* **2021**, *418*, 129481. [CrossRef]
74. Lee, M.; Wu, Z.; Li, K. 2—Advances in ceramic membranes for water treatment. In *Advances in Membrane Technologies for Water Treatment*; Basile, A., Cassano, A., Rastogi, N.K., Eds.; Woodhead Publishing: Oxford, UK, 2015; pp. 43–82.

75. Guillen, G.R.; Pan, Y.; Li, M.; Hoek, E.M.V. Preparation and Characterization of Membranes Formed by Nonsolvent Induced Phase Separation: A Review. *Ind. Eng. Chem. Res.* **2011**, *50*, 3798–3817. [CrossRef]
76. Fillaudeau, L.; Boissier, B.; Moreau, A.; Blanpain-avet, P.; Ermolaev, S.; Jitariouk, N.; Gourdon, A. Investigation of rotating and vibrating filtration for clarification of rough beer. *J. Food Eng.* **2007**, *80*, 206–217. [CrossRef]
77. Blowes, D.W.; Ptacek, C.J.; Benner, S.G.; McRae, C.W.; Bennett, T.A.; Puls, R.W. Treatment of inorganic contaminants using permeable reactive barriers. *J. Contam. Hydrol.* **2000**, *45*, 123–137. [CrossRef]
78. Akhoundi, A.; Nazif, S. Sustainability assessment of wastewater reuse alternatives using the evidential reasoning approach. *J. Clean. Prod.* **2018**, *195*, 1350–1376. [CrossRef]
79. Beganskas, S.; Gorski, G.; Weathers, T.; Fisher, A.T.; Schmidt, C.; Saltikov, C.; Redford, K.; Stoneburner, B.; Harmon, R.; Weir, W. A horizontal permeable reactive barrier stimulates nitrate removal and shifts microbial ecology during rapid infiltration for managed recharge. *Water Res.* **2018**, *144*, 274–284. [CrossRef]
80. Acero, J.L.; Benitez, F.J.; Real, F.J.; García, C. Removal of phenyl-urea herbicides in natural waters by UF membranes: Permeate flux, analysis of resistances and rejection coefficients. *Sep. Purif. Technol.* **2009**, *65*, 322–330. [CrossRef]
81. Rodriguez, E.; Campinas, M.; Acero, J.L.; Rosa, M.J. Investigating PPCP Removal from Wastewater by Powdered Activated Carbon/Ultrafiltration. *Water Air Soil Pollut.* **2016**, *227*, 177. [CrossRef]
82. Sheng, C.; Nnanna, A.G.A.; Liu, Y.; Vargo, J.D. Removal of Trace Pharmaceuticals from Water using coagulation and powdered activated carbon as pretreatment to ultrafiltration membrane system. *Sci. Total Environ.* **2016**, *550*, 1075–1083. [CrossRef] [PubMed]
83. Wray, H.E.; Andrews, R.C.; Bérubé, P.R. Surface shear stress and retention of emerging contaminants during ultrafiltration for drinking water treatment. *Sep. Purif. Technol.* **2014**, *122*, 183–191. [CrossRef]
84. Acero, J.L.; Benitez, F.J.; Teva, F.; Leal, A.I. Retention of emerging micropollutants from UP water and a municipal secondary effluent by ultrafiltration and nanofiltration. *Chem. Eng. J.* **2010**, *163*, 264–272. [CrossRef]
85. Yoon, Y.; Westerhoff, P.; Yoon, J.; Snyder, S.A. Removal of 17β Estradiol and Fluoranthene by Nanofiltration and Ultrafiltration. *J. Environ. Eng.* **2004**, *130*, 1460–1467. [CrossRef]
86. Ferrari, H.Z.; Rodrigues, D.M.; Bernard, F.L.; dos Santos, L.M.; Roux, C.L.; Micoud, P.; Martin, F.; Einloft, S. A new class of fillers in mixed matrix membranes: Use of synthetic silico-metallic mineral particles (SSMMP) as a highly selective component for CO_2/N_2 separation. *Chem. Eng. J. Adv.* **2023**, *14*, 100488. [CrossRef]
87. Awwad, M.; Al-Rimawi, F.; Dajani, K.J.K.; Khamis, M.; Nir, S.; Karaman, R. Removal of amoxicillin and cefuroxime axetil by advanced membranes technology, activated carbon and micelle-clay complex. *Environ. Technol.* **2015**, *36*, 2069–2078. [CrossRef]
88. Chon, K.; Cho, J.; Shon, H.K. A pilot-scale hybrid municipal wastewater reclamation system using combined coagulation and disk filtration, ultrafiltration, and reverse osmosis: Removal of nutrients and micropollutants, and characterization of membrane foulants. *Bioresour. Technol.* **2013**, *141*, 109–116. [CrossRef]
89. Hu, Z.; Si, X.; Zhang, Z.; Wen, X. Enhanced EDCs removal by membrane fouling during the UF process. *Desalination* **2014**, *336*, 18–23. [CrossRef]
90. Krzeminski, P.; Schwermer, C.; Wennberg, A.; Langford, K.; Vogelsang, C. Occurrence of UV filters, fragrances and organophosphate flame retardants in municipal WWTP effluents and their removal during membrane post-treatment. *J. Hazard. Mater.* **2017**, *323*, 166–176. [CrossRef]
91. Löwenberg, J.; Zenker, A.; Baggenstos, M.; Koch, G.; Kazner, C.; Wintgens, T. Comparison of two PAC/UF processes for the removal of micropollutants from wastewater treatment plant effluent: Process performance and removal efficiency. *Water Res.* **2014**, *56*, 26–36. [CrossRef]
92. Hu, J.Y.; Jin, X.; Ong, S.L. Rejection of estrone by nanofiltration: Influence of solution chemistry. *J. Membr. Sci.* **2007**, *302*, 188–196. [CrossRef]
93. Zazouli, M.A.; Susanto, H.; Nasseri, S.; Ulbricht, M. Influences of solution chemistry and polymeric natural organic matter on the removal of aquatic pharmaceutical residuals by nanofiltration. *Water Res.* **2009**, *43*, 3270–3280. [CrossRef] [PubMed]
94. Azaïs, A.; Mendret, J.; Gassara, S.; Petit, E.; Deratani, A.; Brosillon, S. Nanofiltration for wastewater reuse: Counteractive effects of fouling and matrice on the rejection of pharmaceutical active compounds. *Sep. Purif. Technol.* **2014**, *133*, 313–327. [CrossRef]
95. Bellona, C.; Drewes, J.E. The role of membrane surface charge and solute physico-chemical properties in the rejection of organic acids by NF membranes. *J. Membr. Sci.* **2005**, *249*, 227–234. [CrossRef]
96. Chang, E.E.; Chang, Y.-C.; Liang, C.-H.; Huang, C.-P.; Chiang, P.-C. Identifying the rejection mechanism for nanofiltration membranes fouled by humic acid and calcium ions exemplified by acetaminophen, sulfamethoxazole, and triclosan. *J. Hazard. Mater.* **2012**, *221–222*, 19–27. [CrossRef]
97. D'Haese, A.; Le-Clech, P.; Van Nevel, S.; Verbeken, K.; Cornelissen, E.R.; Khan, S.J.; Verliefde, A.R.D. Trace organic solutes in closed-loop forward osmosis applications: Influence of membrane fouling and modeling of solute build-up. *Water Res.* **2013**, *47*, 5232–5244. [CrossRef]
98. García-Vaquero, N.; Lee, E.; Jiménez Castañeda, R.; Cho, J.; López-Ramírez, J.A. Comparison of drinking water pollutant removal using a nanofiltration pilot plant powered by renewable energy and a conventional treatment facility. *Desalination* **2014**, *347*, 94–102. [CrossRef]
99. Gur-Reznik, S.; Koren-Menashe, I.; Heller-Grossman, L.; Rufel, O.; Dosoretz, C.G. Influence of seasonal and operating conditions on the rejection of pharmaceutical active compounds by RO and NF membranes. *Desalination* **2011**, *277*, 250–256. [CrossRef]

100. Kim, J.-H.; Park, P.-K.; Lee, C.-H.; Kwon, H.-H. Surface modification of nanofiltration membranes to improve the removal of organic micro-pollutants (EDCs and PhACs) in drinking water treatment: Graft polymerization and cross-linking followed by functional group substitution. *J. Membr. Sci.* **2008**, *321*, 190–198. [CrossRef]
101. Kimura, K.; Iwase, T.; Kita, S.; Watanabe, Y. Influence of residual organic macromolecules produced in biological wastewater treatment processes on removal of pharmaceuticals by NF/RO membranes. *Water Res.* **2009**, *43*, 3751–3758. [CrossRef]
102. Košutić, K.; Dolar, D.; Ašperger, D.; Kunst, B. Removal of antibiotics from a model wastewater by RO/NF membranes. *Sep. Purif. Technol.* **2007**, *53*, 244–249. [CrossRef]
103. Koyuncu, I.; Arikan, O.A.; Wiesner, M.R.; Rice, C. Removal of hormones and antibiotics by nanofiltration membranes. *J. Membr. Sci.* **2008**, *309*, 94–101. [CrossRef]
104. Cartagena, P.; El Kaddouri, M.; Cases, V.; Trapote, A.; Prats, D. Reduction of emerging micropollutants, organic matter, nutrients and salinity from real wastewater by combined MBR-NF/RO treatment. *Sep. Purif. Technol.* **2013**, *110*, 132–143. [CrossRef]
105. Chon, K.; Sarp, S.; Lee, S.; Lee, J.-H.; Lopez-Ramirez, J.A.; Cho, J. Evaluation of a membrane bioreactor and nanofiltration for municipal wastewater reclamation: Trace contaminant control and fouling mitigation. *Desalination* **2011**, *272*, 128–134. [CrossRef]
106. Heo, J.; Boateng, L.K.; Flora, J.R.V.; Lee, H.; Her, N.; Park, Y.-G.; Yoon, Y. Comparison of flux behavior and synthetic organic compound removal by forward osmosis and reverse osmosis membranes. *J. Membr. Sci.* **2013**, *443*, 69–82. [CrossRef]
107. Kim, S.D.; Cho, J.; Kim, I.S.; Vanderford, B.J.; Snyder, S.A. Occurrence and removal of pharmaceuticals and endocrine disruptors in South Korean surface, drinking, and waste waters. *Water Res.* **2007**, *41*, 1013–1021. [CrossRef]
108. Jin, X.; Hu, J.; Ong, S.L. Removal of natural hormone estrone from secondary effluents using nanofiltration and reverse osmosis. *Water Res.* **2010**, *44*, 638–648. [CrossRef]
109. Nghiem, L.D.; Manis, A.; Soldenhoff, K.; Schäfer, A.I. Estrogenic hormone removal from wastewater using NF/RO membranes. *J. Membr. Sci.* **2004**, *242*, 37–45. [CrossRef]
110. Schäfer, A.I.; Nghiem, L.D.; Waite, T.D. Removal of the Natural Hormone Estrone from Aqueous Solutions Using Nanofiltration and Reverse Osmosis. *Environ. Sci. Technol.* **2003**, *37*, 182–188. [CrossRef]
111. Huang, H.; Cho, H.; Schwab, K.; Jacangelo, J.G. Effects of feedwater pretreatment on the removal of organic microconstituents by a low fouling reverse osmosis membrane. *Desalination* **2011**, *281*, 446–454. [CrossRef]
112. Kimura, K.; Toshima, S.; Amy, G.; Watanabe, Y. Rejection of neutral endocrine disrupting compounds (EDCs) and pharmaceutical active compounds (PhACs) by RO membranes. *J. Membr. Sci.* **2004**, *245*, 71–78. [CrossRef]
113. Dolar, D.; Gros, M.; Rodriguez-Mozaz, S.; Moreno, J.; Comas, J.; Rodriguez-Roda, I.; Barceló, D. Removal of emerging contaminants from municipal wastewater with an integrated membrane system, MBR-RO. *J. Hazard. Mater.* **2012**, *239–240*, 64–69. [CrossRef] [PubMed]
114. Sahar, E.; David, I.; Gelman, Y.; Chikurel, H.; Aharoni, A.; Messalem, R.; Brenner, A. The use of RO to remove emerging micropollutants following CAS/UF or MBR treatment of municipal wastewater. *Desalination* **2011**, *273*, 142–147. [CrossRef]
115. Xie, M.; Nghiem, L.D.; Price, W.E.; Elimelech, M. Comparison of the removal of hydrophobic trace organic contaminants by forward osmosis and reverse osmosis. *Water Res.* **2012**, *46*, 2683–2692. [CrossRef] [PubMed]
116. Cartinella, J.L.; Cath, T.Y.; Flynn, M.T.; Miller, G.C.; Hunter, K.W.; Childress, A.E. Removal of Natural Steroid Hormones from Wastewater Using Membrane Contactor Processes. *Environ. Sci. Technol.* **2006**, *40*, 7381–7386. [CrossRef]
117. Xie, M.; Nghiem, L.D.; Price, W.E.; Elimelech, M. Relating rejection of trace organic contaminants to membrane properties in forward osmosis: Measurements, modelling and implications. *Water Res.* **2014**, *49*, 265–274. [CrossRef]
118. Hancock, N.T.; Xu, P.; Heil, D.M.; Bellona, C.; Cath, T.Y. Comprehensive Bench- and Pilot-Scale Investigation of Trace Organic Compounds Rejection by Forward Osmosis. *Environ. Sci. Technol.* **2011**, *45*, 8483–8490. [CrossRef]
119. Huang, M.; Chen, Y.; Huang, C.-H.; Sun, P.; Crittenden, J. Rejection and adsorption of trace pharmaceuticals by coating a forward osmosis membrane with TiO_2. *Chem. Eng. J.* **2015**, *279*, 904–911. [CrossRef]
120. Jin, X.; Shan, J.; Wang, C.; Wei, J.; Tang, C.Y. Rejection of pharmaceuticals by forward osmosis membranes. *J. Hazard. Mater.* **2012**, *227–228*, 55–61. [CrossRef]
121. Liu, P.; Zhang, H.; Feng, Y.; Shen, C.; Yang, F. Integrating electrochemical oxidation into forward osmosis process for removal of trace antibiotics in wastewater. *J. Hazard. Mater.* **2015**, *296*, 248–255. [CrossRef]
122. Kong, F.-X.; Yang, H.-W.; Wu, Y.-Q.; Wang, X.-M.; Xie, Y.F. Rejection of pharmaceuticals during forward osmosis and prediction by using the solution-diffusion model. *J. Membr. Sci.* **2015**, *476*, 410–420. [CrossRef]
123. Obiri-Nyarko, F.; Grajales-Mesa, S.J.; Malina, G. An overview of permeable reactive barriers for in situ sustainable groundwater remediation. *Chemosphere* **2014**, *111*, 243–259. [CrossRef] [PubMed]
124. Thakur, A.K.; Vithanage, M.; Das, D.B.; Kumar, M. A review on design, material selection, mechanism, and modelling of permeable reactive barrier for community-scale groundwater treatment. *Environ. Technol. Innov.* **2020**, *19*, 100917. [CrossRef]
125. Ahmed, M.B.; Zhou, J.L.; Ngo, H.H.; Guo, W. Adsorptive removal of antibiotics from water and wastewater: Progress and challenges. *Sci. Total Environ.* **2015**, *532*, 112–126. [CrossRef]
126. Ribeiro, R.S.; Frontistis, Z.; Mantzavinos, D.; T Silva, A.M.; Faria, J.L.; Gomes, H.T. Screening of heterogeneous catalysts for the activated persulfate oxidation of sulfamethoxazole in aqueous matrices. Does the matrix affect the selection of catalyst? *J. Chem. Technol. Biotechnol.* **2019**, *94*, 2425–2432. [CrossRef]

127. Ribeiro, R.S.; Vieira, O.; Fernandes, R.; Roman, F.F.; de Tuesta, J.L.D.; Silva, A.M.; Gomes, H.T. Synthesis of low-density polyethylene derived carbon nanotubes for activation of persulfate and degradation of water organic micropollutants in continuous mode. *J. Environ. Manag.* **2022**, *308*, 114622. [CrossRef] [PubMed]
128. Zheng, C. The Application of Carbon Nanotubes in Permeable Reactive Barriers (PRBs) for Groundwater Remediation. In Proceedings of the 2022 International Conference on Social Sciences and Humanities and Arts (SSHA 2022), Nanjing, China, 25–27 February 2022; pp. 920–923.
129. Gomes, J.; Costa, R.; Quinta-Ferreira, R.M.; Martins, R.C. Application of ozonation for pharmaceuticals and personal care products removal from water. *Sci. Total Environ.* **2017**, *586*, 265–283. [CrossRef]
130. Budania, R.; Dangayach, S. A comprehensive review on permeable reactive barrier for the remediation of groundwater contamination. *J. Environ. Manag.* **2023**, *332*, 117343. [CrossRef]
131. Santos Silva, A.; Seitovna Kalmakhanova, M.; Kabykenovna Massalimova, B.; Juliana, G.S.; Diaz de Tuesta, J.L.; Gomes, H.T. Wet peroxide oxidation of paracetamol using acid activated and Fe/Co-pillared clay catalysts prepared from natural clays. *Catalysts* **2019**, *9*, 705. [CrossRef]
132. Bekturganov, Z.; Tussupova, K.; Berndtsson, R.; Sharapatova, N.; Aryngazin, K.; Zhanasova, M. Water related health problems in Central Asia—A review. *Water* **2016**, *8*, 219. [CrossRef]
133. Jones, E.R.; Van Vliet, M.T.; Qadir, M.; Bierkens, M.F. Country-level and gridded estimates of wastewater production, collection, treatment and reuse. *Earth Syst. Sci. Data* **2021**, *13*, 237–254. [CrossRef]