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One-Step Reverse Osmosis Based on Riverbank Filtration for Future Drinking Water Purification

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ABSTRACT

The presence of newly emerging pollutants in the aquatic environment poses great challenges for drinking water treatment plants. Due to their low concentrations and unknown characteristics, emerging pollutants cannot be efficiently removed by conventional water treatment processes, making technically, economically, and environmentally friendly water purification technologies increasingly important. This article introduces a one-step reverse osmosis (OSRO) concept consisting of riverbank filtration (RBF) and reverse osmosis (RO) for drinking water treatment. The OSRO concept combines the relatively low-cost natural pretreatment of river water with an advanced engineered purification system. RBF provides a continuous natural source of water with stable water quality and a robust barrier for contaminants. With the pre-removal of particles, organic matter, organic micro-pollutants (OMPs), and microbes, RBF becomes an ideal source for a purification system based on RO membranes, in comparison with the direct intake of surface water. OSRO treatment removes almost 99.9% of the particles, pathogens, viruses, and OMPs, as well as the vast majority of nutrients, and thus meets the requirements for the chlorine-free delivery of drinking water with high biostability. The OSRO treatment is cost effective compared with the standard conventional series of purification steps involving sprinkling filters, softening, and activated carbon. Artificial bank filtration (ABF), which functions as an artificial recharge in combination with a sand filtration system, is proposed as an alternative for RBF in the OSRO concept to supply drinking water from locally available resources. It is also suggested that the OSRO concept be implemented with wind power as an alternative energy source in order to be more sustainable and renewable. An OSRO-based decentralized water system is proposed for water reclaiming and reuse. It is suggested that future water treatment focus on the combination of natural and engineered systems to provide drinking water through technically efficient, financially feasible, resource reusable, and environmentally relevant means.

1. Introduction

In the last few decades, water supply companies have been confronted with increasing amounts of newly emerging pollutants or contaminants of emerging concern in water sources [1]. This fact, combined with the ongoing improvement of laboratory equipment capable of detecting more compounds at increasingly lower detection limits and the highly sensitive and intuitive public repulsion against the idea of pharmaceuticals in drinking water, has led to the ongoing improvement of existing water purification technologies [2]. The challenges confronting the water sector in a changing world emphasize the need to update existing water purification technologies in order to allow us to use water resources sustainably in the future.

Emerging pollutants such as pharmaceuticals, personal care products, ultraviolet (UV) filters, endocrine disruptors, illicit drugs, additives, metabolites, disinfection byproducts, fire retardants, and pesticides are the surplus results of chemical and/or biological substances generated mainly by human activities [3]. Once released into the aquatic environment (e.g., groundwater and surface water), these emerging pollutants are subject to chemical, photochemical, and biodegradation processes, changing their

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environmental behavior and ecotoxicological profile [4]. The bioaccumulation, biomagnification, persistency, and toxicity of emerging pollutants are harmful for both aquatic organisms and humans, causing endocrine-disturbing effects, estrogenic or hormone disruption, fetal malformation, or even DNA damage [5].

To ensure drinking water safety, global legal water-quality standards have been established for a limited number of anthropogenic compounds. For example, the US Environmental Protection Agency has recently established health advisory levels of 70 parts per trillion (70 $ng \cdot L^{-1}$) for perfluorooctanesulfonate (PFOS) and perfluorooctanoic acid (PFOA) in drinking water [6], which is incredibly low compared with the generally accepted threshold of toxicological concern (TTC), where values below 0.1 $mg \cdot L^{-1}$ were found to be insignificant [7]. In the Netherlands, where non-chlorinated drinking water is distributed, the prevention of bacterial regrowth in the distribution network is an extra topic of concern. Research strongly indicates that the presence of fewer particles and fewer nutrients in drinking water reduces the risk of opportunistic pathogen growth [8].

Today's high standards for drinking water production and distribution are resulting in the addition of extra purification steps to existing treatment plants. Emerging pollutants in water sources due to industrial development potentially affect human health [9], while conventional drinking water treatment methods cannot fully remove trace concentrations of such individual compounds or chemical mixtures. Depending on the water source and the key parameters for specific water utilities, the conventional series of biological, chemical, and physical purification steps (i.e., coagulation, sedimentation, slow sand filtration, softening, and trickling filters) are enhanced with additional treatment processes. For example, advanced oxidation processes including UV/ozone (O_3)-based applications, Fenton processes, and photocatalytic oxidative processes have been reported to be effective in removing natural organic matter and mitigating disinfection byproducts [10]. However, advanced oxidation only breaks down natural organic matter into small aliphatic and hydrophilic compounds, without complete oxidation. Low-molecular-weight hydrophilic compounds may be either degradable or persistent and toxic, and the development of unwanted byproducts poses challenges to large-scale application [11].

Granular or powder-activated carbon adsorption along with silica, alumina, zeolites, and metal oxide adsorbents are also used to remove emerging pollutants in drinking water facilities, although the energy consumption and cost of adsorbents are very high [12]. Moreover, the impact of each stage of a drinking water treatment plant (e.g., construction, operation, chemical use, treatment processes) on climate change (i.e., energy consumption and greenhouse gas emissions) means that improvements in and more sustainable techniques for water supply are in great demand [13].

Therefore, the water sector urgently needs a technology that is nature-based and green, with high efficiency in removing emerging pollutants. To supply drinking water with high quality and low risk, drinking water utilities tend to use the cleanest available water source in combination with advanced treatments to improve treatment efficiency, while lowering the investment, labor, operating costs, and energy demand as much as possible. Thus, the water sector requires a combination of natural and engineered systems (cNES) based on naturally occurring processes in order to improve water quality [14].

2. One-step reverse osmosis based on riverbank filtration: A natural and efficient process for drinking water production

This article proposes the use of reverse osmosis (RO) as a single-step treatment to produce high-quality drinking water from riverbank filtrate. While RO membranes can remove almost all kinds of substances from feed water, they are usually equipped with pretreatment steps for conditioning and modifying the feed water to prevent clogging and fouling of the membrane modules [15]. As a result of its natural pretreatment and capability for water quality improvement, riverbank filtration (RBF) is a favorable source for RO in comparison with direct river intake. To further increase both drinking water quality and RO performance, we propose that RBF be combined with RO as a one-step RO (OSRO) treatment process, with the aim of achieving natural purification with low energy consumption and fewer chemical additions. As illustrated in Fig. 1, river water travels through the soil passage to remove particles, organic substances, bacteria, and viruses. Afterwards, the RBF pretreated water is pumped up from abstraction wells and further purified with RO membranes to supply drinking water.

2.1. River bank filtration

Surface water and groundwater are two of the main water sources for drinking water production around the world. However, surface water is increasingly worsening in quality, and urbanization and civilization have led to the depletion and contamination of freshwater resources, especially in dry areas. Under these conditions, a stable and reliable drinking water supply is essential to ensure human health. Having undergone more than 150 years of use and improvement, RBF has been recognized as a proven technology for drinking water purification in Europe [16]. Its natural cleaning capacity (i.e., filtering, sorption, and biodegradation) has been demonstrated in a number of studies, and RBF has been shown to have global potential for supplying water, in contexts such as in United States [17], Republic of Korea [18], India [19], Egypt [20], and Brazil [21].

RBF is a natural water purification process. In RBF, instead of directly extracting river water, water is allowed to flow through a soil passage in riverbank soil to collection wells before being abstracted as drinking water [22]. RBF can remove suspended solids, organic matter, nutrients, soluble chemicals, microorganisms, and emerging contaminants [23]. RBF contains two basic parts: a soil aquifer and abstraction wells. The soil aquifer is hydraulically connected with the riverbed on one side and with the abstraction wells on the other side. Once water abstraction starts, the groundwater level is lowered, and water flows from the surface to the soil aquifer through the riverbed and toward the wells. In this way, surface water is purified by the soil [24].

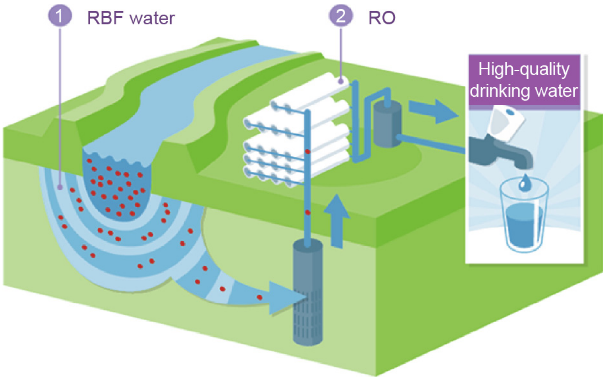

Fig. 1. An illustration of OSRO based on RBF. Natural purification processes occur in RBF as river water flows through the riverbank soil passage to collection wells before being abstracted as a drinking water source. The abstracted riverbank filtrate is passed through RO membranes as an advanced treatment to produce high-quality drinking water.

Physiochemical and biological processes occur in the soil aquifer over a long residence time, such as straining, biodegradation, sorption, and ion exchange [25]. RBF performance largely depends on the aquifer characteristics. Environmental factors such as seasonality, redox conditions, and the river water matrix can affect the efficiency of contaminant removal [26]. Seasonal variations due to agricultural or medical application and degradation determine the initial concentration of contaminants in the river water. The aerobic and/or anaerobic conditions are selective for different kinds of containment removal, and the organic matter content in the river water promotes the co-metabolization of certain organic micro-pollutants (OMPs) [27]. RBF performance is also driven by the geological profile and thickness of the riverbank, along with the detention time, travel distance, flow velocity, and so forth. These hydrogeological factors also influence the attenuation of contaminants through the aquifer [28]. Recently, RBF has not only been applied by itself, but also been combined with artificial recharging, constructed wetlands, and other natural water purification processes [29]. In comparison with surface water that is directly taken as source water, RBF water has a higher and more stable quality that allows simpler posttreatments.

2.2. Reverse osmosis

Although RBF is capable of removing biological and chemical impurities, not all contaminants (e.g., OMPs and anthropogenic compounds) are eliminated during infiltration through the riverbank [30]. Additional treatment may still be necessary in order to obtain drinking water with high quality. RO uses a partially permeable membrane under an applied pressure and is commonly used for advanced drinking water purification [31]. Previous RO studies related to the production of drinking water were primarily performed under the assumption that RO elements are used for desalination [32]. The energy use, scaling, and retention of RO are influenced by the concentration polarization [33]. When RO is applied to freshwater, the effects of concentration polarization on energy use become significantly smaller because the osmotic pressure difference is negligible. Recently, more attention has been focused on using RO for the purification of freshwater resources [34–36]. The main reason to use RO for freshwater purification is that it provides an effective barrier against continuously emerging micro- and nano-contaminants, which cannot be (easily) removed by conventional treatment technologies [37].

RO is a physical separation process in which the natural flow of water is forced through a membrane toward a more concentrated solution by means of a positive hydrostatic pressure in order to overcome the osmotic pressure [38]. The polymeric material of RO membranes forms a layered, web-like structure, and the water molecules must follow a tortuous pathway through the membrane to reach the permeate side [39]. The fluid flow depends on the membrane porosity, fraction of membrane volume, and tortuosity (i.e., the distance a molecule must travel through the membrane divided by the thickness of the membrane) [40]. Fluid flux through a membrane is assumed to follow the solution–diffusion model [41], which is dependent on complex solute–membrane interactions including steric hindrance [42], electrostatic interactions [43], and hydrophobic–hydrophilic interactions [44]. Compared with other membranes, including nanofiltration (NF), ultrafiltration (UF), and microfiltration (MF), RO membranes (with a pore size between 0.1 and 1.0 nm) can reject the smallest contaminants and monovalent ions [45]. RO membranes are typically operated in crossflow mode and are most commonly available as spiral-wound membranes (SWMs), in which the membrane sheets are wound around an inner tube that collects the permeate. Studies have shown that RO can remove ionic material to an impressive extent [46]. The energy consumption is considered to be intensive when RO is incorporated into conventional treatment processes [47]. However, by using natural waters that require minimum pretreatment as feed water for stand-alone RO, the combination of RBF and RO comprises a new process that can produce high-quality drinking water with low operational costs and little environmental impact.

3. RBF-based OSRO: Feasibility and effectiveness assessment in a case study in the Netherlands

To visualize the OSRO concept, a pilot study combing RBF with RO was conducted in the drinking water treatment station of Oasen Drinkwater (51°53′37.5″N 4°38′29.2″E, at a site along the Lek river in the Netherlands). The feasibility and effectiveness of OSRO were assessed from the aspects of temperature fluctuations, redox conditions, water quality, biological stability, potential necessary posttreatments, and energy consumption.

Seasonal temperature variation in the river water changes the water flow rate and may reduce RO performance [48]. When RO is combined with pretreatment involving RBF, the river water travels through a soil passage that dampens the seasonal temperature variation, and thus provides water at a constant temperature to the RO membrane. In areas where the river water temperature varies from 4 to 25 °C, the temperature of the abstracted RBF water is always 11–12 °C. This stable temperature provides favorable conditions for stable process conditions of the RO membrane unit, resulting in a non-varying pressure regime and less scaling due to less concentrated polymerization along the membranes.

The redox condition of the feed water is an important factor in the design and operation of a downstream RO system. Biofouling from nutrients and oxygen requires extra attention and maintenance [49]. Moreover, feed water containing both Fe^{2+} and O_2 often leads to the precipitation of $Fe(OH)_3$. This precipitation can seriously hinder the performance of RO membranes, making an extra pretreatment step necessary for the feed water, such as a trickling filter before the membrane filtration unit [49]. Anaerobic groundwater can minimize problems with biofouling in RO units due to the lack of oxygen and nutrients. Pure aerobic river bank filtrate is therefore an adequate source for an RO membrane purification unit.

Particles in the raw water source are of major concern for an RO treatment facility. The presence of particles in the feed water can foul the membranes and decrease the removal efficiency of the RO membranes [50]. In abstracted water from RBF wells, the turbidity of the raw water is already decreased by 95%–99%, which increases the water quality in the feed water for RO membranes. In addition to particles, pathogens in the source-river water, and especially viruses, are removed to up to 6 log units (i.e., sterilization rate of 99.9999%) by the (an)aerobic riverbank subsurface passage after 60–110 days. After RBF, both particles and pathogens are efficiently removed, increasing the purification capacity of the RO posttreatment. Thus, the OSRO treatment is perfectly capable of producing chlorine-free drinking water [51].

Emerging OMPs, which include pesticides, pharmaceuticals and personal care products, household chemicals, and industrial waste products, enter natural water sources and may pose a high risk to those who drink the water [5]. Due to the physical infiltration, chemical adsorption, and biodegradation processes involved in RBF, OMPs are naturally pretreated, and can then be further removed by RO treatment. In the pilot-scale OSRO treatment, the removal of ten selected OMPs was monitored from 2018 to 2019 (Fig. 2). More than 75% removal efficiency of most OMPs was observed, and the OMPs of atrazine, bentazon, carbamazepine, diglyme, iopamidol, 1,4-dioxaan, phenazon, and 1,2-dichlorobenzene were found to be totally removed (100%) from

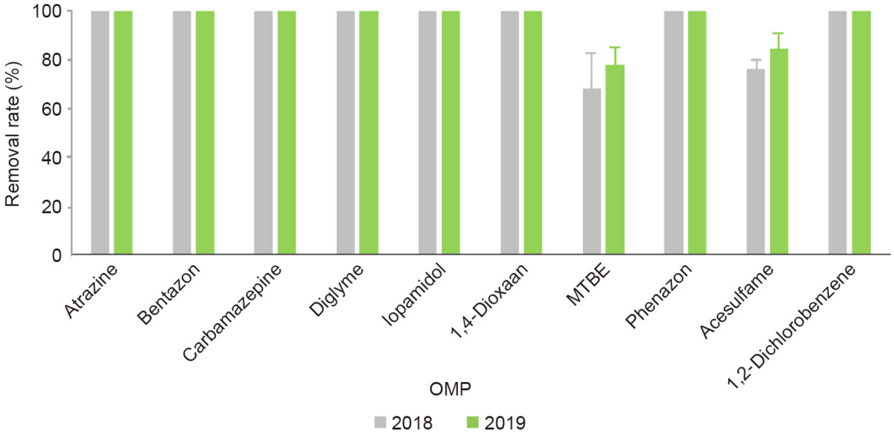

Fig. 2. Removal efficiency of selected OMPs using OSRO treatment. OMP concentrations were measured both in the Lek River and in the OSRO permeate in the years 2018 and 2019. MTBE: metyl *tert*-butyl ether.

the raw water in 2018 and 2019. Moreover, our previous study investigated the robustness of OSRO in treating raw anaerobic riverbank filtrate mixed with 30 selected model OMPs [31]. These OMPs included neutral and moderately hydrophobic, neutral hydrophilic, anionic, and cationic compounds that can enter the water source through the use of pharmaceuticals and personal care products, pesticides, industrial chemicals, and wastes. The removal efficiency observed for the model OMPs ranged from 75% to 99%. Therefore, RBF as a natural treatment in combination with RO as an engineered process can be considered to be a robust barrier against most emerging OMPs.

To obtain drinking water with no chlorine disinfection and no residual disinfectant in the distribution network, the drinking water supply from production to distribution must be biologically stable [52,53]. Drinking water quality is negatively affected by microbes present in the treated water and distribution system, and opportunistic pathogens such as *Legionella* are harmful to human health [54]. The biological stability of drinking water is related to the biodegradable organic carbon (BDOC) and assimilable organic carbon (AOC) concentrations [55]. This organic matter can be removed by RO membranes, thereby reducing the potential for microbial growth in treated water [56]. Our previous study observed that the adenosine triphosphate (ATP) concentrations in biofilm fed with OSRO water were ten-fold lower than those for conventionally treated groundwater, and the *Legionella* growth potential in OSRO water was 1000-fold lower than that of conventionally treated water [57,58]. This pilot study indicates that OSRO is effective in limiting the growth of biofilm and opportunistic pathogens, which ensures biological stability in supplying drinking water.

The permeate from RO membranes requires posttreatments for remineralization (e.g., calcium and magnesium) and reconditioning (e.g., pH and chemical stability) to meet the requirements of drinking water regulations and to improve the taste [59]. However, posttreatments can introduce organic and inorganic components into the RO permeate, thereby providing nutrients for bacterial growth and potentially deteriorating the water quality [60]. In the pilot-scale OSRO treatment, posttreatments including ion exchange, calcite filtration, and degasification are processed after the RO membranes (Fig. 3). Our previous study found that although the bacterial growth potential (BGP) and nutrient content of the RO permeate increased after posttreatment, the BGP was much lower compared with that of conventionally treated water (treated with dry sand filtration, aeration, trickling filtration, softening, rapid sand filtration, activated carbon filtration, and UV disinfection) [57]. Improvements in posttreatments are suggested in order to mitigate negative influences on biological stability; examples include using calcite with high purity and cleaning the aeration tower more frequently to reduce bacterial growth.

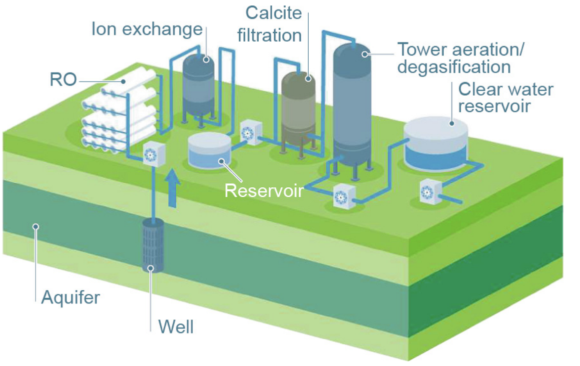

Fig. 3. Full-scale OSRO treatment process at a drinking water treatment plant.

To optimize the permeate flow in the OSRO treatment, the Optiflux® RO design for water treatment was applied to minimize the hydraulic pressure losses and the osmotic pressure difference across the membrane surface [61]. In brief, one pressure vessel was equipped with a center port in the middle, and three elements on each side. The feed water passes through the elements from each side, and the concentrate is collected in the center port and then feeds into the second stage. The permeate flows through the center tube of the SWM. The Optiflux® RO design increases the RO permeate productivity by 20%. In addition to the increased productivity, OSRO is cost effective and less energy intensive than the traditional alternative. We compared the energy consumption, expropriate cost, and investment of traditional treatment processes (i.e., a combination of aeration, sand filtration, softening, granular active carbon filtration, and UV disinfection) with those of OSRO treatment in the same treatment station, that is, Oasen Drinkwater. As shown in Fig. 4, the energy consumption of OSRO ranges between 0.57 and 0.66 kW·h·m^{-3}, which is comparable to the total energy consumption of traditional treatment processes (0.22–0.73 kWw·h·m^{-3}). However, OSRO's small footprint, few chemicals, and savings in labor costs lower its expropriate cost (0.42–0.43 EUR·m^{-3}) and investment cost (12 million–14 million EUR) in comparison with those of traditional treatment processes (0.41–0.50 EUR·m^{-3} and 18 million–20 million EUR, respectively). With decreased dependency on space, chemicals, labor, and energy demand in comparison with traditional processes, OSRO is a sustainable technology for drinking water production.

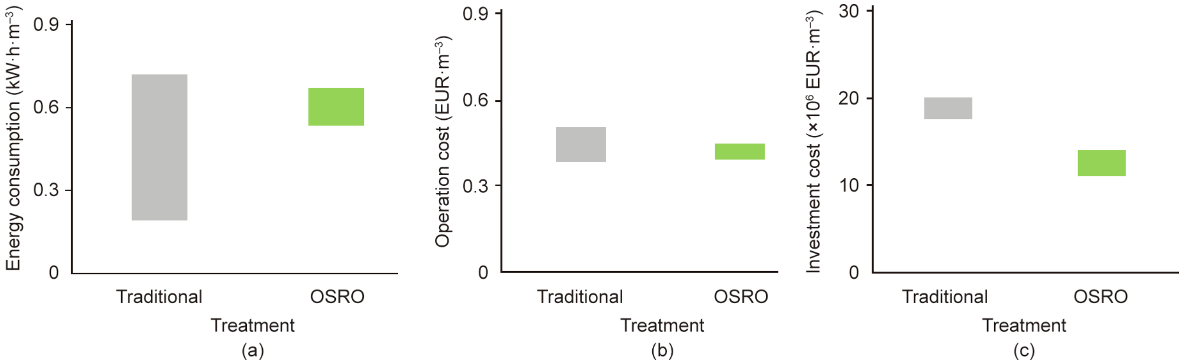

Fig. 4. Comparisons of (a) energy consumption, (b) operation cost, and (c) investment cost between traditional and OSRO treatments. Treatment plants are located in the drinking water treatment station of Oasen Drinkwater. Traditional treatment processes include dry sand filtration, aeration, trickling filtration, softening, rapid sand filtration, activated carbon filtration, UV disinfection, and reservoir storing. OSRO treatment processes include RBF extraction, RO membrane filtration, ion exchange, calcite filtration, degasification, and reservoir storage.

4. The applicability and sustainability of OSRO: Artificial bank filtration and renewable energy

However, RBF is only applicable in locations where the hydrogeological situation is favorable. A river with an almost continuous flow and the ability to infiltrate water toward the aquifers surrounding the river is a necessity. To generally promote the OSRO concept—for example, to supply drinking water in isolated and dry districts where the use of RBF is unrealistic—artificial bank filtration (ABF) is an alternative to RBF. ABF functions as an artificial recharge; when combined with sand filtration systems, it forms a simple and efficient water treatment process based on locally available resources. Multiple source waters such as rainwater, runoff, and wastewater can be harvested, pretreated, recharged into an underground aquifer, stored, and recovered. Recharging takes on different forms depending on the local situation. Pretreated water can be injected into confined aquifers via wells for aquifer storage and recovery, or into unconfined aquifers by means of sand filtration systems composed of a column filled with sand (usually a combination of fine and coarse sand) as a filter medium that allows water to seep through [62]. The recharged water is thus potentially purified through contact with the sand before reaching the aquifer, which reduces the pathogens, harmful inorganic and organic substances, and turbidity of the water. Purification of the recharged water by sand infiltration basically integrates physical, chemical, and biological processes. Large particles that cannot fit through the pores between sand grains can be removed by straining. Particles can also be mechanically removed during transport through the sand bed and may be attached to sand grains via electrostatic and molecular forces [63]. Organic substances can be broken down by various oxidation reactions due to the long-time residence of raw water in passing through the sand bed [64]. Contaminations can be removed, transformed, and degraded through the biological activity of the developed microbial community (e.g., bacteria, diatoms, protozoans, and metazoans) of the sand bed. The production of microbial extracellular products is beneficial for reducing viruses in raw water [65]. Bacteria in the raw water can be eliminated through adsorption onto the sand surface and predation by protozoans [63].

In addition to the alternative of ABF for pretreatment, alternative energy sources for producing drinking water are suggested in order to reduce the cost and environmental impact of traditional carbon-based fossil fuels. As renewable sources are becoming an encouraging option, we propose that wind power be integrated with OSRO systems for drinking water supply. We compared the impact of drinking water production chains between a Dutch county's energy mix and wind power in terms of climate change (CO_2 emission), acidification (SO_2 emission), eutrophication (phosphorous content), cumulative energy demand, and human toxicity potential in traditional treatment and OSRO treatment scenarios (Fig. 5 [66]). Severe impacts are largely driven by the second production step (i.e., RO membrane filtration) of the OSRO scenario and by the third step (i.e., softening) of the traditional treatment scenario, both of which can be largely reduced (56%–92%) by replacing the energy mix with wind power. Moreover, upon changing from the energy mix to wind, the CO_2, SO_2, and phosphorus emissions, energy consumption, and toxicity of the OSRO scenario were observed to be lower than the impacts observed in the conventional scenario. This is because the latter process depends more on chemicals; in particular, NaOH production requires significant energy consumption. Overall, compared with traditional drinking water treatment processes using a conventional energy mix, the OSRO concept implemented with wind power was found to be more sustainable and renewable.

5. Perspectives: Closing the water loop

Surface water and groundwater are purified for municipal, agricultural, and industrial use, and then finally end up as wastewater. The collected wastewater is further treated to meet the requirements for discharging into surface water or recharging into underground aquifers, after which it can be reused to produce drinking water. Moreover, rainwater, storm water, and high-flow flood streams can be stored in the groundwater base flow in order to augment the domestic and industrial water supply through managed aquifer recharge. The result would be a closed water loop in which water is recycled from and to its source to meet increasing water demand and reduce water waste [67]. From the perspectives of technical efficiency, financial feasibility, resource reusability, and environmental relevance, it is suggested that future water treatment focus on closing the water loop by integrating the quality of the water intake (depending on the use) and the treatment of wastewater discharge (Fig. 6).

The OSRO concept, which integrates artificial sand filtration and RO, is an example of a solution for water reclamation and reuse in both centralized and decentralized water supply systems. OSRO can be used on a large scale for urban water supplies, on a smaller scale for regional water supplies, or even on an individual scale for personal use. From the perspectives of sustainable water resources management and ensuring an adequate water supply, an OSRO-based decentralized water system is more cost effective than other options at the community or household level, due to its low cost in central conveyance, treatment capacity, and potable water transmission [68]. For example, wastewater is collected and treated

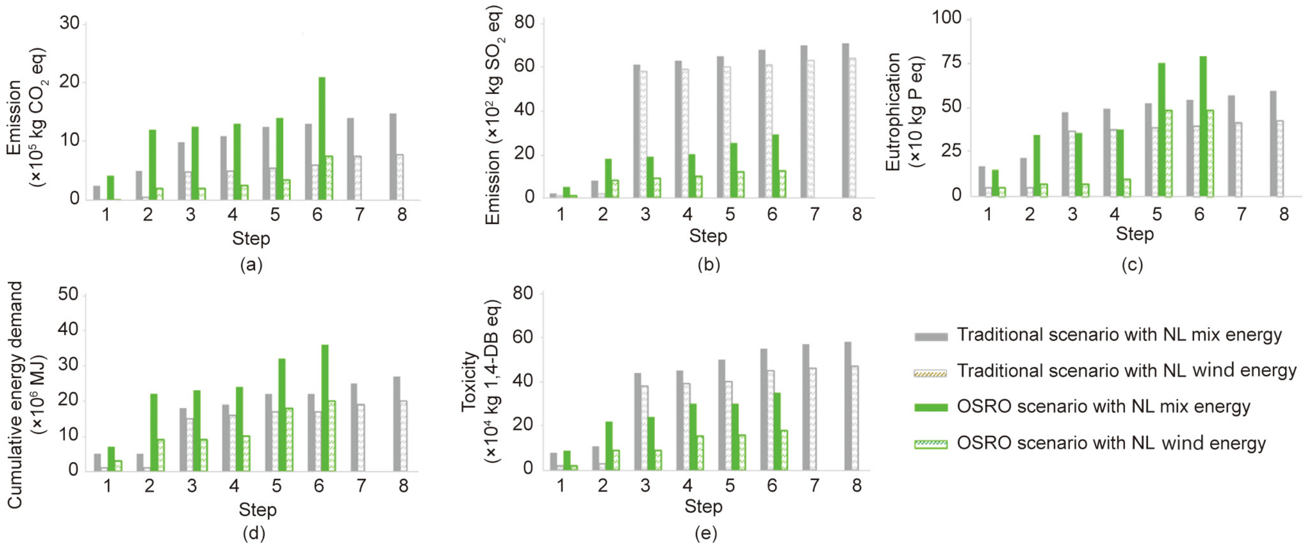

Fig. 5. A comparison between the two production scenarios (OSRO and traditional treatments) using two energy sources (the Netherlands (NL) energy mix and wind power). Impacts are assessed on (a) climate change (CO_2 emission), (b) acidification (SO_2 emission), (c) eutrophication (phosphorous content), (d) cumulative energy demand, and (e) human toxicity potential (1,4-dichlorobenzene (DB) toxicity) of the production of 2.4×10^6 m^3 drinking water. NL energy mix consists of 87.28% fossil, 7.77% wind, 1.25% solar, 0.1% hydro, and 3.6% nuclear. Steps 1–8 for traditional scenario are: dry sand filtration, aeration, trickling filtration, softening, rapid sand filtration, activated carbon filtration, UV disinfection, and reservoir storing. Steps 1–6 for OSRO scenario are: RBF extraction, RO membrane filtration, ion exchange, calcite filtration, degasification, and reservoir storing. Eq: equivalent.

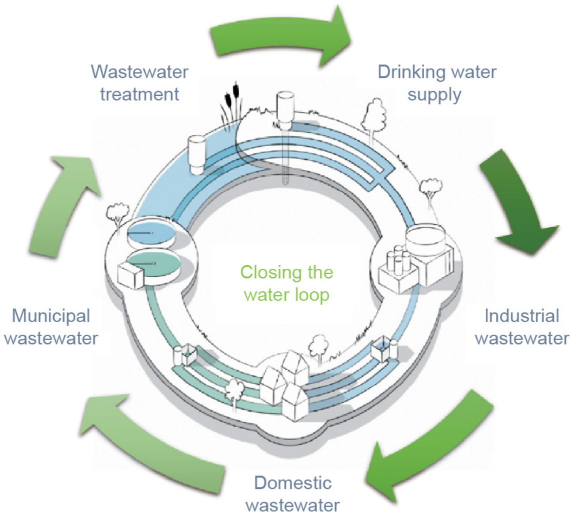

Fig. 6. An illustration of the concept of closing the water loop. Municipal, domestic, agricultural, and industrial wastewaters are collected and further treated to meet the requirements for discharging into the surface water or recharging into underground aquifers, after which the water can be reused to produce drinking water. The result is a closed water loop that recycles water from and to its source.

locally, such as in a bioreactor or artificial sand filtration system; it is then purified using membrane filtration such as UF/RO, and further disinfected using UV–O_3. The purified water is supplied for use, and the concentrate from the RO membrane filtration is repeatedly treated. In addition, decentralization can be coupled with rainwater collection to treat rainwater and storm water. This is especially beneficial for areas with water scarcity, where decentralization could provide alternative water sources when the centralized water system is isolated.

With an increasing global population, mega urbanization, extreme river pollution, and high requirements for drinking water quality, new additional sources and techniques for drinking water production are required [5]. Groundwater reserves are seriously over exploited, especially in heavily populated areas, and river water is not likely to improve in the coming years. The OSRO concept can potentially be applied in areas where surface water is available but the quality is not good enough to be used for drinking water production. Moreover, the OSRO concept is robust, which is prepared for hydrological system changes such as upcoming brackish water or seawater intrusion as a result of climate change [69], and for the emergent situations such as the outbreak of waterborne viruses as a natural but efficient barrier for drinking water biosafety [70]. Continuous exploration into and focus on combinations of natural processes and engineered systems are encouraged in order to produce, reclaim, and reuse water sources in a more sustainable and renewable way.

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Compliance with ethics guidelines

Yujia Zhai, Gang Liu, and Walter G.J. van der Meer declare that they have no conflict of interest or financial conflicts to disclose.

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