

Advanced wastewater reclamation – a response of the municipal sector to climate change and water scarcity

Zaawansowany odzysk wody ze ścieków
– odpowiedź sektora komunalnego na zmiany klimatu i niedobór wody

PIOTR ZAWADZKI, MARTA WIESNER-SĘKALA

DOI 10.36119/15.2024.12.12

This paper presents systematised information concerning advanced technologies for municipal wastewater reclamation in 15 selected facilities worldwide. The analysed plants include both low-capacity facilities, designed to service specific needs, as well as major wastewater reclamation plants that service entire communities or cities, where the daily output can reach even up to 500 000 m³/d. These facilities serve from 4 000 to even up to 2.3 million people equivalent. State-of-the-art wastewater reclamation plants typically employ a combination of multiple treatment methods, such as physical (e.g. sand traps, filtration), biological (e.g. biological reactors, membrane bioreactors) and chemical (coagulation, flocculation). However, it is becoming more common for wastewater treatment plants to expand their processing systems with a tertiary wastewater recycling. These include filtration processes (e.g. sand or carbon filters), biological (e.g. biological activated carbon) and membrane, particularly microfiltration, ultrafiltration and reverse osmosis. Reclaimed water is primarily used for irrigating green space, recreational areas, crop cultivation in agriculture, as well as potable water.

Keywords: municipal wastewater, wastewater reclamation, advanced wastewater treatment, water scarcity, climate change, wastewater management

W niniejszym artykule przedstawiono usystematyzowane informacje dotyczące zaawansowanych technologii odzysku wody ze ścieków komunalnych w 15 wybranych oczyszczalniach na całym świecie. Analizowane obiekty obejmują zarówno instalacje o niskiej wydajności, zaprojektowane do zaspokajania konkretnych potrzeb, jak i duże zakłady odzysku ścieków, obsługujące całe społeczności lub miasta, w których dzienna produkcja może osiągać nawet 500 000 m³/d. Obiekty te obsługują od 4 000 do nawet 2,3 miliona osób. Najnowocześniejsze instalacje odzysku wody ze ścieków zazwyczaj wykorzystują kombinację wielu metod oczyszczania, takich jak fizyczne (np. piaskowniki, filtracja), biologiczne (np. reaktory biologiczne, bioreaktory membranowe) i chemiczne (koagulacja, flokulacja). Jednak coraz częściej oczyszczalnie ścieków rozbudowują swoje systemy oczyszczania o trzeci stopień oczyszczania ścieków. Obejmują one procesy filtracji (np. filtry piaskowe lub węglowe), biologiczne (np. biologiczny węgiel aktywny) i membranowe, w szczególności mikrofiltrację, ultrafiltrację i odwróconą osmozę. Odzyskana woda jest wykorzystywana głównie do nawadniania terenów zielonych, terenów rekreacyjnych, upraw w rolnictwie, a także jako źródło wody do picia.

Słowa kluczowe: ścieki komunalne, odzysk wody ze ścieków, zaawansowane oczyszczanie ścieków, niedobór wody, zmiany klimatu, gospodarka ściekowa

Introduction

The progressing global water crisis results in a shortage of sufficient natural water resources due to the adverse influence of the climate and the increased demand for water, which make access to clean and safe water more difficult (World Health Organization, 2019). According to the estimates of the United Nations (UN), the availability of clean and safe water intended for human consumption may fall even by 40% in the coming decade. By 2050, the water demand will double, and more than half of the global population will be at risk of water shortage (Chen et al., 2022; Greve et al., 2018).

Reclaimed water, depending on its operating parameters, can be used to wash public squares and streets, irrigate green space or wash vehicles (urban areas), but it also finds application in agricultural purposes (rural areas) and industrial operations (process water in industrial plants) (Shahid et al., 2022; Yadav et al., 2019). Risks of water shortage should be limited by striving for increased water recycling, meaning the use of adequately treated wastewater for purposes broader than irrigation. Literature data indicates that municipal wastewater can constitute a source of water for supplying electrolyzers (Chauhan and Ahn, 2023; Maddaloni et al., 2023; Zawadzki et al., 2023), or

even a source of water intended for human consumption (Ding, 2023; Manisha et al., 2023). The reuse of wastewater minimises the environmental risks related to its disposal and relieves the pressure on ecosystems as a result of fresh water intake. In this case, wastewater becomes an additional resource facilitating the achievement of sustainable water management (Wójcicka, 2021). However, the time-variable composition of the wastewater poses a significant problem. The composition of municipal wastewater varies over time and depends e.g. on factors such as: changing atmospheric and climatic conditions (precipitation, thaw, temperature variations), the character and size of an

dr inż. Piotr Zawadzki <https://orcid.org/0000-0003-1020-5926>, mgr Marta Wiesner-Sękala – Department of Water Protection, Central Mining Institute – National Research Institute, Katowice, Poland. Corresponding author's e-mail: pzawadzki@gig.eu

agglomeration, the inflow of industrial wastewater, changes in manufacturing processes, malfunctions and routine maintenance work. These factors affect the wastewater composition, resulting e.g. in additional inflows of suspended solids and biogenic substances, which influences the final treatment effect (Friedler et al., 2021; Sánchez et al., 2021; Zawadzki, 2023).

The global water crisis and the dynamically changing formal and legal circumstances related to the necessity of obtaining appropriate water intake permits mean that the use of tap water for processing or irrigation may exacerbate the challenges related to water shortage (Qadir et al., 2020). Literature data indicates that by 2030 the global yearly water demand may reach 6 900 billion m³, which will constitute over 64% of the total available volume (Maryam and Büyükgüngör, 2019). This demonstrates that the water demand already exceeds the supply, which intensifies the water shortages over the world (du Plessis, 2023). Therefore, it is a legitimate necessity to identify alternative methods of water recovery. Municipal wastewater treatment methods, with appropriately selected technology and processing parameters, could support the recovery process for safe, reliable and stable water (Sikosana et al., 2019). The recycling of treated wastewater under safe and cost-effective conditions is a valuable though unpopular method of increasing the water supply and relieving the overly exploited water resources in the European Union (Fito and Van Hulle, 2021).

About 380 billion m³ of wastewater is produced globally each year, and it is expected that its global production, relative to the current level, will rise by 24% by 2030 and by 51% by 2050 (Zhang and Liu, 2022). It is estimated that in the United States about 45 billion m³ of municipal wastewater is discharged into the environment each year, and under 10% of the wastewater is recycled (Li et al., 2017; National Academies Press, 2023). In China, the estimated quantity of municipal wastewater discharged into the environment is about 70 – 74 billion m³ per year (Lu et al., 2019; Xu et al., 2020). The recycling rate is about 10% (Goh et al., 2016). In Europe, the calculated annual quantity of produced municipal wastewater is about 55 billion m³ (Statista, 2023). If such great volumes of wastewater were treated according to defined criteria of water quality, they would become a valuable resource with the potential to be reused for various purposes.

A clearly increasing interest in wastewater reclamation, including municipal wastewater reclamation, can be observed over the last years (Figure 1). This is related to the rapid scientific and technological developments in the water and wastewater sector (Wu et al., 2021), as well as the fact that considerably more rigorous requirements pertaining to water and wastewater management are being implemented globally (Capodaglio and Olsson, 2020; Qin et al., 2023). More efficient and sustainable wastewa-

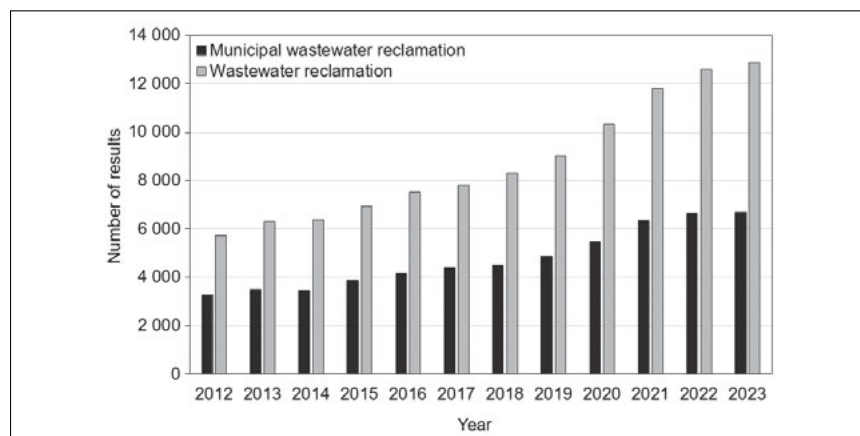


Figure 1.

Trend of the number of publications per year search by words in SCHOLAR database: "Wastewater reclamation" and "Municipal wastewater reclamation" from the years 2010 to 2023. Source: own study based on (GOOGLE SCHOLAR, 2024)

Rysunek 1. Roczne zmiany liczby publikacji wyszukiwanych w bazie SCHOLAR według słów: "Odzysk wody ze ścieków" i "Odzysk wody ze ścieków komunalnych" w latach 2010 do 2023. Źródło: opracowanie własne na podstawie (GOOGLE SCHOLAR, 2024)

ter treatment plant operation has currently become the most pressing issue to solve in the entire municipal wastewater sector. Optimising the operation of Wastewater Treatment Plants (WWTPs) requires full knowledge on the current state of treatment and the auxiliary facilities involved in both the wastewater treatment itself and in sewage sludge management. Issues related to the wastewater treatment and reclamation are becoming particularly significant given that wastewater treatment plants exhibit slow development (Soares, 2020), while new technologies are focused more on gas emissions from the plants (Maktabifard et al., 2023; Parravicini et al., 2022) as well as on materials of biological origin, e.g. the recovery of bioplastics (Kumar et al., 2022; Vasudevan and Natarajan, 2022) or cellulose (Akyol et al., 2022; Ragi et al., 2022). An additional problem can be found in the constantly identified new pollutants occurring in water and wastewater, including e.g. micropollutants such as: chlorinated methanesulphonic acids, microplastics, compounds used in UV filters and suntan creams, contrast media used in computer-assisted tomography, or even illegal drugs such as cocaine and its metabolites (Lempart et al., 2020; Pistocchi et al., 2022; Verovšek et al., 2023). As the micropollutant concentrations increase constantly with the release of new, resistant substances, it is necessary to move beyond conventional wastewater treatment methods and proceed towards more innovative solutions. Therefore this paper presents systematised data concerning advanced municipal wastewater treatment processes as well as a compilation of the most important technologies used for wastewater reclamation, based on information obtained from actual municipal wastewater treatment plants in the world. Hence, the currently secondary municipal wastewater treatment processes were discussed, including advanced processes for wastewater reclamation, such as membrane filtration, membrane bioreactors and advanced oxidation processes. Select-

ed municipal facilities in the world that use at least one of the processes acknowledged as technologies for municipal wastewater reclamation were summarised.

Municipal wastewater recycling technologies

The currently conventional municipal wastewater treatment methods are not designed toward wastewater reclamation (Cicekalan et al., 2023; Sangamneri et al., 2023). In order to decrease the pollutant loads (expressed as Biological Oxidation Demand – BOD, Chemical Oxidation Demand – COD, total suspended solids, total nitrogen, total phosphorus), municipal wastewater treatment plants use conventional (mechanical-biological) wastewater treatment technologies (Russell, 2019). Each case of processes applied for wastewater reclamation should be analysed individually. The selection of the appropriate treatment method depends on the purpose of the water, its target quality and quantity, the treated medium (wastewater) composition and local conditions.

Commonly applied methods for wastewater reclamation include (Figure 2): coagulation and flocculation, sedimentation, filtration, adsorption, membrane processes, membrane bioreactors, advanced oxidation processes.

Coagulation consists in destabilising the colloidal system by adding the appropriate reagents (coagulants, flocculants) to the water or wastewater (Abujazar et al., 2022). Coagulation is applied primarily to remove colloids, which do not undergo sedimentation by virtue of their small size. The reagent addition leads to the neutralisation of the suspended solids, the generation of sludge flocs (flocculation), and finally their removal by sedimentation and/or filtration. The purpose of filtration is the elimination of suspended solids (Vries et al., 2017). Filtration processes are also intended to protect

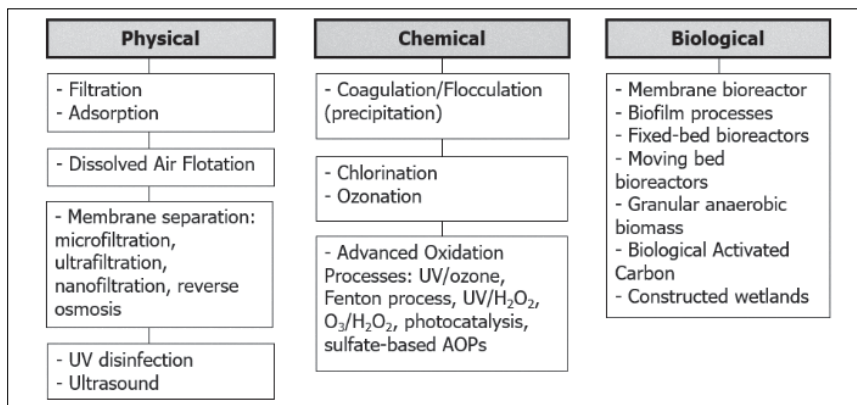


Figure 2. Municipal wastewater reclamation methods Source: own study based on 130779751 (Garg et al., 2022; Ghernaout, 2018; Sturm et al., 2022)

Rysunek 2. Technologie odzysku wody ze ścieków komunalnych Źródło: opracowanie własne na podstawie 130779751 (Garg et al., 2022; Ghernaout, 2018; Sturm et al., 2022)

downstream processing equipment from mechanical damage. Filtration can be applied to wastewater treated over the course of the primary treatment plant processing chain, but it can also be used for wastewater pre-treated through other means (e.g. coagulation/sedimentation). Prefiltration can utilise pressure filters (in cases of low output) or (open) gravity filters for high flows (Verma et al., 2017). Pressure-driven membrane processes are more advanced wastewater pre-treatment methods, which include: microfiltration (MF), ultrafiltration (UF), nanofiltration (NF) and reverse osmosis (RO) (Cevallos-Mendoza et al., 2022). The separation efficiency is primarily determined by the applied pressure and membrane pore sizes (microfiltration, ultrafiltration) or the membrane material (reverse osmosis – dissolution and diffusion mechanism). The unquestionable advantages of pressure-driven membrane separation include the lack of chemical dosing, as the system operation is based only on pressure as the driving force, while the separation occurs at room temperature, with no phase transition (Hube et al., 2020; Obotey Ezugbe and Rathilal, 2020).

Technologies for wastewater reclamation often require the simultaneous integration of a number of processes. Examples of such solutions include biofiltration and membrane bioreactors. The primary purpose of biofiltration is the biological oxidation of biodegradable organic compounds and ammonia nitrogen (Lasocka-Gomula et al., 2018; Paredes et al., 2016). Biofiltration combines the use of ozone and filtration on activated carbon. The combination of ozonation and filtration on activated carbon makes it possible to provide microorganisms with growth conditions on a porous bed. At a correctly selected ozone dose, it is possible to decompose the organic micropollutants into simple compounds that are both easily accessible and non-toxic to the microorganisms (Peterson and Summers, 2021). Membrane bioreactors combine micro – and/or ultrafiltration with activated sludge (Aslam et al., 2017). The processes that

occur in a membrane bioreactor include the simultaneous pollutant biodegradation by means of microorganism cells and capture in the reactor using micro – or ultrafiltration membranes. In this system, the membrane serves as a selective and passive screen, enabling the separation of the treated wastewater (reclaimed water) from the activated sludge. When combined with disinfection methods, it yields a maximum treatment effect (including the elimination of microbiological hazards, micropollutants and oxidation product precursors) (Al-Asheh et al., 2021).

Due to the anthropogenic characteristics of chemical pollutants, conventional municipal wastewater treatment methods are insufficient. As regards the necessity of eliminating specific pollutants such as micropollutants from wastewater, pioneer methods in this context include advanced oxidation processes (AOPs) (Babu Ponnusami et al., 2023; Saravanan et al., 2022). The common feature of AOPs is the chemical reaction between organic pollutants and oxidative radicals: hydroxyl or sulphate (Duan et al., 2020; Giannakis et al., 2021; Pandis et al., 2022). The oxidative radicals are distinct from other, commonly applied oxidants primarily due to their high oxidation potential (E^0). For example, the oxidation potential of ozone, one of the strongest oxidants used in water and wastewater treatment, is $E^0 = 2.08$ V in an acidic medium. Meanwhile the oxidation potential of a hydroxyl radical is $E^0 = 1.8 - 2.8$ V, while for a sulphate radical it is $E^0 = 2.5 - 3.1$ V (Cuerda-Correa et al., 2020; Xia et al., 2020). The AOPs that are the subject of the most intense research are photocatalytic processes (oxidation reactions using light, or photocatalysis) (Fang et al., 2021; Wang et al., 2022), the Fenton process (oxidation reactions using hydrogen peroxide) and its modifications (Nidheesh et al., 2023), oxidation processes based on reactive sulphate radicals (oxidation reactions using persulphates and peroxymonosulphates) (Oyekunle et al., 2022; Wang and Wang, 2022; Zhang et al., 2023) and ozonation (oxidation reactions using ozone) (Azuma

et al., 2022; Rekhate and Shrivastava, 2020; Scaria and Nidheesh, 2022). During the AOPs, the oxidative radicals enter into a reaction with organic substances, enabling their decomposition into environmentally-neutral compounds. Therefore, the AOPs lead to a conversion of macromolecular compounds into substances with lower molecular mass, with water and carbon dioxide as the final reaction products. The key criterion that makes it possible to evaluate the practical usefulness of advanced oxidation processes, i.e. for wastewater pre-treatment, eliminating compounds resistant to biological decomposition or for micropollutant degradation, is the pollutant concentration in the treated stream (Duan et al., 2022). However, due to the high costs of AOPs (e.g. costs of reagents, expensive equipment), the use of these methods should not replace but supplement conventional treatment methods such as biological or physical processes (Ren et al., 2023; Sangeetha et al., 2023). It is recommended to apply advanced oxidation as the final stage of municipal wastewater treatment.

Advanced wastewater reclamation at selected municipal WWTPs

In recent years, problems with access to clean water as well as the global water crisis and strict legal regulations in wastewater management have forced municipal facilities all over the world to implement additional degrees of wastewater treatment (Echevarría et al., 2022; Teoh et al., 2022; Zawadzki and Smoliński, 2023). The use of secondary treatment processes depends on the locations of the treatment plants as well as the hydrogeological conditions, e.g. recreational, protected or agricultural areas, or the proximity of industrial plants or receiving water bodies, therefore the purposes of secondary treatment can include e.g. irrigating green space and agricultural areas, golf fields, supplying industrial plants with water and replenishing aquifers (Drechsel et al., 2022; Helmecke et al., 2020; Khan et al., 2022). Examples of secondary wastewater treatment application by means of advanced water reclamation processes can be found in a number of municipal facilities in the world (Table 1). A broad selection of wastewater recycling plants were analysed – from treatment plants with minor outputs (up to 2 000 m³/d and up to Population Equivalent (PE) = 5 000), designed to service specific sites, as well as major water reclamation plants that service entire communities or cities, where the daily production often exceeds 100 000 m³, and can reach even up to 500 000 m³/d, where the PE can be as high as 2.3 million. In addition, five plants were selected for an in-depth discussion of the wastewater reclamation processes. These sites differ in output, the serviced population number, the applied processing methods as well as the purpose of the recycled water.

Goreangab Reclamation Plant, Windhoek, Namibia, Africa

Current technologies for wastewater reclamation enable the treatment of wastewater to standards that fulfil the criteria for water that is safe for human consumption, which finds confirmation in the practical application of these methods all over the world. For example, about 20 000 – 24 000 m³ of municipal wastewater is recycled daily in the water reclamation plant in Windhoek (Namibia) to produce water for human consumption. Built in 1968 (Haarhoff and Van der Merwe, 1996), this wastewater treatment plant in Namibia was the first facility of this type, where recycling processes were implemented to produce water fit for human consumption from municipal wastewater, and it is probably one of the few that still operates. The plant produces about 25% of the total potable water demand for the capital city of Windhoek, with a population of over 430 000 residents.

In 2003, during the modernization of the plant, a number of innovative tools for wastewater reclamation were installed, including biofiltration and granular activated carbon filtration as well as “multi-barrier” processes such as the mixing of reclaimed water with other potable water sources. These tools are focused on eliminating the physical and organoleptic characteristics as well as the microbiological hazards from the wastewater and to provide water safe for human consumption. Furthermore, the reclaimed water must fulfil the requirement of anthropogenic dissolved organic carbon (aDOC) content lower than 1 mg dm⁻³. The combination of multiple different technologies and tools enables the elimination of pollutants and solids in order to obtain clean and potable water (du Pisani and Menge, 2013; Lahnsteiner et al., 2017).

To ensure the total removal of pathogens and other potentially harmful pollutants, the processing in the water reclamation plant consists 10 stages of treatment (Figure 3). The treatment system involves the following single treatment barriers: powdered activated carbon (PAC) dosing (optional), pre-ozonation, coagulation and flocculation, dissolved air flotation (DAF), sand filters, primary ozonation, biological activated carbon (BAC) filters, adsorption on granular activated carbon (GAC), ultrafiltration (UF) as well as chlorination and pH correction by NaOH dosing. The reclaimed water is tested every 30 minutes (Ander and Forss, 2011).

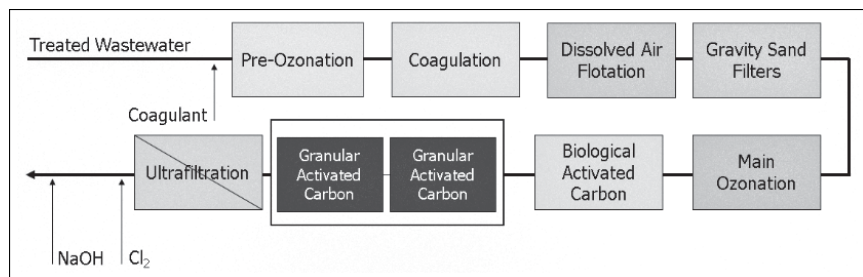


Figure 3.
Process Flow Diagram of wastewater reclamation at Goreangab Plant
Rysunek 3. Schemat przepływowy procesu odzysku wody ze ścieków w zakładzie Goreangab

The treatment stage begins with removing organic substances by dosing iron chloride-based coagulants into the wastewater. The sludge generated after flocculation is separated by dissolved air flotation (DAF). Dissolved air flotation is a special type of sedimentation. DAF uses the generation of a stable agglomerate formed from the dispersed phase (post-coagulation suspension aggregates) and gas vesicles (Muñoz-Alegria et al., 2021). During this process, very small gas vesicles are generated by the pressure drop in the stream, which is first subjected to saturation under pressure greater than atmospheric. Dissolved air flotation is primarily used to remove suspended solids and colloidal particles. The advantage of DAF over sedimentation is the shorter suspended solids separation (about 5 to 15 minutes) and the greater hydraulic load (about 5 to 12 m³ m⁻² h⁻¹), which results in smaller equipment, thereby limiting the investment costs (Kłos and Tokarczyk, 2010). The remaining suspended solids is removed by rapid filters. Pre-ozonation is also used in the Goreangab wastewater treatment plant. Given the high rate of the occurring reactions, low doses of ozone and short contact times are typically applied in pre-ozonation. The purposes of pre-ozonation include organic compound oxidation, manganese and iron compound removal and oxidation of by-products (Kondo Nakada et al., 2020). Pre-ozonation also improves the capability of sludge flock aggregation during coagulation and flocculation (Yan et al., 2007). The technological system is also assisted by hydrogen peroxide dosing (H₂O₂) for advanced water oxidation as well as excess ozone removal before biological filtration. The method based on the interaction of ozone and hydrogen peroxide (H₂O₂/O₃) is described by Equation (1). A series of chain reactions that include a hydroperoxyl anion and an O₃⁻ ion initiate processes that generate

highly reactive hydroxyl radicals (•OH) (Feng, 2022).



Primary ozonation is carried out in a tank divided into three parts. The ozone dose is controlled by detecting the ozone remaining in the water and generally ranges within 5 – 10 mg O₃ dm⁻³. The residual ozone depends on the quantity of the dissolved organic carbon in the water (1.0 – 1.5 mg O₃ mg⁻¹ Dissolved Organic Carbon – DOC) (Ander and Forss, 2011).

Membrane ultrafiltration is used to remove particles larger than 0.05 µm. Ultrafiltration is applied e.g. to control microorganisms and turbidity as well as, the colour of the water. The final stage of wastewater reclamation is disinfection through chlorine dosing. Considering the various forms of chlorine presence in water (depending on pH), NaOH is also added to the water to a level of 7.8 – 8.2. The water remains in contact with the chlorine for about 1 hour.

„Kasina Ski & Bike Park” ski station, Kasina Wielka, Poland

Membrane bioreactor technology is used for wastewater reclamation in the “Kasina Ski & Bike Park” ski resort (Kasina Wielka, Poland). In 2021, the facility obtained a water permit to discharge treated domestic wastewater, originating from existing and future facilities forming the “Kasina-Ski & Bike Park” complex, into the earth by means of snow guns and sprinklers. The MBR (Membrane Bioreactor) technology by SCHWANDER POLSKA Sp. z o.o. sp. k. involves the application of membrane filtration together with treated wastewater recycling after UV lamp disinfection to produce snow on the ski slope in winter and to irrigate green space in the summer (SCHWANDER POLAND, 2020).

Figure 4 presents a flow chart of the treatment plant. The nominal output of the technolo-

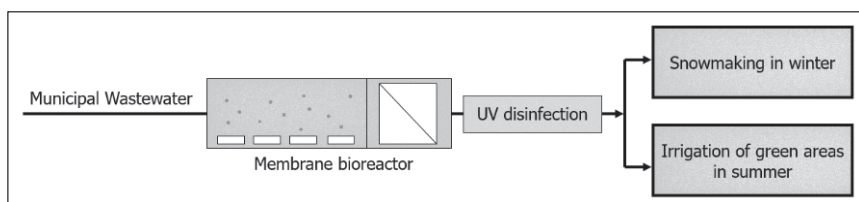


Figure 4.
Process Flow Diagram of wastewater reclamation at „Kasina Ski & Bike Park” ski station
Rysunek 4. Schemat przepływowy procesu oczyszczania ścieków w stacji narciarskiej „Kasina Ski & Bike Park”

gy is about 600 m³/d of domestic wastewater and it can service wastewater originating from about 4 000 people. The technology uses membrane bioreactors consisting of six MFM 300 microfiltration membranes. The microfiltration enables the separation of pathogenic bacteria, viruses, pharmaceuticals, antibiotics and suspended solids. UV lamp disinfection is used as a final stage to eliminate the remaining microorganisms. The domestic wastewater treatment efficiency ranges from 95-99% for parameters such as: COD, BOD, total suspended

solids, total nitrogen and total phosphorus (SCHWANDER POLAND, 2021). Since the wastewater treated by MBR is completely free of suspended solids, the plant also uses the filtrate as process water. Reclaimed water can be used as municipal water for watering and irrigating cultivated land, cleaning public squares and streets and supplying car washes, or as process water for equipment operation and industrial cleaning, making it possible to conserve precious natural potable water resources (WODOCIĄGOWIEC, 2021).

Nartelle Wastewater Treatment Plant (Sainte-Maxime, France)

Another example of a site using reclaimed water for irrigation purposes is the Nartelle treatment plant (Sainte-Maxime, France). Sainte-Maxime is located on the north coast of the Bay of Saint-Tropez, close to the estuary of the river Le Préconil. The expansive, over 10-kilometre-long coastline of the Sainte-Maxime commune offers tourists several major as well as numerous minor sand beaches separated from one another by small rocky bays. The city also offers tourists a number of attractions such as its many golf fields (SAINTE-MAXIME, 2023). In the summer season, Sainte-Maxime must face peak water consumption due to the enormous tourist traffic. The Nartelle WWTP uses a part of the reclaimed water for golf field and green space irrigation purposes. Each year, about 300 000 m³ of water is required to irrigate 60 hectares of a golf field. The Nartelle WWTP can service about 60 000 PE, at a constant local population of about 15 000. The daily wastewater production is about 5 500 m³/d (UNEP, 2011). The designed output of the facility is about 12 000 m³ of wastewater, while its maximum flow capacity is 960 m³/h (SAINTE-MAXIME, 2023).

The first stage of wastewater treatment involves the biological elimination of oils and fats by means of the Biolix™ technology, microsand-assisted Actiflo™ flocculation to remove turbidity and suspended solids, and the Biostyr™ technology to eliminate pollutants (COD and BOD, nitrogen compounds – ammonia and nitrate and total suspended solids) (David et al., 2015) (Figure 5).

The Biolix™ technology uses biomass capable of assimilating oils and fats, resulting in

the production of sludge and carbon dioxide. The unit comprises an array of sieves for separating floating non-biodegradable fractions and for supplementing nutrients for microorganisms as well as an aeration system. The efficiency of the technology ranges within 70 – 75% for COD reduction, 85 – 95% for HEM (n-Hexane extractable material) reduction and 50 – 60% for total suspended solid reduction (VEOLIA, 2023a).

The Actiflo™ technology is an interesting alternative to classic coagulation, flocculation and sedimentation processes that additionally uses microsand as the basis for producing flocks (Zych and Heidrich, 2019). Microsand is a ballast for sludge flock, which exhibit very good sedimentation properties, which makes it possible to decrease the required equipment size by several factors, as well as to greatly simplify and shorten the processing, thereby increasing the possibility of controlling its course and optimising the costs of water or wastewater treatment (VEOLIA, 2023b). The technology finds application particularly in the water and/or wastewater treatment where the sludge flock sizes are too small to produce bigger particles (Samaei et al., 2020). An advantage of this technology is its smaller size compared to classic water purification systems (about 20 times), the short start-up time (up to 10 minutes) and its resistance to variations in the quality of the inflowing wastewater. A significant element of the equipment is a hydrocyclone, which purifies and recirculates the reclaimed microsand, enabling its repeated use in the process (VEOLIA, 2023c). The removal efficiency for total suspended solids is at least 90%, while for BOD and COD it is at least 60% (VEOLIA, 2015).

The Biostyr™ technology combines biological processes, clarification and filtration within one combined unit. The technology is intended for removing pollutants (BOD and COD, nitrogen compounds – ammonia, nitrate, and suspended solids) (VEOLIA, 2023d). The wastewater treatment process in the Nartelle plant is conducted in six aerated biological reactors with a fluid bed. The biomass is deposited on polystyrene beads and retained by a pre-cast concrete nozzle deck. The wastewater flows upwards through the fluid bed. Air is injected through an air grate located beneath the bed, at the bottom of the chamber, and it rises parallel to the treated wastewater (VEOLIA, 2023e).

In order to adapt the treatment plant to the requirements of water reclamation for the purposes of golf field irrigation, an additional stage of treated wastewater recycling was implemented in 2006. It consists of filtration processes on four sand filters as well as disinfection by UV and chlorine (David et al., 2015). By reusing the recycled water, the city no longer has to take water from natural sources, which makes it possible to increase the quantity of potable water available to the residents. Simultaneously, it reduces the operating costs related to purchasing tap water, as over 280 000 m³ of potable water is annually replaced by reclaimed water (about 2 000 m³/d, depending of the season and irrigation needs). Wastewater reclamation makes it possible to save about 12% of the annual tap water consumption (VEOLIA, 2023f).

SHAFDAN Wastewater Treatment Plant (Israel)

The SHAFDAN plant is the biggest WWTP in Israel as well as one of the biggest in the

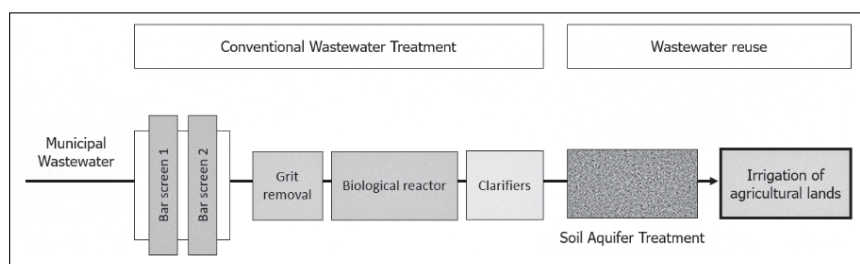


Figure 6. Process Flow Diagram of wastewater reclamation at Shafdan Wastewater Treatment Plant
Rysunek 6. Schemat przepływowy procesu odzysku wody ze ścieków w oczyszczalni ścieków Shafdan

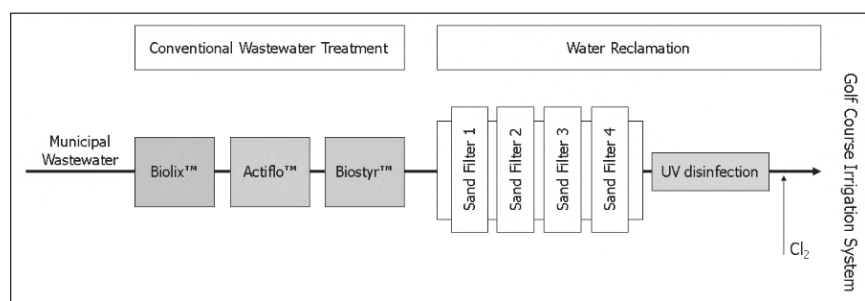


Figure 5. Process Flow Diagram of wastewater reclamation at Nartelle wastewater treatment plant
Rysunek 5. Schemat przepływowy procesu odzysku wody ze ścieków w oczyszczalni ścieków Nartelle

Middle East. The facility has been the primary source of water for Israeli agriculture for over thirty years (Global Water Intelligence, 2022). The WWTP output is 360,000 m³/d, which constitutes about 92% of its total output. In order to reduce the WWTP loading, the site is planned to be upgraded to a capacity of 500,000 m³/d by 2030 (Messing and Sela, 2016). Furthermore, it is predicted that by 2050 the annual consumption of the reclaimed water may double (Global Water Intelligence, 2022).

The wastewater reclamation process is conducted in two stages (Figure 6). First, the raw

municipal wastewater is subjected to mechanical treatment on bar screens and in a sand trap in order to remove the solids, suspended solids, sand and major fragments of various materials found in municipal wastewater, which could otherwise flow into the downstream elements of the facility and result in an unnecessary increase of the processed material dimensions or lead to the damage or clogging of the equipment. Afterwards, the wastewater is subjected to biological treatment in rotating bioreactors with activated sludge, after which the sludge is ultimately eliminated from the wastewater in secondary settling tanks (Center for Water Research, 2019). The pollutant removal efficiency is relatively high, within 90% – 98.5%.

The final stage of the advanced water reclamation process is injecting the treated wastewater into the soil aquifer. Soil aquifer treatment (SAT) effectively removes the bacterial flora, nitrogen, organic solids as well as various micropollutants (Abdel Sattar et al., 2019; Sallwey et al., 2020). The treated wastewater remains in the sandy soil aquifer for an average retention time of 1 year. However, the pollutant removal efficiency in the SAT system depends on a several factors, including the quality of the injected wastewater, the hydrogeological conditions and the applied injection methods (Alam et al., 2021; Brooks et al., 2020). The applied technology prevents the mixing of the injected wastewater with the water found naturally in the soil (Global Water Intelligence, 2022). The treated wastewater undergoes further natural

filtration in the soil aquifer until it achieves the quality of “grey water”. The reclaimed water is pumped and supplied for agricultural purposes, thereby meeting over 70% of the irrigation needs (Messing and Sela, 2016).

Doha West (Qatar)

Due to the considerable economic growth and the consequent increase in water demand, the Doha West treatment plant in Doha has nearly doubled its output to 245,000 m³/d in recent times, becoming the biggest operational wastewater treatment plant in the country (Ashghal, 2023). The facility uses a combination of physical, chemical and biological processes in order to reclaim water from municipal waste-

water for the purposes of agricultural, green space and market garden irrigation as well as for soil aquifer replenishment. Nearly 85% of the reclaimed water is reused (SUEZ, 2023a).

The wastewater treatment is carried out using the Degrémont® technology and involves three stages: primary, secondary and tertiary treatment (Figure 7). The primary stage consists in the mechanical wastewater treatment and elimination of solids, suspended solids and sand by means of step screens and sand traps. The secondary stage involves the biological degradation of pollutants based on activated sludge and clarification. The tertiary treatment includes advanced wastewater treatment by means of sand filters and the membrane ultrafiltration

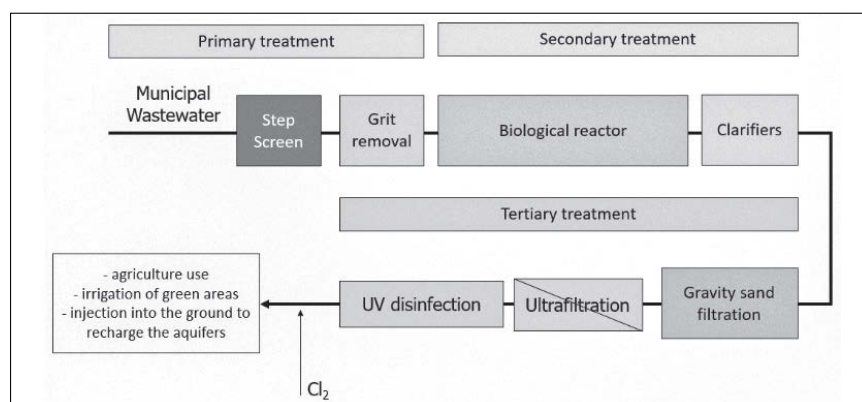


Figure 7. Process Flow Diagram of wastewater reclamation at DOHA WEST Wastewater Treatment Plant
Rysunek 7. Schemat przepływu procesu odzysku wody ze ścieków w oczyszczalni ścieków DOHA WEST

Table 1. Examples of municipal wastewater reclamation plants

Tabela 1. Przykłady komunalnych zakładów odzysku wody ze ścieków

Plant	Capacity	PE	Wastewater reclamation processes	Possible use of reclaimed water	References
	m ³ /d				
Goreangab Water Reclamation Plant (WRP) (Windhoek, Namibia)	20 000 – 24 000	n/d	Pre-ozonation, coagulation, dissolved air filtration, rapid gravity sand filters, main ozonation, biological activated carbon, granular activated carbon, ultrafiltration, chlorination, NaOH dosing	Blending in the distribution system	(Ander and Forss, 2011; Lahnsteiner et al., 2017)
Howard F. Curren WWTP (Florida, USA)	av. 208 000	600 000	Screen, grit, primary sedimentation tanks, secondary clarifier, nitrification, denitrification, denitrification filter, post-aeration	Discharge into Hillsborough Bay, but also meets standards for public-access reuse: irrigating green areas, filling decorative ponds and fountains, direct irrigation and indirect irrigation	(TAMPA, 2023a, 2023b, 2023c)
Nartelle WWTP (Sainte-Maxime, France)	12 000	60 000	Biological removal of oil and fats (Biolix™), suspended solids removal using microsand (Actiflo™), removal of BOD, COD, nitrogen, and solids (Biotyrt™)	Golf course irrigation system, irrigation of green areas	(SAINTE-MAXIME, 2023; VEOILIA, 2023f)
Milano San Rocco WWTP (Milan, Italy)	av. 345 600	1 050 000	Mechanical treatment, activated sludge biological treatment, Aquazur® sand filters, settling clarifier process by Densadeg®, UV disinfection	The final step of water recycling by ultra-violet disinfection produces the water for agricultural irrigation in the amount of 14,400 m ³ /h in the dry season	(SUEZ, 2023c, 2023d)
SHAFDAN WWTP (Israel)	360 000 by 2030: 500 000	2 300 000	Mechanical treatment, aerated biological reactors, Soil Aquifer Treatment (SAT)	Injection of treated wastewater into the aquifer. In the aquifer, further natural filtration process treats wastewater to the “gray water” quality that is used in agriculture. Reclaimed water is pumped and supplied entirely for agricultural purposes	(Center for Water Research, 2019; Global Water Intelligence, 2022; Messing and Sela, 2016)
Big Spring Raw Water production Facility (RWPF) (Texas, USA)	7 600	n/d	The Big Spring RWPF takes ca. 7 600 m ³ /d of treated wastewater from the Big Spring WWTP. The Big Spring WWTP treats the wastewater in the mechanical processes (screens, grit removal), biological (single rock media trickling filter, aeration basin), clarification in final clarifier, chlorination, sand filtration and dichlorination. The Big Spring RWPF treats the treated wastewater by microfiltration, reverse osmosis, and advanced oxidation process (H ₂ O ₂ /UV)	ca. 7 600 m ³ /d of reclaimed water is blending with surface water and used as raw water for drinking water treatment plants	(Lahnsteiner et al., 2017; Sloan and Dhanapal, 2007)
Terminal Island WRP (San Pedro, USA)	ca. 45 000	130 000	Microfiltration, reverse osmosis, ammonia injection to reduce bromate formation in the AOP UV reactors, advanced oxidation process by UV and sodium hypochlorite	Injection into the Dominguez Gap Barrier to protect groundwater from saltwater intrusion, transport to industrial users in the Harbor area	(Civiltec, 2023; LA Sanitation, 2023; XYLEM, 2015)

Beaufort West WRP (Beaufort West, South Africa)	2 000	n/d	Conventional wastewater treatment: screening, grit removal, biological reactor, FeCl ₃ dosing, sedimentation, pre-chlorination Tertiary wastewater treatment: sedimentation, intermediate chlorination, rapid sand filtration, ultrafiltration, reverse osmosis, advanced oxidation process (H ₂ O ₂ /UV), final chlorination	Blending of 20-30% of reclaimed water in the distribution system	(Ivarsson and Olander, 2011; Lahnsteiner et al., 2017; The Water Wheel, 2015)
Bee Ridge Water Reclamation and Advanced WWTP (Sarasota County, USA)	ca. 45 400 By 2025: ca. 68 100	n/d	Mechanical treatment, biological reactors, membrane bioreactor, disinfection	Golf course irrigation system, roadways and irrigation of green areas	(ABC7, 2022; Carollo, 2023; Sarasota County, 2023)
Doha West WWTP (Doha, Qatar)	245 500	650 000	Primary treatment by step screen and grit removal, activated sludge secondary treatment, gravity sand filtration, ultrafiltration, chlorination	Agriculture use (55%), irrigation of green areas (42%) injection into the ground to recharge the aquifers (3%)	(SUEZ, 2023b, 2023a)
Wichita Falls (Texas, USA)	19 000	150 000	chlorination, chloramination, coagulation, sedimentation, microfiltration, reverse osmosis, UV disinfection	Blending in the distribution system. A blend of recycled water and raw water is distributed to the drinking water facilities	(Lahnsteiner et al., 2017; Water Online, 2014; Wichita Falls, 2023)
Médiouna WWTP (Casablanca, Morocco)	3 800	80 000	Pre-filtration, membrane bioreactor	Irrigation of agricultural lands	(Freyberg, 2013; Nahli et al., 2016)
„Kasina Ski & Bike Park” ski station (Kasina Wielka, Poland)	600	4 000	Membrane bioreactor, UV disinfection	Snowmaking in winter, irrigation of green areas in summer	(SCHWANDER POLAND, 2020; WODOCIĄGOWIEC, 2021)
Haliotis 2 (Nicea, France) a	n/d	680 000	Wastewater treatment and reuse, microplastic removal, sewage sludge removal, recovery of resource materials (e.g. biomethane)	Recycling of 5 000 000 m ³ water per year to irrigate green areas and clean roads of the Nice city	(Smart Water Magazine, 2023; SUEZ, 2024)
Fred Hervey Water Reclamation Plant (El Paso, Texas, USA) b	37 850	865 000	microfiltration/ultrafiltration, nanofiltration/reverse osmosis, UV/H ₂ O ₂ (AOPs), GAC, stabilization, Cl ₂ disinfection	Pipe-to-pipe direct potable reuse of reclaimed water	(Villalobos, 2023)

n/d – no data; a The start of works is scheduled for the second half of 2024, and the commissioning will take place gradually between 2025 and 2030; b Anticipated to start up in 2027

process. The final stage is the physical (UV) and chemical (chlorination) disinfection of the reclaimed water (SUEZ, 2023b).

The key process to guarantee the full reclamation of water from wastewater is the membrane filtration stage (ultrafiltration). The membrane filtration system consists of Ultrablue™ ZW1000 immersed ultrafiltration membranes with a nominal pore size of 0.02 µm and a minimum filtration module surface of 42 m². The membranes are characterised by a modular structure with potential for a future expansion of the system. The membranes are located in a gravity-fed tank. Combined with the UV and chlorine-based disinfection processes, ultrafiltration provides an excellent sanitary barrier and enables water recycling. The combination of these processes makes it possible to use 100% of the wastewater, over half of which is used in agriculture, about 42% for green space irrigation, while the remainder (about 3%) is injected into the soil aquifers (SUEZ, 2023b).

Conclusion

The implementation of wastewater reclamation technologies is an important element of circular economy. Reclaimed water should limit the global water consumption and decrease the volumes of pollutants discharged into the environment. The technologies applied all over the world ensure the reclamation of water that fulfils the physicochemical and microbiological safety standards for water supply systems. The technology selection must consider both the target group of the reclaimed water users as well as the desired water quality. The ideal technology should allow the free rearrangement of individual process devices to produce water of a quality needed at a given moment. For example, in the winter it could be the production of artificial snow in ski resorts, while in the summer it would produce potable water, water replenishment in

ponds and lakes, or crop irrigation. In regions with low population densities but a great contribution of agriculture, it would be appropriate to select a technology that meets the current requirements concerning water intended for agricultural irrigation. On the other hand, in regions with great industrial presence, the potential target groups could be interested in the supply of both potable and process water. The primary challenges related to municipal wastewater reclamation include microbiological hazards (viruses, bacteria, fungi, etc.). Information campaigns, advertising brochures and meetings serve an important role in weakening the social opposition to the reuse of water reclaimed from wastewater. Certainly, the success of wastewater recycling will be driven by demonstrators and pilot plants showing local communities the methods of water purification and wastewater conditioning before reuse. The currently employed technologies make it possible to treat wastewater to standards that fulfil the criteria of water safe for human consumption, which finds confirmation in both test results as well as the practical applications of these technologies all over the world.

Acknowledgements

The presented study was performed in the framework of the research work in the Central Mining Institute in Poland, financially supported by the Polish Ministry of Education and Science [No. 11131013-340]

REFERENCES

- [1] ABC7, 2022. Sarasota breaks ground on new water reclamation facility [WWW Document]. <https://www.mysuncoast.com>. URL <https://www.mysuncoast.com/2022/03/24/sarasota-breaks-ground-new-water-reclamation-facility/> (accessed 8.1.24).
- [2] Abdel Sattar, A.M., Bonakdari, H., Negm, A., Gharabaghi, B., Elhakeem, M., 2019. Soil Aquifer Treatment System Design Equation for Orga-

- nic Micropollutant Removal, in: Negm, A.M. (Ed.), *Groundwater in the Nile Delta*, The Handbook of Environmental Chemistry. Springer International Publishing, Cham, pp. 307–326. https://doi.org/10.1007/978-3-319-13613-6_13
- [3] Abujazar, M.S.S., Karaağaç, S.U., Abu Amr, S.S., Alazaiza, M.Y.D., Bashir, M.J.K., 2022. Recent advancement in the application of hybrid coagulants in coagulation-flocculation of wastewater: A review. *Journal of Cleaner Production* 345, 131133. <https://doi.org/10.1016/j.jclepro.2022.131133>
- [4] Akyol, Ç., Eusebi, A.L., Cipolletta, G., Bruni, C., Foglia, A., Giosuè, C., Frison, N., Tittarelli, F., Canestrari, F., Fatone, F., 2022. Chapter 8 – Cellulosic materials recovery from municipal wastewater: from treatment plants to the market, in: An, A., Tyagi, V., Kumar, M., Cetecioglu, Z. (Eds.), *Clean Energy and Resource Recovery*. Elsevier, pp. 125–136. <https://doi.org/10.1016/B978-0-323-90178-9.00013-5>
- [5] Alam, S., Borthakur, A., Ravi, S., Gebremichael, M., Mohanty, S.K., 2021. Managed aquifer recharge implementation criteria to achieve water sustainability. *Science of the Total Environment* 768, 144992. <https://doi.org/10.1016/j.scitotenv.2021.144992>
- [6] Al-Asheh, S., Bagheri, M., Aidan, A., 2021. Membrane bioreactor for wastewater treatment: A review. *Case Studies in Chemical and Environmental Engineering* 4, 100109. <https://doi.org/10.1016/j.csee.2021.100109>
- [7] Ander, H., Forss, M., 2011. Microbiological Risk Assessment of the Water Reclamation Plant in Windhoek, Namibia.
- [8] Ashghal, 2023. DOHA WEST – Project Details [WWW Document]. URL <https://www.ashghal.gov.qa/en/Projects/Pages/projectdetails.aspx?pid=396> (accessed 8.1.24).
- [9] Aslam, M., Charfi, A., Lesage, G., Heran, M., Kim, J., 2017. Membrane bioreactors for wastewater treatment: A review of mechanical cleaning by scouring agents to control membrane fouling. *Chemical Engineering Journal* 307, 897–913. <https://doi.org/10.1016/j.cej.2016.08.144>
- [10] Azuma, T., Usui, M., Hayashi, T., 2022. Inactivation of Antibiotic-Resistant Bacteria in Wastewater by Ozone-Based Advanced Water Treatment Processes. *Antibiotics* 11, 210. <https://doi.org/10.3390/antibiotics11020210>

- [11] Babu Ponnusami, A., Sinha, S., Ashokan, H., V Paul, M., Hariharan, S.P., Arun, J., Gopinath, K.P., Hoang Le, Q., Pugazhendhi, A., 2023. Advanced oxidation process (AOP) combined biological process for wastewater treatment: A review on advancements, feasibility and practicability of combined techniques. *Environmental Research* 237, 116944. <https://doi.org/10.1016/j.envres.2023.116944>
- [12] Brooks, J., Weisbrod, N., Bar-Zeev, E., 2020. Revisiting Soil Aquifer Treatment: Improving Biodegradation and Filtration Efficiency Using a Highly Porous Material. *Water* 12, 3593. <https://doi.org/10.3390/w12123593>
- [13] Capodaglio, A.G., Olsson, G., 2020. Energy Issues in Sustainable Urban Wastewater Management: Use, Demand Reduction and Recovery in the Urban Water Cycle. *Sustainability* 12, 266. <https://doi.org/10.3390/su12010266>
- [14] Carollo, 2023. Bee Ridge WRF Expansion – Sarasota County, Florida. Carollo. URL <https://carollo.com/solutions/bee-ridge-water-reclamation-facility-expansion/> (accessed 8.1.24).
- [15] Center for Water Research, 2019. Visiting Israel's Water Treatment Facility at Shafdan – Center for Water Research [WWW Document]. URL <https://water.northwestern.edu/2019/09/25/get-water-blog-5-visiting-israels-water-treatment-facility/> (accessed 8.1.24).
- [16] Cevallos-Mendoza, J., Amorim, C.G., Rodríguez-Díaz, J.M., Montenegro, M. da C.B.S.M., 2022. Removal of Contaminants from Water by Membrane Filtration: A Review. *Membranes* 12, 570. <https://doi.org/10.3390/membranes12060570>
- [17] Chauhan, D., Ahn, Y.-H., 2023. Alkaline electrolysis of wastewater and low-quality water. *Journal of Cleaner Production* 397, 136613. <https://doi.org/10.1016/j.jclepro.2023.136613>
- [18] Chen, X., Zhao, B., Shuai, C., Qu, S., Xu, M., 2022. Global spread of water scarcity risk through trade. *Resources, Conservation and Recycling* 187, 106643. <https://doi.org/10.1016/j.resconrec.2022.106643>
- [19] Cicekalan, B., Kosar, S., Cingoz, S., Eyt, N., Ersahin, M.E., Ozgun, H., 2023. Techno-economic and environmental assessment of different municipal wastewater treatment systems. *Journal of Water Process Engineering* 53, 103822. <https://doi.org/10.1016/j.jwpe.2023.103822>
- [20] Civiltec, 2023. Terminal Island Advanced Oxidation Process Effluent Recirculation [WWW Document]. Civiltec Engineering, Inc. URL <https://www.civiltec.com/terminal-island-advanced-oxidation-process-effluent-recirculation/> (accessed 8.1.24).
- [21] Cuerda-Correa, E.M., Alexandre-Franco, M.F., Fernández-González, C., 2020. Advanced Oxidation Processes for the Removal of Antibiotics from Water. An Overview. *Water* 12, 102. <https://doi.org/10.3390/w12010102>
- [22] David, B., Briol, M., Hercule-Bobroff, S., 2015. Reuse in practice: a review of selected French case studies. *Water Practice and Technology* 10, 312–318. <https://doi.org/10.2166/wpt.2015.037>
- [23] Ding, G.K.C., 2023. Wastewater Treatment, Reused and Recycling – A Potential Source of Water Supply, in: Reference Module in Earth Systems and Environmental Sciences. Elsevier. <https://doi.org/10.1016/B978-0-323-90386-8.00062-0>
- [24] Drechsel, P., Qadir, M., Galibourg, D., 2022. The WHO Guidelines for Safe Wastewater Use in Agriculture: A Review of Implementation Challenges and Possible Solutions in the Global South. *Water* 14, 864. <https://doi.org/10.3390/w14060864>
- [25] du Pisaní, P., Menge, J.G., 2013. Direct potable reclamation in Windhoek: a critical review of the design philosophy of new Goreangab drinking water reclamation plant. *Water Supply* 13, 214–226. <https://doi.org/10.2166/ws.2013.009>
- [26] du Plessis, A., 2023. Water Resources from a Global Perspective, in: du Plessis, A. (Ed.), *South Africa's Water Predicament: Freshwater's Unceasing Decline*, Water Science and Technology Library. Springer International Publishing, Cham, pp. 1–25. https://doi.org/10.1007/978-3-031-24019-5_1
- [27] Duan, X., Niu, X., Gao, J., Waclawek, S., Tang, L., Dionysiou, D.D., 2022. Comparison of sulfate radical with other reactive species. *Current Opinion in Chemical Engineering* 38, 100867. <https://doi.org/10.1016/j.coche.2022.100867>
- [28] Duan, X., Yang, S., Waclawek, S., Fang, G., Xiao, R., Dionysiou, D.D., 2020. Limitations and prospects of sulfate-radical based advanced oxidation processes. *Journal of Environmental Chemical Engineering* 8, 103849. <https://doi.org/10.1016/j.jece.2020.103849>
- [29] Echevarría, C., Pastur, M., Valderrama, C., Cortina, J.L., Vega, A., Mesa, C., Aceves, M., 2022. Techno-economic assessment of decentralized polishing schemes for municipal water reclamation and reuse in the industrial sector in coastal semiarid regions: The case of Barcelona (Spain). *Science of The Total Environment* 815, 152842. <https://doi.org/10.1016/j.scitotenv.2021.152842>
- [30] Fang, M., Tan, X., Liu, Z., Hu, B., Wang, X., 2021. Recent Progress on Metal-Enhanced Photocatalysis: A Review on the Mechanism. *Research (Wash D C)* 2021, 9794329. <https://doi.org/10.34133/2021/9794329>
- [31] Feng, L., 2022. Study on the Mechanism and Kinetics of O₃/H₂O₂ Advanced Oxidation Reaction. *J. Phys.: Conf. Ser.* 2329, 012030. <https://doi.org/10.1088/1742-6596/2329/1/012030>
- [32] Fito, J., Van Hulle, S.W.H., 2021. Wastewater reclamation and reuse potentials in agriculture: towards environmental sustainability. *Environ Dev Sustain* 23, 2949–2972. <https://doi.org/10.1007/s10668-020-00732-y>
- [33] Freyberg, T., 2013. Casablanca membrane wastewater reuse plant first in North Africa, says GDF Suez [WWW Document]. *Water-World*. URL <https://www.waterworld.com/home/article/16208008/casablanca-membrane-wastewater-reuse-plant-first-in-north-africa-says-gdf-suez> (accessed 8.1.24).
- [34] Friedler, E., F. Chavez, D., Alfiya, Y., Gilboa, Y., Gross, A., 2021. Impact of Suspended Solids and Organic Matter on Chlorine and UV Disinfection Efficiency of Greywater. *Water* 13, 214. <https://doi.org/10.3390/w13020214>
- [35] Garg, A., Gautamb, P., Salunke, D., 2022. Advanced Treatment Technologies for Industrial Wastewater, in: Roy, S., Garg, A., Garg, S., Tran, T.A. (Eds.), *Advanced Industrial Wastewater Treatment and Reclamation of Water: Comparative Study of Water Pollution Index during Pre-Industrial, Industrial Period and Prospect of Wastewater Treatment for Water Resource Conservation*, Environmental Science and Engineering. Springer International Publishing, Cham, pp. 25–44. https://doi.org/10.1007/978-3-030-83811-9_2
- [36] Ghernaout, D., 2018. Increasing Trends Towards Drinking Water Reclamation from Treated Wastewater. *WJAC* 3, 1. <https://doi.org/10.11648/j.wjac.20180301.11>
- [37] Giannakis, S., Lin, K.-Y.A., Ghanbari, F., 2021. A review of the recent advances on the treatment of industrial wastewaters by Sulfate Radical-based Advanced Oxidation Processes (SR-AOPs). *Chemical Engineering Journal* 406, 127083. <https://doi.org/10.1016/j.cej.2020.127083>
- [38] Global Water Intelligence, 2022. Shafdan expansion project [WWW Document]. Global Water Intelligence. URL <https://www.global-waterintel.com> (accessed 8.1.24).
- [39] Goh, P.S., Matsuura, T., Ismail, A.F., Hilal, N., 2016. Recent trends in membranes and membrane processes for desalination. *Desalination, Advances in Membrane Des: Keynotes from MEMDES 2-Singapore* 391, 43–60. <https://doi.org/10.1016/j.desal.2015.12.016>
- [40] GOOGLE SCHOLAR, 2024. SCHOLAR DATABASE [WWW Document]. URL <https://scholar.google.com/> (accessed 8.1.24).
- [41] Greve, P., Kahil, T., Mochizuki, J., Schinko, T., Satoh, Y., Burek, P., Fischer, G., Tramberend, S., Burtscher, R., Langan, S., Wada, Y., 2018. Global assessment of water challenges under uncertainty in water scarcity projections. *Nat Sustain* 1, 486–494. <https://doi.org/10.1038/s41893-018-0134-9>
- [42] Haarhoff, J., Van der Merwe, B., 1996. Twenty-five years of wastewater reclamation in Windhoek, Namibia. *Water Science and Technology, Wastewater Reclamation and Reuse* 1995 33, 25–35. [https://doi.org/10.1016/0273-1223\(96\)00403-9](https://doi.org/10.1016/0273-1223(96)00403-9)
- [43] Helmecke, M., Fries, E., Schulte, C., 2020. Regulating water reuse for agricultural irrigation: risks related to organic micro-contaminants. *Environmental Sciences Europe* 32, 4. <https://doi.org/10.1186/s12302-019-0283-0>
- [44] Hube, S., Eskafi, M., Hrafnkelsdóttir, K.F., Bjarnadóttir, B., Bjarnadóttir, M.Á., Axelsdóttir, S., Wu, B., 2020. Direct membrane filtration for wastewater treatment and resource recovery: A review. *Science of The Total Environment* 710, 136375. <https://doi.org/10.1016/j.scitotenv.2019.136375>
- [45] Ivarsson, O., Olander, A., 2011. Risk Assessment for South Africa's first direct wastewater reclamation system for drinking water production.
- [46] Khan, M.M., Siddiqi, S.A., Farooque, A.A., Iqbal, Q., Shahid, S.A., Akram, M.T., Rahman, S., Al-Busaïdi, W., Khan, I., 2022. Towards Sustainable Application of Wastewater in Agriculture: A Review on Reusability and Risk Assessment. *Agronomy* 12, 1397. <https://doi.org/10.3390/agronomy12061397>
- [47] Kłós, M., Tokarczyk, J., 2010. Application of dissolved air flotation in surface water treatment – solution for full scale process. *Instal nr* 2, 32–36.
- [48] Kondo Nakada, L.Y., Urbano Dos Santos, L., Guimarães, J.R., 2020. Pre-ozonation of surface water: An effective water treatment process to reduce the risk of infection by Giardia in drinking water. *Environ Pollut* 266, 115144. <https://doi.org/10.1016/j.envpol.2020.115144>
- [49] Kumar, M., Devgon, I., Bala, R., Rana, A., Somal, M.K., Sachan, R.S.K., Karnwal, A., 2022. Chapter 12 – Integrated production of polyhydroxyalkonate (bioplastic) with municipal wastewater and sludge treatment for sustainable development, in: Kumar, V., Kumar, Manish (Eds.), *Integrated Environmental Technologies for Wastewater Treatment and Sustainable Development*. Elsevier, pp. 283–303. <https://doi.org/10.1016/B978-0-323-91180-1.00011-9>
- [50] LA Sanitation, 2023. Terminal Island Water Reclamation Plant. Advanced Oxidation Process (AOP) Improvements.
- [51] Lahnsteiner, J., van Rensburg, P., Esterhuizen, J., 2017. Direct potable reuse – a feasible water management option. *Journal of Water Reuse and Desalination* 8, 14–28. <https://doi.org/10.2166/wrd.2017.172>
- [52] Lasocka-Gomuła, I., Michalkiewicz, M., Cybulski, Z., Kołaski, P., Wysocka, A., 2018. Removal of Organic Matter from Water During

- Rapid Filtration through a Biologically Active Carbon Filter Beds – a Full Scale Technological Investigation. *Technologia Wody* Nr 5 (61).
- [53] Lempart, A., Kudlek, E., Dudziak, M., 2020. The potential of the organic micropollutants emission from swimming accessories into pool water. *Environment International* 136, 105442. <https://doi.org/10.1016/j.envint.2019.105442>
- [54] Li, W., Jain, T., Ishida, K., Liu, H., 2017. A mechanistic understanding of the degradation of trace organic contaminants by UV/hydrogen peroxide, UV/persulfate and UV/free chlorine for water reuse. *Environ. Sci.: Water Res. Technol.* 3, 128–138. <https://doi.org/10.1039/C6EW00242K>
- [55] Lu, J.-Y., Wang, X.-M., Liu, H.-Q., Yu, H.-Q., Li, W.-W., 2019. Optimizing operation of municipal wastewater treatment plants in China: The remaining barriers and future implications. *Environment International* 129, 273–278. <https://doi.org/10.1016/j.envint.2019.05.057>
- [56] Maddaloni, M., Marchionni, M., Abbà, A., Mascia, M., Tola, V., Carpanese, M.P., Bertanza, G., Artioli, N., 2023. Exploring the Viability of Utilizing Treated Wastewater as a Sustainable Water Resource for Green Hydrogen Generation Using Solid Oxide Electrolysis Cells (SOECs). *Water* 15, 2569. <https://doi.org/10.3390/w15142569>
- [57] Maktabifard, M., Al-Hazmi, H.E., Szulc, P., Mousavizadegan, M., Xu, X., Zaborowska, E., Li, X., Mąkinia, J., 2023. Net-zero carbon condition in wastewater treatment plants: A systematic review of mitigation strategies and challenges. *Renewable and Sustainable Energy Reviews* 185, 113638. <https://doi.org/10.1016/j.rser.2023.113638>
- [58] Manisha, M., Verma, K., Ramesh, N., Anirudha, T.P., Santrupt, R.M., Rao, L., 2023. Water, sanitation, and hygiene implications of large-scale recycling of treated municipal wastewater in semi-arid regions. *Science of The Total Environment* 904, 166631. <https://doi.org/10.1016/j.scitotenv.2023.166631>
- [59] Maryam, B., Büyükgüngör, H., 2019. Wastewater reclamation and reuse trends in Turkey: Opportunities and challenges. *Journal of Water Process Engineering, SI: Sust Water Processing* 30, 100501. <https://doi.org/10.1016/j.jwpe.2017.10.001>
- [60] Messing, A., Sela, Y., 2016. SHAFDAN (Greater Tel Aviv Wastewater Treatment Plant): recent upgrade and expansion. *Water Practice and Technology* 11, 288–297. <https://doi.org/10.2166/wpt.2016.032>
- [61] Muñoz-Alegria, J.A., Muñoz-España, E., Flórez-Marulanda, J.F., 2021. Dissolved Air Flotation: A Review from the Perspective of System Parameters and Uses in Wastewater Treatment. *Tecnol.* 24, e2111. <https://doi.org/10.22430/22565337.2111>
- [62] Nahli, A., Sakhraoui, N., Hebabaze, S., Hmididi, C., Brand, C., Chlada, M., 2016. Membrane biological treatment and agricultural reuse of Mediouna wastewaters (Casablanca, Morocco). *Journal of Materials and Environmental Sciences* 7.
- [63] National Academies Press, 2023. Managing Wastewater in Coastal Urban Areas. <https://doi.org/10.17226/2049>
- [64] Nidheesh, P.V., Ganiyu, S.O., Martínez-Huitle, C.A., Mousset, E., Olvera-Vargas, H., Trelu, C., Zhou, M., Oturan, M.A., 2023. Recent advances in electro-Fenton process and its emerging applications. *Critical Reviews in Environmental Science and Technology* 53, 887–913. <https://doi.org/10.1080/10643389.2022.2093074>
- [65] Obotey Ezugbe, E., Rathilal, S., 2020. Membrane Technologies in Wastewater Treatment: A Review. *Membranes* 10, 89. <https://doi.org/10.3390/membranes10050089>
- [66] Oyekunle, D.T., Gendy, E.A., Ifthikar, J., Chen, Z., 2022. Heterogeneous activation of persulfate by metal and non-metal catalyst for the degradation of sulfamethoxazole: A review. *Chemical Engineering Journal* 437, 135277. <https://doi.org/10.1016/j.cej.2022.135277>
- [67] Pandis, P.K., Kalogiourou, C., Kanellou, E., Vaitis, C., Savvidou, M.G., Sourkouni, G., Zorpas, A.A., Argiris, C., 2022. Key Points of Advanced Oxidation Processes (AOPs) for Wastewater, Organic Pollutants and Pharmaceutical Waste Treatment: A Mini Review. *ChemEngineering* 6, 8. <https://doi.org/10.3390/chemengineering6010008>
- [68] Paredes, L., Fernandez-Fontaina, E., Lema, J.M., Omil, F., Carballa, M., 2016. Understanding the fate of organic micropollutants in sand and granular activated carbon biofiltration systems. *Science of The Total Environment* 551–552, 640–648. <https://doi.org/10.1016/j.scitotenv.2016.02.008>
- [69] Parravicini, V., Nielsen, P.H., Thornberg, D., Pistocchi, A., 2022. Evaluation of greenhouse gas emissions from the European urban wastewater sector, and options for their reduction. *Science of The Total Environment* 838, 156322. <https://doi.org/10.1016/j.scitotenv.2022.156322>
- [70] Peterson, E.S., Summers, R.S., 2021. Removal of effluent organic matter with biofiltration for potable reuse: A review and meta-analysis. *Water Research* 199, 117180. <https://doi.org/10.1016/j.watres.2021.117180>
- [71] Pistocchi, A., Andersen, H.R., Bertanza, G., Brander, A., Choubert, J.M., Cimbritz, M., Drewes, J.E., Koehler, C., Krampe, J., Launay, M., Nielsen, P.H., Obermaier, N., Stanev, S., Thornberg, D., 2022. Treatment of micropollutants in wastewater: Balancing effectiveness, costs and implications. *Science of The Total Environment* 850, 157593. <https://doi.org/10.1016/j.scitotenv.2022.157593>
- [72] Qadir, M., Drechsel, P., Jiménez Cisneros, B., Kim, Y., Pramanik, A., Mehta, P., Olaniyan, O., 2020. Global and regional potential of wastewater as a water, nutrient and energy source. *Natural Resources Forum* 44, 40–51. <https://doi.org/10.1111/1477-8947.12187>
- [73] Qin, Y., Wang, K., Xia, Q., Yu, S., Zhang, M., An, Y., Zhao, X., Zhou, Z., 2023. Up-concentration of nitrogen from domestic wastewater: A sustainable strategy from removal to recovery. *Chemical Engineering Journal* 451, 138789. <https://doi.org/10.1016/j.cej.2022.138789>
- [74] Ragi, K.B., Ekka, B., Mezule, L., 2022. Zero pollution protocol for the recovery of cellulose from municipal sewage sludge. *Bioresource Technology Reports* 20, 101222. <https://doi.org/10.1016/j.biteb.2022.101222>
- [75] Rekhate, C.V., Shrivastava, J.K., 2020. Decolorization of Azo Dye Solution by Ozone Based Advanced Oxidation Processes: Optimization Using Response Surface Methodology and Neural Network. *Ozone: Science & Engineering* 42, 492–506. <https://doi.org/10.1080/01919512.2020.1714426>
- [76] Ren, Y., Chu, Y., Li, N., Lai, B., Zhang, W., Liu, C., Li, J., 2023. A critical review of environmental remediation via iron-mediated sulfite advanced oxidation processes. *Chemical Engineering Journal* 455, 140859. <https://doi.org/10.1016/j.cej.2022.140859>
- [77] Russell, D., 2019. *Practical Waste water Treatment*. John Wiley & Sons, Inc.
- [78] SAINTE-MAXIME, 2023. Accueil [WWW Document]. Site officiel de la ville de Sainte-Maxime. URL <https://www.sainte-maxime.fr/ma-ville/cadre-de-vie/assainissement/> (accessed 8.1.24).
- [79] Sallwey, J., Jurado, A., Barquero, F., Fahl, J., 2020. Enhanced Removal of Contaminants of Emerging Concern through Hydraulic Adjustments in Soil Aquifer Treatment. *Water* 12, 2627. <https://doi.org/10.3390/w12092627>
- [80] Samaei, S.M., Gato-Trinidad, S., Altaee, A., 2020. Performance evaluation of reverse osmosis process in the post-treatment of mining wastewaters: Case study of Costerfield mining operations, Victoria, Australia. *Journal of Water Process Engineering* 34, 101116. <https://doi.org/10.1016/j.jwpe.2019.101116>
- [81] Sánchez, M., Gonzalo, O.G., Yáñez, S., Ruiz, I., Soto, M., 2021. Influence of nutrients and pH on the efficiency of vertical flow constructed wetlands treating winery wastewater. *Journal of Water Process Engineering* 42, 102103. <https://doi.org/10.1016/j.jwpe.2021.102103>
- [82] Sangamner, R., Misra, T., Bherwani, H., Kapley, A., Kumar, R., 2023. A critical review of conventional and emerging wastewater treatment technologies. *Sustain. Water Resour. Manag.* 9, 58. <https://doi.org/10.1007/s40899-023-00829-y>
- [83] Sangeetha, A., Gandhimathi, R., Nidheesh, P.V., 2023. Treatment of stabilized landfill leachate using pyrite-activated persulfate oxidation process. *Process Safety and Environmental Protection* 171, 413–422. <https://doi.org/10.1016/j.psep.2023.01.012>
- [84] Sarasota County, 2023. Bee Ridge Water Reclamation Facility | Sarasota County, FL [WWW Document]. URL <https://www.scgov.net/government/public-utilities/wastewater-division/bee-ridge-water-reclamation-facility> (accessed 8.1.24).
- [85] Saravanan, A., Deivayanai, V.C., Kumar, P.S., Rangasamy, G., Hemavathy, R.V., Harshana, T., Gayathri, N., Alagumalai, K., 2022. A detailed review on advanced oxidation process in treatment of wastewater: Mechanism, challenges and future outlook. *Chemosphere* 308, 136524. <https://doi.org/10.1016/j.chemosphere.2022.136524>
- [86] Scaria, J., Nidheesh, P.V., 2022. Comparison of hydroxyl-radical-based advanced oxidation processes with sulfate radical-based advanced oxidation processes. *Current Opinion in Chemical Engineering* 36, 100830. <https://doi.org/10.1016/j.coch.2022.100830>
- [87] SCHWANDER POLAND, 2021. Porównanie badań filtratu i wody w Potoku Kasinianka [WWW Document]. URL <https://www.schwander.pl/pl/nws/porownanie-badan-filtratu-i-wody-w-potoku-kasinianka> (accessed 8.1.24).
- [88] SCHWANDER POLAND, 2020. Odzysk wody ze ścieków [WWW Document]. URL <https://www.schwander.pl/pl/nws/w-tym-roku-ue-wdrozy-rozporzadzenie-umozliwiajace-odzyskanie-wody-ze-ściekow-oczyszczonych-polska-firma-technologiczna-od-lat-opracowuje-takie-rozwiazania> (accessed 8.1.24).
- [89] Shahid, M.K., Kashif, A., Pathak, P., Choi, Y., Rout, P.R., 2022. Chapter 3 – Water reclamation, recycle, and reuse, in: An, A., Tyagi, V., Kumar, M., Cetecioglu, Z. (Eds.), *Clean Energy and Resource Recovery*. Elsevier, pp. 39–50. <https://doi.org/10.1016/B978-0-323-90178-9.00028-7>
- [90] Sikosana, M.L., Sikhwihlu, K., Moutloali, R., Madyira, D.M., 2019. Municipal wastewater treatment technologies: A review. *Procedia Manufacturing, The 2nd International Conference on Sustainable Materials Processing and Manufacturing, SMPM 2019, 8-10 March 2019, Sun City, South Africa* 35, 1018–1024. <https://doi.org/10.1016/j.promfg.2019.06.051>
- [91] Sloan, D.W., Dhanapal, L.P., 2007. Big Spring Regional Water Reclamation Project. Preliminary Design Report.
- [92] Smart Water Magazine, 2023. SUEZ and Nice Metropolitan unveil France's largest

- wastewater treatment plant [WWW Document]. Smart Water Magazine. URL <https://smartwatermagazine.com/news/suez/suez-and-nice-metropolitan-unveil-frances-largest-wastewater-treatment-plant> (accessed 8.1.24).
- [93] Soares, A., 2020. Wastewater treatment in 2050: Challenges ahead and future vision in a European context. *Environ Sci Ecotechnol* 2, 100030. <https://doi.org/10.1016/j.ese.2020.100030>
- [94] Statista, 2023. Wastewater generation in Europe by country [WWW Document]. Statista. URL <https://www.statista.com/statistics/1393764/wastewater-treatment-generation-europe/> (accessed 8.1.24).
- [95] Sturm, M.T., Myers, E., Schober, D., Thege, C., Korzin, A., Schuhen, K., 2022. Adaptable Process Design as a Key for Sustainability Upgrades in Wastewater Treatment: Comparative Study on the Removal of Micropollutants by Advanced Oxidation and Granular Activated Carbon Processing at a German Municipal Wastewater Treatment Plant. *Sustainability* 14, 11605. <https://doi.org/10.3390/su141811605>
- [96] SUEZ, 2024. Presentation of Haliotis 2, a wastewater recovery and treatment complex for Nice Côte d'Azur Métropole – SUEZ Group [WWW Document]. URL <https://www.suez.com/en/news/press-releases/presentation-haliotis-2-wastewater-treatment-and-recovery-complex-nice-cote-azur-metropolis> (accessed 8.1.24).
- [97] SUEZ, 2023a. Wastewater treatment plant Doha West (Qatar) [WWW Document]. URL <https://www.suezwaterhandbook.com/case-studies/wastewater-treatment/Doha-West-wastewater-treatment-plant-Qatar> (accessed 8.1.24).
- [98] SUEZ, 2023b. Doha West wastewater treatment and reuse plant.
- [99] SUEZ, 2023c. Milano San Rocco wastewater treatment plant.
- [100] SUEZ, 2023d. Wastewater treatment plant of Milan San Rocco [WWW Document]. URL <https://www.suezwaterhandbook.com/case-studies/wastewater-treatment/Milan-San-Rocco-wastewater-treatment-plant-Italia> (accessed 8.1.24).
- [101] TAMP, 2023a. Advanced Wastewater Treatment Plant Facts Of Interest | City of Tampa [WWW Document]. URL <https://www.tampa.gov/wastewater/info/advanced-wastewater-treatment-plant/facts-of-interest> (accessed 8.1.24).
- [102] TAMP, 2023b. Howard F. Curren Advanced Wastewater Treatment Plant | City of Tampa [WWW Document]. URL <https://www.tampa.gov/wastewater/info/advanced-wastewater-treatment-plant> (accessed 8.1.24).
- [103] TAMP, 2023c. Reclaimed Water | City of Tampa [WWW Document]. URL <https://www.tampa.gov/water/conservation/water-smart-lawns/reclaimed-water> (accessed 8.1.24).
- [104] Teoh, G.H., Jawad, Z.A., Ooi, B.S., Low, S.C., 2022. Simultaneous water reclamation and nutrient recovery of aquaculture wastewater using membrane distillation. *Journal of Water Process Engineering* 46, 102573. <https://doi.org/10.1016/j.jwpe.2022.102573>
- [105] The Water Wheel, 2015. Water reclamation. Water – precious resource to be used again, and again and again...
- [106] UNEP, 2011. Inventory of municipal wastewater treatment plants of coastal mediterranean cities with more than 2000 inhabitants.
- [107] Vasudevan, M., Natarajan, N., 2022. Towards achieving sustainable bioplastics production and nutrient recovery from wastewater—a comprehensive overview on polyhydroxybutyrate. *Biomass Conv. Bioref.* <https://doi.org/10.1007/s13399-022-02399-z>
- [108] VEOLIA, 2023a. Biolix™ – Fats and oils removal [WWW Document]. Veolia Water Technologies. URL <https://www.veoliawatertechnologies.com/en/technologies/biolix> (accessed 8.1.24).
- [109] VEOLIA, 2023b. Actiflo® Pack (MINI series) [WWW Document]. Veolia Water Technologies. URL <https://www.veoliawatertechnologies.pl/actiflo-pack-mini-series> (accessed 8.1.24).
- [110] VEOLIA, 2023c. Actiflo® [WWW Document]. Veolia Water Technologies – North America. URL <https://www.veoliawatertech.com/en/solutions/technologies/actiflo> (accessed 8.1.24).
- [111] VEOLIA, 2023d. Biostyr™ [WWW Document]. Veolia Water Technologies. URL <https://www.veoliawatertechnologies.com/en/products/biostyr> (accessed 8.1.24).
- [112] VEOLIA, 2023e. BIOSTYR. Biological Aerated Filter (BAF). Brochure.
- [113] VEOLIA, 2023f. L'irrigation des terrains de golf avec de l'eau recyclée: le Reuse [WWW Document]. Veolia France. URL <https://www.veolia.fr/si-on-utilisait-leau-recyclee-irriguer-golfs-espaces-verts> (accessed 8.1.24).
- [114] VEOLIA, 2015. Actiflo. The ultimate clarifier.
- [115] Verma, S., Davey, A., Sharma, A., 2017. Slow sand filtration for water and wastewater treatment – a review. *Environmental Technology Reviews* 6, 47–58. <https://doi.org/10.1080/21622515.2016.1278278>
- [116] Verovšek, T., Šuštarčič, A., Laimou-Geraniou, M., Krizman-Matašić, I., Prosen, H., Eleršek, T., Kramarič Zidar, V., Mislej, V., Mišmaš, B., Stražar, M., Levstek, M., Cimrmančič, B., Lukšič, S., Uranjek, N., Kozlovič-Bobič, T., Kosjek, T., Kocman, D., Heath, D., Heath, E., 2023. Removal of residues of psychoactive substances during wastewater treatment, their occurrence in receiving river waters and environmental risk assessment. *Science of The Total Environment* 866, 161257. <https://doi.org/10.1016/j.scitotenv.2022.161257>
- [117] Villalobos, S., 2023. Sustainable, Droughtproof Supply. *Water Environment Federation* 36–41.
- [118] Vries, D., Bertelkamp, C., Schoonenberg Kegel, F., Hofs, B., Dusseldorp, J., Bruins, J.H., de Vet, W., van den Akker, B., 2017. Iron and manganese removal: Recent advances in modelling treatment efficiency by rapid sand filtration. *Water Research* 109, 35–45. <https://doi.org/10.1016/j.watres.2016.11.032>
- [119] Wang, B., Wang, Y., 2022. A comprehensive review on persulfate activation treatment of wastewater. *Science of The Total Environment* 831, 154906. <https://doi.org/10.1016/j.scitotenv.2022.154906>
- [120] Wang, H., Li, X., Zhao, X., Li, C., Song, X., Zhang, P., Huo, P., Li, X., 2022. A review on heterogeneous photocatalysis for environmental remediation: From semiconductors to modification strategies. *Chinese Journal of Catalysis* 43, 178–214. [https://doi.org/10.1016/S1872-2067\(21\)63910-4](https://doi.org/10.1016/S1872-2067(21)63910-4)
- [121] Water Online, 2014. Texas Leads The Way With First Direct Potable Reuse Facilities In U.S. [WWW Document]. URL <https://www.wateronline.com/doc/texas-leads-the-way-with-first-direct-potable-reuse-facilities-in-u-s-0001> (accessed 8.1.24).
- [122] Wichita Falls, 2023. Wichita Falls Resource Recovery Facility | Wichita Falls, TX – Official Website [WWW Document]. URL <https://www.wichitafallstx.gov/691/Resource-Recovery> (accessed 8.1.24).
- [123] WODOCIĄGOWIEC, 2021. Water recovery from wastewater in Poland – membrane filtration and UV disinfection [WWW Document]. Odzysk wody ze ścieków w Polsce – filtracja membranowa i dezynfekcja UV. URL <https://wodociagowiec.pl/szczegoly-artykulu/odzysk-wody-ze-sciekow-w-polsce-filtracja-membranowa-i-dezynfekcja-uv/> (accessed 8.1.24).
- [124] Wójcicka, K., 2021. The efficiency of municipal sewage treatment plants inspiration for water recovery. *Technical Transactions* 118. <https://doi.org/10.37705/TechTrans/e2021023>
- [125] World Health Organization, 2019. 1 in 3 people globally do not have access to safe drinking water – UNICEF, WHO [WWW Document]. URL <https://www.who.int/news/item/18-06-2019-1-in-3-people-globally-do-not-have-access-to-safe-drinking-water-unicef-who> (accessed 8.1.24).
- [126] Wu, J., Zhang, Y., Wang, J., Zheng, X., Chen, Y., 2021. Municipal wastewater reclamation and reuse using membrane-based technologies: a review, in: *DESALINATION AND WATER TREATMENT*. pp. 65–82. <https://doi.org/10.5004/dwt.2021.27175>
- [127] Xia, X., Zhu, F., Li, J., Yang, H., Wei, L., Li, Q., Jiang, J., Zhang, G., Zhao, Q., 2020. A Review Study on Sulfate-Radical-Based Advanced Oxidation Processes for Domestic/Industrial Wastewater Treatment: Degradation, Efficiency, and Mechanism. *Frontiers in Chemistry* 8.
- [128] Xu, A., Wu, Y.-H., Chen, Z., Wu, G., Wu, Q., Ling, F., Huang, W.-E., Hu, H.-Y., 2020. Towards the new era of wastewater treatment of China: Development history, current status, and future directions. *Water Cycle* 1, 80–87. <https://doi.org/10.1016/j.watcyc.2020.06.004>
- [129] XYLEM, 2015. City of Los Angeles Terminal Island Water Reclamation Plant selects innovative water reuse solution to address need for water security [WWW Document]. URL <https://www.xylem.com/pl-pl/about-xylem/newsroom/press-releases/city-of-los-angeles-terminal-island-water-reclamation-plant-selects-innovative-water-reuse-solution-to-address-need-for-water-security/> (accessed 8.1.24).
- [130] Yadav, M., Gupta, R., Sharma, R.K., 2019. Chapter 14 – Green and Sustainable Pathways for Wastewater Purification, in: Ahuja, S. (Ed.), *Advances in Water Purification Techniques*. Elsevier, pp. 355–383. <https://doi.org/10.1016/B978-0-12-814790-0.00014-4>
- [131] Yan, M., Wang, D., Shi, B., Wang, M., Yan, Y., 2007. Effect of pre-ozonation on optimized coagulation of a typical North-China source water. *Chemosphere* 69, 1695–1702. <https://doi.org/10.1016/j.chemosphere.2007.06.014>
- [132] Zawadzki, P., 2023. Odnowa wody ze ścieków – korzyści, wyzwania, in: *Najnowsze Trendy w Gospodarce Odpadami Komunalnymi i Przemysłowymi*. Wydawnictwo Naukowe TYGIEL Sp. z o.o., pp. 7–25.
- [133] Zawadzki, P., Kończak, B., Smoliński, A., 2023. Municipal wastewater reclamation: Reclaimed water for hydrogen production by electrolysis – A case study. *Measurement* 216, 112928. <https://doi.org/10.1016/j.measurement.2023.112928>
- [134] Zawadzki, P., Smoliński, A., 2023. Synthesis of green hydrogen in the electrolysis process of water reclaimed from municipal wastewater. *3xW (Węgiel, Wodór, Wiedza)* 1, 17–20.
- [135] Zhang, T., Wu, S., Li, N., Chen, G., Hou, L., 2023. Applications of vacancy defect engineering in persulfate activation: Performance and internal mechanism. *Journal of Hazardous Materials* 449, 130971. <https://doi.org/10.1016/j.jhazmat.2023.130971>
- [136] Zhang, X., Liu, Y., 2022. Resource recovery from municipal wastewater: A critical paradigm shift in the post era of activated sludge. *Biore-source Technology* 363, 127932. <https://doi.org/10.1016/j.biortech.2022.127932>
- [137] Zych, H., Heidrich, Z., 2019. Application of ACTIFLO technology in the surface water treatment. *Gaz, Woda i Technika Sanitarna* 2. <https://doi.org/10.15199/17.2019.2.6>