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Review

Current challenges and future perspectives for the full circular economy of water in European countries

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ABSTRACT

This paper reviews the current problems and prospects to overcome circular water economy management challenges in European countries. The geopolitical paradigm of water, the water economy, water innovation, water management and regulation in Europe, environmental and safety concerns at water reuse, and technological solutions for water recovery are all covered in this review, which has been prepared in the frame of the COST ACTION (CA, 20133) FULLRECO4US, Working Group (WG) 4. With a Circular Economy approach to water recycling and recovery based on this COST Action, this review paper aims to develop novel, futuristic solutions to overcome the difficulties that the European Union (EU) is currently facing. The detailed review of the current environmental barriers and upcoming difficulties for water reuse in Europe with a Circular Economy vision is another distinctive aspect of this study. It is observed that the biggest challenge in using and recycling water from wastewater treatment plants is dealing with technical, social, political, and economic issues. For instance, geographical differences significantly affect technological problems, and it is effective in terms of social acceptance of the reuse of treated water. Local governmental organizations should support and encourage initiatives to expand water reuse, particularly for agricultural and industrial uses across all of Europe. It should not also be disregarded that the latest hydro politics approach to water management will actively contribute to addressing the issues associated with water scarcity.

1. Introduction

Many industrial activities use natural resources as a constant and endless supply, creating a linear economy with a take-use-dispose mentality (Hetgroenebrein, 2020). The European Commission (EC) emphasizes the importance of sustainable water and wastewater management as one of the key elements in the transition to a circular economy (CE) of water. The first EC communication on CE is closely linked to waste management as it focuses on the 'zero waste strategy" (Smol et al., 2020). Subsequently, this strategy is followed to apply CE approaches such as Refuse, Rethink, Reduce, Reuse, Repair, Refurbish,

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Remanufacture, Repurpose, Recycle, and Recover (commonly referred to as R-strategies (Morseletto et al., 2022). The declared CE pathways generally refer to solid waste management and the circularity of water is often poorly considered (Mannina et al., 2022). The United Nations (UN) has set 17 Sustainable Development Goals (SDGs) to which 193 countries have committed (UN, 2016). These goals were updated and renewed in 2018. The CE holds particular promise for achieving several SDGs, including SDG7 on energy, SDG8 on economic growth, SDG11 on sustainable cities, SDG12 on sustainable consumption and production, SDG13 on climate change, SDG14 on oceans, and SDG15 on land (United Nations (UN), 2018). SDG6's target 6.3 for water and sanitation specifically states that by 2030, the world must significantly increase recycling and safe reuse while halving the proportion of untreated wastewater and reducing pollution, stopping dumping, and releasing hazardous chemicals and materials into the environment. To address water scarcity and drastically lower the number of people affected by it, Target 6.4 intends to significantly increase water-use efficiency across all sectors and assure sustainable freshwater abstraction and supply. Target 6. a, by 2030, scale up international cooperation and capacity-building support to developing countries for water and sanitation-related activities and programs, including water harvesting, desalination, water efficiency, wastewater treatment, recycling, and reuse technologies in 2030 will be launched.

The CE approach can guide water innovations to technology and regulations that assist activities for water reuse and recycling. Since it is one of the most crucial resources for the production of food, water has come to govern discussions on the CE. Almost all sectors, including aquaculture and agriculture, rely on it. As a result, numerous studies on the function of water in a CE have been conducted (Casiano Flores et al., 2018). The integration of energy production and resource recovery (nutrient and water recycling) in urban wastewater treatment plants can play an important role in circular sustainability in the whole water sector. Soon, wastewater treatment plants will be an "environmentally sustainable" center for water recycling and reuse. Over the last 25 years, several important factors have underlined the importance of recovering the resources contained in wastewater. Although waste recycling and value-adding techniques are gradually being adopted across national borders in Europe, harmonization is needed as the level of implementation is not uniform. Water recycling solutions can be divided into two types based on technologies: nature-based solutions (NbS) and engineering-based solutions. However, depending on geographical differences and climatic conditions, there may be problems in applying these methods.

The biggest challenge in using and recycling water from wastewater treatment plants is dealing with technical, social, political, and economic issues. On the technical issues, there are geographical differences, as will be discussed in the next sections of this paper. Administratively, it is still evident that different countries, even in Europe, have different regulations for the use of treated water, especially when it comes to public health. Therefore, the research questions of this study, including the objectives of WG 4 in the CA 20133, can be formulated as follows.

List of acronyms & abbreviations

AI	Artificial Intelligence
AMR	Antimicrobial Resistance
AOPs	Advanced Oxidation Processes
ARB	Antibiotic-Resistant Bacteria
ARGs	Antibiotic Resistance Genes
BOD5	Biochemical Oxygen Demand
CAGR	Compound Annual Growth Rate
Cd	Cadmium
CE	Circular Economy
CFU	Colony-Forming Units
COD	Chemical Oxygen Demand
CA	COST ACTION
DBP	Disinfectant By-Products
DPR	Direct Potable Reuse
E. coli	*Escherichia coli*
EC	European Commission
EEA	European Environment Agency
EEC	European Economic Community
EPA	Environmental Protection Agency
EU	European Union
FO	Forward Osmosis
FP	Framework Program
GDP	Gross Domestic Product
IPR	Indirect Potable Water Reuse
ISO	International Organization for Standardization
JRC	Joint Research Center
K	potassium
KRMs	Key Risk Management elements
MBR	Membrane Bioreactor
MF	Microfiltration
ML	Machine Learning
MoU	Memorandum of Understanding
N	Nitrogen
n.a.	not available
NbS	Nature-based Solutions
NDMA	N-nitroso dimethylamine
NF	Nanofiltration
NRMMC-EPHC-AHMC	Australian Natural Resource Management Ministerial Council, Environment Protection and Heritage Council, and Australian Health Ministers Conference
NTU	Nephelometric Turbidity Unit
P	Phosphorus
Pb	Lead
PFAS	Per- and poly-fluoroalkyl substances
PPCPs	pharmaceuticals and personal care products
RO	Reverse Osmosis
SAR	Sodium Adsorption Ratio
SDG	Sustainable Development Goals
TMP	Transmembrane Pressure
TOC	Total Organic Carbon
TSS	Total Suspended Solids
UF	Ultrafiltration
UK	United Kingdom
UN	United Nations
UNEP	United Nations Environment Programme
US -	United States
USD	United States Dollar
US EPA	US Environmental Protection Agency
UV	Ultraviolet
WEs	wastewater effluents
WG	Working Group
WHO	World Health Organization
WWTP	Wastewater Treatment Plant
WWTPs	wastewater treatment plants

- What are the new future perspectives (research and development activities) for dealing with the current challenges of resource recovery in Europe?
- How can we use a snapshot of current conditions to forecast future requirements for a fully circular European economy?
- What opportunities and challenges are based on regional differences?

The COST ACTION FULLRECO4US was established in response to the general trends and future aspects of waste valorization and will serve as a discussion platform for new cross-border interdisciplinary and cross-sectoral networks and holistic approaches to waste recycling and value creation identified by the Memorandum of Understanding (MoU) of the COST20133 Action. Researchers from Europe are working on multidisciplinary topics and represent 35 EU countries in the Action. There are four main WGs to achieve the Action's objectives. These WGs are WG1: Bioenergy recovery from wastes, WG2: Biochemical recovery from wastes, WG3: Biological extraction of food and feed from residues and wastes, and WG4: Water and recovery nutrients from wastewater.

This review paper aims to find innovative, forward-looking solutions to the problems currently facing the EU, with a CE approach to water recycling and recovery based on our COST Action. The novelty of this study is also the comprehensive overview of the current situation, existing barriers, and future challenges for water reuse in Europe with a CE vision. Aspects such as scientific advances, legal frameworks, social and environmental dimensions, product quality and safety, and financial aspects are discussed in this work and possible solutions to the identified problems are proposed. The organizational structure of this review is as follows: recent scientific developments related to water reclamation in Europe are discussed in Section 3, EU regulations on water reclamation are explained in Section 4, the causes of environmental and safety problems in Europe are outlined in Section 5, technological solutions are discussed in Section 6 and the CE approach is discussed in Section 7.

2. Water economy in europe

This section investigates the water economy with the sub sections; current situation, and circular water economy.

2.1. Current situation

In the usual urban water cycle, as shown in Fig. 1, water is withdrawn from sources such as groundwater, lakes, and reservoirs and distributed after treatment for domestic, industrial, and agricultural uses. At the end of use, the generated wastewater needs to be treated. In the classical cycle, this wastewater is discharged into the receiving water bodies after being treated according to regulations (EC (2022/C 298/01); EC (2022/0345). This urban water cycle has created a huge industry and market that includes subcategories such as project design, construction, equipment, chemical materials, operational services, consultancy, and maintenance. Due to the increasing awareness of environmental protection and human health issues, this sector is growing inexorably. The market for water treatment chemicals in Europe alone was worth USD 2.93 billion in 2021 and is expected to reach USD 7.5 billion by the end of 2027, growing at a Compound Annual Growth Rate (CAGR) of 4.35% (Europe Water Treatment Chemicals Market, 2023). Germany leads the production of processing chemicals in Europe due to its high industrialization. Besides these chemicals, Europe has the second-largest market for water and wastewater treatment plants with an expected CAGR of 3.4% (Mordor-intelligence, 2023). 8.7 million m^3/day, or around 9% of the installed capacity worldwide, is thought to be the desalination capacity in Europe. Spain is home to 60% of this capacity (MacErlean, 2022). Desalination is required in Europe mostly due to the drought in the continent's southern regions. Desalination is also used in various areas to clean brackish water or recycle wastewater.

2.2. Circular water economy

Attention to a CE in water management is increasing because there is an imbalance between the available water resources and the ever-increasing water demands of the linear economy approach (Kakwani and Kalbar, 2020). In addition to the decline in available water resources, the increasing discharge criteria for wastewater is leading to water reuse and circular use of water. In Fig. 1, the green arrows show the path of water reuse and circular water economy in the current urban water cycle. Here, reclaimed wastewater is sent for reuse and recycling, and the input of freshwater from sources is reduced. In addition, domestic wastewater can be divided into gray and black water, and gray water can be reused in appropriate applications. For all these purposes of water reuse, innovative technologies have been developed so far and continue to be increasingly used. These initiatives have an enormous potential for creating new green jobs in the water sector. According to projections, the water sector in Europe might provide up to 20,000 new jobs with a 1% rise of the Gross domestic product (GDP) (EC 2023).

Although there have been remarkable advances in wastewater recycling and reuse technologies for the CE, there is a need for efficient business models to implement these technological solutions (Kakwani and Kalbar, 2020). In this context (Salminen et al., 2022), recommends the holistic use of economic, informative, and regulatory tools such as

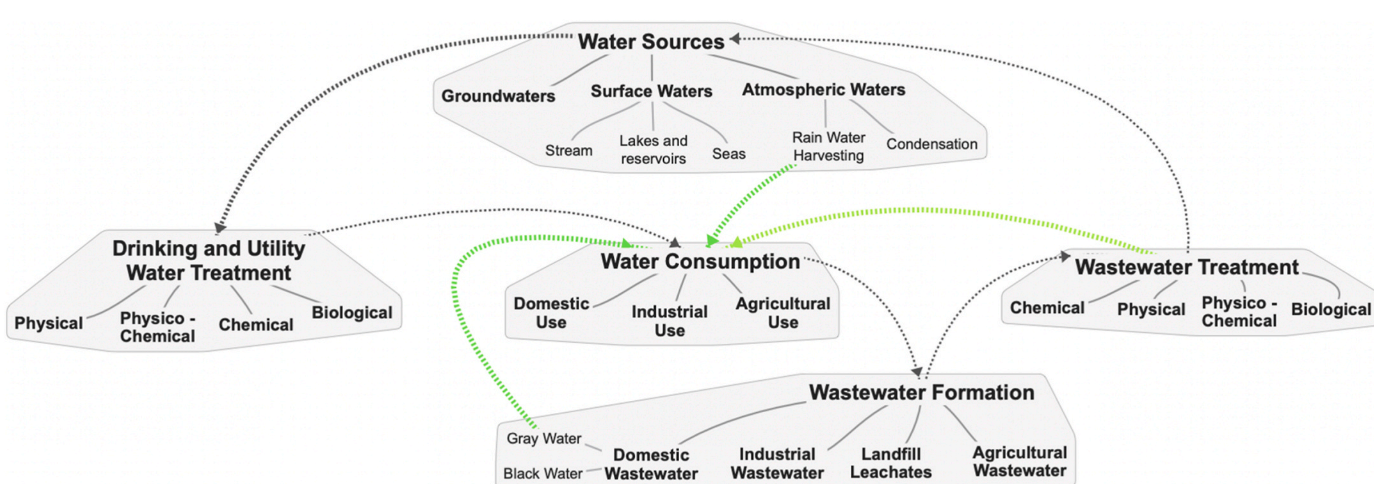

Fig. 1. Urban water cycle and CE paths (green arrows).

water use taxation, tax incentives for recycled water use, and pollutant-focused regulation to promote smart CE water management. Three main principles make it possible to transform current water systems using the CE approach: 1) rebuilding natural capital (protecting the source to ensure the sustainability of its functionality) 2) conserving resources (preserving the water source by closing the loop and maintaining its value through recycling, recovery, and reuse) and shaping the externalities of waste (by avoiding the negative impacts of waste or extracting value from it) (Ramírez-Agudelo et al., 2021). Sauvé et al. (2021) suggests identifying water use and classifying it as sustainable and unsustainable before implementing a CE approach, as this allows us to take more targeted initiatives to reduce the most harmful water use. The example of Singapore, where the CE for water has been applied for many years, is one of the most advanced examples of water circularity in cities. According to reports, the water circularity is steadily increasing in Singapore, and in 2019, 24.9% of the total water demand was met by secondary flows (Arora et al., 2022). However, circular water management in Singapore is practiced with a centralized approach. Van de Walle et al. (2022) state that decentralized circular water management can increase local endurance and reduce the negative impacts of climate change and water scarcity. They used a MATLAB/Simulink model for decentralized water management alternatives for Flanders (Belgium) including rainwater harvesting, wastewater reuse, and discharge via infiltration to be independent of the water and sewer network. They found that pollutant accumulation is a major limitation of using a decentralized system, as 59% of the stored rainwater is needed to remove pollutants. In systems with high pollutant retention (above 95%), full decentralization based on rainwater as a water source has been found feasible in Flanders, Belgium. The principles of circular water economy do not only include water recycling or the recovery of energy and materials from wastewater. In addition, optimal asset management strategies can help to avoid or minimize waste production, which is a requirement of CE. Castellet-Viciano et al. (2022) found that the environmental impact of water and wastewater facilities can be reduced by up to 25% by applying optimal maintenance tasks. They showed that the principles of circular economy in water plants can be achieved without additional and innovative technologies.

3. Water innovation in europe

Three keywords, such as “water recovery”, “water recycling” and “water reuse”, were identified to explore the spread of research in the EU on circular water economy, which we presented with the current situation in the previous section. These words in quotation marks were searched in titles, keywords, and abstracts in the entire Web of Science database between 2000 and 2022, considering only research and review articles. EU member countries and EU-recognized candidate countries are involved in 26%, 34%, and 37% of the global publications on these keywords, respectively.

While the topics of water recycling and water reuse took a significant leap after 2003, the number of articles on water recovery increased significantly after 2015. The increase in the number of publications on each topic over the years shows that this topic is one of the most important research areas in Europe. Italy, the Netherlands, Spain, Poland, Germany, Belgium, France, Denmark, Portugal, and Greece are the top 10 EU members with the most publications on water recovery. These numbers are also in line with the values of industrial production in the EU (Eurostat, 2023). For instance, Germany recorded the highest value of industrial products sold in 2021, equivalent to 27% of the EU total, followed by Italy (16%), France (11%), Spain (8%), Poland (6%), and the Netherlands (4%) (Eurostat, 2023). The research environment in Europe also contributes to the increase in scientific collaborations and outputs. The EUhas been funding many research and development activities under the multi-annual Framework Programs (FP): The 4th RTD FP (1994–1998), the 5th FP (1998–2002), the 6th FP (2002–2006), the 7th FP (2007–2013), Horizon 2020 (EC, 2010) (2014–2020) and Horizon Europe (2021–2027) (EC, 2010).

4. Water management and regulations in the EU

This section examines how water is managed in the EU and the current practices and laws that are followed in this field, particularly when it comes to the reuse of wastewater, reused water quality, and the current wastewater reuse.

4.1. Need for regulations

Guidelines and regulations for the safe use of treated wastewater have been developed in an increasing number of nations due to the need to reduce the health and environmental concerns associated with water reuse. Numerous national and international organizations, including the US Environmental Protection Agency (US EPA), the World Health Organization (WHO), the United Nations Environment Programme (UNEP), the Australian Natural Resource Management Ministerial Council, Environment Protection and Heritage Council, and the Australian Health Ministers Conference (NRMMC-EPHC-AHMC), have proposed reference guidelines for water reuse (Alcalde Sanz and Gawlik, 2014). These frameworks aim to establish a common approach to the rational reuse of water, assuming minimal health and environmental risks from water reuse. A comprehensive account of water reuse guidelines proposed by international organizations and existing criteria in non-EU member countries, United States of America (USA) and Australia is provided in a European Commission’s Joint Research Center (JRC) technical report (Alcalde Sanz and Gawlik, 2014). In the EU, minimum quality requirements for water reuse have been suggested by the JRC indicated in Table 1 (Laura and Bernd, 2017). Minimum quality requirements for the reuse of water for agricultural irrigation and aquifer recharge have been indicated. For instance, Luxembourg identifies the quality classes for reclaimed water and associated uses according to the barriers considered, as well as the corresponding quality criteria for reclaimed water (Table 1). The JRC aimed to develop a common approach to water reuse across the EU. In doing so, a risk management approach was proposed to address risks related to knowledge gaps on the role of the transmission pathway and the potential effects of long-term exposure to organic micropollutants in agricultural systems.

4.2. Wastewater management and reuse regulations in europe

In 2020, the EC introduced a new regulation on minimum requirements for water reuse (EU, 2020b) and published a guide to support the implementation of water reuse in agriculture in 2022 (EC, 2022/C 298/01). The Water Reuse Regulation, which will apply from June 2023, sets out the minimum water quality, monitoring, and risk management requirements to support the safe use of treated urban wastewater in agricultural irrigation. The new regulation categorizes the quality of treated water into four classes based on the intended use and irrigation method. For each class, the minimum water quality requirements (including *E. coli*, Biological Oxygen Demand (BOD), Total Suspended Solids (TSS), and in some cases turbidity, *Legionella* spp., and intestinal nematodes) are specified.

The regulation states that a competent authority must ensure the preparation of a risk management plan for water reuse to identify site-specific risks to the environment or humans and animals. 11 key elements of risk management (KRMs), such as hazard identification, risk assessment, or preventive measures, are specified to derive measures and requirements for risk reduction and monitoring. In the context of relevant hazards, identification, and risk assessment, all relevant EU, national, and local legislation (e.g., Urban Wastewater Directive (91/271/EEC), Water Framework Directive (2000/60/EC), Environmental Quality Standards Directive (2008/105/EC), Groundwater Directive (2006/118/EC), Nitrates Directive (91/676/EEC), Bathing Water

Table 1
Reclaimed wastewater quality criteria for irrigation, as suggested by JRC (Laura and Bernd, 2017).

Reclaimed water quality class	Indicative technology target	Quality criteria				
		E. coli (CFU/100 ml)	BOD5 (mg/l)	TSS (mg/l)	Turbidity (NTU)	Additional criteria
Class A All food crops, including root crops consumed raw and food crops where the edible portion is in direct contact with reclaimed water	Secondary treatment, filtration, and disinfection (advanced water treatments)	≤10 or below detection limit	≤10	≤10	≤5	Legionella spp.: ≤1000 CFU/l when there is a risk of aerosolization. Intestinal nematodes (helminth eggs): ≤1 egg/l when irrigation of pastures or fodder for livestock
Class B Food crops consumed raw where the edible portion is produced above ground and is not in direct contact with reclaimed water, processed food crops, and non-food crops, including crops to feed milk or meat-producing animals	Secondary treatment, and disinfection	≤100	According to Directive 91/271/EEC	According to Directive 91/271/EEC	–	
Class C As class B, but using drip irrigation only	Secondary treatment, and disinfection	≤1000	According to Directive 91/271/EEC	According to Directive 91/271/EEC	–	
Class D Industrial, energy, and seeded crops	Secondary treatment, and disinfection	≤10,000	According to Directive 91/271/EEC	According to Directive 91/271/EEC	–	

Directive (2006/7/EC), Drinking Water Directive (2020/2184)) should be taken into account. The WHO and International Organization for Standardization (ISO) guidelines for the assessment and management of health risks associated with the reuse of non-potable water (ISO, 20426:2018) or the use of treated wastewater for irrigation (ISO 16075:2015) are also available. In addition, the recently proposed revision of the Urban Waste Water Directive (EC, 2022/0345) states that the reuse of treated urban wastewater should be applied whenever appropriate. To encourage Member States to adopt suitable measures to promote wastewater reuse, the EU Water Strategy gives wastewater reuse as an alternative resource a high priority, particularly in water-scarce regions. Because they use a lot of water and have a greater impact on the environment than other industries, agriculture, industry, and energy production are the main sectors with a high potential for wastewater reuse. The nature and magnitude of these industries encourage investment in wastewater reuse projects in these fields, where using treated water can lower operational costs while easing demand for freshwater sources. Efforts to increase water reuse, especially for irrigation and industrial purposes, cover a wide range of relevant aspects of wastewater treatment and reuse such as institutional and legal frameworks, technical feasibility, private sector involvement, and water awareness. However, the adoption of a common strategy by the participating countries is a difficult task due to the different conditions in each Member State and depends to a large extent on each country's experience and level of development in wastewater treatment and reuse. As a result, there are significant variations among EU member states. Cyprus, France, Greece, Italy, Portugal, and Spain have set norms among the member states that employ water reuse. These requirements are mandated by law in all countries except Portugal. Table 2 displays the variations in the wastewater reuse criteria established by different countries.

Table 2
Reclaimed water standards based on agricultural use set by different EU member states (EU, 2020b).

Parameters	Cyprus	France	Greece	Italy	Portugal	Spain
***E. coli* (CFU/100 ml)**	5–10^3	250–10^5	5–200	10	–	0–10^4
Fecal coliforms (CFU/100 ml)	–	–	–	–	100–10^4	–
TSS (mg/l)	10–30	15	2–35	10	60	5–35
Turbidity (NTU)	–	–	2-no limit	–	–	1–15
BOD5, mg/l	10–70	–	10–25	20	–	–
COD, mg/l	70	60	–	100	–	–
Total nitrogen, mg/l	15	–	30	15	–	10

Based on the analysis of the legal frameworks relevant to the reuse of water in EU countries, three main situations were identified (i) Countries without a legal framework for water reuse; for example, the legal framework in Romania allows for the reclamation of wastewater, although the large-scale application of reused water is not possible as no specific regulations for irrigation have been enacted (ii) Countries that have adopted national standards for the reuse of wastewater in agricultural irrigation, these are less restrictive than the proposed EU standards. These countries, e.g. France, should align their framework with the minimum EU suggestions for water reuse (iii) Countries with national standards that are more stringent than the proposed EU regulations on water reuse. In these countries, such as Spain, Italy, Cyprus, and Greece, adopting the EU requirements could be associated with lower costs for producing reclaimed water of adequate quality.

4.3. Current wastewater management in europe

Approximately 90% of urban wastewater is collected and treated throughout the EU following the EU Wastewater Treatment Directive across the entire EU. According to the country profiles, four countries Austria, Germany, Luxembourg, and the Netherlands-, treat 100% of their urban wastewater following the Directive's requirements, while ten other countries have achieved compliance of more than 90%. On the other side of the spectrum, five countries -Ireland, Bulgaria, Romania, Croatia, and Malta, meet the same standards in less than half of their urban areas (EEA Report, 2021). In the EU, water reuse projects are more numerous and take place in Southern European countries such as Cyprus, France, Greece, Malta, Portugal, and Spain. Several reuse projects have also been implemented in central and northern countries such as Belgium, Sweden, and the United Kingdom (Table 3) (Helmecke et al., 2020).

4.4. Reused water quality

It is difficult to define water quality as a criterion and to establish standards that satisfy all uses and user needs (Ritchie and Schiebe, 2000). This topic, also known as emerging contaminants (ECs), has lately come to light due to its frequent reference in the literature. ECs are recently found, typically unmonitored substances that can be either synthetic or natural in origin. These ECs can pollute the environment

Table 3
Water use in European countries in 2019 (Eurostat, 2022).

Country	Urban wastewater generated – total, Million cubic meters	Urban wastewater treated- total inflow, Million cubic meters	Urban wastewater treated as a percentage of total urban wastewater generated
Czechia	893.2	873.1	98
Denmark	316.51 p	n.a.	n.a.
Germany	9767.84*	9662.57**	99
Estonia	103.6	103.04	99
Greece	n.a.	n.a.	n.a.
Spain**	5870 e	4995 e	85
Croatia	200.89	200.89	100
Latvia	107.84	103.21	96
Lithuania	230.72	162.12	70
The Netherlands***	1897.76	1841.32	97
Austria	1094.01	1076.63	98
Poland	1344.22	n.a.	n.a.
Slovenia	n.a.	n.a.	n.a.
Turkey	5090.98	4388.48	86

n.a. – not available, * -data from 2016, ** - data from 2018.

and have negative health consequences on people (Chacón et al., 2022).

Given that many types of contaminants may be present in reclaimed water which is intended for reuse, its quality and usability are critical (Table 4). Numerous more organic and inorganic pollutants are primarily uncontrolled, in addition to the conventional pollutants that are largely regulated, such as suspended solids, organic matter, nutrients, microbes, and heavy metals (Ahmed et al., 2022; Roccaro, 2018). While there are several treatment methods capable of removing selected pollutants, scientifically sound recommendations for appropriate combinations of treatment processes to comply with EU water reuse legislation are currently limited and represent a knowledge gap.

The use of alternate water resources, such as brackish water, saltwater, and stormwater for agriculture and landscape irrigation has increased recently due to water scarcity in numerous parts of the world (Mechiche-Alami et al., 2022; Qin and Horvath, 2020). Furthermore, using treated urban wastewater has grown in significance as a tactic to safeguard and boost agricultural production in many countries (Connor et al., 2017; Hashem and Qi, 2021). Since agriculture uses more than 70% of the freshwater on Earth (FAO, 2017), using treated wastewater for agricultural purposes not only conserves freshwater resources but also reduces the need for chemical fertilizers by providing crops with essential nutrients (such as N, P, and K) (Al-Busaidi and Ahmed, 2017; Pratap et al., 2021) and fertigation (de Morais et al., 2022). Despite the recognized benefits, the reuse of treated wastewater has raised some health and environmental concerns (Table 4), including the risk of human exposure to biological (e.g. pathogens) and chemical (e.g. metals) contaminants, and changes in soil structure and biology due to excess nutrients, salts, and toxic compounds (Deng et al., 2019; Partyka and Bond, 2022). The risks associated with chemical and biological contaminants depend on the source, composition, and type of treatment of the wastewater, type of irrigation system, agricultural practices, and edaphoclimatic conditions (Helmecke et al., 2020; Krzeminski et al., 2019).

The EC unveiled the European Regulation (EU, 2020b) in May 2020, which establishes the minimum quality standards for the use of reclaimed water for agricultural irrigation, to harmonize the regulations for the reuse of treated urban wastewater in all EU member states. Starting on June 26, 2023, this regulation will be implemented across all Member States. Although the treatment of urban wastewater aids in reducing the levels of microbial pathogens, it is insufficient to completely eradicate them (Krzeminski et al., 2019; Shakir et al., 2017). For example, the presence of the intestinal parasites *Cryptosporidium* and *Giardia* in treated wastewater (Razzolini et al., 2020). Similarly, Cui & Liang (2019) reported high levels of pathogens, including *Bacillus cereus*, *Legionella* sp., and *Mycobacterium*, in the effluent even after treatment with an anaerobic reactor. According to Bonetta et al. (2022), the type of treatment is a crucial factor in reducing microbial pathogens in effluents. The authors reported that membrane bioreactor (MBR) technology is more efficient than disinfection with chlorine dioxide in removing *Escherichia coli*, total coliform bacteria, *Enterococci*, and spores of *Clostridium perfringens* from wastewater. According to Abi Saab et al. (2022) crops su ch as onions or radishes should not be irrigated with water containing more than 2 log *E. coli* CFU/100 ml. On the other hand, the authors stated that the irrigation of vegetables to be consumed raw with water containing less than 3 log *E. coli* CFU/100 ml is safe. Orlofsky et al. (2016) showed no transmission of fecal indicator bacteria or microbial

Table 4
Type of contaminants, main exposure routes, and receptors associated with the usage of reclaimed wastewater for irrigation.

	Type	Exposure Routes and Receptors	
Biological contaminants	Microbial pathogens •Viruses •Bacteria •Protozoa •helminths) Antibiotic resistance genes Endotoxins	<u>Direct contact:</u> inhalation of aerosols, dermal absorption; accidental ingestion <u>Ingestion:</u> contaminated edible plant parts; drinking water	•Farmers, farm workers, and the surrounding community •Humans and grazing animals •Environment and wildlife
Chemical compounds	Inorganic compounds •Metals	<u>Direct contact:</u> inhalation of aerosols, dermal absorption; accidental ingestion <u>Ingestion:</u> contaminated edible plant parts; drinking water	•Farmers, farm workers, and the surrounding community •Humans and grazing animals •Environment and wildlife
	Organic compounds •Persistent organic pollutants •Pharmaceuti, endocrine disrupting compounds, personal care products	<u>Direct contact:</u> inhalation of aerosols, dermal absorption; accidental ingestion <u>Ingestion:</u> contaminated edible plant parts; drinking water	•Farmers, farm workers, and the surrounding community •Humans and grazing animals •Environment and wildlife

pathogens to the irrigated soil or crops when surface drip irrigation was used. Similar results were obtained by Obayomi et al. (2019), who indicated that irrigation with reclaimed/recycled wastewater does not pose a risk of fecal contamination to irrigated crops. However, Qureshi et al. (2016) and Tripathi et al. (2019) came to opposite conclusions as they reported high levels of total coliforms and *E. coli* in edible parts of spinach, radish, eggplants, and cauliflower after irrigation with treated wastewater. The type of irrigation also influences the microbial load of irrigated plants. According to Balkhair (2016), microbial counts were lower in plants irrigated with subsurface irrigation systems than in plants irrigated with surface systems. To effectively control antibiotic resistance (AR), as well as other emerging contaminants, a multi-barrier treatment may be required, consisting of several advanced treatment methods (Rizzo et al., 2020). Among advanced treatment methods, membrane processes such as ultrafiltration, nanofiltration, and reverse osmosis, as well as ozonation and advanced oxidation processes, are effective barriers to Antibiotic resistance genes (ARGs) (Hiller et al., 2019; Iervolino et al., 2020; Manoharan et al., 2022). Nevertheless, there is currently insufficient science-based evidence on the effectiveness of full-scale advanced treatment methods and the appropriate combinations of treatment processes. Therefore, the use of treated wastewater for irrigation should be carefully analyzed and limited to non-food crops such as fiber crops and/or crops with a low risk of transferring microbial pathogens into the food chain. The use of adequate amounts of treated wastewater for irrigation purposes is also considered a good strategy to reduce the use of chemical fertilizers in agricultural soils, as it contains essential nutrients such as N, P, K, and Ca, among others (Al-Busaidi and Ahmed, 2017; Albdaiwi et al., 2022; Cui and Liang, 2019; Moretti et al., 2020) while contributing to the CE. However, overuse of highly nutrient-enriched water, especially with N, could lead to excessive accumulation of nutrients in plants and hinder their growth (Chen et al., 2013; Elgallal et al., 2016). In addition, irrigation with reclaimed water can negatively affect the physicochemical properties of soil, including pH and salinity, and increase the accumulation of chemical contaminants (e.g. pharmaceuticals and personal care products (PPCPs), metals), which can leach into groundwater (Jaramillo and Restrepo, 2017) and/or accumulate in crop tissues and enter and biomagnified to the food chain (Albdaiwi et al., 2022). The presence of emerging contaminants such as PPCPs in treated wastewater has been widely reported (Lozano et al., 2022; Tarpani and Azapagic, 2018). Their introduction and accumulation in agroecosystems is a matter of great concern due to the potential risk of uptake and accumulation in food production systems (Fu et al., 2019). Indeed, several authors have reported the increased concentration of various PPCPs in the soil and tissues of plants irrigated with treated wastewater (Abdallat et al., 2022; Fu et al., 2019). However, their accumulation is highly dependent on the properties of molecules, the wastewater source and quality of treatment, concentrations in irrigation water, soil properties, and plant species (Mordechay et al., 2021; Wu et al., 2014). A study conducted by Mordechay et al. (2021) showed the presence of pharmaceutical and other emerging contaminants in irrigation water, soils, and crops from more than 400 commercial fields intensively irrigated with treated wastewater. The highest number and concentrations of pharmaceuticals were found in leafy vegetables, while carbamazepine, lamotrigine, and gabapentin were the predominant compounds found in all matrices tested. Furthermore, the reuse of wastewater effluents (WEs) as irrigation water (e.g., in agriculture) is complicated by the presence of emerging organic contaminants such as per- and poly-fluoroalkyl substances (PFAS), the presence of which can have negative impacts on crops, soils, aquatic ecosystems, and human health; therefore, it is important to remove PFAS in WEs before water reclamation and reuse (Xia et al., 2022). Irrigation of plants with effluents containing various PPCPs also resulted in a high accumulation of carbamazepine in both topsoil and mint leaves (Abdallat et al., 2022). Similar results were obtained for the accumulation of metals in soils and plant tissues. According to the study by Albdaiwi et al. (2022), continuous irrigation of lemon trees with treated wastewater also enhances the accumulation of Cd and Pb in soils and plant tissues, especially in fruits. Similarly, Parveen et al. (2015) presented that continuous irrigation resulted in excessive accumulation of metals in the leaves and roots of beets, even though the concentrations of the metals in the treated wastewater were within the permissible limits. A higher yield was observed in edible vegetables irrigated with treated wastewater compared to plants irrigated with tap water. This effect was accompanied by an increase in the accumulation of metals in the edible parts of carrots, spinach, and radish (Hussain et al., 2019). The use of treated wastewater in agriculture is also not free from undesirable effects on the physicochemical and microbiological properties of the soil (Jaramillo and Restrepo, 2017). Reclaimed water often contains high levels of salts, which can increase salinization and softening of irrigated soils and consequently reduce crop yield (Gao et al., 2021). This is exacerbated by the long dry seasons and high evaporation rates in arid regions (Elgallal et al., 2016). In addition, irrigation with reclaimed water will most likely increase the sodium adsorption ratio (SAR), which will negatively affect soil properties. Erel et al. (2019) reported a 14% increase in SAR after 8 years in soils irrigated with treated wastewater. A number of studies have revealed the presence of antibiotic-resistant bacteria (ARB) and antibiotic-resistance genes (ARG), showing that secondary treatment is not particularly successful in getting removal of ARB and ARG (Hong et al., 2018). Reuse of treated wastewater: addressing safety issues related to antibiotic-resistant bacteria and antibiotic resistance genes (Hong et al., 2018; Krzeminski et al., 2019). Secondary effluents may contribute to the increase of ARB and ARG in receiving aquifers, thus contributing to the spread of AR in the environment, although other potential sources such as stormwater runoff or atmospheric deposition have also been identified (Wang et al., 2021). Antibiotics and antibiotic-resistance genes can be found in reclaimed wastewater treatment plants and aquatic bodies that receive effluent from Wastewater Treatment Plants (WWTPs) (Wang et al., 2021). However, specific emphasis should be given to the fate of ARGs in a wastewater treatment plant, especially during the subsequent disinfection processes of chlorination or ozonation, which have been shown to have low removal capacity, and in irrigation water and the impact on human health (Fahrenfeld et al., 2013).

4.5. Current wastewater reuse in europe

In 2006, approximately 1 billion m^3/year of wastewater was reused, representing 2.4% of municipal wastewater and less than 0.5% of annual freshwater consumption (ACTeon et al., 2016). Research conducted in 2015 indicated that the volume of wastewater reuse is around 1.1 billion m3/year, or 0.4% of the yearly freshwater demand (WATER REUSE TECHNOLOGY APPLICATION GUIDE, 2020). In general, water reuse figures decrease further north of Europe. Israel, on the other hand, has the greatest rate of water recycling among the Mediterranean countries that are experiencing severe water shortages. Farming-related issues Up to 90% of recycled wastewater is used for irrigation, and recycled wastewater accounts for around 50% of all irrigation water (Helmecke et al., 2020). The detailed information belonging to case studies can be explained as follows: The case study from Italy presented that farmers in the area must pay a concession fee to be permitted to take out water from the Vettabbia stream. This payment is not observed in case studies in other countries. It sets an important example in terms of the proper implementation of legal practices and deterrence (Supplementary Material 1). The survey of water reuse rates in EU Member States found that only a small percentage of treated wastewater is reused, while the EU's potential for water reuse is considered much greater: A volume in the order of 6 billion m3/year by 2025 could be appropriate with stronger regulatory and financial incentives at EU level. In the worst-case scenario, without the adoption of specific measures to promote wastewater reuse, a volume of 1.7 billion m^3/year could be achieved by 2025 (Amec Foster Wheeler Environment and Infrastructure UK Ltd ACTeon, IMDEA and NTUA, 2016). However, the establishment of wastewater reuse projects necessitates a long-term strategy that calls for appropriate wastewater collection and reclamation in agricultural areas' infrastructures and distribution networks, which may have an impact on water management at the basin, aquifer, and even national levels. A long-term national perspective on the economic effects of agricultural reuse of treated wastewater in Israel (Reznik et al., 2017). Furthermore, efficient reuse of water requires the establishment of appropriate quality standards for reclamation, taking into account human and animal health, including food safety factors, and environmental health in terms of soil and water contamination. Towards that direction, epidemiological and quantitative risk assessment models suggest that water reuse guidelines should be region-specific and based on local farming practices, available wastewater treatment technologies, and general population health (Partyka and Bond, 2022).

5. The geopolitical paradigm of water

Natural resource availability and distribution in the world varies drastically from country to country. One of the primary causes of conflict and power in international relations is resource shortages (Bixio et al., 2006). Water-related issues have a long history, and water and water systems have historically been used as weapons of war, including intentional attacks on water systems during conflicts (EC, 2010). Meanwhile, water scarcity is an increasingly frequent and worrying phenomenon affecting at least 11% of the European population and 17% of the EU territory (EC (European Commission), 2011). Hydropolitical analyses explain cooperation and conflict over shared water resources, including governance and political arrangements between countries, and explain power asymmetries between these states (Nagheeby and Warner, 2018). Such hydro-political frameworks help us understand how water and society shape and complement each other, consider the spatial implications of changing hydrological relationships, and identify different governance techniques for water management (Rogers and Crow-Miller, 2017). Limited clean water resources, regional water scarcity, imbalances in the distribution of water resources, climate change, economic and technological difficulties, political situations, sub-optimal water management, and inadequate regulatory structures, inexistence among other problems may mean that water needs cannot be met from clean water resources in all countries. Therefore, any additional water recovery through the reduction of water losses, redistribution between sectors, wastewater recovery, and desalination benefits industry, agriculture, and/or environmental protection (Katz and Shafran, 2020). Throughout Europe, there are modern and efficient technological alternatives that offer the possibility of water recovery and reuse. Nevertheless, water problems are not isolated from national and regional contexts. Thus, water is essentially a consequence of the relative ability or inability of different states and societies to address their political, economic, and social problems (including water) (Nagheeby and Warner, 2018). Therefore, aligning elements of the CE towards water reclamation and conservation in the cycle should be a central part of both technological developments and policy development systems. The EC emphasizes the importance of sustainable water and wastewater management as one of the elements in the transition to a CE (Smol et al., 2020). However, the budgets allocated to water and sanitation investments in European countries vary, as do differences in areas such as technological innovation, education, and policy elements. Therefore, in the context of the CE and the relationship between geopolitical importance and differences, the EC is trying to harmonize the situation at the European level so that such differences do not exist in member states and regions (Bixio et al., 2006).

6. Environmental and safety concerns at water reuse

Environmental health and safety are the main issues that we encounter when using recycled water. In this context, the first issue that comes to our mind is the contamination of the water obtained after treatment. In addition to strict control of physicochemical and microbiological quality, the presence of various pollutants such as pharmaceuticals and pesticides must be taken into account when assessing water reuse, especially when recharging groundwater for drinking purposes and for agricultural use to ensure that the environment and public health are not harmed. Bioassays such as e-screen can be used to assess the endocrine function of a substance (Marin-Morales et al., 2016).

6.1. Social acceptance/willingness toward wastewater reuse

The reuse of treated wastewater is currently being studied and reported on in detail due to the increasing demand for water and the reduced availability of freshwater resources. Globally, the extent of water reclamation and reuse in each country is highly dependent on the corresponding water availability: reuse of wastewater for non-potables is practiced in several developed and developing countries (Wwap, 2017). Yet there are few cases of potable water reuse, mainly in the US and United Kingdom (UK), Australia, Singapore, and Namibia (Nkhoma et al., 2021; Wilcox et al., 2016). The concept of wastewater reclamation and reuse has become common knowledge among researchers, regulatory agencies, and wastewater and water treatment authorities. However, widespread implementation of wastewater reuse practices is often constrained by public acceptance of reuse, social challenges being more important than technical barriers in an effective water management plan. It has been revealed that although wastewater is subjected to advanced and complicated treatment processes, and the corresponding health risks are thoroughly addressed, social perception is the main parameter that determines the failure or success of a wastewater reuse project. Public perception of water reuse is related to knowledge of water reclamation techniques and, above all, awareness of potential health risks (Russell and Lux, 2009). However, new surveys demonstrated that the 'yuck factor might not be as important as it is assumed to be, as the public may be more open to the issue of water recycling than in the past (Compared to 67% in the UKand 73% in Spain, 75% of respondents supported or strongly supported the use of recycled water for drinking) (WRE team, 2021). Furthermore, in the three countries where the study was conducted (the Netherlands, Spain, and the UK), a greater shift in public opinion was observed toward food produced with nutrients recovered from wastewater than towards products irrigated with recycled water of drinking quality (Only 50% of respondents thought recycled water was drinkable, compared to 79% who thought desalinated water was suitable. Drinking recycled water raised health worries for 61% of people, whereas desalinated water only raised them for 33% of people) (Dolnicar and Schäfer, 2009).

As mentioned in the work of Nancarrow et al. (2008), public concern about potential risks to human health from wastewater reuse is the most important risk factor that directly affects intentional behavior. On the other hand, studies revealing the relationship between demographic characteristics (gender, education level) and public acceptance yielded contradictory conclusions (Dolnicar et al., 2011; Mahjoub et al., 2018; Nkhoma et al., 2021). Furthermore, the public is less inclined towards water reuse in close contact applications, with recycled water being the last option after desalinated water and rainwater, due to concerns about contamination and the presence of pathogens (Kemp et al., 2012). Advances in current treatment technologies can successfully combat the health risk threat. In this sense, methods for effective public involvement should be applied at all stages of the project cycle, from planning and design to implementation and decision-making (Saurí and Arahuetes, 2019). Building trust and transparency are crucial to removing barriers to any kind of reuse. Efforts must focus on giving the public access to all information by involving them in the consultation phase (Ooi et al., 2014).

In that direction, informing and communicating with the public about relevant water reuse issues is a crucial factor in a water reclamation and reuse project. Due to the complexity of the process and the numerous parameters encountered in a campaign (type of information provided, the timing of the communication campaign, negative or positive approach, initial attitudes, etc), special attention should be paid to designing an appropriate communication process to increase public acceptance (Nkhoma et al., 2021). For example, information about the low risks of recycled water used for drinking water applications and compliance with drinking water guidelines has been shown to positively influence public attitudes and to be more critical than information about the benefits of water reuse (Price et al., 2012). In another case, increasing consumer approval might be achieved by using the word "recycled water" rather than "treated water." The public may perceive these two terms differently even if they refer to the same procedure since the latter has a lot stronger content that is closer to pure terms than the former (Robbins et al., 2022).

7. Technological solutions for water recovery

The topic has been intended to be examined under two sub-headings in this section as follows.

7.1. Nature-based solutions for water recovery

According to the EC (EU, 2020a), "NbS to societal challenges are solutions that are inspired and supported by nature that are cost-effective while providing environmental, social and economic benefits and helping to build resilience. Such solutions bring more diverse nature and natural features and processes to cities, landscapes, and seascapes through locally adapted, resource-efficient, and systemic interventions. NbS must benefit biodiversity and support the delivery of a range of ecosystem services." In 2018 the UN World Water Development Report was dedicated to NbS for water, highlighting their benefits for improving water quality, increasing water availability, and reducing water-related risks. In terms of water planning and management, NbS thus has the potential to outperform the end-of-pipe solutions, but also to work alongside existing gray infrastructure, given the situation of infrastructure aging and often inadequate or insufficient to meet current demands (WWAP, 2018). According to the EU Research and Innovation policy agenda, the integration of NbS in cities is of paramount importance towards renaturing cities and territorial resilience (EU Commission for Research, D.-G., & Innovation, 2015). They have also been highlighted in the Manifesto of the UN Climate Action Summit (NBSC (Nature-based Solutions Coalition), 2019) and in the EU Green Deal (EC (European Commission), 2019a, 2019b, 2019c) as a fundamental component of climate and biodiversity action, including the importance of their contribution to achieving the goals of the Paris Agreement on Climate Change. NbS can support and enable the implementation of several policies and strategies related to water resources and management, including the Water Framework Directive (WFD) (EC (European Commission), 2014, 2019a, 2019b, 2019c). Examples of these solutions include constructed wetlands (Oral et al., 2020) and vertical greening systems, and green roofs (Pearlmutter et al., 2021).

Atanasova et al. (2021) have identified six urban circularity challenges, that can be addressed with NbS, to achieve the transition to a circular management of resources, three of which are directly related to water, namely i) Restoring and maintaining the water cycle (by rainwater management), ii) Water and waste treatment, recovery, and reuse, and iii) Nutrient recovery and reuse. Castellar et al. (2021) and Van Hullebusch et al. (2021) emphasized in their review the role of NbS as building blocks for resource recovery systems in cities, operating at a micro or mesoscale and applied at technology readiness levels higher than 5; and Oral et al. (2020)

Emphasized in their review the role of NbS in urban water management. Nevertheless, NbS is pivotal either in urban or rural contexts toward water recovery. For example, it can be seen through the application of constructed wetlands towards water treatment and recovery as reported by (C S C Calheiros et al., 2018; Cristina S C Calheiros et al., 2015). Souliotis & Voulvoulis (2022) having as a target the design of water management interventions has considered the operationalization of NbS for this purpose. They focused on wetlands as an NbS application for improving the effluent quality of water recycling centers, demonstrating their contribution to achieving water quality targets, and also assessing the economic value of the ecosystem services produced such as benefits through carbon sequestration and provision of habitat for species.

7.2. Engineering-based solutions for water recovery

Treated wastewater (secondary effluent) discharged into the environment from WWTP cannot be directly reused due to microbial contamination by potentially pathogenic and/or AR microorganisms, their ARGs and toxins, and a variety of different inorganic and organic chemicals. They are all listed in Table 4 and their impact on humans and the environment is discussed in detail in Section 4.4.

Currently, there are many methods and technologies available to remove these pollutants and provide the treated wastewater with water quality that can be used for agricultural irrigation or other purposes, such as supplying industrial facilities, fire-fighting tanks, toilet flushing, wetlands, recreational irrigation, groundwater recharge for indirect potable water reuse (IPR) and direct potable reuse (DPR) (Lee and Jepson, 2020; Yang et al., 2020). Water reclamation technologies are based on 4 main groups of processes: membrane processes, advanced oxidation processes (AOPs), disinfection, and sorption processes (Cosenza et al., 2022; Mannina et al., 2022; Yang et al., 2020). The most widespread membrane-based technologies used for separation employ pressure-driven membrane processes – microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO). They differ in transmembrane pressure (TMP), types of membranes, and mechanisms of action. Porous membranes are used for MF, UF, and NF but non-porous membranes are used in the case of RO. In the case of MF and UF, the sieving mechanism is responsible for the separation. However, in the case of NF and RO, solution/diffusion and exclusion play an important role. As a result, the membrane processes differ in terms of the compounds retained. MF enables the retention of biomass and the largest particles (suspended solids, most bacteria, and viruses) while RO retains the smallest molecules and ions (Yang et al., 2020). Another membrane technology that has shown its promising potential for the retention of heavy metals and micropollutants at the laboratory scale is forward osmosis (FO) driven by osmotic pressure. Pilot studies show that MF and UF can in some cases be sufficient solutions for secondary WWTP effluents processing and reclaimed water that meets WHO guidelines for crop irrigation (Pollice et al., 2004; Yang et al., 2020). However, in most cases, MF and UF alone are not sufficient and water recovery technologies consist of several processes. The membrane processes are often preceded by chemical processes of coagulation with Ca, Al, and Fe salts and adsorption on activated carbon. Combined coagulation/flocculation with MF/UF improves phosphorus and turbidity removal and adsorption on activated carbon in granular or powder form increases Total Organic Carbon (TOC) removal including micropollutants and disinfection by-products (Yang et al., 2020). RO and NF, similar to MF and UF, require additional pretreatment of secondary effluents. They are usually preceded by MF and/or UF because they are more effective in protecting NF/RO membranes from fouling than conventional pretreatment processes (Boddu et al., 2016; Yang et al., 2020). While membrane processes provide an opportunity for water recovery, they also accumulate membrane-retained contaminants in the concentrate stream that require further processing. Municipal secondary wastewater effluents treated with combined MF/UF and NF/RO can meet EPA and WHO guidelines for potable and non-potable reuse (Tam et al., 2007; Yang et al., 2020).

Disinfection is a very popular technique applied as a polishing step of secondary treated wastewater effluent when reuse of wastewater is not planned, but sanitary reasons and the protection of water bodies against pathogens are the priority. In 2018, in the EU (EU-27), where 23,697 urban WWTPs were active, chlorination was used in 3603 WWTPs, UltraViolet (UV) radiation in 1152 WWTPs, and ozonation in only 46 WWTPs (EEA, 2017). European Environment Agency (EEA) EEA Report (2022) shows that chlorination of urban secondary treated effluents is the most popular in Hungary, Italy, Greece, and Spain. UV disinfection is mainly applied in urban WWTPs in Romania, Bulgaria, Italy, and in Spain, France, Great Britain, and Ireland, where treatment facilities with UV irradiation are located on the coasts. Chlorination in combination with UV radiation is used for secondary effluent disinfection in coastal areas of the Mediterranean Sea in Italy, Spain, and Greece. It should be remembered that although UV does not generate by-products, it also has no disinfection remnant effect, hence chlorination, despite the generation of disinfectant by-products (DBP), is still more popular than UV.

AOPs complement disinfection and can be referred to as "post-disinfection" treatment as they are not only very effective in removing micropollutants but are also involved in the elimination of bacteria. Ozonation is a good example of combining the removal of micropollutants (Zoumpouli et al., 2020) with the inactivation of bacteria (Yang et al., 2020).

A common feature of AOPs is the generation of free radicals, of which hydroxyl radicals are the most active. AOPs may also generate some DBPs (e.g., N-Nitrosodimethylamine (NDMA), bromate) or transformation products during ozonation and thus are often followed by biological filtration or adsorption processes to mitigate the potential risk. AOPs used in wastewater treatment are listed in Table 5.

Among the processes listed in Table 5, AOPs, O_3, UV/O_3, UV/H_2O_2, and photocatalysis are most often recommended as promising and economically viable processes for water reclamation. On a technical scale, they are combined with adsorption on activated carbon and membrane processes (Sgroi et al., 2021; Yang et al., 2020).

A noteworthy example of a large-scale post-treatment for removing micropollutants from the secondary effluent using ozonation and sand filtering is the Neugut WWTP (Dübendorf, Switzerland) (Bourgin et al., 2018; Kienle et al., 2022). It is a typical municipal treatment facility (105,000 p. e.), using an activated sludge technique with biological P removal to treat urban wastewater with a 50% contribution from industrial wastewater. The effluent exits the secondary clarifier and enters a 530 m^3 multi-chamber reactor, where it is ozonated with a concentration of 0.55 g O_3/g DOC and a retention duration of 43 min. The wastewater is filtered after ozonation using a large-scale sand filter with a quartz sand bed after ozonation. Implemented ozonation significantly decreases the ecotoxicity of wastewater and eliminates micropollutants by > 80% on average. Additionally, sand filtration removes total suspended solids, biodegradable ozonation byproducts, and dissolved organic carbon (Bourgin et al., 2018). According to Kienle et al. (2022), activated carbon filtration surpasses sand filtration due to the increased sorption of micropollutants and the effective reduction of mutagenicity due to ozonation by-products. As a result, ozonation with activated carbon was introduced as a secondary effluent post-treatment at the WWTP Altenrhein in Switzerland.

Table 5
AOPs used in wastewater treatment (Sgroi et al., 2021; Yang et al., 2020).

Ozone-based AOPs	O3/UV, O3/H2O2, O3/H2O2/UV, O3/Cl2/UV
H2O2-based AOPs	H2O2/UV, Fenton, photo-Fenton, and other Fenton-like processes
Heterogeneous photocatalysis	TiO2/UV, TiO2/H2O2/UV, other catalysts/UV
Solar driven AOPs	H2O2/sunlight, TiO2 (and other catalysts)/sunlight, H2O2/TiO2 (and other catalysts)/sunlight, natural photo-Fenton
Other	Sonochemical and electrochemical AOPs

8. Conclusion

The purpose of this review paper is to create new, creative solutions to the challenges the EU is now facing. It accomplishes this by employing a CE approach to water recycling and recovery that is based on the COST Action 20,133. Another standout feature of this paper is the thorough analysis of the current state, current challenges, and upcoming challenges for water reuse in Europe from a CE perspective. As a result, this review study presented that Europe is experiencing a water crisis. In contrast to common assumption, the Northern Hemisphere's geographical location does not assure that this continent will not suffer from the impacts of climate change. Water scarcity issues will manifest sooner than anticipated as a result of the population's rapid expansion, the uncontrolled consumption of natural resources that come along with it, and the inadequate implementation of the SDG's perspectives. Urban wastewater treatment plants can combine energy generation with resource recovery (nutrient and water recycling) to quickly implement circular sustainability across the whole water sector. The European community needs to have a detailed discussion about the use of hydroponics in the field of water management. Local governments should quickly encourage public acceptance of the local reuse of treated water. Water management strategies need to be successfully linked with cutting-edge solutions like NbS.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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Appendix A. Supplementary data

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