Wastewater-Based Crop Irrigation: An Issue or a Solution?

Navodnjavanje usjeva otpadnom vodom: problem ili rješenje?

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WASTEWATER-BASED CROP IRRIGATION: AN ISSUE OR A SOLUTION?

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SUMMARY

Paper's objective was to provide a critical overview of the current state of wastewater generation in different processes around the world and their use in irrigation. As a follow-up, a brief overview of the classification of wastewater and its potential for end use is presented. Furthermore, a specific overview of irrigation using wastewater is presented, together with the relevant scientific papers in which the research on wastewater irrigation impacts on the plants, soil, humans, and the environment are studied. Finally, a special reference was given to the guidelines and policies proposed by the EU stakeholders regarding the integration of wastewater reuse into water planning and management in the context of circular economy, with special emphasis put on novel technologies.

Keywords: wastewater, irrigation, reuse, treatment methods, circular economy

INTRODUTION

On a global scale, the usage of wastewater is increasing, and it is estimated that the reuse of wastewater will reach 1.66% of the total amount of used water, or 26 km^3/year by the year 2030. Globally, agricultural irrigation makes up the largest percentage (32%) of reused water, followed by landscape irrigation (20%), industrial wastewater use (19%), and groundwater recharge (only 2%; EC, 2016). Wastewater is an important source of water for many countries, particularly for those in which water is scarce (Jiménez, 2006; Table 1). Not only are the arid and semi-arid countries the areas that gain advantages while using wastewater: advantages are gained, too, in rural areas, in which agricultural production is not only a predominant and essential economic activity but also a means of survival (Serrao et al., 2020; Christou et al., 2014). An increase in wastewater usage was recorded in Australia (41%), Europe, China, and the USA (10–29%). Up to 400 trillion m^3 of wastewater is discharged into the environment annually, contaminating 5,500 trillion m^3 of water.

Daily, 15 million m^3 of wastewater is used for irrigation in approximately 44 countries, whereas approximately 10% of the world's population is estimated to consume food produced by wastewater irrigation (Khalid et al., 2018). Developing countries—that is, the countries with a lower income in the agricultural sector—often lack the clearly defined legal frameworks, regulations, and awareness about environmental and economic consequences of an improper wastewater management.

Because of those reasons, wastewater irrigation carries significant risks in the aforementioned countries. China is a leading country concerning the quantities of generated wastewater, with 68.5 trillion tons, or 108.16 trillion m^3 to 34.3 trillion m^3 from household sources and 78.83 trillion m^3 from industrial sources, while 260 million m^3 of untreated wastewater is used for irrigation in India. In Mexico, the treated wastewater was used on 70,000 hectares, whereas the untreated wastewater was used on 230,000 hectares (Khalid et al., 2018).

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Table 1. Treated and untreated water from urban sources by countries (Valipour and Singh, 2016).

Tablica 1. Tretirana i netretirana voda iz urbanih izvora po državama (Valipour i Singh, 2016.).

Country / *Država*	**Untreated wastewater (%)** / *Tretirana voda*	**Treated wastewater (%)** / *Netretirana voda*
Netherlands	77	23
Bosnia and Herzegovina	4	96
Mexico	38	62
Croatia	61	39
Mongolia	60	40
Egypt	57	43
Cyprus	100	0
Greece	99.6	0.4
Italy	99	1
Germany	98	2
France	90	10

The frequency of wastewater discharge is significantly lesser in the developed countries. In the undeveloped or developing countries, 92% of untreated wastewater is discharged into the environment, whereas the developed countries discharge 30% of untreated wastewater into the environment. Such significant differences can be explained by the adequate legal regulations, with a more developed sense of awareness, and with better wastewater-treatment plants. Eighty percent of wastewater treatment plants are located in the countries like Japan, the USA, and EU Member States. For instance, France has 17,000 wastewater treatment plants (Khalid et al., 2018). The farmers could cede their freshwater rights to the cities and/or communities, and they would get a source of wastewater enriched with plant nutrients in return, which is a win-win situation. There are numerous regions and cities that would benefit from this kind of trade, like Mexico City, because the farmers could alleviate the growing problem of water scarcity and could reciprocally benefit from enriched wastewater that could cut down the costs of agricultural production. In 2010, there were over 3,300 water reclamation facilities with varying applications, for instance, agriculture, landscaping, industrial cooling, and the like and the varying degrees of treatment. It is estimated that, by the year 2060, 40% of world's population will live in the countries that face water scarcity or water stress. For example, Tunisia is a country that has a high sanitation coverage and has a policy in place that subsidizes the pre-treatment processes, whereby 75% of wastewater is treated to various degrees (Winpenny et al., 2010).

The treated wastewater has been used continuously in the EU for many years. In 2006, 964 million m^3 of treated wastewater was utilized, while it was estimated that 1,100 million m^3 of wastewater was used in 2016 (EC, 2016). Some of the crops that are produced in Europe thanks to the use of untreated and treated wastewater are eucalyptus, poplar, apples, lemons, peaches, artichokes, sugar beets, potatoes, cotton, wheat, broccoli, sunflowers, barley, clover, and the like (Asano, et al., 2007; Jiménez and Asano, 2008; Winpenny et al., 2010).

Table 2. Usage of treated wastewater in the EU in 2006 (EC, 2016).

Tablica 2. Upotreba pročišćenih otpadnih voda u EU u 2006. godini (EC, 2016.).

Member state, EU / *Država članica, EU*	**Wastewater used (mil. /m^3/year)** / *Korištena otpadna voda*
EU	964
Spain	347
Italy	233
Germany	42
Greece	23

Although the EU is not in danger of water shortage, there are still significant differences in the supply of safe water sources between the Member States. The Mediterranean Member States have limited water sources and a lower rainfall, while some Member States located in Central or Northern Europe have faced extreme drought (EC, 2015).

According to Table 2, Spain and Italy used more than 60% of the total amount of treated wastewater in the EU, which supports the statement that the Southern European Member States (except Greece) use larger quantities of water from this source because of their climate and smaller water sources.

A competition for water between different manufacturing branches, industries, and agriculture and extreme climate conditions result in the increasing risks to the safety of water sources across Europe (Fig. 1). There are many advantages and opportunities when using secondary water sources between various sectors, and these kinds of exchange models were developed in the world regions with limited water sources like Israel, Australia, Tunisia, and California (EC, 2016). The usage of water in the European industry is decreasing because of innovations and the reuse of water, which can alleviate the strain on the environment (Gereš, 2001).

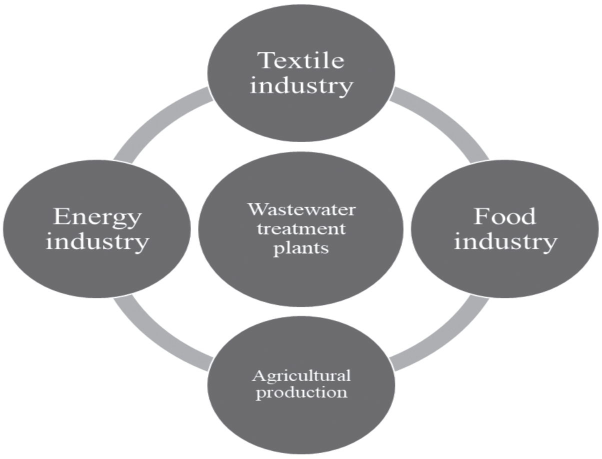

Figure 1. The exchange of secondary water sources between different branches of industry.

Slika 1. Razmjena sekundarnih izvora vode između različitih grana industrije.

This paper's purpose was to present the state of affairs concerning wastewater utilization globally and, in the EU, the EU legislation related to wastewater, and to emphasize some novel treatment methods applied to its reuse worldwide.

WASTEWATER COMPOSITION AND TREATMENT METHODS

The composition of industrial wastewater changes drastically with regard to the predominantly organic compounds such as the human excreta, and thus may contain toxic compounds like heavy metals. The quality of wastewater, as well as the effect it will have, depends on various factors, like the quantity of wastewater used, the source of wastewater, the level of treatment, and the wastewater composition (Hussain et al., 2001). Since wastewater can be utilized in different applications, seven microbial water qualities were proposed by a regulation recommended by Spain, in cooperation with the Organization for Economic Cooperation and Development (OECD) and the European Commission (EC) (OECD, 2023), whereas four chemical water qualities were proposed with different uses for each category (Salgot et al., 2006; Table 3).

Table 3. Water quality categories and their different final uses (Salgot et al., 2006).

Tablica 3. Kategorije kakvoće vode te različite vrste upotrebe (Salgot i sur., 2006.).

Microbial category / *kategorija mikroba*	**Chemical category** / *kemijska kategorija*	**Specific final use** / *Specifična krajnja primjena*
I	1	Different residential uses like gardening, car washing, toilet flushing, etc.
	-1	Recharge of the aquifer by direct injection
II	1	Bathing water
III	1	Street cleaning, landscape irrigation, ornamental fountain water, irrigation of raw-consumed food crops.
IV	1	Irrigation of pastures (milk and meat production), industrial crops (for canning), crops that are not consumed raw, fruit trees (not by sprinkling), etc.
	2	Bodies of water where human contact with water is permitted but not bathing
V	1	Forestry irrigation
	2	Impoundments and water bodies where human contact with water is permitted but not bathing
	3	Recharge of the aquifer by localized percolation through the soil
VI	2	Water bodies where human contact with water is not permitted
VII	4	Industrial cooling but not for the food industry

In a broader sense, wastewater can be divided into domestic (sanitary) wastewater, also known as sewage, industrial (trade) wastewaters, and municipal wastewater, which is a mixture of the two (Gray, 2017). Domestic wastewater can additionally be classified as (i) blackwater, (ii) greywater, and (iii) yellow water. Blackwater is characterized by a high amount of feces and fecal bacteria, urine, toilet paper, and small particles of food waste since they are mostly produced in toilets and kitchens, while greywater is a wastewater produced by domestic washing machines or by industrial processes. Yellow water is the urine collected by a special toilet system (Beler-Baykal, 2015; Crini and Lichtfouse, 2019; Pabbati et al., 2021).

Wastewater composition is a function of applications to which the water was subjected, and they may vary with climate, social, economic situation, and population habits (von Sperling, 2007). Also, to describe the pollution level of wastewater and propose a suitable treatment process, the Wastewater Quality Index (WWQI) classification has been developed (Hsien et al., 2019). Wastewater treatment processes can be defined as physical, chemical, and/or biological ones, conducted to remove the dissolved and suspended solids, organic matter, and nutrients from wastewater and produce an effluent with the physical, chemical, and/or biological parameters lower than the maximum concentration levels stipulated by regulations (Sonune and Ghate, 2004;

Seow et al., 2016; Crini and Lichtfouse, 2018). Based on the applied method and the effluent quality, wastewater treatments are qualified as preliminary, primary, secondary, tertiary, and advanced and as a land application (Pabbati et al., 2021; Yeoh et al., 2022).

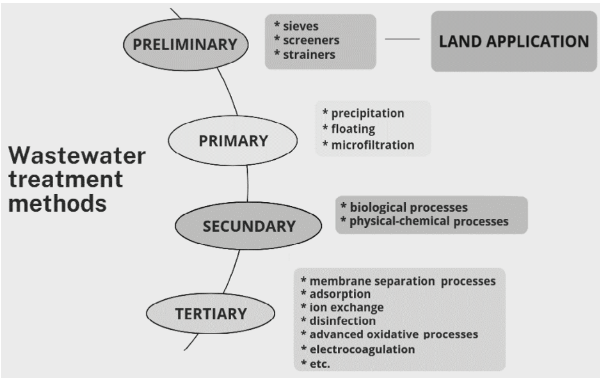

Figure 2. Classification of wastewater treatment methods.

Slika 2. Klasifikacija metoda obrade otpadnih voda.

The water-demand estimations quote that the global population consumes around 4 trillion m^3 of freshwater per year, while an increase in population directly causes an augmentation of that number too. Between 75 and 90% of global yearly consumption is related to agricultural activities (World Counts, 2023).

Water scarcity is one of the worst results of water cycle disturbance caused by climate change, especially affecting current and future agriculture strategies, particularly in the manner of irrigation (DeNicola et al., 2015; Vörösmarty and Sahagian, 2000; Haddeland et al., 2014). One of the possible solutions and a way of wastewater disposal is the land application method, which implies a direct application of municipal wastewater to agricultural lands. This method enables simultaneous irrigation and fertilization, because domestic wastewater is rich in N and P compounds. Prior to this usage, wastewater should be treated by a preliminary treatment, and it is necessary to conduct the chemical and microbiological wastewater analyses to avoid a possible heavy metal occurrence/accumulation in carcasses and to comply with the required waiting period regarding a possible occurrence of parasitic nematodes, unsegmented roundworms, bacteria, and viruses that originate from the fecal matter (Banach and Van Der Fels-Klerx, 2020; Singh, 2021; Yeoh et al., 2022). An efficient and improved version of the land application method is the application of yellow water, which represents 1% of conventional domestic wastewater, with the high nitrogen (80%), phosphorus, and potassium contents (around 50% each; Beler-Baykal, 2015).

Among the greywater, efficient irrigation results can be obtained by the usage of cooling water. Soliman and associates (2022) reported that efficient resurge cooling water for irrigation purposes can be obtained if this type of wastewater is treated by a membrane separation process prior to its application, electrocoagulation, or the so-called ballasted sand flocculation process.

THE PROS AND CONS OF WASTEWATER USAGE FOR IRRIGATION

Since the EU is already experiencing water scarcity conditions, there is an increasing need to use alternative water resources such as wastewater. The United Nations Program for Water Assessment distinguishes the three main types of treated wastewater reuse: a) a direct potable reuse, b) an indirect potable reuse, and c) a reuse for non-drinking purposes, including irrigation. The treated wastewater that has undergone treatment in a wastewater treatment plant can be used to irrigate the food crops, processed food crops, and non-food crops (Deviller et al., 2020). However, wastewater treatment processes are not fully effective in removing all contaminants, particularly pharmaceuticals, personal care products, and antibiotic residues, as well as the antimicrobial resistant bacteria and antimicrobial resistance genes (Slobodiuk et al., 2021). Nonetheless, in practice, untreated wastewater is currently used in many parts of the world to irrigate the food crops, and it does not seem to cause significant sociocultural disapproval, being driven solely by an economic demand (Ungureanu et al., 2018). According to an extensive study conducted by Thebo (2016), approximately 35.9 million ha worldwide are affected by wastewater flaws to a large degree. Of this total area, 29.3 million ha are in the countries with a very limited use of wastewater treatment, presenting serious health risks to 885 million consumers, as well as to the farmers and traders. The world population is estimated to consume at least 10% of food irrigated by the wastewater, and over 20 million ha (10% of all irrigated land) of irrigated land are irrigated with the untreated, partially treated/diluted, or treated wastewater. Even though wastewater is treated in the developed countries, the rate of reuse is low and mainly based on biomass and the development of biogas production (Ungureanu et al., 2018; Toczyłowska-Mamińska and Mamiński, 2022).

The effects of irrigation by wastewater are not uniform for every plant. Its usage can have different benefits or drawbacks for plants, humans, and the environment (Gupta et al., 2010). Both the soil and the water compartments can be exposed to the treated wastewater releases according to the type of crops and farming practices applied. The water compartments are the water bodies near agricultural landscapes that could receive the water releases during irrigation—that is, surface waters, coastal zones, and groundwater. Consequently, the organisms to be protected are those living in these ecosystems and being directly exposed to the reused wastewater, as well as the organisms that consume water or food from these ecosystems and can be indirectly exposed through the accumulation of chemical contaminants in a food chain (secondary poisoning; Deviller et al., 2020).

In a study by Mkhinini and associates (2018), wastewater had significant and diverse effects on the Vicia faba, where 50% diluted, and 100% wastewater had positive effects on the root weight of the plant if compared to the control batch. The diluted wastewater had a more pronounced impact on the root weight of the Vicia faba than 100% of wastewater. In contrast to the effects of wastewater on the roots, the weight of shoots was larger in the control batch than in the one subjected to wastewater irrigation, and its length progressively decreased with the usage of wastewater.

In the study by Singh and Agrawal (2012), in which they investigated the changes in physical and biochemical characteristics of soil and metal partitioning in the Beta vulgaris L. grown in farmer's fields irrigated with wastewater in India, wastewater significantly affected organic carbon (C), available phosphorus (P), and total nitrogen (N). It was concluded that the sites on which irrigation was carried out with wastewater had a significantly higher content of the mentioned elements than the sites on which the irrigation was carried out with clean water. The soil enzyme activities were affected by the choice of water, so the dehydrogenase and urease activity in the soil was significantly higher on the sites where wastewater was used when compared to the sites on which the clean water was used. The choice of water did not only affect the aforementioned characteristics, but it did affect the microbial biomass (C, N, and P), whereby the sites irrigated with wastewater had significantly higher concentrations.

Although there are numerous positive effects of wastewater usage, there are significant risks too, like soil contamination with zinc (Zn), chromium (Cr), cadmium (Cd), copper (Cu), nickel (Ni), lead (Fe), mercury (Hg), and parasitic worms and a danger of soil hardening and pollution of groundwater (Wang et al., 2013; Nazif et al., 2006; Flores-Magdaleno et al., 2011; Hussain et al., 2001). Jahan and associates (2019) presented the results of a study conducted to investigate the effects of wastewater irrigation on the soil's physicochemical properties and yield and the yield-contributing characteristics of tomatoes. Available sulfur (S) was detected to be the highest in the treatments with the domestic wastewater if compared to the municipal and industrial wastewater, whereas the lowest concentrations were in the cases of normal water irrigation. Wastewater affected the height of tomato plants. The highest plants were recorded in a municipal wastewater irrigation treatment, while the lowest plants were recorded in the domestic wastewater irrigation treatment. Leaf area index was the highest in the industrial wastewater irrigation treatment, whereas the lowest one was in a normal water irrigation treatment. The yield was at the highest in municipal wastewater irrigation and at the lowest in a normal water irrigation treatment. The concentrations of both NH_4^+ -N and NO_3^- -N were increased on the sites on which the wastewater was used if compared to the sites on which the clean water was used, which can lead to the higher rates of nitrification. The exchangeable potassium (K) and sodium (Na) concentrations were about two times higher, and the concentration of calcium (Ca) was four times higher on the sites irrigated with wastewater than on the sites irrigated with clean water. According to Singh and Agrawal (2012), heavy metal phytoavailability values were higher on the sites irrigated with wastewater, and the aforementioned concentrations were too high in the roots and shoots of plants on the sites irrigated with wastewater, as opposed to the sites irrigated with clean water.

The usage of wastewater in agricultural production has a potential to replenish the groundwater sources but also the risk of contaminating it due to the percolation of excess nutrients, pathogens, and salts. Inadequately processed wastewater can cause eutrophication if it gets to the groundwater sources and if it contains P in the form of orthophosphate, which negatively affects the biodiversity of aquatic systems (Hussain et al., 2001; Jhansi and Mishra, 2013; Sun et al., 2020).

Table 4. The countries with an increase in certain toxic elements due to the use of wastewater in irrigation (Khalid et al., 2018).

Tablica 4. Države u kojima je zabilježeno povećanje određenih toksičnih elemenata upotrebom otpadnih voda u navodnjavanju (Khalid i sur., 2018.).

Countries / *Država*	**Increase of levels of elements** / *Povećana razina elemenata*
Mexico	Fe, Cr, Co, Mn, Ni, Cu, Zn, Pb
China	Cr, Pb, Ni, Zn
India	Cu, Zn, Pb, Cr, Mn, Ni
Saudi Arabia	Cd, Cr, Cu, Pb, Zn
Vietnam	Cd, Ni, Cr, Zn, Cu, Pb

The accumulation of toxic elements (Table 4) is particularly evident in the soils of both the developing and the developed countries around the globe as a result of wastewater application (Mireles et al., 2004; Lu et al., 2015; Sharma et al., 2007; Balkhair and Ashraf, 2016; Huong et al., 2010; Nguyen et al., 2014). The toxic elements can pose a threat to the human health because of their mobility, but they do not cause phytotoxicity due to the smaller quantities. It is established that a continuous usage of wastewater in irrigation can cause larger accumulation of Pb, Cu, Zn, Ni, Cd, and Cr in sugar beet, spinach, and beans; Cr, Po, Ni, and Zn in corn; Cd, Cu, Cr, Ni, Pb, and Zn in vegetables; Cu, Fe, Mn, Zn, Pb, Cd, and Ni in red cabbage and cauliflower; and Cr, Pb, Ni, and Cd in okra. The authors state that fungal diseases and dermatitis have been diagnosed in the farmers who have been exposed to the untreated wastewater in Hanoi, Vietnam. The South African farmers who used the wastewater had a higher percentage of Helminth infection (42%) than the residents of the control village (27.5%) who did not use the wastewater (Dickin et al., 2016; Khan et al., 2013; Mahmood and Malik, 2014).

Next to the pH levels, the soil's organic matter content, which regulates the availability of nutrient mobility therein, is the most important parameter of soil quality. Wastewater irrigation can cause the accumulation of organic matter, whereby such an occurrence is considered useful for agricultural production. The addition, or the accumulation of organic matter, could improve the soil structure, moisture content, and cation exchange capacity, along with the retention and decrease of metal availability. The increased amounts of organic matter can have a negative effect on the soil porosity and can create anaerobic conditions in the root zone or can cause hypoxic conditions that affect the mortality in aquatic ecosystems (Khalid et al., 2018) if they get into the ground waters. A continuous usage of wastewater in irrigation can cause salinization (i.e., the accumulated cations and anions in the soil; Ofori et al., 2021), soil overflooding, and a decrease in production capacity and yields (Hussain et al., 2001). A perennial usage of wastewater in irrigation usually results in a significant increase in soil pH, but the pH value can still potentially remain unchanged or may decrease. The changes in the pH values are directly caused by the pH values of wastewater used in the irrigation—that is, they depend on the source of wastewater (Khalid et al., 2018).

Also, a knowledge about potential environmental impacts of emerging contaminants in wastewater, such as the pharmaceutically active compounds, endocrine disruptors, as well as new and re-emerging pathogenic microorganisms, microplastics, and the antibiotic-resistant genes, is limited. Thus, the fate and transport under the subsurface, and the risks associated with the unintentional transfer of these chemicals and pathogens to the humans and animals, are fairly obscure (Asano et al., 2007; Li et al., 2021; Ofori et al., 2021). The humans can be exposed to the wastewater directly through inhalation, wastewater consumption, or skin contact during a household usage, work, floods, or recreation (swimming). A discharge of wastewater in the surrounding ecosystems affects 24,500 km^2 of marine ecosystems, ponds, and food chains. An indirect exposure occurs through the consumption of contaminated water, fish, or crops, while the accumulation of toxic elements in the human body can cause serious diseases affecting the cardiovascular system, kidneys, and nervous system, as well as the bone and circulatory system diseases (Khalid et al., 2018).

WASTEWATER IRRIGATION IN THE CONCEPT OF CIRCULAR ECONOMY

The concept of circular economy is a global strategy that was initially introduced in China in 2002 as a key strategy for the national development plan. In the EU, a circular economy concept was adopted in 2014, in the first communication entitled Toward a Circular Economy: A Zero-Waste Program for Europe. The EC defined the circular economy as a system in which the value of products, materials, and resources is maintained in the economy for as long as possible, and the generation of waste is minimized. Here, two important aspects play a key role—a more reasonable use of resources and waste management which, in this context, means a more rational usage of water resources and more sustainable wastewater-related practices (Smol et al., 2020).

Nowadays, wastewater is considered to be a resource rather than waste because the water plays an important role in the transport of other sources (e.g., nutrients, chemicals, minerals, and organics) and energy (Mannina et al., 2022). Because of a high content of organic and inorganic matter (particularly N and P) in the wastewater, which, in a wastewater treatment process, are deposited in the sewage sludge or are released in the atmosphere, the wastewater sector is identified as having a high potential for alternative fertilizer production, which can replace mineral fertilizers. Due to the limited P reserves and the location of main deposits outside the EU Member States, the EC placed a special accent on the P recovery. The most applied method for P recovery is currently based on the production of sewage sludge ashes (in Germany, Austria, Belgium, and Finland) or struvite precipitation (in the Netherlands), while many other EU countries still have not introduced the P recovery processes in the wastewater treatment sector (Preisner et al., 2022).

Furthermore, by applying different membrane technologies in wastewater treatment, the water for different purposes can be produced. For instance, Czuba and associates (2021) have reclaimed a secondary effluent from the wastewater treatment plant in an integrated, low-cost three-stage pilot-scale membrane process technology (comprised of micro/ultrafiltration, nanofiltration, and reverse osmosis) and have produced water for several types of applications (i.e., water as a cooling medium in different industrial processes, for urban non-potable purposes such as irrigation, potable water, and groundwater for remediation). Bermúdez and associates (2022) have studied whether the treated wastewater from a pilot plant with an ultrafiltration-membrane bioreactor technology can satisfy the quality standards required for a reuse in agriculture and have assessed the possibility of producing other resources during a wastewater treatment, such as biogas and stabilized sludge. The authors concluded that the results have provided the promising data regarding the reuse of treated wastewater for the sake of irrigation and stabilized sludge as soil fertilizer or for the sake of a soil conditioner because they have obtained the products complying with the quality standards specified in European regulations. In addition, during the various stages of wastewater treatment, biogas can be produced. Bolognesi and associates (2021) presented a possibility of utilization of sewage sludge, which remained subsequent to the wastewater treatment process, as a valuable resource for the production of biochar. Microalgae were added to the sewage sludge as a feedstock to determine which conditions are more favorable for an optimal recovery of valuable by-products. The microalgae were previously used in a wastewater treatment system to remove both the C and the nutrients (particularly the N and P) from the wastewater. The substrates (i.e., the sewage sludge and the microalgae) were pyrolyzed in a thermostatic sand bath under varying treatment parameters. Subsequent to the completion of pyrolysis, the solid (biochar) and liquid (bio-oil) product fractions were recovered. As biochar originates from a renewable feedstock, it could substitute the fossil fuels for the caloric equivalent and mitigate the related greenhouse gas emissions. Furthermore, biochar can be used in agriculture as a soil amendment, where its use will effectively work as a long-term carbon sequestration, or it can be implemented in the wastewater or contaminated site remediation as a pollutant adsorbent due to a high C and mineral content. It consists of many micro- and macropores, whose pattern and size depend on the composition of feedstock material and the process temperature used during its formation (Oni et al., 2019).

CONCLUSIONS AND FUTURE PERSPECTIVES

In compliance with the EU's ambition to become climate-neutral by 2050, the EC presented the European Green Deal in December 2019. Afterward, in April 2020, the EU Parliament adopted a new legislation, setting out a framework for sustainable investments, also known as the EU Taxonomy Regulation 24, which entered into force in July 2020. The legislation establishes six environmental objectives (i.e., climate change mitigation, climate change adaptation, sustainable use of water and marine resources, circular economy, pollution prevention, and healthy ecosystem) and allows an economic activity to be classified as environmentally sustainable if it significantly contributes to at least one of the objectives and if it does not have any substantial adverse effect on other objectives. A potential to contribute to all six objectives can be achieved through the wastewater reuse management activities, either directly or indirectly (European Investment Bank, 2022).

Although there is sufficient progress in the area of wastewater treatment research, our knowledge about wastewater irrigation is scarce due to the limited data on wastewater quality guidelines for the reuse and optimal combinations of conventional and advanced wastewater treatment processes. Therefore, it was of great concern to carry out a thorough research related to the impact of wastewater irrigation on the society, environment, and human and animal health (Al-Hazmi et al., 2023). Thus, a series of case studies organized by the Joint Research Center (being the EC's science and knowledge service) were conducted within the EU Member States in 2021 regarding the testing of guidelines for wastewater reuse and Risk Management Plan (RMP). The RMP addresses additional requirements for the operators of wastewater treatment plants, which need to be fulfilled before the water is delivered to the other actors in the chain. To ensure the safety of a wastewater reuse system, the RMP also requires appropriate preventive and corrective measures and barriers, monitoring, and other procedures to be applied to the wastewater reuse system (JRC, 2022). Subsequent to the thorough research studies conducted, a new EU regulation on the minimum requirements for water reuse in agriculture is enacted as of June 2023. According to the EC, the new regulation could increase the water reuse six times, from 1.7 billion m³ to 6.6 billion m³ per year, reduce the water stress by 5%, and also create the "green jobs" in the water-related industry. The regulation points out that, due to the limited uptake of wastewater reuse within the EU, additional large investments are necessary to upgrade the existent wastewater treatment plants, and additional financial incentives are also necessary to practice the wastewater reuse in agriculture. Moreover, it also indicates that the promotion of innovative schemes and economic incentives could address these issues (European Investment Bank, 2022). In line with that, numerous wastewater treatment approaches are used by scientists from all over the globe. Various physical, chemical, and biological methods have been studied as a tertiary treatment process when specific constituents, substances, or contaminants cannot be completely removed subsequent to a secondary treatment process (Younas et al., 2021; Kesari et al., 2021). Although many wastewater reuse technologies have been studied worldwide, only a few have indeed been applied on a large scale because of their technical immaturity or a lack of non-technical constraints. Most of the constraints identified relate to the economics and to the value chain, particularly to the market potential and competition. Besides, to allow the stakeholders to understand and start seeing the wastewater as a resource, the technological solutions and management models need to be supported by a full demonstration, market validation, and policy changes (European Investment Bank, 2022). However, the wastewater sector provides significant opportunities for economic development, growth, and jobs. A change in policy, legislation, and norms can unlock a full wastewater potential, which is a direction the EU is promoting by its policy too.

REFERENCES

1. Al-Hazmi, H.E., Mohammadi, A., Hejna, A., Majtacz, J., Esmaeili, A., Habibzadeh, S., Saeb, M.R., Badawi, M., Lima, E.C., Mąkinia, J. (2023). Wastewater reuse in agriculture: Prospects and challenges. Environmental Research 236(1), 116711. https://doi.org/10.1016/j.envres.2023.116711
2. Asano, T., Burton, F., Leverenz, H. (2007). Water Reuse: Issues, Technologies, and Applications. 1st ed. New York: McGraw-Hill. Metcalf & Eddy, Inc. an AECOM Company.
3. Balkhair, K.S., Ashraf, M.A. (2016). Field accumulation risks of heavy metals in soil and vegetable crop irrigated with sewage water in western region of Saudi Arabia. Saudi Journal of Biological Science 23, S32–S44. https://doi.org/10.1016/j.sjbs.2015.09.023

4. Banach, J.L. & Van Der Fels-Klerx, H.J. (2020). Microbiological Reduction Strategies of Irrigation Water for Fresh Produce. Journal of Food Protection, 83(6), 1072-1087. https://doi.org/10.4315/JFP-19-466

5. Beler-Baykal, B. (2015). Stream Segregation in Household Use: A Review of Grey Water as an Alternative Source of Water and Yellow Water as an Alternative Source of Fertilizers. Water Qual Expo Health 7, 27–37. https://doi.org/10.1007/s12403-013-0105-3

6. Bermúdez, L.A., Díaz, J.C.L., Pascual, J.M., Martínez, M.M.M., Capilla, J.M.P. (2022). Study of the Potential for Agricultural Reuse of Urban Wastewater with Membrane Bioreactor Technology in the Circular Economy Framework. Agronomy 12, 1877. https://doi.org/10.3390/agronomy12081877

7. Bolognesi, S., Bernardi, G., Callegari, A., Dondi, D., Capodaglio, A.G. (2021). Biochar production from sewage sludge and microalgae mixtures: properties, sustainability and possible role in circular economy. Biomass Conversion and Biorefinery *11, 289–299.* https://doi.org/10.1007/s13399-019-00572-5

8. Christou, A., Eliadou, E., Michael, C., Hapeshi, E., Fatta-Kassinos, D. (2014). Assessment of long-term wastewater irrigation impacts on the soil geochemical properties and the bioaccumulation of heavy metals to the agricultural products. Environmental Monitoring and Assessment 186, 4857–4870. https://doi.org/10.1007/s10661-014-3743-4

9. Crini, G. & Lichtfouse, E. (2018). Wastewater treatment: an overview. Green Adsorbents for Pollutant Removal, 18, Springer Nature, pp.1-22, 2018, Environmental Chemistry for a Sustainable World, 978-3-319-92111-2. https://doi.org/10.1007/978-3-319-92111-2_1

10. Crini, G. & Lichtfouse, E. (2019). Advantages and disadvantages of techniques used for wastewater treatment. Environmental Chemistry Letters 17, 145–155. https://doi.org/10.1007/s10311-018-0785-9

11. Czuba, K., Bastrzyk, A., Rogowska, A., Janiak, K., Pacyna, K., Kossińska, N., Kita, M., Chrobot, P., Podstawczyk, D. (2021). Towards the circular economy — A pilot-scale membrane technology for the recovery of water and nutrients from secondary effluent. Science of The Total Environment 791, 148266. https://doi.org/10.1016/j.scitotenv.2021.148266

12. DeNicola, E., Aburizaiza, O., Siddique, A., Khwaja, H., Carpenter, D.O. (2015). Climate Change and Water Scarcity: The Case of Saudi Arabia. Annals of Global Health 81, 3. http://dx.doi.org/10.1016/j.aogh.2015.08.005

13. Deviller, G., Lundy, L., Fatta-Kassinos, D. (2020). Recommendations to derive quality standards for chemical pollutants in reclaimed water intended for reuse in agricultural irrigation. Chemosphere 240, 124911.

14. Dickin, S.K., Schuster-Wallace, C.J., Qadir, M., Pizzacalla, K. (2016). A Review of Health Risks and Pathways for Exposure to Wastewater Use in Agriculture. Environmental Health Perspectives, 124(7), 900–909. https://doi.org/10.1289/ehp.1509995

15. European Investment Bank (2022). Environment and Natural Resources Department: Wastewater as a resource.

16. Flores-Magdaleno, H., Mancilla-Villa, O.R., Mejía-Saenz, E., Olmedo-Bolaños, M.D.C., Bautista-Olivas, A.L. (2011). Heavy metals in agricultural soils and Irrigation wastewater of Mixquiahuala, Hidalgo, Mexico. African Journal of Agricultural Research 6(24), 5505-5511. https://doi.org/10.5897/AJAR11.414

17. Gereš, D. (2001). Održivo iskorištavanje vode u Hrvatskoj i Europi, Građevinar, 54, 6, 345-353.

18. Gray, N. (2017). Water Technology: An Introduction for Environmental Scientists and Engineers. London, CRC Press.

19. Gupta, S., Satpati, S., Nayek, S., Garai, D. (2010). Effect of wastewater irrigation on vegetables in relation to bioaccumulation of heavy metals and biochemical changes. Environmental Monitoring and Assessment 165, 169-177. https://doi.org/10.1007/s10661-009-0936-3

20. Haddeland, I., Heinke, J., Biemans, H., Eisner, S., Flörke, M., Hanasaki, N., Konzmann, M., Ludwig, F., Masaki, Y., Schewe, J., Stacke, T., Tessler, Z.D., Wada, Y., Wisser, D. (2014). Global water resources affected by human interventions and climate change. Proceedings of the National Academy of Sciences of the United States of America 111(9), 3251-3256. https://doi.org/10.1073/pnas.1222475110

21. Hsien, C., Low, J.S.C., Chung, S.Y., Tan, D.Z.L. (2019). Quality-based water and wastewater classification for waste-to-resource matching. Resources, Conservation and Recycling 151, 104477. https://doi.org/10.1016/j.resconrec.2019.104477

22. Huong, N.T.L., Ohtsubo, M., Li, L., Higashi, T., Kanayama, M. (2010). Heavy-Metal Contamination of Soil and Vegetables in Wastewater-Irrigated Agricultural Soil in a Suburban Area of Hanoi, Vietnam. Communications in Soil Science and Plant Analyses 41, 390–407. https://doi.org/10.1080/00103620903494350

23. Hussain, I., Raschid, L., Hanjra, M.A., Marikar, F., van der Hoek, W. (2001). A framework for analyzing socioeconomic, health and environmental impacts of wastewater use in agriculture in developing countries: Working Paper 26. Colombo, Sri Lanka: International Water Management Institute, IWMI.

24. Jahan, K.M., Khatun, R., Islam M.Z. (2019.) Effects of wastewater irrigation on soil physicochemical properties, growth and yield of tomato. Progressive Agriculture 30(4), 352-359.

25. Jhansi, S.C. & Mishra, S.K. (2013). Wastewater Treatment and Reuse: Sustainability Options. Consilience: The Journal of Sustainable Development 10, 1-15.

26. Jiménez, B. (2006). Irrigation in Developing Countries Using Wastewater. International Review for Environmental Strategies 6(2), 229 – 250.

27. Jiménez, B. & Asano, T. (2008). Water reclamation and reuse around the world. In: Water Reuse: An International Survey of Current Practice, Issues and Needs (Jimenez, B., Asano, T., Eds.), IWA Publishing, London, 648.

28. JRC (Joint Research Centre) Technical Report – Technical Guidance Water Reuse Risk Management for Agricultural Irrigation Schemes in Europe. Luxembourg: Publications Office of the European Union, 2022.

29. Kesari, K.K., Soni, R., Jamal, Q.M.S., Tripathi, P., Lal, J.A., Jha, N.K., Siddiqui, M.H., Kumar, P., Tripathi, V., Ruokolainen, J. (2021). Wastewater Treatment

and Reuse: a Review of its Applications and Health Implications. Water, Air & Soil Pollution 232, 208. https://doi.org/10.1007/s11270-021-05154-8

30. Khalid, S., Shahid, M., Natasha, Bibi, Sarwar, T., Haidar Shah, A., Niazi, N.K. (2018). A Review of Environmental Contamination and Health Risk Assessment of Wastewater Use for Crop Irrigation with a Focus on Low and High-Income Countries. International Journal of Environmental Research and Public Health 15, 895. https://doi.org/10.3390/ijerph15050895
31. Khan, M.U., Malik, R.N., Muhammad, S. (2013). Human health risk from Heavy metal via food crops consumption with wastewater irrigation practices in Pakistan. Chemosphere 93(10), 2230-2238. https://doi.org/10.1016/j.chemosphere.2013.07.067
32. Li, P., Karunanidhi, D., Subramani, T., Srinivasamoorthy, K. (2021). Sources and Consequences of Groundwater Contamination. Archives of Environmental Contamination and Toxicology 80(1), 1-10. https://doi.org/10.1007/s00244-020-00805-z
33. Lu, Y., Yao, H., Shan, D., Jiang, Y., Zhang, S., Yang, J. (2015). Heavy metal residues in soil and accumulation in maize at long-term wastewater irrigation area in Tongliao, China. Journal of Chemistry 2015, 628280. https://doi.org/10.1155/2015/628280
34. Mahmood, A. & Malik, R.N. (2014). Human health risk assessment of heavy metals via consumption of contaminated vegetables collected from different irrigation sources in Lahore, Pakistan. Arabian Journal of Chemistry 7(1), 91-99. https://doi.org/10.1016/j.arabjc.2013.07.002
35. Mannina, G., Gulhan, H., Ni, B.-J. (2022). Water reuse from wastewater treatment: The transition towards circular economy in the water sector. Bioresource Technology 363, 127951. https://doi.org/10.1016/j.biortech.2022.127951
36. Mireles, A., Solís, C., Andrade, E., Lagunas-Solar, M., Piña, C., Flocchini, R.G. (2004). Heavy metal accumulation in plants and soil irrigated with wastewater from Mexico City. Nuclear Instruments and Methods in Physics, Research Section B: Beam Interactions with Materials and Atoms 219–220, 187–190. https://doi.org/10.1016/j.nimb.2004.01.051
37. Mkhinini, M., Boughattas, I., Hattab, S., Amamou, C., Banni, M. (2018). Effect of treated wastewater irrigation on physiological and agronomic properties of beans Vicia faba. International Journal of Environment, Agriculture and Biotechnology 3, 4. http://dx.doi.org/10.22161/ijeab/3.4.37 ISSN: 2456-1878
38. Nazif, W., Perveen, S., Shah, S.A. (2006). Evaluation of irrigation water for heavy metals of Akbarpura area. Journal of Agricultural and Biological Science 1(1), 51-54.
39. Nguyen, T.L.H., Kanayama, M., Higashi, T., Le, V.C., Doan, T.H., Daochu, A. (2014). Heavy Metal of Soil in Wastewater–Irrigated Agricultural Soil in a Surrounding Area of the Nhue River, Vietnam. Journal of the Faculty of Agriculture, Kyushu University 59, 149–154. https://doi.org/10.5109/1434405
40. Ofori, S., Puškáčová, A., Růžičková, I., Wanner, J. (2021). Treated wastewater reuse for irrigation: Pros and cons. Science of the total Environment 760, 144026. https://doi.org/10.1016/j.scitotenv.2020.144026
41. OECD - Organisation for Economic Co-operation and Development. (Accessed on: October 6th 2023).
42. Oni, B.A., Oziegbe, O., Olawole, O.O. (2019). Significance of biochar application to the environment and economy. Annals of Agricultural Sciences 64(2), 222-236. https://doi.org/10.1016/j.aoas.2019.12.006
43. Pabbati R., Jhansi V., Venkateswar Reddy K. (2021). Conventional Wastewater Treatment Processes. In: Advances in the Domain of Environmental Biotechnology (Maddela, N.R., García Cruzatty, L.C., Chakraborty, S., Eds.). Springer, Singapore, 455-479. https://doi.org/10.1007/978-981-15-8999-7_17
44. Preisner, M., Smol, M., Horttanainen, M., Deviatkin, I., Havukainen, J., Klavins, M., Ozola-Davidane, R., Kruopienė, J., Szatkowska, B., Appels, Houtmeyers, S., Roosalu, K. (2022). Indicators for resource recovery monitoring within the circular economy model implementation in the wastewater sector. Journal of Environmental Management 304, 114261. https://doi.org/10.1016/j.jenvman.2021.114261
45. Salgot, M., Huertas, E., Weber, S., Dott, W., Hollender, J. (2006). Wastewater reuse and risk: definition of key objectives. Desalination 187, 29-40. https://doi.org/10.1016/j.desal.2005.04.065
46. Seow, T.W., Lim, C.K., Nor, M.H.M., Mubarak, M.F.M., Lam, C.Y., Yahya, A., Ibrahim, Z. (2016). Review on Wastewater Treatment Technologies. International Journal of Applied Environmental Sciences 11(1), 111-126.
47. Serrao, L., Molinos-Senante, M., Bezzi, M., Ragazzi, M. (2020). Assessment of wastewater reuse potential for irrigation in rural semi-arid areas: the case study of Punitaqui, Chile. Clean Technologies and Environmental Policy 22, 1325–1338. https://doi.org/10.1007/s10098-020-01874-3
48. Sharma, R.K., Agrawal, M., Marshall, F. (2007). Heavy metal contamination of soil and vegetables in suburban areas of Varanasi, India. Ecotoxicology and Environmental Safety 66, 258–266. https://doi.org/10.1016/j.ecoenv.2005.11.007
49. Singh A. (2021). A review of wastewater irrigation: Environmental implications. Resources, Conservation and Recycling 168, 105454. https://doi.org/10.1016/j.resconrec.2021.105454
50. Singh, A. & Agrawal, M. (2012). Effects of Waste Water Irrigation on Physical and Biochemical Characteristics of Soil and Metal Partitioning in Beta vulgaris L. Agricultural Research 1(4), 379–391. https://doi.org/10.1007/s40003-012-0044-4
51. Slobodiuk, S., Niven, C., Arthur, G., Thakur, S., Ercumen, A. (2021). Does Irrigation with Treated and Untreated Wastewater Increase Antimicrobial Resistance in Soil and Water: A Systematic Review. International Journal of Environmental Research and Public Health 18(21), 11046.
52. Smol, M., Adam, C., Preisner, M. (2020). Circular economy model framework in the European water and wastewater sector. Journal of Material Cycles and Waste Management 22, 682–697. https://doi.org/10.1007/s10163-019-00960-z
53. Soliman, M., El Jack, F., Kazi, M.K., Almomani, F., Ahmed, E., El Jack, Z. (2022). Treatment Technologies for Cooling

Water Blowdown: A Critical Review. Sustainability, 14(1), 376. https://doi.org/10.3390/su14010376

54. Sonune, A. & Ghate, R. (2004). Developments in wastewater treatment methods. Desalination 167, 55–63. https://doi.org/10.1016/j.desal.2004.06.113
55. Sun, J., Donn, M.J., Gerber, P., Higginson, S., Siade, A.J., Schafer, D., Seibert, S., Prommer, H. (2020). Assessing and Managing Large-Scale Geochemical Impacts from Groundwater Replenishment with Highly Treated Reclaimed Wastewater. Water Resources Research 56(11), e2020WR028066. https://doi.org/10.1029/2020WR028066
56. The world counts, www.theworldcounts.com. (Accessed on: October 5th 2023)
57. Thebo, A.L. (2016). Wastewater Reuse in Irrigated Agriculture: Global Perspectives on Water Quantity, Quality, and Exposure to Health Risks. Doctoral dissertation, University of California, Berkeley.
58. Toczyłowska-Mamińska, R., Mamiński, M.Ł. (2022). Wastewater as a Renewable Energy Source - Utilisation of Microbial Fuel Cell Technology. Energies 15, 6928. https://doi.org/10.3390/en15196928
59. Ungureanu, N., Vlăduț, V., Zăbavă, B.S.T., Andrei, P., Constantinescu, M. (2018). Current state of wastewater use in irrigated agriculture. Conference: The 14th Annual Meeting Durable Agriculture – Agriculture of the Future, Craiova, Romania.
60. Valipour, M. & Singh, V.P. (2016). Global Experiences on Wastewater Irrigation: Challenges and Prospects. In: Balanced Urban Development: Options and Strategies for Liveable Cities (Maheshwari, B., Thoradeniya, B., Singh, V.P., Eds.). Water Science and Technology Library, vol 72. Springer, Cham, 289-327. https://doi.org/10.1007/978-3-319-28112-4_18
61. Von Sperling (2007). Wastewater Characteristics, Treatment and Disposal. IWA Publishing, New Delhi, India. https://doi.org/10.2166/9781780402086
62. Vörösmarty, C.J. & Sahagian, D. (2000). BioScience 50(9), 753-765. https://doi.org/10.1641/0006-3568(2000)050[0753:ADOTTW]2.0.CO;2
63. Wang, H., Wang, T., Zhang, B., Li, F., Toure, B., Omosa, I.B., Chiramba, T., Abdel-Monem, M., Pradhan, M. (2013). Water and Wastewater Treatment in Africa – Current Practices and Challenges. Soil, Air, Water 42(8), 1029-1035. https://doi.org/10.1002/clen.201300208
64. Winpenny, J., Heinz, I., Koo-Oshima, S. (2010). The wealth of waste: The economics of wastewater use in agriculture. Food and Agriculture Organization of the United Nations, ISBN 978-92-5-106578-5.
65. Yeoh, J.X., Md. Jamil, S.N.A., Syukri, F., Koyama, M., Nourouzi Mobarekeh, M. (2022). Comparison between Conventional Treatment Processes and Advanced Oxidation Processes in Treating Slaughterhouse Wastewater: A Review. Water 14(22), 3778. https://doi.org/10.3390/w14223778
66. Younas, F., Mustafa, A., Farooqi, Z.U.R., Wang, X., Younas, S., Mohy-Ud-Din, W., Hameed, M.A., Abrar, M.M., Maitlo, A.A., Noreen, S., Hussain, M.M. (2020). Current and Emerging Adsorbent Technologies for Wastewater Treatment: Trends, Limitations, and Environmental Implications. Water 13(2), 215. https://doi.org/10.3390/w13020215

NAVODNJAVANJE USJEVA OTPADNOM VODOM: PROBLEM ILI RJEŠENJE?

SAŽETAK

Cilj ovoga rada bio je dati kritički pregled trenutačnoga stanja nastanka otpadnih voda u različitim procesima u svijetu te njihovu upotrebu u navodnjavanju. Zatim je dan kratak pregled klasifikacije otpadnih voda i njihove mogućnosti krajnje uporabe. Nadalje, dan je konkretan pregled navodnjavanja otpadnim vodama, uz relevantne znanstvene radove u kojima su proučavani utjecaji navodnjavanja otpadnim vodama na biljke, tlo, ljude i okoliš. Naposljetku, poseban osvrt dan je na smjernice i politike koje su predložili dionici EU-a u vezi s integracijom ponovne upotrebe otpadnih voda u planiranje i upravljanje vodama u kontekstu kružnoga gospodarstva, s posebnim naglaskom na nove tehnologije.

Ključne riječi: otpadne vode, navodnjavanje, ponovna uporaba, metode pročišćavanja, kružno gospodarstvo

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