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Water contamination by pharmaceutical products: constructed wetlands as an alternative treatment solution in arid zones of Mexico

Jessica Alejandra Aguilar-Gutiérrez[1], Marisela Yadira Soto-Padilla[1], Edith Flores-Tavizón[1], Lizett Trujillo-Morales[2] and Luis Gerardo Bernadac-Villegas[1]*

[1]Departamento de Ingeniería Civil y Ambiental, Instituto de Ingeniería y Tecnología, Universidad Autónoma de Ciudad Juárez, Av. del Charro # 450 Norte, Col. Partido Romero, 32584, Ciudad Juárez, Chihuahua, México. [2]Departamento de Estomatología, Instituto de Ciencias Biomédicas, Universidad Autónoma de Ciudad Juárez, Av. Benjamín Franklin # 4650, Zona PRONAF, 32310, Ciudad Juárez, Chihuahua, México. E- mail: *luis.bernadac@uacj.mx

ABSTRACT

In recent decades, the scientific community, aware of the importance in the prevention of pollution as a method to avoid alterations in the ecosystem, has studied the presence and effects of pharmaceutical products in wastewater. Water contamination by pharmaceutical products is a topic of growing interest, considering that they have been found in various water bodies and are not usually monitored by environmental authorities, except in highly developed countries in terms of environmental regulation. This review study addresses the recurrence of these pollutants, their effects on the environment and the use of constructed wetlands, and the benefits of their implementation for wastewater treatment in arid areas. The objective of the present review is focus in forming a research framework for its application in the sustainable development of arid zones and to inform of the advantages and disadvantages represented by the introduction of green techniques for wastewater treatment.

Keywords: wastewater, emerging pollutants, pharmaceutical products, sustainable development, green techniques.

Contaminación de agua por fármacos: humedales construidos como alternativa de tratamiento en zonas áridas

RESUMEN

En las últimas décadas, la comunidad científica consciente de la importancia en la prevención de la contaminación como método para evitar alteraciones en el ecosistema, ha estudiado la presencia y efecto de los productos farmacéuticos en el agua residual. La contaminación de cuerpos de agua por fármacos es un tema de interés mundial, con un aumento significativo en la actualidad, debido a los compuestos químicos que se han encontrado tanto en cuerpos de agua superficiales como subterráneos; en el caso de México se carece de una regulación estricta en términos de normatividad, a excepción de los países desarrollados. En esta revisión, se aborda la frecuencia de estos contaminantes, sus efectos en el medio ambiente y el uso de humedales construidos por los beneficios que otorga su implementación para el tratamiento del agua residual en zonas áridas. El objetivo de la presente es que se logre crear un marco de investigación que derive en un plan de desarrollo sustentable para su aplicación y un análisis de las ventajas y desventajas que representaría la introducción de técnicas verdes para el tratamiento del agua residual.

Palabras clave: agua residual, contaminantes emergentes, fármacos, desarrollo sustentable, tecnologías verdes.

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INTRODUCTION

Water is a resource on which all forms of life in the world depend, three-quarters of the Earth surface is covered by water, however, as the human population grows this resource is subjected to greater pressure in terms of availability and quality (Boyd, 2019). Water pollution is an issue that affects everyone, and it is part of Goal 6 of the 2030 Agenda for Sustainable Development, which promotes ensuring the availability and sustainable management of water and sanitation, and in conjunction with other objectives that include the conservation of oceans and protection of diverse ecosystems and biodiversity and water treatment are of great importance for the health of people and the rest of living organisms (ONU, 2015).

Water contamination by pharmaceutical products is a topic of growing interest, considering that they have been found in various water bodies and are not usually monitored by environmental authorities, except in highly developed countries in terms of environmental regulation. Pharmaceutical products fall into the group of emerging pollutants, in their category: pharmaceuticals and personal care products, PPCPs, which is a term that was born in 1999 (Chinnaiyan, Thampi, Kumar & Mini, 2018; Daughton, 2009). There is a wide range of pharmaceuticals such as lipid regulators, non-steroidal anti-inflammatory drugs such as e.g. ibuprofen or acetylsalicylic acid, and estrogen type such as 17β-estradiol (Gomes, Justino, Rocha-Santos, Freitas, Duarte & Pereira, 2017). Pharmaceutical products as emerging contaminants are also considered trace contaminants since their concentrations in the environment are low in amounts of micrograms or milligrams per kilogram, however, they possess high potential in causing adverse effects to humans and the environment which has been proven by *in vivo* and *in vitro* analysis in research laboratories (Gomes *et al.*, 2017). A general route that presents the channels through which the pharmaceutics can enter aquatic systems is presented in Figure 1. It is known that the effects they can cause are endocrine disruption, growth, and behavioral changes such as feeding, reproduction, and predation mainly in aquatic organisms (Blair, Kehl & Klaper, 2016; Anderson, 2003; Carballa, Omil & Lema, 2008; Gros, Petrović, Ginebreda & Barceló, 2010; Verlicchi, Aukidy & Zambello, 2012). About 4,000 pharmaceuticals are in use till date. Prescription rates of pharmaceuticals have almost tripled in the past 14 years and about 9.1 million kg of antibiotics of which 73.6% were used for the increasing production of food-

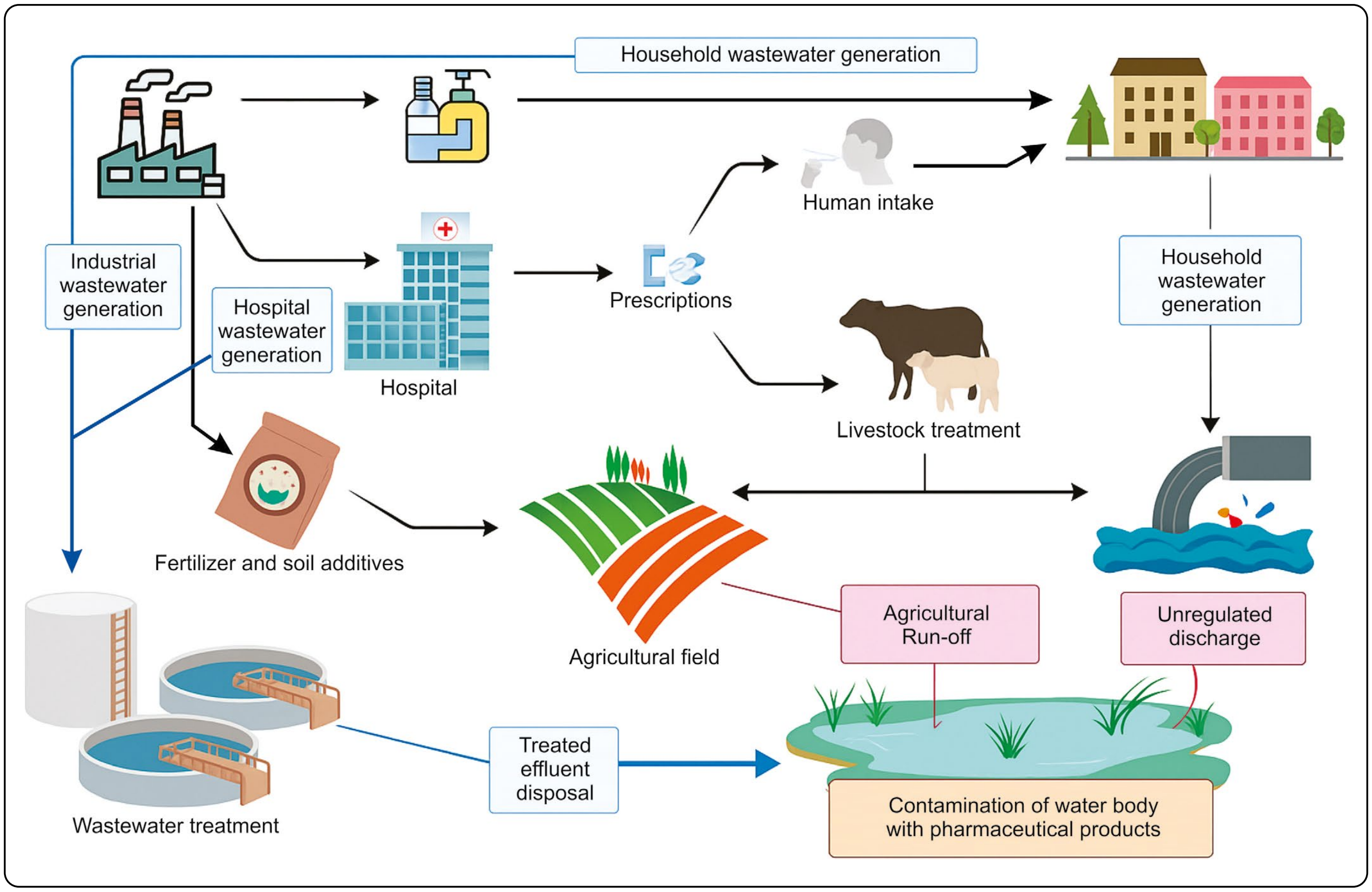

Figure 1. Pathways through which pharmaceutical products are distributed and enter to aquatic systems (Rathi, Kumar & Show, 2021).

producing animals in the year 2013 (Pennington, Rothman, Jones, McFrederick, Gan & Trumble, 2017).

The origin and distribution of pharmaceutical products in the environment is a complex process, mainly these types of contaminants come from wastewater treatment plants that are not very efficient for their removal, as well runoff from soils, wastes from medical facilities, livestock, domestic wastewater, and industry (Enachi, Bahrim & Ene, 2019). Several studies, such as the one conducted by Renau-Pruñonosa *et al.*, 2020), conclude that although the initial concentrations of emerging contaminants in wastewater are high, prior to their processing by wastewater treatment plants that have primary and secondary treatment, the concentrations are lower, although these low concentrations can still have an impact on groundwater. It is important to note that their presence or recurrence depends on the characteristics of the soil and the contaminant molecules themselves (Renau-Pruñonosa *et al.*, 2020). Figure 1 shows a possible scenario of the origin and distribution of emerging contaminants, especially pharmaceutical products, which eventually reach human exposure directly, by consuming poor-quality water, or indirectly, by exposing crops or livestock to effluents with the presence of pharmaceuticals.

To achieve sustainable development in countries, especially in arid areas, water reuse is important, and, therefore, ensuring its quality with treatments that eliminate trace contaminants such as pharmaceuticals is of great interest. It is not the main objective of wastewater treatment plants to remove emerging contaminants, so some authors point out that their degradation is partial and inefficient (Guedes-Alonso, Montesdeoca-Esponda, Pacheco-Juárez, Sosa-Ferrera & Santana-Rodríguez, 2020; Kaplan, 2013; Wang & Wang, 2016). The treatments that can be applied to wastewater from industries and households are: conventional type, used mainly in urban communities, involving biological reactors and chlorination oxidation systems; or they can be natural type, recommended for rural areas where their operation is based on taking advantage of the natural capabilities of bacteria, plants, and soils for treatment, although the disadvantage for these techniques could be the demand for large areas of land that in cities is limited, as an advantage for natural methods, it is that they require little energy and chemicals for their operation while generating little solid waste (Guedes-Alonso *et al.*, 2020; Crites, Middlebrooks & Reed, 2010).

There is currently an interest in the use of constructed and natural wetlands for wastewater treatment, which is a natural type of technique, and recently it has been seen that they can be exploited for the removal of pharmaceutical products. Constructed wetlands consist of soil beds containing emergent vegetation (Özengin & Elmaci, 2016; Cole, 1998). This water treatment technology is low cost compared to alternative technologies such as advanced oxidation or sorption with activated carbons and/or membranes, which makes constructed wetlands a viable option for regions with low water treatment budgets, and considering cost-effectiveness in construction, maintenance, and their eye-catching design, makes them a good option for removing pharmaceuticals from water (Li, Zhu, Ng & Tan, 2014). Different authors point out that constructed wetlands are efficient for the treatment of various types of domestic, agricultural, industrial, and mining wastewater (Li *et al.*, 2014; Choudhary, Kumar & Sharma, 2011; Cooper, 1996; Davies Burnett, Fan, Linfield & Cunningham, 2008; Kadlec & Wallace, 2008; Vymazal, 2008; Stottmeister *et al.*, 2003; Sundaravadivel & Vigneswaran, 2001; Vymazal, 1998). The objective of this work is to review the research on the presence of pharmaceutical products in the world, mainly in Mexico, the effects they have on the environment, as well as the description and use of wetlands as a proposal for pharmaceutical removal and the advantages of their application in arid areas such as northern Mexico.

PRESENCE OF PHARMACEUTICALS AT A GLOBAL AND REGIONAL LEVEL

Globally, it is estimated that 300 million tons of synthetic compounds such as pharmaceutical products, industrial additives, among others, are released into surface water bodies (Robledo *et al.*, 2017; Kümmerer, 2009). Specifically, for the case of pharmaceuticals, eco-pharmacovigilance was created, which is responsible for detecting, evaluating, understanding, and preventing harmful effects or different problematic issues with respect to pharmaceuticals (Castro-Pastrana, Baños-Medina, López-Luna & Torres-García, 2015; Velo & Moretti, 2010). In the American continent (North), the first investigations are given from the 1970s in the United States that reported the presence of pharmaceutical products in municipal wastewater and ten years later in the European continent, in England, the same situation is mentioned. For its part, Canada has conducted studies in wastewater and surface water, has reported the incidence of acid and neutral type drugs, demonstrating that their elimination is partially within the wastewater treatment plants, which makes them an environmental problem recognized worldwide (Castro-Pastrana *et al.*, 2015; Velo & Moretti, 2010; Kümmer & Velo, 2006; Fowler & Schnall, 2014; Brun, Bernier, Losier, Doe, Jackman & Lee, 2006; Smith *et al.*, 2002; Rodriguez-Mozaz & Weinber, 2010).

Due to its recurrence, the interest in studying pharmaceutical products in surface water and groundwater is a global issue in which each country contributes to new studies for the determination and distribution of these contaminants in the hydrological cycle, analyses carried out in developed countries such as China, where up to 14 different drug molecules have been found in raw water from a drinking water treatment plant near Lake Taihu, which after being treated by advanced procedures such as oxidation, indomethacin, caffeine, and sulfamethoxazole were found in the effluent, although in concentrations below 2 ng/L which are a health risk, so researchers recommend that these types of pollutants should be prioritized for regulation within policies (Lin, Yu & Chen, 2016). Similarly, in China, the distribution of drugs in estuaries and specifically in the Jiulong River has been studied during rainy seasons and seasonal variations, finding recurring drugs such as diclofenac, metoprolol, and caffeine. During permanence analysis, it has been seen that certain molecules have conserved and pseudo conservative behaviors, which are attributed to dilution in rainy seasons or by seawater, as well as by different physical, chemical, or biological processes to which these polluting substances may be exposed. This leads to the analysis that the main entry of pharmaceutical products into water is due to the introduction of untreated wastewater into estuaries (Sun *et al.*, 2016).

In the Latin American and Caribbean region, which includes 48 countries, it is reported that about 60% of wastewater is discharged into nature without treatment of any kind (Rodriguez-Dominguez, Konnerup, Brix & Arias, 2020; FAO, 2017), although estimates of wastewater that does not receive treatment may vary by author, all agree that there are little water treatment and sanitization in the Latin American and Caribbean region (Rodriguez-Domínguez *et al.*, 2020). Among the Latin American countries is Brazil, where the presence of pharmaceuticals has been reported in the bay of Todos Los Santos, which for more than 450 years has received drainage from different basins and for years was the recipient of sewage discharges from the capital, Salvador, Bahia. In this bay, concentrations of 52.5 ng/g galaxolide, 27.9 ng/g tonalide, 23.4 ng/g caffeine, 14.3 ng/g ibuprofen, 9.84 ng/g atenolol, and 1.06 ng/g diclofenac were reported. The above shows that pharmaceutical products are in the sediments of the study area where the clay soil type is a relevant factor for the deposition and adhesion of drug molecules (Beretta, Britto, Mascarenhas, Teixeira & Lowe, 2014).

It is estimated that in Mexico 54% of wastewater is untreated and discharged to water bodies or reused for crop irrigation (Robledo *et al.*, 2017; CONAGUA, 2015). A study by Robledo *et al.* (2017) in urban and industrial wastewater collected in a treatment plant in Morelia, Michoacán, Mexico, reported the presence of tetracycline, cefaclor, ampicillin, paracetamol, levothyroxine, among others, where detected by electronebulization ionization mass spectroscopy with time-of-flight detector (Robledo *et al.*, 2017). Other studies conducted by Félix-Cañedo, Durán-Álvarez & Jiménez-Cisneros (2013), in groundwater and surface water in the valley of Mexico showed the detection of salicylic acid, 4-nonylphenol and 2-diethylhexyl phthalate in concentrations of 1 to 464, 1 to 47, and 1 to 232 ng/L, respectively, in groundwater, their same detection was performed in surface water, but in higher concentrations in ranges of 29 - 309, 89 to 655, 75 to 2282 ng/L, respectively. In turn, they report the presence of diclofenac, triclosan, bisphenol A and butyl benzyl phthalate in groundwater, which leads them to conclude that the presence of organic micropollutants in drinking water sources in Mexico City is a problem to water quality (Félix-Cañedo *et al.*, 2013). Likewise, the presence of naproxen and triclosan has been reported in sediments of the Hidalgo River in Mexico at concentrations of parts per billion (ng/L), (Díaz & Peña, 2017).

However, investigations of pharmaceuticals´ presence in surface and groundwater, as well as raw and treated wastewater in Mexico are limited and few. In Ciudad Juárez, Chihuahua a study by Bernadac-Villegas *et al.* (2019) reported the detection of diclofenac in treated wastewater. Besides this study, on issues of treated wastewater or surface water quality with the presence of pharmaceuticals, no further information was found available in the northern part of the country of Mexico.

EFFECTS ON THE BIOTA

Extensive research on the ecotoxicological effects caused by pharmaceutical products in water mentions that given the low concentrations found, they are of a sublethal type. Sublethal effects occur at concentrations or doses low enough not to produce somatic death. These effects are identified in animal models by observing important physiological changes such as growth, reproduction, behavior, development, or similar life-threatening characteristics without immediate death. Some of these effects have ecological consequences, for example, an environment in which an individual normally competes successfully with others, evades predation, and reproduces, once contaminated can still survive, but its ability to evade predators, or finding food diminishes. Therefore, in nature, the consequence of a sublethal effect can lead to death (Newman, 2014).

Low concentrations of emerging pollutants and their constant release into the environment lead to chronic effects, where their mode of action is associated with endocrine or cytostatic modulation, they can also cause taxonomic variations that, at the same time cause metabolic inefficiencies affecting excretion and detoxification systems depending on age, sex, population, and exposed species (Arnold, Brown, Ankley & Sumpter, 2014). Several ecotoxicological studies have shown that these pollutants generate abnormalities in aquatic organisms, hormones such as estrone and 17-β-estradiol cause feminization, antibiotics such as penicillin, sulfonamides, and tetracyclines generate resistance to pathogenic bacteria, as do disinfectants and antiseptics such as triclosan, which also acts as a biocide (Bolong, Ismail, Salim & Matsuura, 2009).

Within the objectives for sustainable development, the issue of quality water available to all is relevant to this topic; however, considering the protection of the seas and wildlife is another valid argument for the identification of risks due to exposure to contaminants such as pharmaceuticals (Figure 2). Exposure to mixtures of caffeine, ibuprofen, and carbamazepine at low concentrations of 0. 1-50 µg/L (parts per billion, ppb) for 28 days, decrease the lysosomal activity of membrane stability in crabs (*Carcinus maenas*), to this same species when in contact with concentrations of 10-50 ppb of novobiocin, for the same

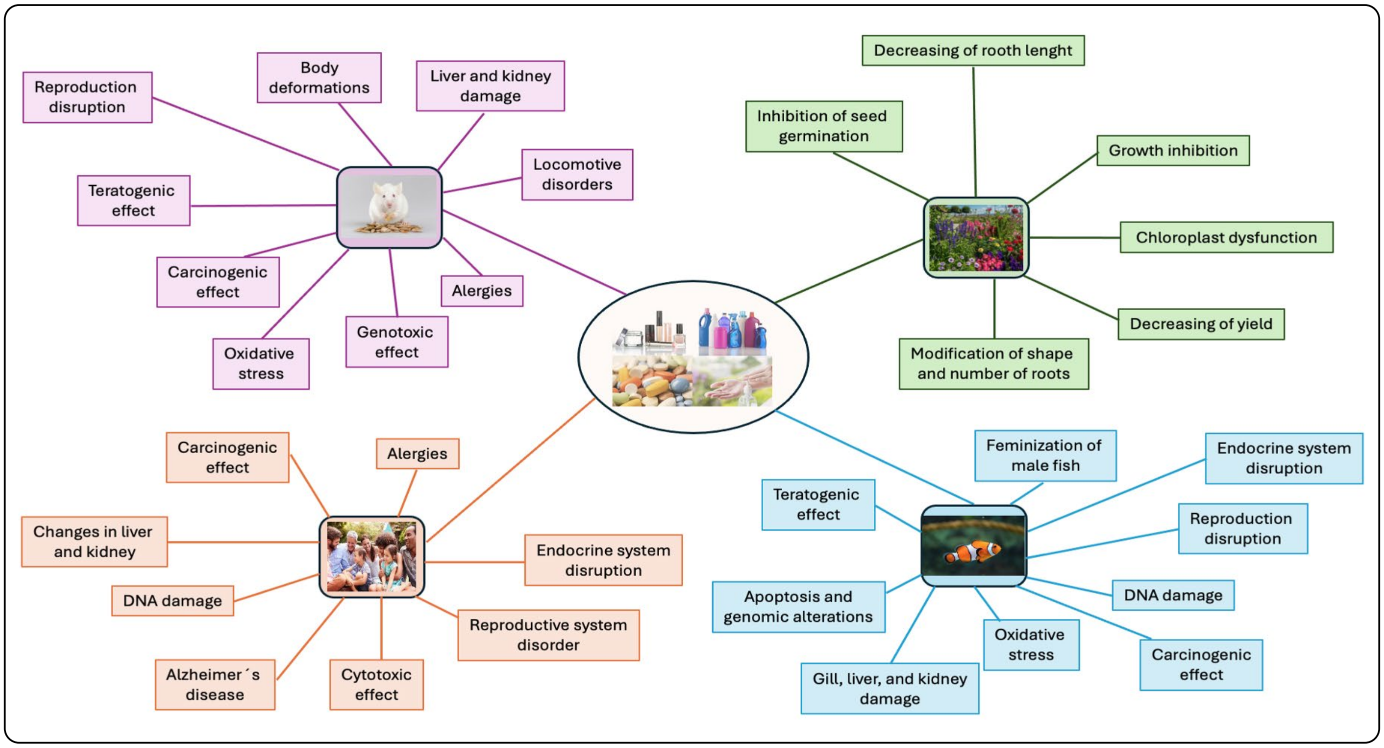

Figure 2. Toxicity of pharmaceutical products in different living organisms (Ortuazar, Esterhuizen, Olicón-Hernández, González-López & Aranda, 2022; Hejana, Kapuścińska & Aksmann, 2022; Fort *et al*., 2011).

period of time, the enzymatic activity of ethoxyresorufin-o-demethylase (belonging to the cytochrome P450 group) increased, as well as the activity of dibenzyl fluorescein dealkylase increased in gills and hepatopancreatic tissue, this induced by carbamazepine. Other enzymes such as glutathione S-transferase and peroxidase are activated (Prichard & Granek, 2016; Aguirre-Martinez, Del Valls & Martín-Díaz, 2013). The cytochrome P450 group is a complex system of multiple enzymes that are present in many tissues, their role is to act in the metabolism of xenobiotic substances, i.e., coming from outside the organism, to inactivate or activate them, depending on the response of the living organism (Ornella & Guajardo, 2004). Pharmaceuticals known to affect fish behavior are listed in Table I and include antidepressants, selective serotonin reuptake inhibitors (SSRIs), hormones, antihistamines, and various psychiatric drugs.

BIOACCUMULATION

Bioaccumulation is the deposition of a contaminant, in some cases, an organism can take it from various sources such as water, air, and solid phases of the environment. Bioconcentration is not synonymous with bioaccumulation, since the former speaks only of the accumulation of a contaminant in an organism by exposure in water (Newman, 2014), for these processes to occur they must go through a whole metabolic system as shown in Figure 3. This explains the process of contaminant entry starting from its exposure, which enters by absorption in different scenarios, the exogenous compound is distributed by the organism and the toxic molecule begins to interact in case the individual does not have an excretion mechanism for the toxic molecule, the contaminant accumulates and sometimes it can be eliminated sometime later. In other cases, the exogenous molecule may undergo transformations to inactivate it so that it can be eliminated or made less harmful. In severe cases, subsequent metabolic processes may render it more toxic.

CONSTRUCTED WETLANDS AS A POTENTIAL ECOTHECNOLOGICAL TOOL FOR THE REMOVAL OF PHARMACEUTICAL PRODUCTS

Wetlands are complex ecological systems in which physical, biological, and chemical processes are involved, they play an important role in the protection of water and different ecosystems such as the marine ecosystem because they remove excess nutrients, thus reducing oxygen demand, and they also eliminate the presence of pathogens, metals, and organic solids in water. These systems also regulate climates and are storm buffers, stabilize soil, and are habitat for wildlife (Nagabhatla & Metcalfe, 2017; Sierszen, Morrice, Trebitz & Hoffman, 2012; Zedler & Kercher, 2005; Engelhardt & Ritchie, 2002). In 1971 the Ramsar convention (International Convention on Wetlands of International Importance) raised the importance for the conservation of wetlands, where it is estimated that

Table I. Studies of pharmaceutical effects on behavior of different fish species, type of substance, and endpoint. Concentrations are given in µg l^{-1} (Lynn, Egar, Walker, Sperry & Ramenofsky, 2007; Nassef *et al.*, 2010; Gebauer, Pagnussat, Piato, Schaefer, Bonan & Lara, 2011; Holmberg *et al.*, 2011; Schultz *et al.*, 2011; Rodrigues, Antunes, Brandao, Castro, Goncalves & Nunes, 2012; Söeffker & Tyler, 2012).

Pharmaceutical	Species	Endpoint	Concentration µg l^{-1}
Anticholinesterasic drugs			
neostigmine	*L. gibbosus*	Boldness	(100 000)
pyridostigmine	*L. gibbosus*	Boldness	(100 000)
Antidepressants			
citalopram	*O. mykiss*	Aggression	(100 000)
bupropion	*P. promelas*	Reproductive behavior	(0.057)
fluoxetine	*B. splendens*	Activity, aggression	3,000
Antiepileptic drugs			
carbamazepine	*O. latipes*	Activity, feeding rate	6,100
Antihistamines			
diphenhydramine	*P. promelas*	Feeding rate	5.6
Beta blockers			
propranolol	*D. rerio*	Activity	3,000
Nsaid[b]			
diclofenac	*O. latipes*	Feeding	1,000
Psychiatric drugs			
clonazepam	*D. rerio*	Activity	300

globally there are from 917 to more than 1,270 million hectares of wetlands (Nagabhatla & Metcalfe, 2017; Lehner & Döll, 2004; Spiers & Finlayson, 1999).

Natural wetlands have been internationally recognized for their importance to the environment and have been established as priority areas for protection according to the criteria of the "Convention on Wetlands of International Importance Especially as Waterfowl Habitat" or Ramsar Convention that was concluded on February 2, 1971. In Mexico, on December 20, 1984, the convention was approved by the Congress Senate and published on July 18, 1985, based on Article 133 of the Mexican Constitution, which states that international treaties that are compatible with the Mexican Constitution shall be signed by the President and the Senate of the Republic, and thereafter shall become the supreme law for the entire country. Currently, the National Commission of Natural Protected Areas (CONANP) promotes compliance with the international commitment, as Mexico is second worldwide with 142 wetlands of international importance (CONANP, 2016).

Classification and types of wetlands

Natural wetlands

Worldwide, the importance of wetlands lies in their role in climate regulation, maintenance of the hydrological cycle, and preservation of ecosystem diversity (Xu *et al.*, 2019; Hu, Niu, Chen, Li & Zhang, 2017). Its major distribution is in Europe and Africa. At least 50% of wetlands are affected 54% by pollution, 53% by their biological exploitation, and 42% by aquaculture (Xu *et al.*, 2019). The use of natural or constructed wetlands has increased in applications for the treatment of wastewater from small municipalities or industrial effluents. For calculations in their performances, input and output concentrations are analyzed or by estimates of pollutant or nutrient exports per unit area. In a study conducted in the Frank Lake flooded wetland in Canada, it was observed that the highest pollutant removal efficiencies were obtained in spring (Zhu, Ryan & Gao, 2019).

Constructed wetlands

The use of wetlands for the removal of pharmaceutical contaminants is a new method that requires analysis, as many mechanisms are involved for the removal of these contaminants. The analysis must consider design aspects, physical and chemical factors, and their possible toxic effects on the wetland since it is a technique that involves living organisms. The types of constructed wetlands classification are shown in Figure 4 and consist of the following:

- Free-surface constructed wetlands (a series of flooded or planted channels or basins).

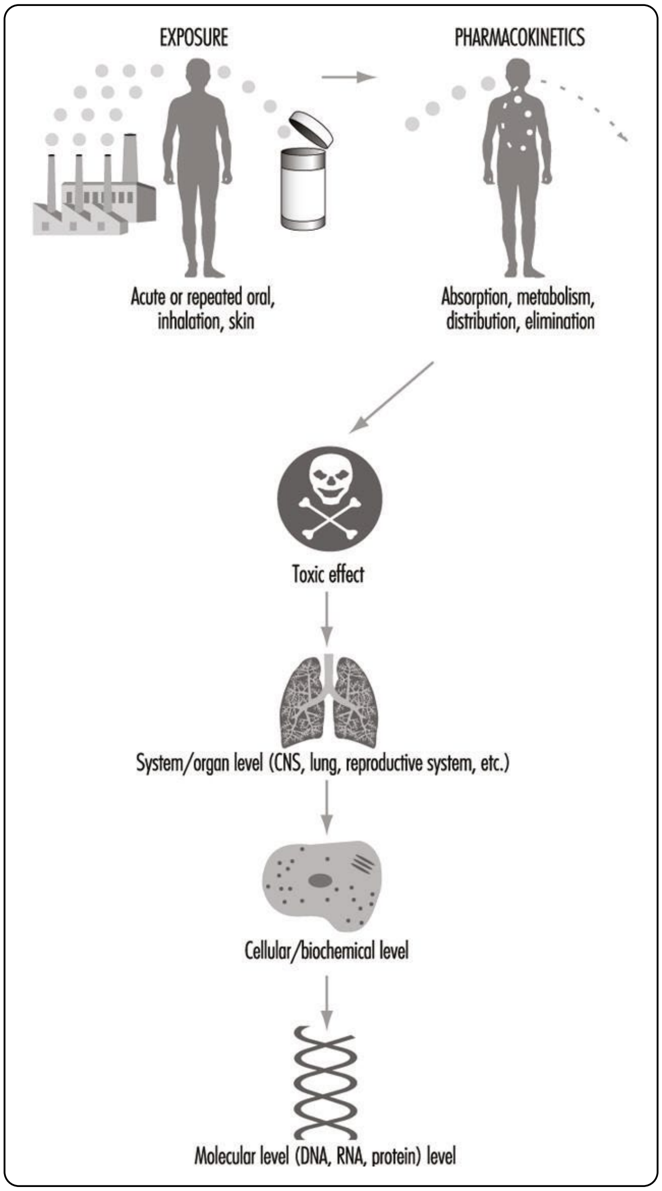

Figure 3. Mechanisms of toxicity (Silbergeld, 1990).

- Horizontal Subsurface Flow Constructed Wetlands (wastewater flows horizontally through the basin).
- Vertical subsurface flow constructed wetlands (water flows vertically down through the filter matrix to the bottom of the basin where it is collected in a drainage pipe).
- Hybrid constructed wetlands (combination of two or more systems), (Li *et al.*, 2014).

Plants present in wetlands have the morphological and physiological properties to tolerate saturated soils; therefore, hydrology is important for this treatment technique. In general, in the treatment of emergent species that develop in wetlands, it is required that the water completely covers the roots of the plants and at a certain point that there is no flow so that the roots can be aerated (Moshiri, 1993).

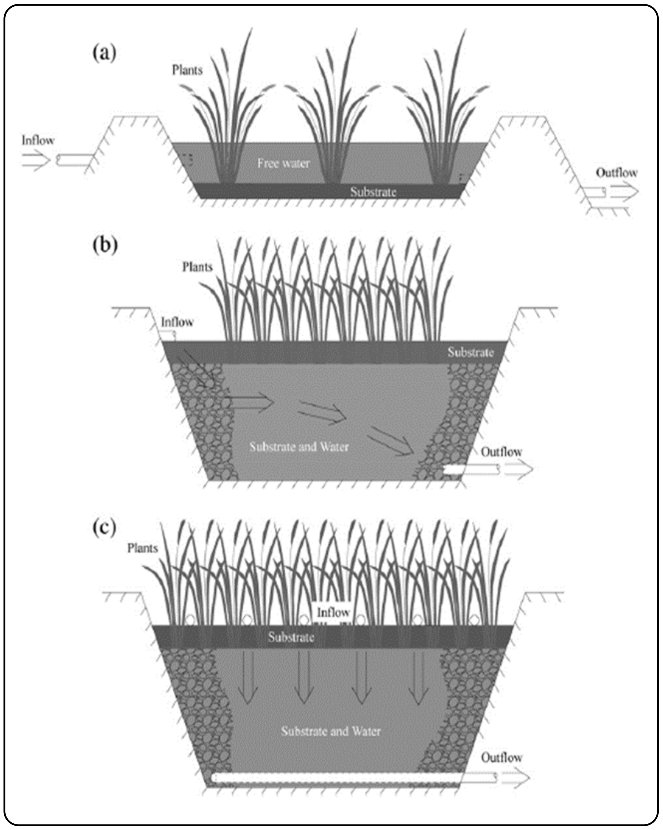

Figure 4. Types of constructed wetlands: a) free-flowing b) horizontal subsurface flow c) vertical subsurface flow (Li *et al.*, 2014).

Their performance for the removal of pharmaceutical products present in water has been studied by several researchers. Hijosa-Valsero, Matamoros, Sidrach-Cardona, Martín-Villacorta, Bécares & Bayona (2010) constructed seven wetlands with different variations: plant species, flow, and gravel beds, covering two seasons of the year, where the removal of naproxen in winter was 27-66%, increasing in summer with 27-83% removal, ibuprofen from 27-74% in winter and 6-96% in summer, acetylsalicylic acid with yields of 35-85% in winter and 84-89% in summer. With less favorable results, diclofenac was only removed by 17-26% in winter and 36-52% in summer. (Hijosa-Valsero *et al.*, 2010). There are parameters that are important to analyze to establish the optimal conditions and maximum removal of pollutants of this type by wetlands. Cancelli, Gobas, Wang & Kelly (2019) analyzed the effects on water inflows in horizontal wetlands for the removal of hydrophobic organic pollutants such as galaxolide, tonalide, pentachlorobenzene, hexachlorobenzene, 1,2,3,4-tetrachlorobenzene, musk ketone, methyl triclosan, PCB52, and endosulfan sulfate. These researchers report that the water balance for the mass removal and concentration reduction study is a factor influencing the process. Water flows to the wetland in conjunction with the addition of wastewater influent and precipitation reduce the concentration of contaminants by dilution but also decrease the hydraulic retention time which in turn reduces the mass of contaminant to be removed. Water loss and evaporation reduce concentration reduction efficiency but increase mass removal efficiency, so the balance between inputs and losses has an important effect on the application of this technique (Cancelli *et al.*, 2019). Zhang, Gersberg, Hua, Zhe, Anh & Keat (2012) studied the performance of subsurface wetlands for the removal of pharmaceutical products: based on the removal capacity, they separated into three categories of pollutants. Within category I, they reported pollutants removed above 85% such as ketoprofen and salicylic acid, in category II pollutants removed moderately in the range of 50-85% such as naproxen, ibuprofen, and caffeine, finally in category III compounds removed poorly with efficiency less than 50% were the drugs carbamazepine, diclofenac, and clofibric acid. In this study they reported that the hydrophobicity of the drugs has little relation with the removal capacity of the wetlands, associating the efficiency to the mass of the influent and the presence of macrophytes in the wetlands (Zhang *et al.*, 2012).

The type and presence of plants correlate with the effectiveness of pollutant removal. Zhang and collaborators (2011) demonstrated this by obtaining removal yields of 91% naproxen in wetlands with *Typha angustifolia*, as opposed to wetlands without the plant where 52% was removed. The authors mention that oxidizing aqueous media and the rhizosphere created by plants play an important role in pollutant removal (Zhang, Gersberg, Sadreddini, Zhu & Tuan, 2011). The application of community-constructed wetlands has been employed as a response to local wastewater treatment. Chen, Liu, Deng & Ying (2019) have worked on the creation of wastewater treatment systems in rural locations in China, making use of wetlands coupled to stabilization ponds for subsequent release to nearby rivers. In the study, they report yields of 97.4% for hormone removal and 92.4% for biocides, both classified as emerging pollutants. The plant species used in the study were *Myriophyllum verticillatum* and *Pontederia cordata*. Based on their results, the application of wetlands for water treatment in small communities is an economically viable option, as well as environmentally beneficial (Chen *et al.*, 2019). Similarly, the construction of wetlands for water treatment has been studied in various effluents and small communities such as Aalbeke a village in the Belgian province, Auvinen *et al*. (2017) conducted a pilot subsurface wetland study for the treatment of municipal wastewater and a hospital effluent. The authors reported that constant aeration in wetlands favors the removal of drugs such as metformin and valsartan with an efficiency of 99% for both cases. In their study, they reveal that hospital effluents contain high concentrations of drugs where they achieved the removal of greater than 75% for atenolol and greater than 50% for bisoprolol (Auvinen *et al.*, 2017).

Mechanisms of operation

Wetlands generate surfaces suitable for the development of microorganisms that may be able to absorb and incorporate pollutants to bio-transformed them into less toxic compounds (Arteaga-Cortez, Quevedo-Nolasco, Valle-Paniagua, Castro-Popoca, Bravo-Vinaja & Ramírez-Zierold, 2019). Vegetation growing within these systems can remove salts such as calcium, magnesium, sodium, chlorine, and sulfates (Arteaga-Cortez *et al.*, 2019; Yang, Sheng, Kan & Liu, 2015). In the same way as vegetation, clay soils by having ion exchange capacity achieve nitrogen removal, the effectiveness of wetlands for pollutant removal depends on the oxygen conditions available. The biological processes involved mainly start with the uptake of oxygen from the plant, based on the hypothesis that some pollutants can be used as nutrients. For its part, microbiological metabolism also adds to water purification, as well as chemical removal processes such as adsorption given by the soil, which immobilizes in its pores, certain types of pollutants (Arteaga-Cortez *et al.*, 2019).

Other studies focused on the specific removal of emerging contaminants, especially pharmaceuticals, indicate that the mechanisms for their removal are diverse and include photolysis, bio-adsorption, microbiological degradation, and sorption (White, Belmont & Metcalfe, 2006). At the same time as the intrinsic properties of such organic molecules, volatilization can be related to the vapor pressure of the contaminants (Gorito, Ribeiro, Almeida & Silva, 2017; Suthersan, 2002). Among the processes that can intervene for the removal of pharmaceutical products is sorption in soil where dependent on the partition coefficient and organic carbon, octanol-water coefficient, hydrophobicity, as well as the pH of the medium, temperature and ionic strength, can be aroused. On the other hand, photodegradation can occur depending on the seasonal radiation intensity and the maximum absorption spectrum of each contaminant molecule (Gorito *et al.*, 2017). For the plant absorption process to occur, it is influenced by the physicochemical characteristics of the drug molecules such as their dissociation capacity in water (pKa), their octanol-water partition coefficient (Kow) and their concentration in the medium, however several authors point out that uptake by plants is a secondary factor and attribute it mainly to microbial degradation which in turn depends on the availability of oxygen and final electron acceptors for microbial metabolism to function in the best way (Gorito *et al.*, 2017; Stottmeister *et al.*, 2003). The processes of removal that can occur within the wetland system are exemplified in Figure 5.

Advantages and challenges

Currently, a large number of constructed wetlands are used for the treatment of different types of wastewater because they are a

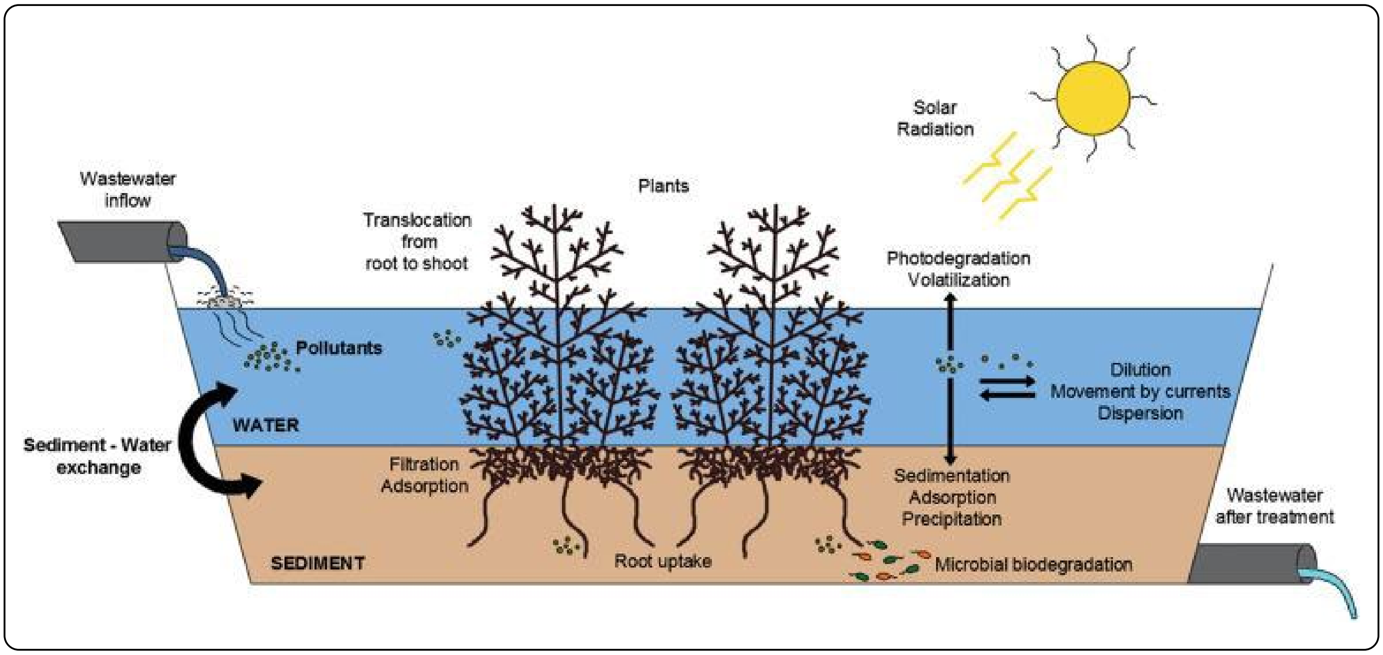

Figure 5. Mechanisms for pharmaceutical products removal in wetlands (Gorito *et al.*, 2017; Zhang *et al.*, 2014).

low-cost technique in maintenance, operation and construction, in addition to being versatile since they can be designed and studied with different conjugations and components depending on the type of wastewater to be treated and the concentrations of pollutants (Rehman, Pervez, Khattak & Ahmad, 2017; Greenway & Woolley, 2001; Herrera-Cárdenas, Navarro & Torres, 2016). Among the advantages of wetlands as a treatment method for wastewater are that, depending on the plant selection, its growth period can be high, with high survival rate and resistance, as well as having an attractive and even economical appearance which is useful for its design and acceptance by communities. And their application in developed cities is that in addition to the advantages already mentioned they serve as flood control and depending on water quality, generate habitat for wildlife and food production (Rehman *et al.*, 2017).

Considering that part of the mechanisms for the removal of pharmaceutical products through wetlands is by phytoremediation, being a green technology of recent introduction, socially it has been expected to gain relevance given its efficiency, economic feasibility and for having a lower environmental impact. Some of the advantages proposed by phytoremediation is its ability to remove large quantities and variety of pollutant molecules, cost-benefit balances being one of the most effective with great social acceptance (Farraji, Zaman, Tajuddin & Faraji, 2016).

Constructed wetlands have a strong advantage as an alternative water source in arid and semi-arid zones due to the continuous supply with which they work, as opposed to rainwater harvesting methods where precipitation and different hydrological conditions are required, this treatment system allows processing wastewater or gray water, eliminating pollutants *in situ*, in addition to adding to a circular economy system, which is of great importance in large cities to achieve sustainability (Collivignarelli, Miino, Gomez, Torretta, Rada & Sorlini, 2020).

However, it is the responsibility of proposing and suggesting different technologies to inform the disadvantages of each one. Among the disadvantages observed when using phytoremediation is the concentration of contamination in plants, and the disadvantageous consequences that could derive from the technique depend on the plant species and its response to the contaminant molecules, that is, on the physiological and limiting properties of each species. The main disadvantages that phytoremediation has involve a deterioration in the quality of the plant such as a decrease in its biomass production (Farraji *et al.*, 2016; Pilipović *et al.*, 2021), slow treatment depending on the type of contaminated water or soil to be remediated (Farraji *et al.*, 2016; Chintakovid Visoottiviseth, Khokiattiwong & Lauengsuchonkul, 2008), as well as contamination of the environment by the subsequent release of pollutants by the plants (Farraji *et al.*, 2016).

Another disadvantage of constructed wetlands as a treatment method is their possible decrease in performance for wastewater treatment in winter seasons (Rehman *et al.*, 2017; Maehlum, Jenssen & Warner, 1995). Finally, the analysis between wastewater treatment techniques and constructed wetlands is the amount of space needed to apply it, wetlands require large areas to be an efficient method, so areas with little space would be complicated to apply them, among the disadvantages as well as traditional systems, unpleasant odors and generation of insects can be problematic that could occur (Tsihrintzis, 2017). Figure 6 shows a comparison between conventional techniques against constructed wetlands for wastewater treatment.

CONCLUSIONS

Inevitably the growth of human population has brought consequences to ecosystems by introducing new chemicals, emerging pollutants are part of the interests of the scientific community both to evaluate their effects on wildlife and humans, as well as to study new optimal treatments for their elimination. The contamination of water resources leads to serious consequences for the sustainable development proposed in the 2030 agenda, both for vulnerable groups in society and for marine and terrestrial life. Therefore, ensuring the quality of drinking and treated water is part of the objectives for sustainable development, contemplating the treatment of water for reuse and being part of the circular economy and this with greater relevance in arid areas such as northern Mexico.

Natural wetlands are part of the biodiversity of the regions, and the importance of their preservation has been recognized worldwide, in Mexico their care is the responsibility of environmental authorities, as well as the population in general. These systems recreated as constructed wetlands are part of green technologies for the treatment of contaminated water, such as water contaminated with pharmaceuticals, and now take on an important value with the global health contingency where human society has resorted to the use of a large number and variety of pharmaceutical products to preserve health, as well as the use of disinfectants to improve hygiene and prevent contagion. We must not forget the care and quality of water resources and, for its part, avoid the deterioration of the environment which, as already mentioned, is on the global agenda 2030 and is vital to ensure a quality human life.

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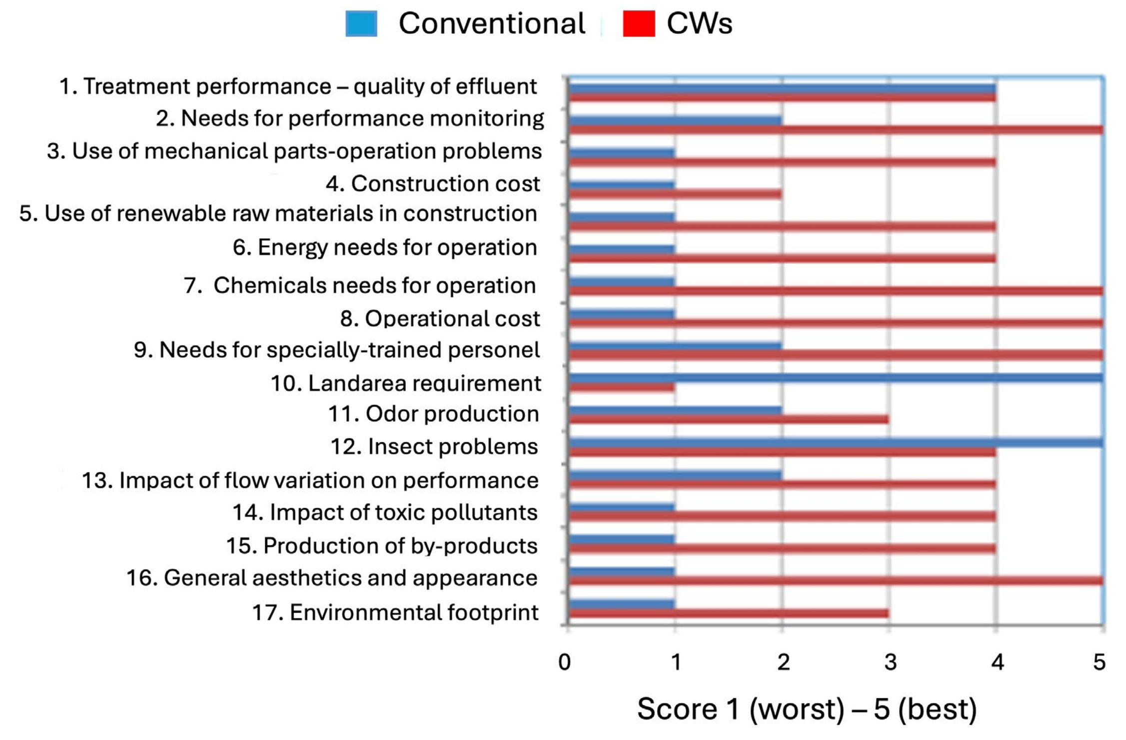

Figure 6. Comparison of conventional treatment systems versus constructed wetlands. Score is given from 1 (worst) to 5 (best), (Tsihrintzis, 2017).

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