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Review Article

Bioremediation strategies for the treatment of Emerging Contaminants: a view from Phytoremediation

Estrategias de Bioremediación para tratamiento de Contaminantes Emergentes: una visión desde la Fito-remediación

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Abstract

Introduction: Emerging Contaminants (ECs) are a broad and growing category of substances found in the environment, which have only recently been recognized as significant water pollutants. The inability of conventional wastewater treatment plants (WWTPs) to effectively remove ECs underscores the need for alternative, cost-effective, and environmentally friendly treatment methods.
Objetive: The objective of this review is to explore bioremediation strategies for emerging contaminants (ECs) using constructed wetlands (CWs) and the role of plants in wastewater phytoremediation. We discuss ECs such as pharmaceuticals, personal care products, pesticides, hormones, perfluoroalkyl substances, and microplastics.
Methodology: The methodology involved a bibliographic review using electronic databases from the Universidad del Valle Library, specifically SCOPUS and ScienceDirect (Elsevier). The search was conducted using keywords such as "Emerging Contaminants (ECs)," "Constructed Wetlands (CWs)," and "Tropical Plants in Phytoremediation" and publications from the last 3 years were prioritized.
Results: The removal of ECs in CWs involves a complex interplay of physical, chemical, and biological processes, which are influenced by the design and operational parameters of the system. CWs vary significantly in design, with major configurations including surface flow (SF) and subsurface flow (SSF), as well as horizontal subsurface flow (HSSF) and vertical subsurface flow (VSSF) systems. These configurations differ in media type, depth, and overall treatment efficiency.
Conclusions: This review examines the presence of ECs in aquatic environments and explores the use of plants in CWs as phytoremediation strategies. Findings indicate that CWs are a sustainable and effective alternative, with key removal mechanisms—including biodegradation, substrate adsorption, and macrophyte uptake—playing a crucial role in eliminating recalcitrant ECs. The design and operational conditions of CWs significantly impact phytoremediation efficiency.

Keywords: Emerging Contaminants (EC). Constructed Wetlands (CW). Wastewater Phytoremediation, Wastewater Treatment Plant (WWTP). Mechanisms and elimination of pollutants.

Resumen

Introducción: Los contaminantes emergentes (CEs) son una amplia y creciente categoría de sustancias encontradas en el ambiente que solo recién se reconoce como significativos contaminantes del agua. La inhabilidad de las plantas de tratamiento de aguas residuales (PTAR) para remover efectivamente CEs hace necesarios métodos de tratamientos alternativos y ambientalmente amigables. **Objetivo**: El objetivo de la revisión es explorar estrategias de bioremediación para contaminantes emergentes usando humedales construidos y el papel de las plantas en la fitoremediación de aguas servidas.
Metodología: Considero una revisión bibliográfica usando las bases de datos electrónicas de la biblioteca de la Universidad del Valle, específicamente SCOPUS y ScienceDirect (Elsevier). La búsqueda usó palabras claves como "Contaminantes Emergentes", "Humedales Construidos" y de "Plantas Tropicales en Fitoremediación" y se priorizaron las publicaciones de los últimos 3 años.
Resultados: La remoción de CEs en HCs involucra complejos procesos físicos, químicos y biológicos, los que son influenciados por el diseño y parámetros operacionales del sistema. Los HC varían significativamente en diseño, con las configuraciones que incluyen sistemas de flujo superficial (FS) y subsuperficial (FSS), así como flujo horizontal (FHSS) y vertical (FVSS). Las configuraciones difieren en tipo de medio, profundidad y en la eficiencia del tratamiento.
Conclusiones: Esta revisión examina la presencia de CEs en ambientes acuáticos y explora el uso de las plantas en HC como estrategias de fitorremediación. Los hallazgos indican que los HCs son una alternativa sostenible y efectiva con mecanismos de remoción claves -incluyendo biodegradación, adsorción de sustrato y ingreso de macrofita- jugando un papel crucial en eliminar CEs recalcitrantes. El diseño y condiciones operacionales de los HCs impactan significativamente la eficiencia de fitorremediacion.

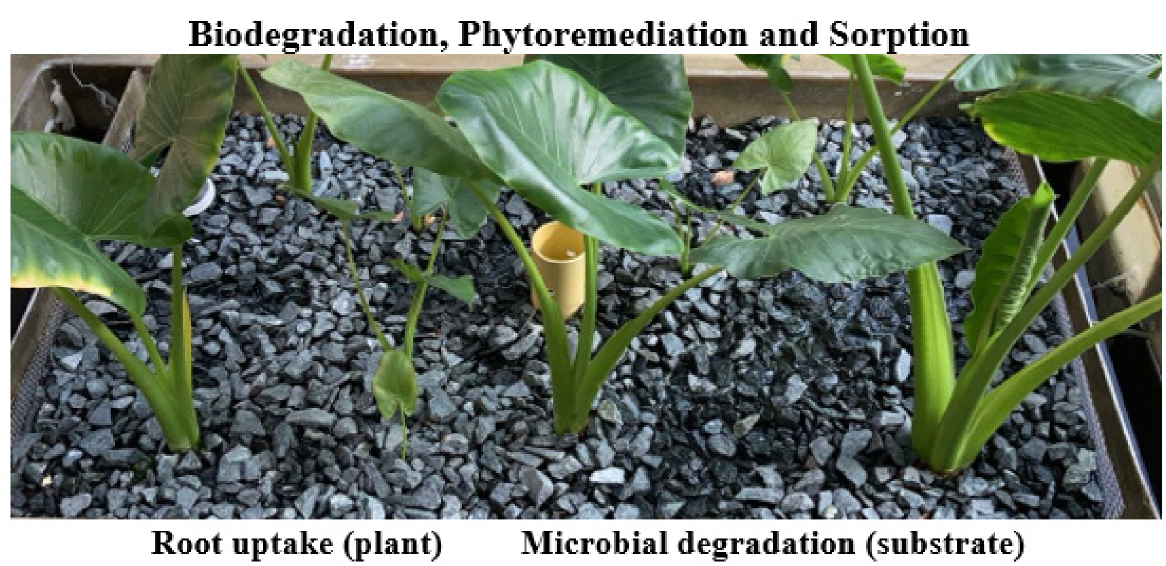
Palabras clave: Contaminantes Emergentes (CE). Humedales Construidos (HC). Fitorremediación de Aguas Residuales, Planta de Tratamiento de Aguas Residuales (PTAR). Mecanismos y Eliminación de Contaminantes

Contribution to the literature

Why was it done?
This review discusses strategies for the bioremediation of Emerging Contaminants (EC) using Constructed Wetlands (CW) and the role of plants in wastewater phytoremediation. In Latin America, a region facing environmental challenges related to EC (a broad and growing category of man-made substances found in the environment, which have been recognized as significant water pollutants) there is limited information on their distribution in the environment. We describe various ECs, including pharmaceuticals, personal care products, pesticides, hormones, perfluoroalkyl substances, and microplastics, in wastewater, as well as the use of plants in phytoremediation with CW.

What were the most relevant results?
Various methodologies have been developed to degrade and eliminate EC, reducing their environmental impact. Previous and ongoing studies have focused on contaminant degradation and removal through (1) physical, (2) chemical, and (3) biological treatments. Effective EC removal relies on mechanisms such as biodegradation, substrate adsorption, and macrophyte uptake. CWs have demonstrated strong performance in EC elimination through the combined actions of substrates, plants, and microorganisms. This review summarizes the performance and efficiency of Pharmaceuticals and Personal Care Products (PPCPs) removal in different systems utilizing CW plants. We review recent advances in understanding the various mechanisms and pathways involved in the attenuation and mitigation of PPCPs and steroid hormones through phytoremediation in CWs.

What do these results contribute?
Most research has focused on the roles of substrates and microorganisms, while fewer studies describe the direct (plant absorption and degradation) and indirect (rhizosphere processes) contributions of CW plants in EC removal. To clarify the mechanisms of EC elimination by plants in CW, we summarize the physiological, biochemical, and cellular processes involved in phytoremediation. The presence of ECs in the environment is particularly concerning because they often occur as mixtures, which may lead to undesirable synergistic effects. The widespread presence of potentially toxic ECs highlights the urgent need to better understand their occurrence, fate, and ecological impact. We provide an analysis of ECs removal potential in CWs, influencing factors, and removal mechanisms.



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Introduction

Wastewater (WW) is water that has been polluted by domestic, industrial, and commercial activities and must be treated before being discharged into other water bodies to prevent groundwater contamination. It contains various pollutants, including heavy metals, organic contaminants, and inorganic contaminants. Emerging Contaminants (ECs) are a broad and growing category of man-made substances found in the environment, which have only recently been recognized as significant water pollutants (1-2). The main sources of ECs include wastewater treatment plants (WWTPs) that process domestic wastewater, hospital effluents, and wastewater from chemical manufacturing plants, livestock operations, and agricultural activities (3). The presence of ECs in the environment is particularly concerning because they often occur as mixtures (4-5), which may lead to undesirable synergistic effects. The widespread presence of potentially toxic ECs highlights the urgent need to better understand their occurrence, fate, and ecological impact.

Research has been conducted on a wide variety of contaminants, but ECs primarily include micropollutants such as pharmaceuticals, hormones or endocrine disruptors, pesticides, toxins (2), and industrial synthetic dyes or dye-containing pollutants (6). Wastewater treatment systems are generally ineffective at removing ECs and are not routinely monitored. In poorer regions of emerging countries, such as some areas in Latin America, inadequate water treatment conditions increase human exposure to ECs. Llorca et al. (7) provided an overview of organic ECs in Latin American freshwater and marine biota between 2002 and 2016. Similarly, Peña-Guzmán et al. (8) reported data on EC levels in the urban water cycle of 11 Latin American countries between 1999 and 2018. Among the most frequently studied ECs are pharmaceuticals, followed by personal care products. The most commonly reported ECs include 17β-estradiol, bisphenol A, and estrone (8).

Comparing EC concentrations across different countries is challenging due to the lack of studies in some regions and the variability of water matrices. Some studies focus on wastewater, while others examine surface water or drinking water. In Latin America, several countries rank among the highest users and consumers of ECs, ranging from pesticides and fertilizers to personal care products. However, there is a significant gap in information regarding the distribution of ECs in the environment, with very few comprehensive reviews on this topic (9).

This data gap in Latin America mirrors trends observed in other regions. In Africa, more than 35 publications have reported on the occurrence and fate of pharmaceuticals, personal care products, and pesticides in water systems, yet little to no data is available on remediation and control strategies (10). Other reviews have examined various classes of ECs in both conventional water sources used for drinking (rivers, streams, lakes, wells) and nonconventional water resources, such as treated wastewater (effluent) used for domestic and agricultural purposes across the five regions of the African continent. Pharmaceuticals, personal care products, endocrine-disrupting chemicals, pesticides, perfluoroalkyl and polyfluoroalkyl substances (PFAS), and microplastics have been identified in both types of water resources (11).

A review was conducted on these ECs, including pharmaceuticals, personal care products, and pesticides-fertilizers, as well as emerging contaminants such as hormones (endocrine-disrupting

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chemicals), PFAS, and microplastics. Pharmaceuticals and personal care products (PPCPs) in aquatic environments are considered among the most critical ECs and are of growing concern (12).

The use of plant-based aquatic systems, such as artificial wetlands, for the treatment of conventional pollutants has been well-documented (13). The removal of PPCPs in CWs involves a complex interplay of physical, chemical, and biological processes, which can be influenced by the design and operating parameters selected for treatment (14-15). This review summarizes the performance and efficiency of PPCP removal in different systems utilizing CW plants. Additionally, we review recent advances in understanding the various mechanisms and pathways involved in the attenuation and mitigation of PPCPs and steroid hormones through phytoremediation in CWs.

Previous studies conducted by our group evaluated the removal of pharmaceutical compounds using High-Rate Algal Lagoons (HRALs) to treat effluent from the WWTP in Cali, Colombia. These studies reported removal efficiencies ranging from 70% to 100% for compounds such as ibuprofen, paracetamol, indomethacin, ketoprofen, and naproxen. Additionally, removal efficiencies between 50% and 70% were observed for diclofenac and gemfibrozil, while carbamazepine and its metabolite CBZ-Diol showed removal efficiencies of approximately 50% (16).

In another study, Jiménez-Bambague et al. (17) evaluated an Electro-Oxidation (EO) process for the removal of pharmaceutical compounds in real, unconditioned wastewater treated by chemically enhanced primary treatment (CEPT). These studies indicate that the coupled treatment can be applied to real, unconditioned wastewater without the need for additional chemical reagents in the EO process. According to Jiménez-Bambague et al. (18), who evaluated the coupled system for EC treatment in real wastewater, removal efficiencies exceeded 80% for compounds belonging to the analgesic/anti-inflammatory, hypolipidemic, and antiepileptic therapeutic groups. The efficiency of the latter group increased by a factor of two to five with the coupled treatment compared to results obtained with High-Rate Algal Lagoons (HRALs). These compounds are hydrophilic and difficult to mineralize through biological processes.

The improved performance of this coupled system is attributed to the fact that 77% of the organic load was removed through biological processes, including ECs eliminated via biodegradation and photodegradation. Consequently, the EO process, using boron-doped diamond (BDD) electrodes, acted as a polishing system, targeting recalcitrant contaminants that are difficult to remove through biological means (17-18). Removal efficiencies were primarily associated with the presence of microalgae and specific removal mechanisms, such as bioaccumulation and biodegradation for diclofenac and biodegradation for ibuprofen (19).

The objective of this review is to explore bioremediation strategies for emerging contaminants (ECs) using constructed wetlands (CWs) and the role of plants in wastewater (WW) phytoremediation. We discuss ECs such as pharmaceuticals, personal care products, pesticides, hormones, perfluoroalkyl substances, and microplastics. CWs are considered a form of “technology coupling” in phytoremediation, and despite being a relatively new technology, they show significant potential as a green alternative for EC management and mitigation. This potential is particularly relevant in tropical regions, where high plant diversity offers opportunities for EC management. However, the

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use of CWs in these areas remains limited due to a lack of studies and the availability of suitable plant species, making plant selection a critical factor in CW implementation.

The methodology involved a bibliographic review using electronic databases from the Universidad del Valle Library, specifically SCOPUS and ScienceDirect (Elsevier). The search was conducted using keywords such as “Emerging Contaminants (EC),” “Constructed Wetlands (CW),” and “Tropical Plants in Phytoremediation.” Additionally, the terms “Pharmaceutical,” “Contaminant,” and “Water” were considered. Publications from the last three years (2021–2023) were prioritized.

Emerging Contaminants (EC)

In recent decades, numerous new substances, both anthropogenic and naturally occurring, have been identified in the aquatic environment, raising growing concerns about their impact on ecosystems and surface waters worldwide. These substances, known as *Emerging Contaminants (ECs)*, are also referred to as micropollutants (MCs), contaminants of emerging concern (CECs), or trace organic compounds (TOCs). Most ECs are organic in nature and typically occur in trace amounts, ranging from parts per trillion (ppt or ng/L) to parts per million (ppm or µg/L) (20). ECs encompass naturally occurring or synthetic substances that are not typically regulated in the environment yet have known or suspected adverse effects on human health and ecosystems. This group includes pharmaceuticals and personal care products (PPCPs), pesticides, and hormones, which can disrupt human and wildlife endocrine systems. As a result, these substances are classified as endocrine-disrupting compounds (EDCs). ECs originating from the pharmaceutical and cosmetic industries, as well as pesticides, fertilizers, and other endocrine-disrupting chemicals, are of significant concern and represent major sources of contamination (1, 21).

Pharmaceutical Products (PP)

The presence of ECs in the environment, particularly in water, is primarily attributed to the discharge of treated wastewater. Conventional secondary treatment processes, such as activated sludge and trickling filters, are not designed to remove ECs, leading to their release into receiving surface waters, including rivers, lakes, and coastal areas (22). The widespread consumption of pharmaceuticals has contributed to their increasing presence in the environment. Due to their persistence and potential harm to aquatic ecosystems, these biologically active compounds are classified into categories such as analgesics, antiseptics, antibiotics, and other chemicals. Major pharmaceutical residues include antibiotics, antidepressants, chemotherapeutic agents, and hormones (4). Approximately 771 active pharmaceutical substances or their transformation products have been detected at concentrations exceeding their respective detection limits, with 528 different compounds identified across 159 countries (23).

Most pharmaceuticals are not highly persistent in the environment. However, their continuous release in small but significant quantities from various sources makes many of them *pseudo-persistent*. Pharmaceuticals encompass a vast group of compounds, with more than 3,000 commonly used pharmaceuticals registered in the European Union alone—a number that continues to grow worldwide. As a result, establishing regulations and guidelines for these compounds, as well as monitoring their distribution in the environment, is a complex and challenging task. This

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challenge is further compounded by the thousands of additional compounds that are registered but not commonly used (24). Legal aspects related to these issues are discussed in Puri et al. (52).

Personal Care Products (PCP)

Personal care products (PCPs) are a diverse group of chemicals used for various purposes, including nutrition, beauty, and hygiene. This category encompasses cosmetics, skincare, hair care, cleaning products, and fragrances. Skincare and personal care products are widely used worldwide (2). Pharmaceuticals and personal care products (PPCPs) in wastewater pose a potential hazard to human health and wildlife, raising concerns among researchers (25). To mitigate the impact of PPCPs, various treatment technologies—such as physical, biological, and chemical methods—have been developed (26). Additionally, ECs, which are commonly found in skincare products, can accumulate to hazardous levels in the environment.

The highest concentrations of ECs have been identified in cosmetics, with ZnO and TiO_2 nanoparticles emerging as the primary potential contaminants. However, other likely ECs found in personal care products include TiO_2 nanoparticles, microplastics, polydimethylsiloxane, UV filters, butylated hydroxytoluene, insect repellents, disinfectants such as triclosan, and fragrance contaminants such as tonalide, phantolide, and galaxolide. Additionally, preservatives like diethyl phthalate, ZnO nanoparticles, benzophenone, octinoxate, methoxycinnamate, and various parabens, including butylparaben, have also been identified as potential ECs (2). The use of macroalgae, microalgae, and aquatic macrophytes has been highlighted for their exceptional bioremediation capacity and ability to acclimate easily to contaminated environments (23). Pharmaceutical and personal care product (PPCP) residues are widely detected in aquatic environments across both industrialized and developing countries, and significant progress has been made in studying their distribution and exposure levels (27).

Pesticides and Fertilizers

Pesticides encompass a broad range of chemical agents designed to control the spread of insects, weeds, and microbes. They are generally classified into four main types: herbicides, fungicides, insecticides, and bactericides. These chemicals enter marine environments primarily through runoff from application sites, and depending on their solubility, they can bioaccumulate in living organisms and plants (2). Herbicides are among the most prevalent contaminants in aquatic systems due to their extensive use in agriculture for weed control. The expansion of agricultural production has led to increased pesticide usage, with a significant portion of these chemicals leaching into soil and water. Consequently, higher pesticide application rates result in elevated concentrations in these environmental matrices. Since agriculture is a major contributor to groundwater contamination due to the widespread use of pesticides, much of the available literature focuses on detecting and analyzing these chemicals in water bodies and irrigation systems (9).

Pesticides are among the most prevalent contaminants found in water samples, with atrazine, organophosphates, organochlorines, and glyphosate being the most commonly detected. Agriculture is the leading cause of soil contamination in Brazil, Argentina, and Colombia, primarily

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due to the excessive use of pesticides and fertilizers, as well as the irrigation of crops with untreated wastewater or contaminated surface water (9).

According to the Inter-American Development Bank (IDB), wastewater treatment plants (WWTPs) represent one of the major environmental challenges in Latin America. A significant portion of industrial wastewater in this region is discharged into the environment without treatment, and most untreated wastewater ultimately enters water bodies (28).

Hormones and Endocrine Disrupting Compounds (EDC)

Steroid hormones belong to a specific class of emerging contaminants (ECs) that have recently received significant attention as endocrine-disrupting chemicals (EDCs). EDCs are a diverse group of molecules that include pharmaceuticals and personal care products (PPCPs), synthetic chemicals used as industrial solvents and lubricants, as well as their by-products, plastics [such as bisphenol A (BPA)], polybrominated biphenyls (PBBs), dioxins, and plasticizers (phthalates) (29). Even at concentrations as low as a few nanograms per liter, EDCs have been shown to be physiologically active and capable of accumulating in the environment, particularly in water. They enter aquatic ecosystems through multiple pathways, including municipal and industrial wastewater, landfills, and nonpoint sources such as agricultural runoff contaminating groundwater (30).

Wastewater treatment plants (WWTPs) discharge a variety of chemicals into the environment. A review (2007–2021) on the occurrence of emerging organic contaminants (EOCs) and EDCs in wastewater, surface water, and groundwater in Mexico identified a total of 174 compounds, including pharmaceuticals, hormones, plasticizers, personal care products, sweeteners, drugs, and pesticides (31). Another study, which used an analytical method to track the fate and transport of organic compounds from WWTPs to rivers, detected 5,783 organic compounds and identified 88 ECs, including 22 EDCs, 12 PPCPs, 12 pesticides, 10 volatile organic compounds (VOCs), 5 persistent organic pollutants (POPs), and 27 other chemicals (5). Additionally, research on influent and effluent samples from WWTPs found pharmaceutical compounds to be the most prevalent (32). These findings highlight the urgent need to redesign conventional WWTPs to minimize EC leakage, preventing their accumulation in environmental compartments where they pose ecological risks (33).

Perfluoroalkylated and polyfluoroalkylated substances (PFAS)

Perfluoroalkylated and polyfluoroalkylated substances (PFASs) are a large family of man-made chemicals characterized by fluorination of all or part of their carbon chain, with a terminal functional group. These pollutants have raised significant concerns due to their high persistence, bioaccumulation, and potential epidemiological impact. The increasing contamination of water sources with PFASs has become a global issue, emphasizing the need for a deeper understanding of their behavior in water and wastewater systems (34). One of the primary concerns regarding PFASs is their high hydrophobicity and the presence of PFAS precursors, which can account for 33% to 63% of the total PFAS concentration in water and wastewater treatment plants (WWTPs) (34). Their high solubility in water and weak adsorption to soil particles facilitate rapid and widespread environmental transport (35). Recently, attention has been drawn to the interaction between PFASs and dissolved organic matter (DOM) derived from soil and water. DOM competes with

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PFASs for adsorption sites on material surfaces, reducing PFAS removal rates or increasing their water solubility. In general, DOM plays a dual role in the adsorption, degradation, and uptake of PFASs by plants, depending on its composition and functional groups (36). The bioaccumulation of PFASs in plants and their associated adverse effects have raised considerable concern (37). High concentrations of PFASs are commonly detected in plants near contaminated sites, including fluorochemical manufacturing facilities, firefighter training grounds, landfills, and wastewater treatment plants. Due to their high-water solubility, PFASs are readily absorbed and translocated within plants, raising interest in their potential biochemical and molecular disruptions (37). Since plants are integral to ecosystems, PFAS uptake and accumulation influence their environmental fate and transport, with significant implications for human health. Therefore, it is crucial to investigate plant-PFAS interactions, particularly the mechanisms governing PFAS bioavailability, uptake, and the factors that influence these processes (35, 38).

Microplastics (MP) and Nanoplastics (NP)

Another emerging concern in the Latin American region is the presence of microplastics (MP) and nanoplastics (NP) in environmental samples. This issue, although relatively new on a global scale, is gaining increasing attention in countries such as Brazil, Mexico, Argentina, and Ecuador. For further information, studies by Tursi et al. (39) on MP, Trevisan et al. (40) on NP, and Mateos-Cárdenas (41) on both MP and NP provide valuable insights. The removal of MP from water remains a significant challenge in mitigating environmental pollution. Traditional water treatment plants—similar to those handling other emerging contaminants (ECs)—are not specifically designed to eliminate MP and have been identified worldwide as a major source of MP discharge into the environment. However, as with other ECs, advanced treatment technologies now offer viable solutions for reducing MP concentrations in water bodies. Several physical, chemical, and biological processes are currently available to treat MP-contaminated water, presenting key opportunities for improving water quality and minimizing environmental impact (39).

Constructed Wetlands (CW)

Pharmaceuticals and personal care products (PPCPs) in the aquatic environment are classified as emerging contaminants (ECs). The use of plant-based aquatic systems, such as constructed wetlands (CWs), for treating these contaminants has been well-documented. The removal of PPCPs in CWs involves a complex interplay of physical, chemical, and biological processes, which are influenced by the design and operational parameters of the system. This review summarizes the efficiency of PPCP removal in plant-based CW systems and highlights recent advancements in understanding the processes, mechanisms, and remediation strategies involved. Conventional wastewater treatment plants (WWTPs) are not specifically designed to remove pharmaceutical compounds, as their primary objective is the elimination of easily degradable or moderately biodegradable substances. As a result, pharmaceuticals are often discharged into surface, groundwater, and coastal waters. While technologies such as ozonation, reverse osmosis, and advanced oxidation processes can effectively reduce pharmaceutical contamination, their high costs limit widespread implementation. Consequently, there is a growing demand for alternative, cost-effective wastewater treatment methods with high removal efficiencies.

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Constructed wetlands (CWs) offer a promising alternative for pharmaceutical removal, utilizing both biotic and physicochemical mechanisms. Biotic processes include microbial degradation, biofilm activity, and uptake by plant roots, while physicochemical processes involve evaporation, photodegradation, oxidation, hydrolysis, and adsorption onto plant roots and the gravel bed. CWs are highly complex systems, creating multiple microenvironments with varying physicochemical conditions that influence these removal mechanisms. These environments—such as pore water, the top layer exposed to sunlight, plant surfaces, biofilm on substrates, and root biofilms—play a crucial role in contaminant breakdown. However, due to this complexity, the exact removal mechanisms in CWs are not yet fully understood.

Constructed Wetlands Configuration

In general, physicochemical parameters such as redox potential and solar exposure in constructed wetlands (CWs) are strongly influenced by the type of flow. Consequently, CWs vary significantly in design, with major configurations including surface flow (SF) and subsurface flow (SSF), as well as horizontal subsurface flow (HSSF) and vertical subsurface flow (VSSF) systems. These configurations differ in media type, depth, and overall treatment efficiency. For example, SSF CWs provide a superior rhizosphere effect and a larger adsorption surface area in the root zone compared to SF CWs, enhancing contaminant removal. Additionally, hybrid systems combine multiple CW types—such as surface, subsurface, horizontal, vertical, and floating flow wetlands—offering tailored treatment solutions based on specific wastewater characteristics.

Constructed Wetland Types and Use of Plants

Constructed wetlands (CWs) are cost-effective, nature-based treatment technologies that have been extensively studied for the removal of pollutants, including organic matter, nutrients (such us nitrogen and phosphorus), as well as pharmaceuticals and personal care products (PPCPs) from wastewater. These artificial systems mimic the functions of natural wetlands, utilizing natural biogeochemical processes to filter and treat water while providing ecological and environmental benefits. CWs typically operate through gravity-driven flow, requiring significantly lower start-up and maintenance costs compared to conventional wastewater treatment plants (WWTPs).

Removal of Contaminants in Constructed Wetlands

Constructed wetlands (CWs) can be classified into different types, including free surface flow (FS), horizontal subsurface flow (HSS), vertical subsurface flow (VSS), floating wetlands (FW), and hybrid systems (Figure 1). Studies comparing pharmaceutical removal efficiencies—targeting compounds such as ibuprofen, naproxen, and diclofenac—between HSS-CWs and conventional wastewater treatment plants (WWTPs) indicate that CWs often outperform WWTPs. However, studies directly comparing CWs and WWTPs for PPCP treatment are limited. Additionally, research on PPCP behavior within CWs and the specific removal mechanisms—particularly the interactions between plants and microbes in PPCP degradation—remains insufficient (25). The following section explores process mechanisms to explain variations in emerging contaminant (EC) removal.

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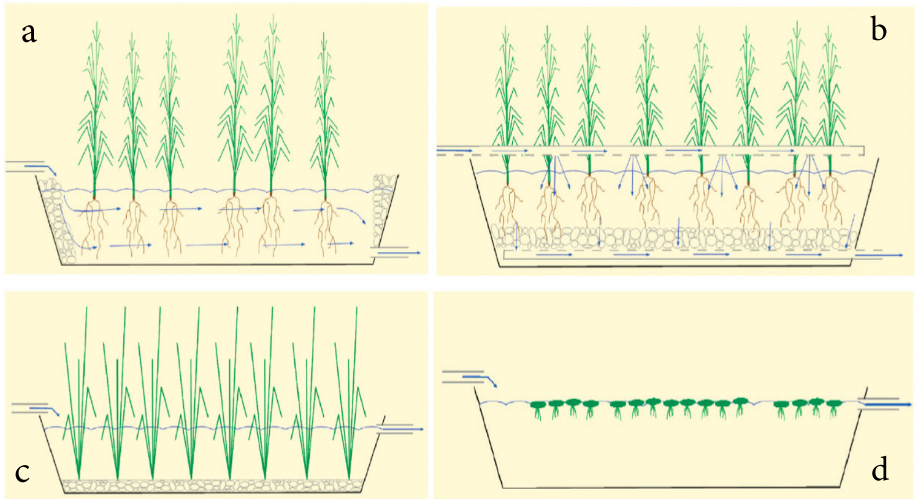

Figure 1. Constructed Wetland of Subsurface flow (a) Horizontal, (b) Vertical,

(c) Superficial flow with Emergent and (d) Floating vegetation.

Pharmaceuticals and Personal Care Products (PPCP)

CWs have gained increasing attention for their high cost-effectiveness and environmental benefits. They are biological wastewater treatment systems that harness natural processes involving vegetation, soils, and microbial assemblages to aid in wastewater treatment. Various technologies have been employed for PPCP removal, including membrane filtration, activated carbon-mediated adsorption, ozonation, and membrane bioreactors (MBRs). However, despite the availability of multiple treatment methods, many PPCP removal technologies suffer from limited efficiency, high construction costs, and expensive long-term maintenance (25, 42, 43).

Recently, interest has grown in the feasibility of using CWs for PPCP removal from wastewater with high efficiency. Studies cited in Salah et al. (44), such as Oliveira et al. (2019), report that a horizontal flow CW containing Eichhornia crassipes removed 89% of ibuprofen (IBU) and 94% of caffeine (CAF). Similarly, Garcia et al. (2020) reported 92% and 98% removal of triclosan (TCS) and diclofenac (DCL) using CWs.

CW removal performance depends on the PPCP species. IBU showed higher removal efficiency (>70 mass %) compared to other PPCPs, such as carbamazepine (CBZ), acesulfame (ACE), diclofenac (DCL), caffeine (CAF), benzotriazole (BTZ), and naproxen (NPX), under the same treatment conditions. Delgado et al. (2020) reported that CBZ exhibited low removal efficiency, likely due to its low biodegradability and limited plant uptake. PPCP removal mechanisms in CWs are complex, involving a combination of chemical, physical, and biological processes such as photodegradation, volatilization, substrate adsorption, precipitation, hydrolysis, microbial degradation, and plant uptake and accumulation. Researchers have attempted to enhance CW performance by optimizing its three key components: plants, substrates, and microorganisms. However, comprehensive reviews and analyses of recent studies on CW-based removal of antibiotics (PPs) and other contaminants (CPs) remain limited (45).

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Therefore, it is necessary to understand the mechanisms of degradation, removal, and retention of PPCPs based on up-to-date statistical information. The application of CWs for PPCP removal is currently gaining attention as a cost-effective secondary treatment system. However, PPCP removal in CWs largely depends on their interactions with substrates, plants, and microbial communities (44). These reviews provide a detailed analysis of PPCP removal potential in CWs, key influencing factors, and critical removal mechanisms (44, 45).

Steroid Hormones (SH)

This section reviews differences in pollutant removal efficiency across four types of constructed wetlands (CWs). Specifically, we examine the removal of steroid hormones in free surface flow (FS), horizontal flow (HF), vertical flow (VF), and hybrid (H) wetlands. The average removal efficiency of 11 steroid hormones (SHs) ranged from 55% to 100%. For most steroid hormones, biodegradation (aerobic and/or anaerobic) is the primary removal mechanism, followed by plant sorption and substrate adsorption. The physicochemical properties of SHs also influence their removal (42). Among the four CW types studied, VF demonstrated the highest removal efficiency, followed by HF, hybrid systems, and FS wetlands. VF CWs outperformed HF CWs due to the higher efficiency of aerobic biodegradation over anaerobic processes. Several SHs, such as 17α-ethinylestradiol, estriol, progesterone, and testosterone, degrade more effectively under aerobic conditions.

Plants and the supporting matrix, along with key design and operational factors—such as area, depth, hydraulic loading rate, hydraulic retention time, and organic loading rate—also influence removal efficiency. Additionally, physicochemical parameters, including effluent dissolved oxygen, temperature, and pH, play a crucial role (42). Therefore, selecting the appropriate CW type, optimizing design and implementation, and considering the physicochemical properties of target compounds are crucial for effective treatment.

As discussed, CWs represent a sustainable and effective alternative for removing emerging contaminants (ECs). However, a thorough understanding of removal mechanisms—including biodegradation, substrate adsorption, and macrophyte uptake—is essential for optimizing CW performance. CW design and operational parameters significantly impact removal efficiency.

Therefore, analyzing design processes and removal mechanisms under different operating conditions is crucial, with a focus on macrophyte types, microbial communities, and substrate variations to determine optimal conditions. In addition to these factors, CW performance is also influenced by substrate surface area, wastewater characteristics, and the physicochemical properties of contaminants. Kamilya et al. (45) discusses the removal of steroids and antibiotics in CW systems, highlighting key factors that affect removal efficiency.

Beyond understanding macrophytes, microorganisms, and substrates, it is also essential to analyze the removal processes and mechanisms involved in CWs. Furthermore, a fundamental aspect of CW optimization is analyzing removal processes such as photodegradation, biodegradation, phytoremediation, and adsorption, which interact in a complex manner (45).

This review consolidates current knowledge on CW-based removal of emerging contaminants (ECs) from wastewater. CW removal mechanisms include biotic processes—such as microbial

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degradation, biofilm formation, and plant uptake—and physicochemical processes, including evaporation, photodegradation, oxidative hydrolysis, and root adsorption onto the substrate. Together with influencing factors, these mechanisms provide a comprehensive framework for optimizing pharmaceutical and EC removal in CWs. However, due to the complex interactions between biotic and physicochemical processes, CW removal mechanisms are not yet fully understood.

Phytoremediation and Species Selection

Phytoremediation

In plants, various phytoremediation strategies—such as extraction, degradation, stabilization, volatilization, and bioconcentration—have been described, along with physiological, biochemical, and cellular mechanisms involved in contaminant mitigation (e.g., metals). An intriguing question is whether these mechanisms could also be applied to emerging contaminants (ECs). This remains a developing area of scientific interest, particularly regarding the use of tropical plant species in CWs.

Another emerging research focus in CWs is the role of ‘direct’ phyto-degradation mechanisms in plants, which appear to play a lesser role compared to ‘indirect’ mechanisms, such as microbial interactions on plant roots in wetlands. It is estimated that ‘direct’ mechanisms account for less than 20% of EC removal in CWs (46). These mechanisms include PPCP precipitation on root surfaces, iron plaque formation, and direct plant uptake and degradation. In contrast, ‘indirect’ effects play a more significant role, enhancing PPCP removal through increased rhizosphere microbial activity—more than twice that of soil—stimulated by radial oxygen loss, exudate secretions, and the formation of supramolecular assemblages between PPCPs and humic acids from decomposing plant material, which can improve PPCP removal efficiency by up to fourfold.

To fully understand the internal mechanisms of PPCP removal by plants in CWs, it is essential to review the factors influencing plant performance and efficiency in phytoremediation. Identifying and analyzing these factors has been recognized as a critical area for future research (46).

Phytoremediation and use of tropical species: Colocasia esculenta **(Araceae)**

One objective of this review is to expand the inventory of plant species suitable for phytoremediation in CWs (Table 1). Recent literature reviews show a lower representation of plant species, particularly those native to Latin America and Colombia.

A pioneering study on phytoremediation using tropical plants was conducted on a pilot scale in CWSS with three species: Gynerium sagittatum, Colocasia esculenta, and Heliconia psittacorum (47). These plants demonstrated suitability for phytoremediation of landfill leachate and were classified as Cr (VI) accumulators. Moreover, CWs proved to be a cost-effective secondary treatment system for intermediate landfill leachate (47).

Table 1. Families and genera distributed in Colombia that may be considered for review as tropical plant species with potential phytoremediation applications in Constructed Wetlands (CWs).

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Pteridaceae Acrostichum aureum L.	https://colplanta.org/taxon/urn:lsid:ipni.org:names:30007207-2
Cyperacea Fimbristylis spp. Vahl	https://colplanta.org/taxon/urn:lsid:ipni.org:names:30000197-2
Heliconiaceae Heliconia spp. L.	https://colplanta.org/taxon/urn:lsid:ipni.org:names:77126726-1
Onagraceae Ludwigia spp. L.	https://colplanta.org/taxon/urn:lsid:ipni.org:names:30000053-2
Poaceae Phragmites australis (Cav.) Trin.	https://colplanta.org/taxon/urn:lsid:ipni.org:names:30337627-2
Pontederia Pontederia azurea Sw.	https://colplanta.org/taxon/urn:lsid:ipni.org:names:30000882-2
Araceae Colocasia esculenta (L.) Schott	https://colplanta.org/taxon/urn:lsid:ipni.org:names:1170772-2

Examples of tropical plant species with potential use in phytoremediation are described below:

Acrostichum aureum is a common fern found in tropical and subtropical regions. While it has potential for research in removing emerging pollutants, its classification as a halophyte (salt-tolerant and adapted to intertidal environments) limits its use in CW systems. Studies indicate that it cannot withstand prolonged waterlogging (several days to weeks), which would keep its roots submerged. The role of halophytes in treating saline wastewater in Latin America is discussed in Turcios et al. (48).

Phragmites australis is a plant with a distribution restricted to Latin America and is commonly studied for its potential use in phytoremediation. Similarly, Pontederia azurea Sw., also known as Eichhornia spp. and commonly referred to as 'Buchón,' is a floating plant frequently examined in phytoremediation research. Figure 2.

Figure 2. Colocasia esculenta (L.) Schott (Family: Araceae) is commonly known as Taro, Papa China, and Malanga. Several Colocasia species have potential applications in phytoremediation within CW (49).

Colocasia esculenta has a worldwide distribution (cosmopolitan), though its native range extends from India to southern China and Sumatra. It is a tuberous geophyte found in tropical climates, with multiple environmental, economic, and social applications. It serves as both animal feed (corm) and a medicinal and dietary resource for humans.

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The selection of this species for ongoing experiments and tests in a current project is based not only on its natural availability (easily found in nurseries) but also on its global significance in agro-food culture—particularly in Asia—and its cultivation in the Colombian Pacific.

Species of the genus Colocasia sp., which have a cosmopolitan distribution not only in the tropics (including Africa, the Mediterranean, Asia, and Oceania), were the most widely cultivated food crops worldwide before the Columbian Exchange (the transfer of food crops between the Americas and the Old World) (49). https://colombia.inaturalist.org/taxa/122835-Colocasia-esculenta

The significance of research in EC, CWs and phytoremediation is evident in an analysis of nearly 700 research papers published in 2019 and 2020. These studies, indexed in the Web of Science under the keyword "constructed wetlands for wastewater treatment," include 132 papers focusing on emerging topics such as CW-treated wastewater, filtration materials, vegetation roles, floating wetlands for treatment, CW microbiology, greenhouse gas emissions, and the sustainability and co-benefits of CWs. This analysis highlights the growing popularity and diversification of CWs, as well as the need for further research on process-properties relationships in CW design and implementation. However, long-term CW studies remain scarce, and to advance CW technology, research should also be conducted under large-scale field conditions (50).

A review of articles from PubChem, ScienceDirect, the National Center for Biotechnology Information (NCBI), and Web of Science (2012–2022) examines global legislation and policies on emerging contaminants (ECs). This state-of-the-art review evaluates ECs and the regulatory frameworks adopted by both developed and developing countries to mitigate EC release and promote water sustainability. Key aspects include water availability, usage patterns, pollution generation and management, aquatic system health, and social vulnerability.

The objective is to provide a comprehensive overview of current global policies and frameworks for assessing and regulating chemicals that pose environmental and biological threats. Additionally, the review highlights future global perspectives, including ongoing governmental initiatives, emerging policy measures, and recommendations for improving the management and disposal of ECs in the environment (51).

Conclusions

Emerging contaminants (ECs) in the aquatic environment pose significant risks to ecosystems and human health. The inability of conventional wastewater treatment plants (WWTPs) to effectively remove ECs underscores the need for alternative, cost-effective, and environmentally friendly treatment methods. This review examines the presence of ECs in aquatic environments and explores the use of plants in constructed wetlands (CWs) as phytoremediation strategies. Findings indicate that CWs are a sustainable and effective alternative, with key removal mechanisms—including biodegradation, substrate adsorption, and macrophyte uptake—playing a crucial role in eliminating recalcitrant ECs.

Additionally, the design and operational conditions of CWs significantly impact phytoremediation efficiency. Reviews focusing on this topic (52) analyze various ECs, the design factors affecting CW removal mechanisms, and the role of sewage phytoremediation as a global bioremediation strategy.

CRediT authorship contribution statemen

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References

1. Rathi BS, Kumar PS, Show P-L. A review on effective removal of emerging contaminants from aquatic systems: Current trends and scope for further research. J Hazard Mater. 2021; 409 (124413):124413. Disponible en: http://dx.doi.org/10.1016/j.jhazmat.2020.124413

2. Khan S, Naushad M, Govarthanan M, Iqbal J, Alfadul SM. Emerging contaminants of high concern for the environment: Current trends and future research. Environ Res. 2022; 207 (112609):112609. Disponible en: http://dx.doi.org/10.1016/j.envres.2021.112609

3. Pal A, Gin KY-H, Lin AY-C, Reinhard M. Impacts of emerging organic contaminants on freshwater resources: review of recent occurrences, sources, fate and effects. Sci Total Environ. 2010; 408 (24): 6062–9. Disponible en: http://dx.doi.org/10.1016/j.scitotenv.2010.09.026

4. Goutam Mukherjee A, Ramesh Wanjari U, Eladl MA, El-Sherbiny M, Elsherbini DMA, Sukumar A, et al. Mixed contaminants: Occurrence, interactions, toxicity, detection, and remediation. Molecules. 2022; 27 (8):2577. Disponible en: http://dx.doi.org/10.3390/molecules27082577

5. Zhang Q, Xu H, Song N, Liu S, Wang Y, Ye F, et al. New insight into fate and transport of organic compounds from pollution sources to aquatic environment using non-targeted screening: A

doi: 10.25100/iyc.v27i1.13470

wastewater treatment plant case study. Sci Total Environ. 2023; 863 (161031):161031. Disponible en: http://dx.doi.org/10.1016/j.scitotenv.2022.161031

6. Sharma R, Malaviya P. Constructed wetlands for textile wastewater remediation: A review on concept, pollutant removal mechanisms, and integrated technologies for efficiency enhancement. Chemosphere. 2022; 290 (133358):133358. Disponible en: http://dx.doi.org/10.1016/j.chemosphere.2021.133358

7. Llorca M, Farré M, Eljarrat E, Díaz-Cruz S, Rodríguez-Mozaz S, Wunderlin D, et l. Review of emerging contaminants in aquatic biota from Latin America: 2002-2016. Environ Toxicol Chem. 2017; 36 (7):1716–27. Disponible en: http://dx.doi.org/10.1002/etc.3626

8. Peña-Guzmán C, Ulloa-Sánchez S, Mora K, Helena-Bustos R, Lopez-Barrera E, Alvarez J, et al. Emerging pollutants in the urban water cycle in Latin America: A review of the current literature. J Environ Manage. 2019; 237:408–23. Disponible en: http://dx.doi.org/10.1016/j.jenvman.2019.02.100

9. Souza MCO, Rocha BA, Adeyemi JA, Nadal M, Domingo JL, Barbosa F Jr. Legacy and emerging pollutants in Latin America: A critical review of occurrence and levels in environmental and food samples. Sci Total Environ. 2022; 848 (157774):157774. Disponible en: http://dx.doi.org/10.1016/j.scitotenv.2022.157774

10. Okoye CO, Okeke ES, Okoye KC, Echude D, Andong FA, Chukwudozie KI, et al. Occurrence and fate of pharmaceuticals, personal care products (PPCPs) and pesticides in African water systems: A need for timely intervention. Heliyon. 2022; 8 (3):e09143. Disponible en: http://dx.doi.org/10.1016/j.heliyon.2022.e09143

11. Shehu Z, Nyakairu GWA, Tebandeke E, Odume ON. Overview of African water resources contamination by contaminants of emerging concern. Sci Total Environ. 2022; 852 (158303):158303. Disponible en: http://dx.doi.org/10.1016/j.scitotenv.2022.158303

12. Yang Y, Ok YS, Kim K-H, Kwon EE, Tsang YF. Occurrences and removal of pharmaceuticals and personal care products (PPCPs) in drinking water and water/sewage treatment plants: A review. Sci Total Environ. 2017; 596–597:303–20. Disponible en: http://dx.doi.org/10.1016/j.scitotenv.2017.04.102

13. Zhang D, Gersberg RM, Ng WJ, Tan SK. Removal of pharmaceuticals and personal care products in aquatic plant-based systems: a review. Environ Pollut. 2014; 184: 620–39. Disponible en: http://dx.doi.org/10.1016/j.envpol.2013.09.009

14. Gorito AM, Ribeiro AR, Almeida CMR, Silva AMT. A review on the application of constructed wetlands for the removal of priority substances and contaminants of emerging concern listed in recently launched EU legislation. Environ Pollut. 2017; 227:428–43. Disponible en: http://dx.doi.org/10.1016/j.envpol.2017.04.060

15. Wang Y, Cai Z, Sheng S, Pan F, Chen F, Fu J. Comprehensive evaluation of substrate materials for contaminants removal in constructed wetlands. Sci Total Environ. 2020; 701 (134736):134736. Disponible en: http://dx.doi.org/10.1016/j.scitotenv.2019.134736

16. Jiménez-Bambague EM, Madera-Parra CA, Ortiz-Escobar AC, Morales-Acosta PA, Peña-Salamanca EJ, Machuca-Martínez F. High-rate algal pond for removal of pharmaceutical compounds from urban domestic wastewater under tropical conditions. Case study: Santiago de Cali, Colombia. Water Sci Technol. 2020; 82 (6):1031–43. Disponible en: http://dx.doi.org/10.2166/wst.2020.362

17. Jiménez-Bambague EM, Madera-Parra CA, Rangel-Delgado MF. Photo-Fenton and Electro-Fenton Performance for the Removal of Pharmaceutical Compounds in Real urban wastewater, Electrochim. Electrochim Acta. 2023; 442, 141905. Disponible en: http://doi.org/10.1016/j.electacta.2023.141905

doi: 10.25100/iyc.v27i1.13470

18. Jiménez-Bambague EM, Villarreal-Arias DS, Ramírez-Vanegas OD, Gómez-Gómez DD, Madera-Parra CA, Peña-Salamanca EJ, et al. Removal of pharmaceutical compounds from real urban wastewater by a continuous bio-electrochemical process at pilot scale. J Environ Chem Eng. 2023; 11 (3):110130. Disponible en: http://dx.doi.org/10.1016/j.jece.2023.110130

19. Jiménez-Bambague EM, Florez-Castillo JS, Gómez-Angulo RD, Morales-Acosta PA, Peña-Salamanca EJ, Machuca-Martínez F, et al. Cell growth and removal capacity of ibuprofen and diclofenac by Parachlorella kessleri at bench scale. J Chem Technol Biotechnol. 2022; 97 (6):1416–23. Disponible en: http://dx.doi.org/10.1002/jctb.6911

20. Rodriguez-Narvaez OM, Peralta-Hernandez JM, Goonetilleke A, Bandala ER. Treatment technologies for emerging contaminants in water: A review. Chem Eng J. 2017; 323:361–80. Disponible en: http://dx.doi.org/10.1016/j.cej.2017.04.106

21. Bilal M, Adeel M, Rasheed T, Zhao Y, Iqbal HMN. Emerging contaminants of high concern and their enzyme-assisted biodegradation - A review. Environ Int. 2019; 124:336–53. Disponible en: http://dx.doi.org/10.1016/j.envint.2019.01.011

22. Petrie B, Barden R, Kasprzyk-Hordern B. A review on emerging contaminants in wastewaters and the environment: current knowledge, understudied areas and recommendations for future monitoring. Water Res. 2015; 72:3–27. Disponible en: http://dx.doi.org/10.1016/j.watres.2014.08.053

23. Couto E, Assemany PP, Assis Carneiro GC, Ferreira Soares DC. The potential of algae and aquatic macrophytes in the pharmaceutical and personal care products (PPCPs) environmental removal: a review. Chemosphere. 2022; 302 (134808):134808. Disponible en: http://dx.doi.org/10.1016/j.chemosphere.2022.134808

24. Patel M, Kumar R, Kishor K, Mlsna T, Pittman CU Jr, Mohan D. Pharmaceuticals of emerging concern in aquatic systems: Chemistry, occurrence, effects, and removal methods. Chem Rev. 2019; 119 (6):3510–673. Disponible en: http://dx.doi.org/10.1021/acs.chemrev.8b00299

25. AL Falahi OA, Abdullah SRS, Hasan HA, Othman AR, Ewadh HM, Kurniawan SB, et al. Occurrence of pharmaceuticals and personal care products in domestic wastewater, available treatment technologies, and potential treatment using constructed wetland: A review. Process Saf Environ Prot. 2022; 168:1067–88. Disponible en: http://dx.doi.org/10.1016/j.psep.2022.10.082

26. Kumar M, Sridharan S, Sawarkar AD, Shakeel A, Anerao P, Mannina G, et al. Current research trends on emerging contaminants pharmaceutical and personal care products (PPCPs): A comprehensive review. Sci Total Environ. 2023; 859 (Pt 1):160031. Disponible en: http://dx.doi.org/10.1016/j.scitotenv.2022.160031

27. Hawash HB, Moneer AA, Galhoum AA, Elgarahy AM, Mohamed WAA, Samy M, et al. Occurrence and spatial distribution of pharmaceuticals and personal care products (PPCPs) in the aquatic environment, their characteristics, and adopted legislations. J Water Proc.engineering. 2023; 52 (103490):103490. Disponible en: http://dx.doi.org/10.1016/j.jwpe.2023.103490

28. Inter-American Development Bank (IDB)- A partner for Latin America and the Caribbean. 2018.

29. Diamanti-Kandarakis E, Bourguignon J-P, Giudice LC, Hauser R, Prins GS, Soto AM, et al. Endocrine-disrupting chemicals: an Endocrine Society scientific statement. Endocr Rev. 2009; 30 (4):293–342. Disponible en: http://dx.doi.org/10.1210/er.2009-0002

30. Kumar R, Qureshi M, Vishwakarma DK, Al-Ansari N, Kuriqi A, Elbeltagi A, et al. A review on emerging water contaminants and the application of sustainable removal technologies. Case Studies in Chemical and Environmental Engineering. 2022; 6 (100219):100219. Disponible en: http://dx.doi.org/10.1016/j.cscee.2022.100219

31. Vázquez-Tapia I, Salazar-Martínez T, Acosta-Castro M, Meléndez-Castolo KA, Mahlknecht J, Cervantes-Avilés P, et al. Occurrence of emerging organic contaminants and endocrine disruptors in different water compartments in Mexico - A review. Chemosphere. 2022; 308 (Pt 1):136285. Disponible en: http://dx.doi.org/10.1016/j.chemosphere.2022.136285

doi: 10.25100/iyc.v27i1.13470

32. Ulucan-Altuntas K, Manav-Demir N, Ilhan F, Gelgor HB, Huddersman K, Tiwary A, et al. Emerging pollutants removal in full-scale biological treatment plants: A case study. J Water Proc.engineering. 2023; 51 (103336):103336. Disponible en: http://dx.doi.org/10.1016/j.jwpe.2022.103336

33. Kasonga TK, Coetzee MAA, Kamika I, Ngole-Jeme VM, Benteke Momba MN. Endocrine-disruptive chemicals as contaminants of emerging concern in wastewater and surface water: A review. J Environ Manage. 2021; 277 (111485):111485. Disponible en: http://dx.doi.org/10.1016/j.jenvman.2020.111485

34. Phong Vo HN, Ngo HH, Guo W, Hong Nguyen TM, Li J, Liang H, et al. Poly‐and perfluoroalkyl substances in water and wastewater: A comprehensive review from sources to remediation. J Water Proc.engineering. 2020; 36 (101393):101393. Disponible en: http://dx.doi.org/10.1016/j.jwpe.2020.101393

35. Adu O, Ma X, Sharma VK. Bioavailability, phytotoxicity and plant uptake of per-and polyfluoroalkyl substances (PFAS): A review. J Hazard Mater. 2023; 447 (130805):130805. Disponible en: http://dx.doi.org/10.1016/j.jhazmat.2023.130805

36. Qi Y, Cao H, Pan W, Wang C, Liang Y. The role of dissolved organic matter during Per- and Polyfluorinated Substance (PFAS) adsorption, degradation, and plant uptake: A review. J Hazard Mater. 2022; 436 (129139):129139. Disponible en: http://dx.doi.org/10.1016/j.jhazmat.2022.129139

37. Li J, Sun J, Li P. Exposure routes, bioaccumulation and toxic effects of per- and polyfluoroalkyl substances (PFASs) on plants: A critical review. Environ Int. 2022; 158 (106891):106891. Disponible en: http://dx.doi.org/10.1016/j.envint.2021.106891

38. Kavusi E, Shahi Khalaf Ansar B, Ebrahimi S, Sharma R, Ghoreishi SS, Nobaharan K, et al. Critical review on phytoremediation of polyfluoroalkyl substances from environmental matrices: Need for global concern. Environ Res. 2023; 217 (114844):114844. Disponible en: http://dx.doi.org/10.1016/j.envres.2022.114844

39. Tursi A, Baratta M, Easton T, Chatzisymeon E, Chidichimo F, De Biase M, et al. Microplastics in aquatic systems, a comprehensive review: origination, accumulation, impact, and removal technologies. RSC Adv. 2022 [citado el 3 de febrero de 2025];12 (44):28318–40. Disponible en: https://pubs.rsc.org/en/content/articlehtml/2022/ra/d2ra04713f

40. Trevisan R, Ranasinghe P, Jayasundara N, Di Giulio RT. Nanoplastics in aquatic environments: Impacts on aquatic species and interactions with environmental factors and pollutants. Toxics. 2022; 10 (6):326. Disponible en: http://dx.doi.org/10.3390/toxics10060326

41. Mateos-Cárdenas A, van Pelt FNAM, O'Halloran J, Jansen MAK. Adsorption, uptake and toxicity of micro- and nanoplastics: Effects on terrestrial plants and aquatic macrophytes. Environ Pollut. 2021; 284 (117183):117183. Disponible en: http://dx.doi.org/10.1016/j.envpol.2021.117183

42. Ilyas H, van Hullebusch ED. Performance comparison of different types of constructed wetlands for the removal of pharmaceuticals and their transformation products: a review. Environ Sci Pollut Res Int. 2020; 27 (13):14342–64. Disponible en: http://dx.doi.org/10.1007/s11356-020-08165-w

43. Lv M, Zhang D, Niu X, Ma J, Lin Z, Fu M. Insights into the fate of antibiotics in constructed wetland systems: Removal performance and mechanisms. J Environ Manage. 2022; 321 (116028):116028. Disponible en: http://dx.doi.org/10.1016/j.jenvman.2022.116028

44. Salah M, Zheng Y, Wang Q, Li C, Li Y, Li F. Insight into pharmaceutical and personal care products removal using constructed wetlands: A comprehensive review. Sci Total Environ. 2023; 885 (163721):163721. Disponible en: http://dx.doi.org/10.1016/j.scitotenv.2023.163721

45. Kamilya T, Yadav MK, Ayoob S, Tripathy S, Bhatnagar A, Gupta AK. Emerging impacts of steroids and antibiotics on the environment and their remediation using constructed wetlands: A critical review. Chem Eng J. 2023; 451 (138759):138759. Disponible en: http://dx.doi.org/10.1016/j.cej.2022.138759

doi: 10.25100/iyc.v27i1.13470

46. Hu X, Xie H, Zhuang L, Zhang J, Hu Z, Liang S, et al. A review on the role of plant in pharmaceuticals and personal care products (PPCPs) removal in constructed wetlands. Sci Total Environ. 2021; 780 (146637):146637. Disponible en: http://dx.doi.org/10.1016/j.scitotenv.2021.146637

47. Madera-Parra CA, Peña MR, Peña EJ, Lens PNL. Cr(VI) and COD removal from landfill leachate by polyculture constructed wetland at a pilot scale. Environ Sci Pollut Res Int. 2015; 22 (17):12804–15. Disponible en: http://dx.doi.org/10.1007/s11356-014-3623-z

48. Turcios AE, Miglio R, Vela R, Sánchez G, Bergier T, Włodyka-Bergier A, et al. From natural habitats to successful application - Role of halophytes in the treatment of saline wastewater in constructed wetlands with a focus on Latin America. Environ Exp Bot. 2021; 190 (104583):104583. Disponible en: http://dx.doi.org/10.1016/j.envexpbot.2021.104583

49. Ahmed I, Lockhart PJ, Agoo EMG, Naing KW, Nguyen DV, Medhi DK, et al. Evolutionary origins of taro (Colocasia esculenta) in Southeast Asia. Ecol Evol. 2020; 10 (23):13530–43. Disponible en: http://dx.doi.org/10.1002/ece3.6958

50. Zhang H, Wang XC, Zheng Y, Dzakpasu M. Removal of pharmaceutical active compounds in wastewater by constructed wetlands: Performance and mechanisms. J Environ Manage. 2023; 325 (Pt A):116478. Disponible en: http://dx.doi.org/10.1016/j.jenvman.2022.116478

51. Vymazal J, Zhao Y, Mander Ü. Recent research challenges in constructed wetlands for wastewater treatment: A review. Ecol Eng. 2021; 169 (106318):106318. Disponible en: http://dx.doi.org/10.1016/j.ecoleng.2021.106318

52. Puri M, Gandhi K, Kumar MS. Emerging environmental contaminants: A global perspective on policies and regulations. J Environ Manage. 2023; 332 (117344):117344. Disponible en: http://dx.doi.org/10.1016/j.jenvman.2023.117344

doi: 10.25100/iyc.v27i1.13470