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Removal of antibiotics in constructed wetlands: a review and bibliometric analysis

VALDEMIR F. DA SILVA & DELMIRA BEATRIZ WOLFF

Abstract: This study offers a comprehensive systematic review on the removal of antibiotics in Constructed Wetlands (CWs), evaluating their efficacy as an alternative to conventional wastewater treatment methods. Data from 82 articles were analyzed, focusing on removal rates, antibiotic types, and system configurations, including scale, vegetation, sediment, flow, hydraulic retention time (HRT), and hydraulic loading rate (HLR). The findings indicate that full-scale CWs, particularly those utilizing vegetation like Cyperus alternifolius L. and materials such as shells, zeolites, medicinal stone, and ceramics, achieved removal rates exceeding 90% for various antibiotics. The study underscores the importance of optimizing both anaerobic and aerobic conditions to enhance removal efficiency, noting that aerobic environments promote oxidative processes effective for β-lactams, while anaerobic environments facilitate reduction processes beneficial for sulfonamides. Hybrid systems combining these zones demonstrated maximal removal efficiency. This review advances the understanding of antibiotic removal in CWs, presenting them as a viable, sustainable solution to mitigate environmental impacts, preserve water quality, and protect public health. Further research is recommended to explore the impact of root types and bed configurations on removal efficiency.

Key words: emerging pollutants, environmental remediation, pharmaceuticals, pollutant degradation, wastewater treatment.

INTRODUCTION

Human development over millennia has positioned humans as dominant in the biosphere, evolving complex social structures and technological advancements that have significantly impacted the global environment. This progress, however, has increased pollution and led to the degradation of critical natural resources like soil and water, often accelerated by the incorrect disposal of pollutants such as pharmaceutical products, which resist conventional treatment methods (Kümmerer 2001, Desai et al. 2022).

The presence of pharmaceuticals in water bodies raises significant environmental and public health concerns, emphasizing the need for more advanced and effective water treatment systems to manage these emerging contaminants (Kümmerer 2001, Costa et al. 2014, Bila & Dezotti 2003, Senta et al. 2013, Bound & Voulvoulis 2004, Gorito et al. 2017). According to WPR (2024), Brazil is ranked as the eighth largest pharmaceutical market in the world in 2024, with total drug sales estimated at approximately $28.2 billion a significant 17.7% increase from the previous year. This ongoing development of Brazil as a key player in the global pharmaceutical industry, driven by rising demand and increased access to medications, necessitates heightened attention to mitigating the resulting environmental impacts.

Antibiotics, crucial among these medicines, are a primary concern for the scientific community. When looking at the classification of antibiotics, it can be seen that the most commonly used are natural and semi-synthetic types, including β-lactams (penicillins, cephalosporins, carbapenems, oxapenems, and monobactams), tetracyclines, aminoglycosides, macrolides, and cyclic peptides (glycopeptides, lipodepsipeptides), along with streptogramins, lincosamides, chloramphenicol, and rifamycins. There are also synthetic antibiotics that are used less frequently, such as sulfonamides, fluoroquinolones, and oxazolidinones (Abraham 2003, Patrick 2005, Pupo et al. 2006). The widespread use of these antibiotics, coupled with their varying degrees of environmental persistence and modes of action, highlights the complexity of managing their impact on public health and ecosystems.

The removal of antibiotics in constructed wetlands can be significantly influenced by the redox conditions of the environment. Aerobic environments, characterized by high oxygen availability, favor degradation processes such as oxidation, which can be effective for antibiotics like β-lactams. In contrast, anaerobic environments, which have low or no oxygen availability, favor processes like reduction, which can be more effective for antibiotics like sulfonamides. Studies show that the combination of aerobic and anaerobic zones in hybrid systems can maximize the removal of a wide range of antibiotics (Verlicchi & Zambello 2014, Matamoros et al. 2012).

Antibiotics, designed for potency and resistance, retain their chemical properties to fulfill therapeutic purposes, yet only 10 to 20% of each dose is absorbed by the human body. The remainder is excreted into the environment through feces and urine, contributing to significant environmental contamination (Senta et al. 2013). This excretion leads to substantial drug residues entering sewage systems and natural water bodies, burdening sewage treatment plants which often lack the capacity to effectively remove these compounds, thereby raising pollution levels (Bila, Dezotti 2003, Bound & Voulvoulis 2004, Senta et al. 2013, Gorito et al. 2017, Alam et al. 2021).

The World Health Organization's 2022 Global Antimicrobial Resistance and Use Surveillance System (GLASS) report reveals escalating resistance in sepsis-causing bacteria and common infections, enhanced by the COVID-19 pandemic. Furthermore, research indicates a 21% increase in antibiotic dispensing during the pandemic (dos Santos et al. 2023), reinforcing the link between antibiotic use and rising microbial resistance, a critical threat to both environmental biodiversity and human health due to the scarcity of new antibiotics (Dalmolin et al. 2022).

The WHO reports a severe global shortage of new antibiotics, noting that none of the 43 drugs currently in development effectively counteract resistance in the most perilous bacteria, many of these drugs are simply modifications of older classes from the 1980s, which could compromise treatment and pose a significant health threat globally (WHO 2020a).

Despite the increase in the search for awareness and control over the use of antibiotics, studies carried out in Portugal show that consumption rates are still high, leading to an increase in the resistance of Gram-positive and Gram-negative bacteria, enhanced by inappropriate antibiotic use (Loureiro et al. 2016). In southern Brazil, studies have identified antibiotic-resistant bacteria and enterotoxins in the Dilúvio stream, which flows into Lake Guaíba, a major water source for Porto Alegre used for recreational activities, highlighting risks from environmental pollution and inadequate sanitation (Basso et al. 2014). Low-and middle-income countries with lower testing coverage reported higher rates of antimicrobial resistance (AMR) (WHO 2022).

Moreover, the environmental role in spreading AMR is increasingly recognized as a severe public health threat. Recent antibiotics are losing effectiveness due to rising antibiotic resistance genes (ARGs), leading to higher mortality, extended hospital stays, and increased healthcare costs (Gashe et al. 2018, Koulenti et al. 2020, Friedman et al. 2016, Flach et al. 2024).

The massive and often unregulated use of antibiotics in both humans and animals has increasingly led to the emergence of antibiotic-resistant bacteria (ARB) and antibiotic resistance genes (ARGs). The persistence of these antibiotics in the environment not only contributes to the development of resistance but also necessitates a closer examination of the types and uses of antibiotics that are most prevalent.

The misuse of antibiotics exacerbates public health issues by increasing bacterial resistance and spreading resistant bacteria and ARGs via industrial effluents and wastewater treatment plants, intensifying soil and water pollution (Denyer et al. 2011, Klein et al. 2018, Jelić et al. 2012, Rodríguez-Mozaz et al. 2015). In addition, antibiotics act as endocrine disruptors, impacting both human health and environmental quality (Ebele et al. 2017). Highlighting the need for effective removal strategies in both aquatic and terrestrial environments (Barbosa et al. 2016, Derakhsheshpoor et al. 2013).

The proliferation of antibiotic resistance genes is hastened by environmental antibiotic exposure, making pathogens less sensitive (Gallego-Maldonado et al. 2018, WHO 2023). Inadequate antibiotic use, subpar water treatment, and poor hygiene contribute to resistance, particularly in medications for urinary tract infections and certain diarrheas (Monteiro et al. 2020, WHO 2020b).

The WHO also notes significant variations in resistance levels, reinforcing the urgency of enhancing health practices and education. This resistance arises partly due to the disposal of antibiotics and their residues into the environment or through ineffective effluent treatment systems that fail to adequately remove these contaminants (Burch et al. 2014). Furthermore, the misuse of antibiotics and lack of proper guidance could result in approximately 10 million deaths annually by 2050 if corrective measures are not implemented (WHO 2020c, Miranda et al. 2020, Arancibia 2019).

To address this scenario, different techniques for removing antibiotics from aquatic environments have been evaluated, various methods for removing antibiotics from water have been assessed, including physicochemical, biological, and advanced processes like adsorption on activated carbon, advanced oxidation, nanofiltration, reverse osmosis, and biological treatment, achieving removal rates of 80 to 100% (Huang et al. 2022, Battak et al. 2022, Ilurdoz et al. 2022).

Various studies highlight the effectiveness of countless wastewater treatment techniques in removing antibiotics and other contaminants. Carballa et al. (2004) reported removal efficiencies of 40% to 90% for different pharmaceuticals using aerobic activated sludge in Spain. Similarly, Watkinson et al. (2007) in Australia noted an 87% reduction in antibiotics using a conventional activated sludge system. In France, Dinh et al. (2017) observed significant reductions in antibiotic concentrations at a WWTP, with decreases ranging from 10% to 86% for different antibiotics.

Activated charcoal has proven particularly effective, achieving antibiotic removal rates of 76% to over 99% depending on the compound, while biochar and nanotubes showed varying effectiveness (Rodriguez-Narvaez et al. 2017). Beyond these, techniques such as automated solid phase extraction, UHPLC-MS, biodegradation, adsorption, coagulation, membrane filtration, reverse osmosis, and advanced methods like photolysis, hydrolysis, and advanced oxidation are used, with removal efficiencies often exceeding 90% (Mthiyane et al. 2023, Tang et al. 2022, Gupta et al. 2022, Safaei et al. 2023, Zheng et al. 2022). These studies underscore the critical need for diverse and effective treatment strategies to address the pervasive issue of antibiotic contamination.

Despite advances in effluent treatment, challenges persist, including the selection of resistant antibiotics and the long-term effectiveness of removal techniques. Studies have found high concentrations of antibiotics and bacterial resistance genes in wastewater treatment facilities (Rodriguez-Narvaez et al. 2017). Antibiotics are also present in aquatic environments, ranging from µg L-1 to ng L-1, with higher concentrations in pharmaceutical effluents, often in the mg L-1 range (Gorito et al. 2017, Fick et al. 2009, Larsson 2014, Yang et al. 2014, Bielen et al. 2017). Given these findings, it is vital to enhance research and develop effective, accessible, and low-cost methods to address this threat and reduce antibiotics in drinking water.

The study of CWs systems has been intensified and, like many other technologies that exist today and are implemented worldwide, it originates from the human view of nature and aim to artificially reproduce the multiple natural processes of pollutant removal in existing wetlands, such as the Brazilian Pantanal (Mattoso 2014). The classification of CWs can be defined according to the growth forms of macrophytes (floating, submerged or emergent plants), the water level (saturated or unsaturated), the form of flow (surface or subsurface) and the preferred direction of flow (horizontal, vertical or hybrid) (Sezerino et al. 2015 & Chen et al. 2016c).

Considering that these are systems that employ natural means of toxin removal, reducing the influence on the molecular structure of bacteria circulating in the aquatic environment, preventing the emergence of bacteria resistant to available treatments, using a less complex methodology and in many cases, at a lower cost (GIZ 2011, Santos et al. 2019).

In principle, CWs were not specifically designed to remove emerging organic pollutants (EOPs) from wastewater (Dotro et al. 2017). However, research on this topic shows year after year that this practice can be promising for reducing various EOPs from domestic wastewater (Hijosa-Valsero et al. 2011, Sochacki et al. 2018). According to Verlicchi & Zambello (2014), CWs do have the capacity to satisfactorily remove a significant number of pharmaceuticals and other organic micropollutants. The main factors responsible for this are the substrates and the microbiota associated with the macrophytes, which have been shown to be efficient at removing some POEs in CWs (Li et al. 2014).

Araújo et al. (2019) observed that CWs systems have emerged as a promising and effective technology for the elimination of pharmaceuticals. The researchers point out that this system reduces the levels of these contaminants in the receiving bodies, achieving elimination efficiencies of over 80% for substances such as diclofenac, dipyrone, and paracetamol.

The results obtained by the authors were promising and indicate that CWs systems can achieve satisfactory levels of antibiotic removal. Therefore, the use of CWs can provide a sustainable solution to mitigate the negative impact of antibiotics on the environment, contributing to the preservation of aquatic ecosystems and, consequently, human health.

This study therefore set out to analyze the effectiveness of effluent treatment systems based on CWs for antibiotic removal or degradation, through a systematic literature review, as well as to present flow configurations, vegetation, and sediments that have shown the best results regarding efficiency of antibiotic removal by class.

Abbreviations

AMR - antimicrobial resistance
ARGs - antibiotic resistance genes
CWs - Constructed Wetlands
GLASS - Global Antimicrobial Resistance and Use Surveillance System
HLR - hydraulic loading rate
HRT - hydraulic retention time
WHO - World Health Organization
WWTPs - wastewater treatment plants

MATERIALS AND METHODS

The methodology of this study was structured to analyze the efficiency of antibiotic removal in different constructed wetlands (CWs) configurations through a bibliometric approach. This quantitative technique involves analyzing publication patterns, citations, and keywords, allowing for the identification of trends and the evaluation of publication impact (Araújo & Alvarenga, 2011, Moraes et al. 2013). A comprehensive search was conducted between October 2021 and December 2023 on the Science Direct©, Web of Science© and Scopus© platforms. Data extracted from selected articles were compiled and analyzed in Microsoft Excel spreadsheets, enhancing the reliability of the results (Wolfram 2017)

The eligible work for inclusion in the study was a result of searches on the platforms, and it presented the stipulated terms in the title, abstract, or key words during the reading process. Once approved, the work was fully read and the research aligned with the objectives of this review had their data extracted, separated, and analyzed.

Data analysis

Data analysis followed several steps. First, relevant studies addressing the presence and removal of antibiotics in different kinds of CWs were collected and revised. Then, data were extracted from papers following criteria such as: CWs flow configurations (horizontal, vertical, surface, subsurface); vegetation; water flow rate; sediment characteristics. The removal rates were then compiled in a spreadsheet and compared with the characteristics of the systems.

In order to carry out a more detailed analysis, the characteristics of each system were observed individually, making it possible to obtain removal rates for each class of antibiotic, which made it possible to infer which antibiotics within their respective classes obtained the best removal results and which configurations proved to be the most suitable, in addition to analyzing removal as a function of flow, vegetation, sediment and HRT.

The results were interpreted considering environmental conditions and operational characteristics of the CWs systems, providing further insight into the main factors affecting antibiotic removal in these environments. The discussion of results emphasized the practical implications for planning and optimizing wasterwater treatment systems based on Cws, this seeking an alternative to mitigate the environmental impacts associated with antibitioc contamination.

RESULTS

The articles were selected from the Science Direct©, Scopus© and Web of Science©. Key words were searched in English: "Constructed wetlands", "Emerging pollutants", "Wetlands constructed" and "Wastewater treatment", "Wetlands constructed" and "Antibiotics", "Constructed wetlands" and "Antibiotic removal", "Constructed wetlands" and "Industrial effluents treatments", "Constructed wetlands" and "Pharmaceutical removal". The number of papers found per platform is shown in Table I, which details the article selection process in terms of number per stage and database origin.

Bibliometric mapping

After papers were submitted to the selection criteria, 82 articles remained. Data was collected from these articles to create bibliometric maps using the VOSviewer® software. The maps present the literature found in the databases and were generated in ".RIS" format, compiled by the Mendeley Web Importer© platform.

A bibliometric review aims to identify the current state of literature. This review evaluated the available knowledge on the removal of antibiotics from effluents, generating significant data using a database formed by 82 selected articles.

To select papers, we first searched for the terms in the titles and kept those that presented them. The authors utilized The VOSviewer® software to identify the most frequently recurring terms and to generate a concept map based on them. Figure 1 displays the top ten most commonly used terms in the titles of the 82 selected articles.

The circle's size corresponds to the frequency of the term appearance in the titles. The line connecting two terms indicates their co-occurrence in the same title, and the thickness

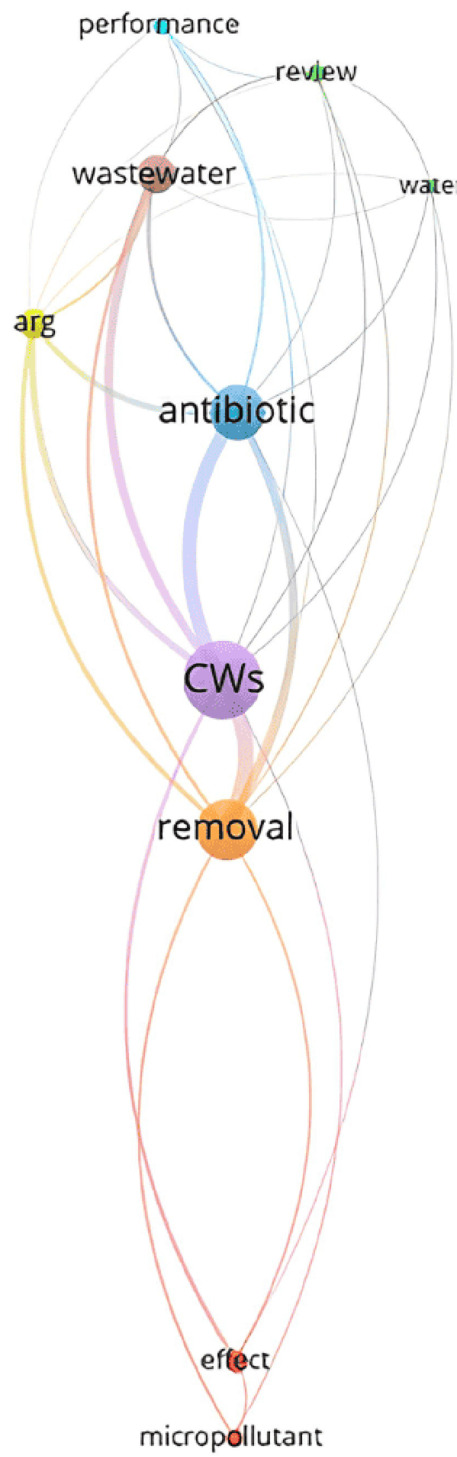

Figure 1. The ten most cited terms in the titles of the 82 articles.

Table I. Selection of artciles based on terms.

	PLATFORMS		
	SCIENCE DIRECT	WEB OF SCIENCE	SCOPUS
Total	1841	787	401
Selection by title	556		
Selection by keywords	409		
Seleção by abstract	82		

of the line shows how frequently these terms were used together in different titles.

The second criterion was applied to the key words. Only research containing recognized terms from the works studied was selected. Based on this data, a bibliometric network map was constructed, showing the 192 most frequently used terms in the key words of the works that comprised the database. The highlighted lines represent connections that link to the term "Constructed Wetlands" (CWs), as shown in Figure 2.

A connection between two terms should be interpreted as the occurrence of both terms together in the same paper. The abbreviation "CWs" was found in the key words of 45 works.

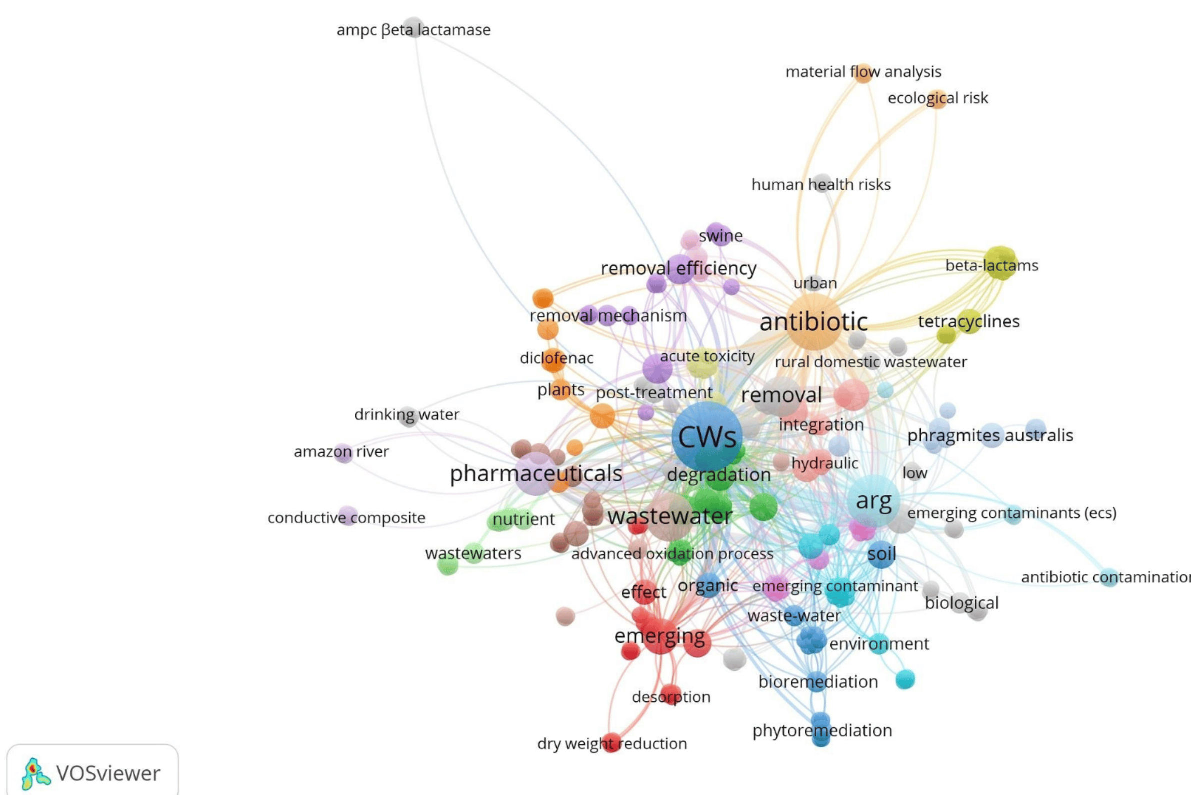

Figure 2. Connection network between terms in key words.

The most commonly used words associated with this term are “antibiotic”, “wastewater”, “pharmaceuticals”, “arg”, “removal” and “removal efficiency”.

The density map, or heat map, was then used to show the terms with the highest occurrence in the abstracts of the 82 papers, as can be seen in Figure 3. The red area indicates the intensity of occurrence for the term’s “WCs”, “antibiotic”, and “removal”, as well as other terms that together support the purpose of this research, such as “pharmaceutical contaminant” and “pollutant”, which appear together frequently on the map. The proximity between terms indicates the frequency with which they co-occurred.

The density map is being used at this stage because it is easily understandable and clearly represents the current state of the literature in the database for this work. In order to understand the map, note that the color scale ranges from blue to green, green to yellow, and yellow to red. Warm colors indicate a higher intensity of occurrences, and proximity on the map indicates correlations with other terms.

Selected works

After reading all 82 articles, 40 papers were selected to contribute to this review, in order to understand the antibiotic removal methods used, their peculiarities, and efficiency. Table II displays the authors, year of publication, and country, ordered chronologically.

Removal of antibiotics according to the characteristics of CWs system

To examine contaminant removal through CWs, researchers test different combinantions of characteristics. These characteristics include flow, vegetation, sedimentation, HRT, and

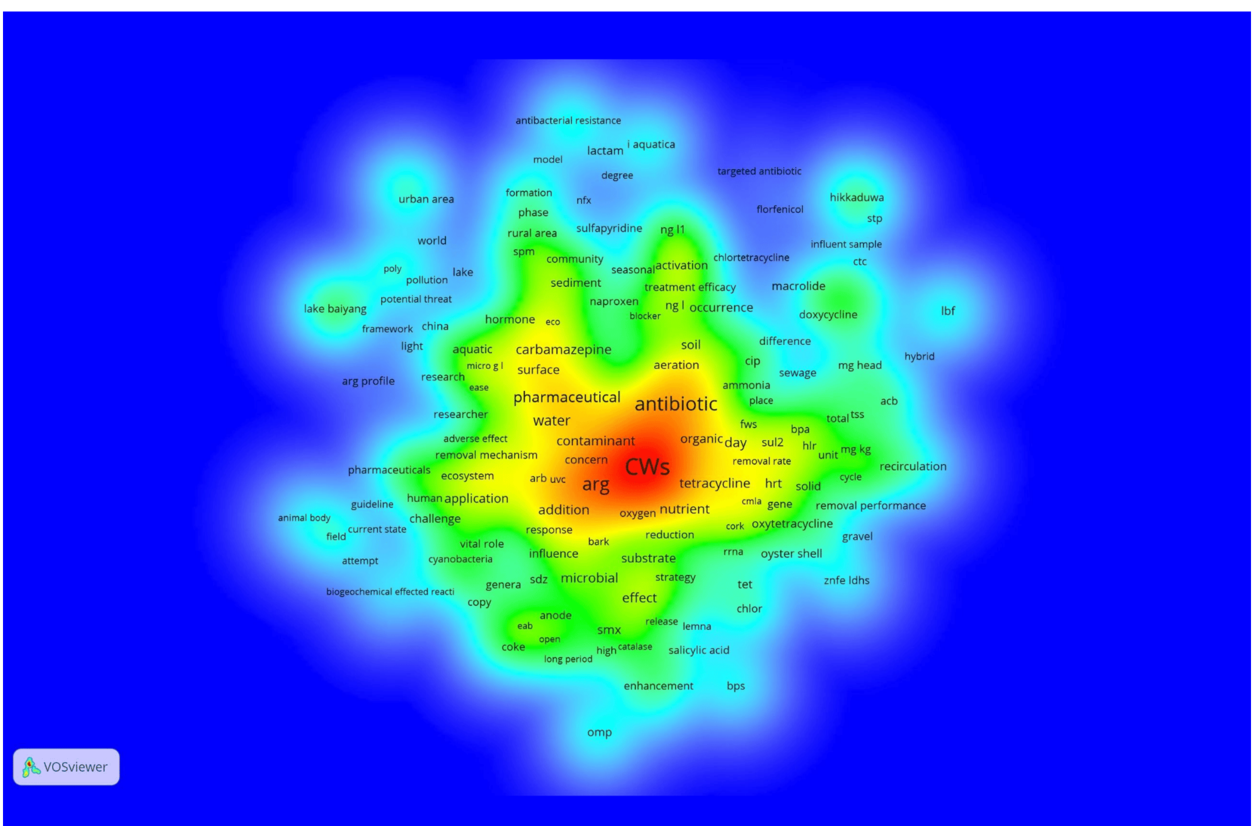

Figure 3. Term density map in the abstracts of 82 articles.

Table II. Works in order of selection.

	AUTHORS	TITLE	YEAR	COUNTRY
16	Hijosa-Valsero, María et al..	Removal of antibiotics from urban wastewater by constructed wetland optimization.	2011	Spain
24	Liu, Lin et al..	Elimination of veterinary antibiotics and antibiotic resistance genes from swine wastewater in the vertical flow constructed wetlands.	2013	China
29	Aquino, S. F. ; Brandt, E. M. F; |Chernicharo, C.,A., L	Remoção de fármacos e desreguladores endócrinos em estações de tratamento de esgoto: revisão da literatura.	2013	Brazil
21	Berglund, Björn et al	Efficient removal of antibiotics in surface-flow constructed wetlands, with no observed impact on antibiotic resistance genes.	2014	Sweden
15	Chen, Jun et al..	Removal of antibiotics and antibiotic resistance genes in rural wastewater by an integrated constructed wetland.	2015	China
20	Yeong-Joo Choi, Lee-Hyung Kim, Kyung-Duk Zoh,	Removal characteristics and mechanism of antibiotics using constructed wetlands.	2016	South Korea
22	Chen, Jun et al..	Removal of antibiotics and antibiotic resistance genes from domestic sewage by constructed wetlands: Optimization of wetland substrates and hydraulic loading.	2016	China
28	Chen, Jun et al..	Removal of antibiotics and antibiotic resistance genes from domestic sewage by constructed wetlands: Effect of flow configuration and plant species.	2016	China
4	Ávila, Cristina et al..	Enhancement of total nitrogen removal through effluent recirculation and fate of PPCPs in a hybrid constructed wetland system treating urban wastewater.	2017	Spain
12	Yi, Xinzhu et al..	Removal of selected PPCPs, EDCs, and antibiotic resistance genes in landfill leachate by a full-scale constructed wetlands system,	2017	Singapore
17	Huang, Xu et al..	Removal of antibiotics and resistance genes from swine wastewater using vertical flow constructed wetlands: Effect of hydraulic flow direction and substrate type.	2017	China
27	Hu, Xia-Lin et al..	Occurrence of 25 pharmaceuticals in Taihu Lake and their removal from two urban drinking water treatment plants and a constructed wetland.	2017	China
8	Chaves-Barquero, Luis G. et al..	Attenuation of pharmaceuticals, nutrients and toxicity in a rural sewage lagoon system integrated with a subsurface filtration technology.	2018	Canada
10	Petrie, Bruce et al..	Biotic phase micropollutant distribution in horizontal sub-surface flow constructed wetlands.	2018	UK

Table II. Continuation.

	AUTHORS	TITLE	YEAR	COUNTRY
3	Huang, Xiaofeng et al..	Influence of Two-Stage Combinations of Constructed Wetlands on the Removal of Antibiotics, Antibiotic Resistance Genes and Nutrients from Goose Wastewate.	2019	China
5	Christofilopoulos, Stavros et al..	Evaluation of a constructed wetland for wastewater treatment: Addressing emerging organic contaminants and antibiotic resistant bactéria.	2019	Greece
11	Filipa Santos, C. Marisa R. Almeida, Inolanda Ribeiro, Ana P. Mucha,	Potential of constructed wetland for the removal of antibiotics and antibiotic resistant bacteria from livestock wastewater,	2019	Portugal
1	Stroski, Kevin M. et al..	Wastewater sources of per- and polyfluorinated alkyl substances (PFAS) and pharmaceuticals in four Canadian Arctic communities.	2020	Canada
2	Xuan Guo, Hua Zhong, Peng Li, Chengjun Zhang	Microbial communities responded to tetracyclines and Cu(II) in constructed wetlands microcosms with Myriophyllum aquaticu.	2020	China
6	García, Joan et al..	A review of emerging organic contaminants (EOCs), antibiotic resistant bacteria (ARB), and antibiotic resistance genes (ARGs) in the environment: Increasing removal with wetlands and reducing environmental impacts.	2020	International review
7	Guedes et al.	A Survey of the Presence of Pharmaceutical Residues in Wastewaters. Evaluation of Their Removal Using Conventional and Natural Treatment Procedures.	2020	Spain
13	Zheng, Yucong et al..	Fate of an antibiotic and its effects on nitrogen transformation functional bacteria in integrated vertical flow constructed wetlands.	2021	China
18	Sakurai, Karen S. I. et al..	Hybrid constructed wetlands as post-treatment of blackwater: An assessment of the removal of antibiotics.	2021	Brazil
19	A, Dan et al..	Removal efficiency, kinetic, and behavior of antibiotics from sewage treatment plant effluent in a hybrid constructed wetland and a layered biological filter.	2021	China
23	Tang, Xiaoyan et al..	Irrigation using hybrid constructed wetland treated domestic sewage: Uptake of phthalic acid esters and antibiotics by Ipomoea aquatica forssk.	2021	China
25	Lu, Shaoyong et al..	Effects of sulfamethoxazole on nitrogen removal and molecular ecological network in integrated vertical flow constructed wetlands.	2021	China
26	Ávila, Cristina et al..	New insights on the combined removal of antibiotics and ARGs in urban wastewater through the use of two configurations of vertical subsurface flow constructed wetlands.	2021	Spain
9	Silvia Venditti, Hana Brunhoferova, Joachim Hansen,	Behaviour of 27 selected emerging contaminants in vertical flow constructed wetlands as post-treatment for municipal wastewater.	2022	Luxembourg

Table II. Continuation.

	AUTHORS	TITLE	YEAR	COUNTRY
14	Du, J., Xu, T., Guo, X., & Yin, D.	Characteristics and removal of antibiotics and antibiotic resistance genes in a constructed wetland from a drinking water source in the Yangtze River Delta.	2022	China
30	Wen, Huiyang et al..	High removal efficiencies of antibiotics and low accumulation of antibiotic resistant genes obtained in microbial fuel cell-constructed wetlands intensified by sponge iron.	2022	China
33	Ramdat, N. et al..	Effects of Enrofloxacin on Nutrient Removal by a Floating Treatment Wetland Planted with Iris pseudacorus: Response and Resilience of Rhizosphere Microbial Communities	2022	China
34	LEI, Yu; Rijnaarts, Huub; Langenhoff, Alette.	Mesocosm constructed wetlands to remove micropollutants from wastewater treatment plant effluent: Effect of matrices and pre-treatments	2022	Netherlands
38	Drzymała, J. et al..	Towards SustainableWastewater Treatment: Bioindication as a Technique for Supporting Treatment Efficiency Assessment	2022	Poland
31	Al-Mashaqbeh, Othman et al..	Assessment of novel hybrid treatment wetlands as nature-based solutions for pharmaceutical industry wastewater treatment.	2023	Jordan
32	Sánchez, M. et al..	Combining Constructed Wetlands and UV Photolysis for the Advanced Removal of Organic Matter, Nitrogen, and Emerging Pollutants from Wastewater	2023	Spain
35	López-Vinent, Núria et al.	Nature-based solution as an efficient wastewater pretreatment to enhance micropollutants abatement by solar photo-Fenton at natural pH	2023	Spain
36	Maldonado, Ingrid; et al..	Maldonado, Ingrid; Terrazas,Edmundo G. Moreno; Mamani, Jesus Miranda; Vilca, Franz Zirena.	2023	Peru
37	Karungamye, Petro; et al..	The removal of ciprofloxacin from synthetic wastewater in constructed wetland	2023	Tanzania
39	Lei, Yu et al..	The removal of micropollutants from treated effluent by batch-operated pilot-scale constructed wetlands	2023	Netherlands
40	Nazir, Alina a et al..	Environmental remediation and generation of green electricity using constructed wetlands coupled with microbial fuel cell model system	2023	Pakistan

effluent load, among others. Researchers may also vary the scale and different combinations of technologies, as well as build hybrid systems, combining different flows, sediments, substrates, and vegetation. These hybrid systems have been shown to significantly remove POEs (Li et al. 2014, Avila et al. 2017).

This section analyses the results obtained for each characteristic individually in regard to the antibiotic removal rates indicated by the researchers, in order to discuss the specific use and impact of characteristics on the results obtained in the CWs. The flow, vegetation, sedimentation, and HRT characteristics of the studies are presented separately, and the appropriate associations of the removal rates found for each of them are described below.

The García et al. (2020) study is not included in this specific analysis, as it is classified as a review.

Of all the CWs systems studied, not all presented all the characteristics, 169 reported the type of flow, 168 the type of vegetation, 149 the substrate and sediment, 102 the HRT and 120 the HLR. The data set revealed that the most information was present in the flow variabe. Therefore, the analysis starts with this characteristic.

Flow

In terms of flow, CWs can be classified in two ways: horizontal and vertical. Horizontal flow can be presented as surface or subsurface flow (Sezerino et al. 2015). In the case of subsurface flow, the flow passes below ground level, and in the case of surface flow, the water level is above ground level.

Among the studies selected, there are horizontal, vertical, surface, and subsurface flows. It is important to note that some studies did not present all the characteristics of the systems, and therefore the observations are made only to those cases that took these aspects into account. Among all the presented systems in the review, 195 had their flow reported.

In the studies, 91 CWs were reported to have horizontal flow, of which 63 were subsurface flow and the rest the surface flow. 84 CWs operated with vertical flow. And 20 CWs were reported to have “hybrid” flow, a term that indicates a combination of different flows, which occurred by aligning different CWs with the measurement of the removal index at the end of the system.

When horizontal subsurface flow CWs were filtered, 178 antibiotic removal rates were observed, of which 50 were removal rates of less than 50%, 84 removal rates above 80%, and approximately 25% of the rates indicated total removal of the contaminant in the effluent. These rates refer to 8 antibiotics: novobiocin, sulfamerazine, ofloxacin, ciprofloxacin, sulfamethoxazole, chloramphenicol, leucomycin, and sulfamethazine.

Among the horizontal surface flow CWs rates, 12,5% of the data, a total of 12 indices, were negative, which indicates recontamination of the effluent. Six antibiotics achieved total removal, with only one index for each: Trimethorpim, Oxytetracycline, Chlortetracycline, Leucomycin, Sulfamethazine, Tilcomycin. 42.71% of the indices were equal to or greater than 50% removal.

Approximately 20% of the indices in CWs with vertical flow exhibited a removal rate below 50%. Conversely, half of the records demonstrated a removal rate exceeding 90%. Additionally, 13 reports documented the complete removal of antibiotics, including sulfamethoxazole, trimethoprim, leucomycin, sulfamethazine, and tilcomycin.

The 20 hybrid flow systems generated 83 removal rates, among which there was no recontamination and only 15 were rates below 50% of removal. There was no record of total removal, but for the Roxithromycin, Erythromycin and Ofloxacin rates above 98% were observed.

It is important to note that a CWs is comprised of a multitude of configurations beyond the mere flow of effluent. To achieve removals, it is essential to consider the entirety of the system’s characteristics. Based on this logic, for the effluent to be treated, it is necessary for there to be vegetation, sediments, substrates, and for these to remain in contact with the effluent for a sufficient duration. This allows for the gradual and continuous entry of the effluent into the system, which is then removed through the mechanisms. The next section examines the role of vegetation in the removal of antibiotics from the selected studies, which were used to compile this review.

Vegetation

Among the works analyzed, 168 CWs had their vegetation presented, which included 26 different species reported. Hybrid systems were also observed, which utilized combinations of vegetation. Among the CWs with vegetation, 55 originated from research that reported the presence of vegetation but did not specify which species were cultivated.

Among the indices presented regarding vegetation, 22 were from works that declared they did not use vegetation. These indices fluctuated from -17 to 96.9% removal, with only 6 indices being above 50%. The antibiotics that had the highest removal indices were lincomycin (96.9%), salinomycin (87.1%), and sulfacetamide (86.7%). In contrast, 73 CWs used two or more species together, accounting for 162 indices. No recontamination reported, 25,31% of reports had removal rates below 50% and 5 total removals: ciprofloxacin, doxycycline, chloramphenicol, azithromycin, and sulfamethoxazole.

Of the cultivated CWs, 101 used single species, while the remaining 67 were cultivated with combinations of different species. Among the species individually cultivated in CWs, those that were used in four or more CWs stand out: Phragmites australis, Miscanthus giganteus, Typha angustifolia, and Cyperus alternifolius.

The species with the highest number of cultures recorded in the CWs included in this study was Phragmites Australis, which was used individually in 34 CWs, and had 80 removal indices recorded, 8.75% of which were negative, and more than 28% were indices of more than 90% of removal rate. This vegetation achieved total removal three times for Tilcomycin.

The second most used species was recorded in 24 CWs. The Miscanteus Giganteus were used for the evaluation of Sulfamethoxazole removal, and recorded high removal rates, ranging from 78,9% to 98%. In third place is Typha Angustifolia, a macrophyte grown individually in 16 CWs, with 63 removal rates recorded in the articles analyzed in this review, none of these studies recorded recontamination, only 14.29% of the removal rates were below 50%, and total removal was achieved with the antibiotics Sulfamethoxazole and Trimethoprim 8 times.

The Cyperus Alternifolius species had 85 removal rates reported in 13 CWs, no recontamination rates, and among all the reports of CWs cultivated exclusively with this vegetation, only around 8,2% had rates of less than 50%, while 36 of these had total removal rates for the antibiotics: Novobiocin, Sulfamerazine and Ofloxacin.

In addition to vegetation and flow, another important component in the configuration of a CWs for effluent treatment are sediments and substrates, elements that can enhance the result obtained in the system, since they provide more ways for removal to occur. The next section will present the sediments and substrates used in the CWs mentioned in the articles that were part of this removal.

Sediments and substrates

175 of the analyzed CWs in the selected papers reported the sediment and/or substrate used, 14 did not use these components, and the rest did not report the configuration used. Among those that did mention the use of different types and sizes of gravel in 88 systems, sand in 83, some type of soil in 58, zeolite in 20, and biochar in 12, used exclusively or together, other types of

sediment and substrate were also used, but in fewer CWs.

Of the CWs that presented data on this configuration, 72 used only one sediment or substrate. Gravel was used exclusively in 21 WCs, generating 96 rates, more than half of which were above 50%, and there were 3 records of complete removal of Doxixycline and Ciprofloxacin, while sand was used as the sole configuration in only one CWs, where removal rates fluctuated from 9% to 53.8%, with the highest rate being achieved for the class of antibiotics called Quinolones, at the time represented by Norfloxacin, Ciprofloxacin, Enrofloxacin, Ofloxacin, Fleroxacin and Sarafloxacin.

In addition to sand, another widely used substrate was "soil", as it tends to be collected from different places, the generic time will be used in this way, the soil was used in 24 CWs without combinations of sediments or other substrates, 80 indices were found, among which there was no recontamination, but there was also no total removal of any of the antibiotics analyzed, 19 of these indices showed removal below 50%, and approximately 34% were of removal equal to or greater than 80%, the highest index was 99,4% for Ofloxacin.

In addition to gravel, zeolite was a sediment that stood out, with exclusive use in 13 CWs, a use that yielded 71 removal rates, with the lowest rate being 11,1%, with only 8 rates below 50% removal and an impressive 21 total removal rates, in five different antibiotics: Novobiocin, Sulfamerazine, Ofloxacin, Sulfamethazine and Leucomycin.

Additionally, 103 of CWs identified combined different sediments and substrates. A general analysis of the performance of these systems resulted in 140 indexes. Only 5,71% of these indexes indicated recontamination, while 75% of the records demonstrated removal greater than 70%. Thirteen indexes revealed complete removal of four different antibiotics, namely: sulfamethoxazole, tilmicosin, trimethoprim, and chloramphenicol.

In addition to these configurations, there are other aspects that are more directly related to the effluent. One such configuration is the hydraulic retention time (HRT), which determines the length of time the effluent will remain in the CWs. This characteristic is manipulated by researchers in many studies to analyze the ideal configuration that will provide the best result.

Hydraulic retention time (HRT)

HRT, despite being an important factor in effluent treatment, had many omissions in the works that form the database of this review. As these data differ greatly from each other, classifications were created to group them together and thus be able to analyze them more comprehensively, therefore, the HRTs of the articles in the database of this review will be presented within the following classifications: less than 3 days, from 3 to 6 days, from 6.1 to 9 days, from 10 to 12 days.

A total of 189 indices were obtained for HRTs of less than 3 days, of which less than 12% indicated recontamination of the effluent, 57 indices showed removal equal to or greater than 80%, and total removal was achieved for four antibiotics with one index each: Ciprofloxacin, Oxytetracycline, Chlortetracycline and Trimethoprim.

For HRTs between 3 and 6 days, there are 80 indices, among which there is no record of recontamination, and more than 43% are above 90% removal. 13 of the indices reported total removal for the antibiotics azithromycin, sulfamethoxazole, tilcomycin, viprofloxacin, doxycycline, and trimethoprim.

The indices included in the classification of HRTs between 6,1 and 9 days amounts to a total of 47, among which there was no recontamination, only 5 indices were below 50% removal and approximately 65% of the recorded indices indicated a removal of more than 92%. This HRT demonstrated no total removal, but for the antibiotics Sulfamethoxazole and Carithromycin, 6 and 8 indices were found, respectively, ranging from 99.1% to 99.7%.

Finally, for HRTs between 10 and 12 days, there were 13 removal rates, with no recontamination recorded, and with all the values above 28%, four of them equal to or greater than 95%. Sulfamethazine stands out with removal records greater than 99%. There was also a single study that used HRT of 22,75 days, but only one removal rate was recorded, also for Sulfamethazine, which was over 99%.

Although very important for successful removal in CWs, the articles do not have a standard for indicating data on the effluent load, and many do not inform it, so the different water loads used in the works in this review will not be explored here. To complement this analysis, the following section presents observations on the classes of antibiotics and the best configuration for achieving removal of these pollutants during treatment in CWs.

Analysis of antibiotic removal and antiobiotic classes

After reading all 82 papers, only 40 were used. These included mentions of 165 CWs, in which the removal of 45 different antibiotics from 11 different classes was studied. The studies provided 666 removal indices for the 45 antibiotics analyzed. Approximately 49.4% of these indices are attributed to seven antibiotics: sulfamethoxazole, sulfamethazine, erythromycin, trimethoprim, ciprofloxacin, ofloxacin, and clarithromycin.

The best removal rate for sulfamethoxazole was 100%, recorded by Lei et al (2022), who pretreated the effluent with UVC lamps and WC sedimented with gravel, glass beads, and sand. Some systems were supplemented with bovine manure shells and biochar. All systems were cultivated with Typha angustifolia. The 24 CWs system studied by Maldonado et al. (2023) also achieved 100% of removal rate. Cultivated with L. gibba and A. filiculoides, the system had a horizontal surface flow and was configured with 10 cm of sand and silt. The lowest removal rate for this antibiotic was reported by Ávila et al. (2017) due to the 50% recirculation of the effluent.

Sulfamethazine had 36 removal rates reported, reaching 100% of removal in 6 CWs evaluated by Chen et al. (2016a). With the lowest index being -9.1% in a surface flow CW1 containing the macrophyte Myriophyllum verticillatum L., as recorded by Chen et al. (2015).

Chen et al. (2016b) also reported a high removal rate of 98.9% for Erythromycin in CW5. The system's configurations included horizontal subsurface flow, Iris tectorum Maxim macrophyte, zeolite sediment, and a hydraulic load of 20 cm d1. The lowest index recorded in the literature studied was -17% in CW2 by Chen et al. (2015), which used subsurface flow, straw, and oil, in full scale.

Trimethoprim had 79 removal rates in 16 studies, one negative removal and seven below zero. Stroski et al. (2020) recorded total removal at the Cambridge Bay WC on a full scale, as did Lei et al. (2023), who cultivated a system using Typha angustifolia, gravel, and sand as sediment, resulting in total removal. Similarly, Lei et al. (2022) achieved total removal using the same macrophyte, along with pretreatment using a UVC lamp and sedimentation with biochar from cow dung. Notwithstanding, Ávila et al. (2017) found negative removal due to recirculation.

The antibiotics ciprofloxacin and ofloxacin obtained, respectively, 54 ad 30 removal rates reported in the literature. Ciprofloxacin had a total removal rate recorded twice: by Berglund et al. (2014) in four CWs with a HRT configuration of 5.7 days and a HLR of 0.1 m d-1, and by Hu et al. (2017), in a full-scale CWs.

Chen et al. (2016a) recorded 12 times the total removal of Ofloxacin in the effluent across four sediments and three different hydraulic loads. The removal rate fell below 90% only three times, two of which were reported by Chen et al. (2015), and the lowest removal rate (-200%) was reported by Ávila et al. (2021).

Venditti et al. (2022) reported a rate of 99.1% for clarithromycin removal in column D. The sediment was in a configuration of 30% activated biochar and 70% sand and was cultivated by Phragmites australis and Iris Pseudacorus.

Table III shows the 11 antibiotic classes found in the 40 analyzed articles, along with the number of drugs representing each class.

Table III. **Occurrences of antibiotics per class.**

CLASS	OCCURRENCES
SULFONAMIDES	12
QUINOLONES	10
MACROLIDES	7
TETRACYCLINE	4
AMPHENICOLS	3
IONOPHORES	3
LINCOSAMIDES	2
PENICILLINS	2
AMINOCOUMARINS	1
CEPHALOSPORINS	1
NITROIMIDAZOLES	1

The database of 40 surveys analyzed shows that approximately 30% of the antibiotics removed by the CWs belong to the classes of sulfonamides, quinolones, or macrolides. Table IV lists the antibiotics that belong to each of these three prominent classes.

Among the sulfonamides, sulfachloropyridazine had the lowest removal rate, not exceeding 29.6%. Sulfasalazine, on the other hand, had the highest removal rate of 51%. Sulfamerazine, sulfamethazine, and trimethoprim recorded 100% removal at least once, while sulfadimethoxine and sulfamethoxazole exceeded the 90% removal rate in five CWs.

In the quinolone class, ciprofloxacin achieved complete removal twice, while ofloxacin achieved this result twelve times. However, there was a record of -200% removal in this class. Difloxacin had indices above 97% for all cases, and enrofloxacin obtained 5 indices above 90%. Sarafloxacin had a maximum removal rate of approximately 75%.

Within the macrolide class, leucomycin demonstrated complete removal six times. Tilmicosin showed total removal in all mentioned indices, while azithromycin achieved complete removal in one-third of the indices. Erythromycin and roxithromycin had four removal indices higher than 96%. Tylosin had the lowest index, with only one occurrence, as reported by Du et al. (2022).

From the 40 articles, removal indices were extracted for 45 different antibiotics from 11 classes: sulfonamides, quinolones, macrolides, tetracyclines, amphenicols, ionophores, lincosamides, penicillins, aminocoumarins, cephalosporins and nitroimidazoles. Those that were represented by at least 3 antibiotics are shown in Table V, which summarizes the CWs configurations that delivered the best removal indices per class.

These configurations correspond to the CWs that resulted in the highest removal rates for each antibiotic class. It is important to note that this does not refer to a specific CWs, but rather to the characteristics of those that were most successful in removing antibiotics from

Table IV. Antibiotics and their respective classes.

CLASS OF ANTIBIOTICS	ANTIBIOTICS
SULFONAMIDES	Sulfacetamide, Sulfachloropyridazine, Sulfadiazine, Sulfadimethoxine, Sulfamerazine, Sulfamethazine, Sulfamethoxazole, Sulfamonomethoxine, Sulfapyridine, Sulfasalazine, Sulfathiazole and Trimethoprim.
QUINOLONES	Pipemidic Acid, Ciprofloxacin, Difloxacin, Enrofloxacin, Fleroxacin, Flumequine, Norfloxacin, Ofloxacin and Sarafloxacin.
MACROLIDES	Azithromycin, Erythromycin, Leucomycin, Roxithromycin, Tilmicosin, Tylosin, and Clarithromycin.

Table V. CWs configurations that provided the best removal rates for the antibiotic classes with the highest number of occurrences.

CLASS	SCALE	VEGETATION	SEDIMENTS	FLOW
SULFONAMIDES	Real and mesocosm	*Cyperus Alternifolius L, A Thalia Delbata Fraser E A Iris Tectorum Maxim.*	Shells and Oysters, Zeolites, Medicinal Stone and Ceramics. Cow dung biochar	All
QUINOLONES	Real and mesocosm	*Cyperus Alternifolius L.*	Shells and Oysters, Zeolites, Medicinal Stone and Ceramics.	Subsurface and horizontal
MACROLIDES	Pilot, real and mesocosm	*Cyperus Alternifolius L, A Thalia Delbata Fraser, Phragmites Australis E Iris Tectorum Maxim*	Shells and Oysters, Zeolites, Medicinal Stone and Ceramics.	All
TETRACYCLINES	Real	*Myriophyllum Aquaticum*	Without sediments	Horizontal
AMPHENICOLS	Real	-	-	-
IONOPHORES	Mesocosm	*Cyperus Alternifolius L, A Thalia Delbata Fraser E Iris Tectorum Maxim*	Shells and Oysters, Zeolites, Medicinal Stone and Ceramics.	All

each class. It should be noted that the classes represented here had at least three antibiotics analyzed in the database.

The table V shows six classes, each with configurations that achieved a minimum antibiotic removal rate of 90%, except for Amphenicols, which obtained 84,8%. Additionally, the reported best indices for this class did not include information on the configurations of their CWs, creating a significant gap in the available data.

DISCUSSION

The results of this research extend beyond the numerical data that indicate the relative efficiency or inefficiency of CWs systems. They also reveal a series of significant findings in several aspects. First, it is possible to identify some of the direct impacts on the environment and human health, and to highlight the adverse effects of the indiscriminate use of antibiotics and the growing resistance of bacteria. Second, it addresses the effectiveness of antibiotic removal in wastewater treatment, with a particular focus on the ability of CWs to mitigate the presence of these compounds. In addition, it presents detailed analysis of the data collected, providing important information on patterns and trends related to the topics covered. A bibliometric mapping was carried out to contextualize the research within the current scientific scenario and identify knowledge gaps. Finally, the main selected works that served as the basis for this investigation are presented, demonstrating the relevance and contribution of these sources to the development of the study. These results provide a comprehensive and well-founded view of the aspects examined in this work, contributing to a better understanding of the challenges and opportunities associated with the topic.

ENVIRONMENTAL EFFECTS AND REMOVALS IN CWs

Impacts on the environment

The high use of antibiotics has raised concerns due to environmental impacts and bacterial resistance. Their toxicity to environmental bacteria contributes to the emergence of resistant strains, rendering medicines ineffective, common bacterial infections are increasingly resistant to treatments. Over 60% of Neisseria gonorrhoeae strains, which cause sexually transmitted diseases, are resistant to ciprofloxacin. Furthermore, over 20% of Escherichia coli strains, common in urinary tract infections, are resistant to first and second-line treatments (WHO 2022).

In recent years, the scientific community has devoted special attention to the presence and fate of antibiotics in natural environments. These compounds are persistent and resistant to biodegradation, resulting in their accumulation in the environment. Even in detectable minimum concentrations, they can cause adverse impacts on both aquatic and terrestrial ecosystems. For those reasons, various removal and degradation processes have been investigated as potential solutions to mitigate environmental contamination caused by these compounds (Ternes 1998, Hernando et al. 2006, Homem & Santos 2011, González-Pleiter et al. 2013, Dalmolin et al. 2022).

Studies have been conducted for several years on the effects of environmental contaminants. It has been observed that with each new study, there is an increase in the existence of bacteria that have acquired resistance to most or all the antibiotics used. This suggests that mutations may result from exposure to residues of these drugs (WHO 2022). Therefore, it is important to adopt measures to mitigate the impacts of antibiotics and their byproducts (unmetabolized) in the environment, as they play a fundamental role in ecosystems (Thiele-Bruhn & Beck 2005, Aminov & Mackie 2007, Baran et al. 2011, Grenni et al. 2018).

Understanding the contamination route is crucial. Antibiotics are mainly introduced into ecosystems through the discharge of treated wastewater, particularly in areas where hospital sewage is included (Korzeniewska & Hamisz 2013, Lien et al. 2017, Wang et al. 2018). One possible explanation for this is the low efficiency of treatment systems or even the absence of treatment of hospital effluents. This is a common issue in many municipalities, particularly in small and medium-sized ones. This accelerates the spread of multidrug-resistant bacteria from hospitals to wastewater treatment plants (WWTPs) and, subsequently, to the environment (Korzeniewska et al. 2013, Ahn & Choi 2016, Lekunberri et al. 2017).

The study by Montagner et al. (2019) demonstrates the negative impacts of inefficient treatment methods used for removing or reducing antibiotics and other pharmaceuticals in effluents. The study reports the presence of amoxicillin, trimethoprim, cephalexin, ciprofloxacin, sulfamethoxazole, norfloxacin, and ampicillin in samples of drinking water, surface water, wastewater, and groundwater in the state of São Paulo from 2015 to 2016. This finding highlights the concern with emerging contaminants and reinforces the need for improvement in treatment strategies to ensure the quality of these water resources, as indicated in the scientific literature.

Impacts on human health

The growing threat to global health posed by AMR is the subject of an increasing number of studies that seek solutions to this serious problem, as the action of drugs such as antibiotics, antifungals and antivirals is impaired when microorganisms develop resistance, resulting in long-lasting and sometimes incurable infections. This phenomenon, known as AMR, threatens not only individual well-being but also public health worldwide.

Exposure to antimicrobials, such as antibiotics, antifungals, antivirals, antimalarials, or anthelmintics, can cause microorganisms, including bacteria, fungi, viruses, and parasites, to undergo alterations in their characteristics, leading to the development of resistance. Microorganisms that are resistant to most antimicrobials are referred to as ultra-resistant. The development of resistance compromises the efficacy of medicines, leading to persistent infections and an increased risk of transmission to others, thus becoming a growing threat to public health worldwide (FIOCRUZ 2019).

According to WHO data, around 700,000 people die each year worldwide from antimicrobial-resistant infections. Many diseases that are considered common, such as respiratory infections, urinary tract infections and sexually transmitted infections, run the risk of becoming untreatable with the current drugs available on the market (PAHO 2021).

Removal of antibiotics in CWs

According to Verlicchi and Zambello (2014), the CWs have the capacity of satisfactorily removing a significant number of drugs and other organic micropollutants. The substrates and microbiota associated with macrophytes are the main factors responsible for the efficient removal of some Emerging Organic Pollutants (EOPs) in CWs (Li et al. 2014).

The removal of antibiotics in constructed wetlands can be significantly influenced by the redox conditions of the environment. Aerobic environments, characterized by high oxygen availability, favor degradation processes such as oxidation, which can be effective for antibiotics like β-lactams (Verlicchi & Zambello 2014). In contrast, anaerobic environments, with low or no oxygen availability, favor processes such as reduction, which can be more effective for antibiotics like sulfonamides (Matamoros et al. 2012). Studies show that the combination of aerobic and anaerobic zones in hybrid systems can maximize the removal of a wide range of antibiotics.

The efficiency of antibiotic removal in constructed wetlands can be enhanced by optimizing anaerobic and aerobic conditions. Aerobic environments promote the activity of aerobic bacteria, efficient in degrading organic compounds through oxidation processes. Conversely, anaerobic environments favor the activity of anaerobic bacteria, which use reduction processes. The combination of these zones in hybrid systems can maximize antibiotic removal, as observed in studies of horizontal and vertical flow wetlands (Sezerino et al. 2015).

Plants play a crucial role in the efficiency of removal in constructed wetlands. In this study, it can be seen that several articles cite the use of species such as Phragmites australis, Typha latifolia and Cyperus alternifolius, which according to the literature, tend to be used more because of their extensive roots that promote the adhesion of microbial biofilms, increasing the degradation of pollutants (Sezerino et al. 2015). Phragmites australis, for example, is known for its dense, fibrous roots that provide a large surface area for microbial activity, while Typha latifolia has robust rhizomes that improve the stability and oxygenation of the substrate. The diverse root structures of these plants enhance aerobic and anaerobic processes, increasing the overall effectiveness of antibiotic removal in constructed wetlands (Vymazal 2011).

The bed depth and applied hydraulic loads are critical factors influencing the efficiency of antibiotic removal. Shallower beds tend to maintain more consistent aerobic conditions, while deeper beds can create anaerobic zones, favoring the combination of oxidation and reduction processes. Studies show that wetlands with hybrid beds and variable loads can optimize the removal of a wide range of antibiotic compounds (Verlicchi & Zambello 2014).

CWs systems effectively eliminate drug compounds through different processes, such as assimilation by plants, photodegradation, hydrolysis, and microbial degradation (Matamoros et al. 2012 & Zhang et al. 2014). The removal efficiency depends on the plant species, water flow, and reactor construction characteristics. It is possible to degrade antibiotics in CWs through physical, chemical, and biological processes (Hijosa-Valsero et al. 2011).

Therefore, it is possible to say that CWs are systems capable of removing drugs as well as conventional stations, and in some cases and depending on the configuration of the system, they can reach removal levels above 90% for diclofenac and paracetamol, for example, this is mainly due to the coexistence of different physicochemical conditions, with both aerobic and anaerobic degradation routes (Araújo et al. 2019).

CONCLUSIONS

This study provides an in-depth analysis of antibiotic removal efficiency rates in various CW configurations, based on an extensive compilation of scientific literature on the subject. The results emphasize the importance of full-scale implementation, vegetation, particularly Cyperus alternifolius L., and materials such as shells, oysters, zeolites, medicinal stones and ceramics to improve contaminant removal. The research also found that the presence of sediment improves removal efficiency. Shells and oysters proved particularly effective in this context. All the streams analysed showed satisfactory antibiotic removal rates, highlighting the importance of considering specific characteristics to maximize the effectiveness of each class of drug.

To solve the problem of water contamination by pharmaceuticals, it is necessary to look for low-cost or easily accessible technologies. Thus, CW systems have shown relevant potential to help with this urgent issue, and hybrid CWs have shown promising results in improving the quality of these environments. However, in order to better optimize CW systems, it is essential to consider the specific characteristics of the antibiotic compounds and the environmental conditions (aerobic and anaerobic) in which they are treated. In CW systems, aerobic conditions favor the degradation of certain antibiotics through oxidative processes, while anaerobic conditions are more effective for others through reductive processes. Combining these environments in hybrid systems can significantly increase overall removal efficiency. In addition, new studies can be developed to further evaluate the impact of root types and bed configurations on antibiotic removal efficiency, as these factors play a vital role in optimizing CW performance.

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VALDEMIR F. DA SILVA[1]
https://orcid.org/0000-0001-7871-5434

DELMIRA BEATRIZ WOLFF[2]
https://orcid.org/0000-0003-2146-1503

[1]Universidade Federal de Santa Maria, Programa de Pós-Graduação em Engenharia Ambiental, Centro de Tecnologia, Av. Roraima, 1000, Cidade Universitária, Bairro Camobi, 97105-900 Santa Maria, RS, Brazil

[2]Universidade Federal de Santa Maria, Departamento de Engenharia Sanitária Ambiental, Avenida Roraima, 1000, Cidade Universitária, Bairro Camobi, 97105-900 Santa Maria, RS, Brazil

Correspondence to: **Valdemir Fonseca da Silva**
E-mail: valdemir.fonseca@acad.ufsm.br

Author contributions

valdemir Fonseca da Silva: Collected literature data; Designed; Wrote the manuscript; Checked and approved the manuscript. Delmira Beatriz Wollf: Edited and revised the manuscript; Checked and approved the manuscript.

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