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REVIEW ARTICLE

Free water surface constructed wetlands: review of pollutant removal performance and modeling approaches

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Abstract
Free water surface constructed wetlands (FWSCWs) for the treatment of various wastewater types have evolved significantly over the last few decades. With an increasing need and interest in FWSCWs applications worldwide due to their cost-effectiveness and other benefits, this paper reviews recent literature on FWSCWs' ability to remove different types of pollutants such as nutrients (i.e., TN, TP, NH_4-N), heavy metals (i.e., Fe, Zn, and Ni), antibiotics (i.e., oxytetracycline, ciprofloxacin, doxycycline, sulfamethazine, and ofloxacin), and pesticides (i.e., Atrazine, S-Metolachlor, imidacloprid, lambda-cyhalothrin, diuron 3,4-dichloroanilin, Simazine, and Atrazine) that may co-exist in wetland inflow, and discusses approaches for simulating hydraulic and pollutant removal processes. A bibliometric analysis of recent literature reveals that China has the highest number of publications, followed by the USA. The collected data show that FWSCWs can remove an average of 61.6%, 67.8%, 54.7%, and 72.85% of inflowing nutrients, heavy metals, antibiotics, and pesticides, respectively. Optimizing each pollutant removal process requires specific design parameters. Removing heavy metal requires the lowest hydraulic retention time (HRT) (average of 4.78 days), removing pesticides requires the lowest water depth (average of 0.34 m), and nutrient removal requires the largest system size. Vegetation, especially *Typha spp.* and *Phragmites spp.*, play an important role in FWSCWs' system performance, making significant contributions to the removal process. Various modeling approaches (i.e., black-box and process-based) were comprehensively reviewed, revealing the need for including the internal process mechanisms related to the biological processes along with plants spp., that supported by a further research with field study validations. This work presents a state-of-the-art, systematic, and comparative discussion on the efficiency of FWSCWs in removing different pollutants, main design factors, the vegetation, and well-described models for performance prediction.

Keywords Nutrients removal · Antibiotics removal · Pesticides removal · Heavy metals removal · Modeling

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Highlights
- FWSCWs ability in removing different pollutants were comprehensively reviewed.
- China followed by the USA have the highest CWs applications.
- Each pollutant requires a different design to achieve optimum removal performance.
- Typha spp. and Phragmites spp., are the most utilized plants in FWSCWs' systems.
- FWSCWs modelling approaches revealed need for involving internal process mechanisms.

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Introduction

Aquatic ecosystems around the world are impacted by the unmediated discharge of diverse effluents with elevated concentrations of various pollutants, including nutrients, heavy metals, antibiotics, and pesticides (El-Sheikh et al. 2010; Nguyen et al. 2019; Sabokrouhiyeh et al. 2020). These pollutants lead to a variety of environmental issues, including eutrophication from excess nutrients, rise of antibiotic resistance genes (ARGs) from antibiotics release, and toxicity impacts to aquatic plants and wildlife from heavy metals and pesticides (Hadad et al. 2018; Hamad 2023, 2020; Hawash et al. 2023; Tournebize et al. 2017; Vymazal and Březinová 2015). It is imperative that concerted efforts are undertaken to mitigate these pollutants at their source, employing cost-effective and environmentally friendly technologies. This approach is essential not only to meet water quality compliance standards but also to safeguard the well-being of humans and animals and preserve the integrity of our ecosystems.

Constructed wetlands (CWs) are a nature-based solution for wastewater management that can effectively remove a variety of pollutants and are relatively inexpensive to build and operate (Gaballah et al. 2021a; Hamad 2023; Page et al. 2010; Peguero et al. 2022; Stefanakis 2020; Stefanakis et al. 2021). Globally, CWs technology has been widely used as a green solution for environmental pollution treatment and the promotion of cleaner production (Ji et al. 2022; Liu et al. 2019a; Mahabali and Spanoghe 2014). CW performance and design has been intensively reviewed in the literature; for instance, the role of substrate in CWs (Ji et al. 2022), pesticides removal (Vymazal and Březinová 2015), metals removal (Wu et al. 2019; Xu et al. 2019), nutrients removal (Gaballah et al. 2022; Li et al. 2018; Stefanakis et al. 2021; Vymazal 2007), antibiotics removal (Gaballah et al. 2021a; Lu et al. 2020), CWs performance under different climates (Ferreira et al. 2023; Stefanakis 2020; Wang et al. (2017),,), treating different wastewaters (Rizzo et al. 2020), landfill leachate treatment (Bakhshoodeh et al. 2017), reasons for clogging (Wang et al. 2021), CWs' operational reassessment (Nuamah et al. 2020), CWs' modelling (Kumari and Singh 2018), and many other reviews as CWs are one of the most growing research technologies for wastewater treatment (Travaini-Lima et al. 2015). These studies have focused on CWs generally with less specific focus on free water surface constructed wetlands (FWSCWs). However, while other CW configurations such as subsurface wetlands may have higher removal rates on average, FWSCWs wetlands offer advantages in terms of cost-effectiveness, scalability, and providing additional sustainable benefits for habitats (Acero-Oliete et al. 2022; Vivant et al. 2019).

FWSCWs is a more natural man-made wetland system consisting of channels or basins characterized by shallow water depth and rich with ecosystem diversity. The design parameters governing these systems play a pivotal role in shaping the physical, chemical, and biological processes that unfold simultaneously (Bakhshoodeh et al. 2020). Nonetheless, there remains an unaddressed research gap, comparing the efficacy of FWSCWs for removing different pollutants, and the tradeoffs in design for optimal pollutant removal. FWSCWs is one of the most applied types of CWs due to its lower cost in comparison with other CWs types, convenient operation, easy maintenance, high efficiency, and its large scale applications (Acero-Oliete et al. 2022; Canet-Martí et al. 2022; Nuamah et al. 2020; Shahid et al. 2018). While FWS performance in phosphorus removal (Kadlec 2016) and nutrient removal more broadly (Li et al. 2018) have been reviewed, scant attention has been devoted to other pollutant removal mechanisms and the design parameters that govern FWS performance. Due to the fact that some wastewater types have several pollutants, CWs often need to be designed to remove different pollutants simultaneously. Therefore, there remains a need to evaluate FWS ability to remove various pollutants, and how design decisions that may increase removal of one pollutant could decrease removal of another.

Researchers have made significant efforts to understand optimal conditions for pollutant removal in CWs, employing a combination of experimental work and modeling approaches. Notwithstanding these efforts, a comprehensive review dedicated exclusively to evaluating the overall efficacy of FWSCWs in the removal of diverse pollutants, including nutrients, heavy metals, antibiotics, and pesticides, from varied wastewater sources remains conspicuously absent. There is a need to synthesize past work on these systems to better understand their performance and provide recommendations for design and future research. The objectives of this review are to: 1) Compare empirical data on FWSCWs ability to remove nutrients, heavy metals, antibiotics, and pesticides, 2) Explore how different designs and operating conditions affect FWSCW performance, 3) Determine the role of aquatic plants in pollutant removal in FWSCWs, and 4) Critically examine the different modeling approaches that have been used to analyze and predict FWSCW performance.

Material and methods

We searched the Scopus database (September 20, 2023) with the keywords of "Constructed wetlands"; "Constructed wetlands, Modelling"; "Free water surface constructed wetlands, Modelling" and found 12,202, 893 and 49 articles, respectively, from 2001 to 2023, which were then used for bibliometric analysis. This bibliometric analysis was used to explore publication patterns in constructed wetlands research (including trends over time and where research is being conducted and published). A separate search using the keyword "Constructed wetlands" found a total of 14,524 documents from 1975 to 2024, focused on all CWs types and purposes. The articles were selected based on their inclusion of the keyword in the article title, keywords, and abstract. The bulk of this review focused on publications related to FWSCWs removal of nutrients, heavy metals, antibiotics, and pesticides published between 2010 and 2023. We reviewed 97, 27, 10, and 9 articles, respectively for these different pollutants (Fig. 1). Those studies with sufficient data were kept for analysis (Tables SI 1, 2, 3, and 4). Statistical analysis was conducted to estimate the mean and standard deviation of the selected studied variables. Correlation and regression analyses were performed, mainly to examine the influence of factors on the performance of FWSCWs.

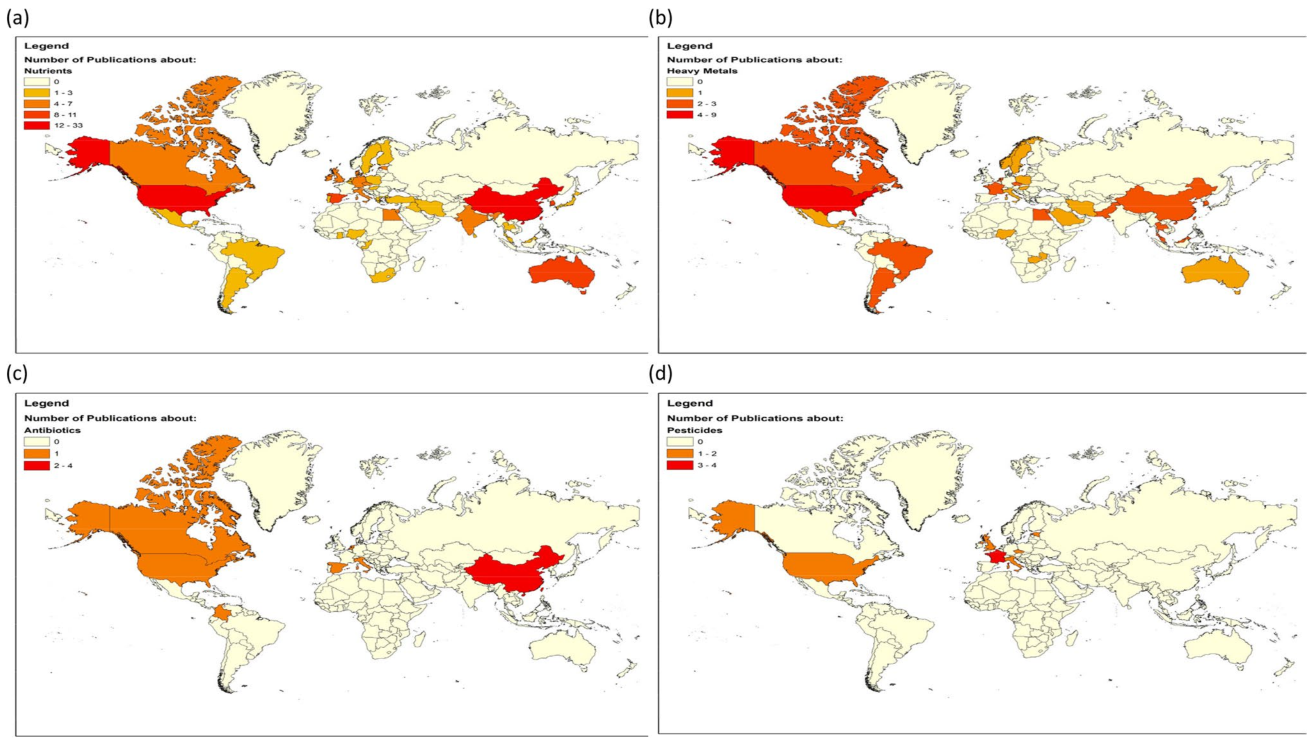

Fig. 1 Distribution of the number of publications regarding FWSCWs worldwide, (**a**) represents nutrients, (**b**) represents heavy metals, (**c**) represents antibiotics, and (**d**) represents pesticides

Bibliometric analysis of constructed wetlands

Increases in the number of publications per year underscores the escalating interest in the field of constructed wetlands (Fig. 2a). However, the field of constructed wetlands modeling receives comparatively less attention compared with experimental work. Moreover, among of modeling contributions, the articles related to FWS (49 studies) are very few compared to the overall constructed wetlands types modeling (893 studies). Kadlec and Wallace (2009) reported that the relative scarcity of literature in this aspect can be attributed to the challenges associated with the calibration of wetlands models. Meanwhile, modeling can improve our understanding of removal processes and lead to more efficient designs. This lack of publications on modeling of FWSCWs therefore may be limiting the application and understanding of these systems.

The VOS Viewer software 1.6.19, an open-access tool, was employed to identify critical keywords from the dataset and construct a co-occurrence network. This co-occurrence network reveals that "constructed wetlands" is closely associated with wastewater, nutrients, modeling, water pollutants, ecosystems, and hydraulics (Fig. 2d). These findings may enrich the literature by highlighting the interconnectedness of constructed wetlands with these related topics, potentially paving the way for new research directions. The Ecological Engineering journal serves as the primary platform for most of the publications on constructed wetlands, followed by Water Science and Technology, Fig. (2c). This information can serve as a valuable guide for researchers when considering where to submit their articles in the future. For FWSCWs in particular, most of the research is being conducted in China, North America, and Europe (Fig. 2b). According to Zhang et al. (2021), studies on CWs in China intensified between 2001 and 2010, with a particular focus on N removal and mechanisms from 2011 to 2020. However, the utilization of surface flow constructed wetlands remains limited in China due to the scarcity of land resources, in contrast to practices in the United States (Zhang et al. 2009). However, other countries have conducted relevant research, especially with regards to nutrients and heavy metals removal.

Free water surface constructed wetlands performance

FWSCWs and subsurface flow constructed wetlands (SSFCW) stand out as two of the most commonly employed CW designs (Ilyas and Masih 2018). However, their costs differ significantly, with FWSCWs and the more cost effective and easier choice for large-scale implementation. In a significant report by Gaballah et al. (2022), it was noted that FWSCWs systems constitute a substantial 25% of the total CWs in Egypt, while the rest were horizontal subsurface flow, vertical subsurface flow, and hybrid systems. However, the performance of FWSCW in removing different pollutants is considered lower than other types of CWs that needs. Therefore, in the current study, the design showcases a comprehensive analysis of its strengths and weaknesses in the context of removing various pollutants from diverse wastewater sources. Beyond its cost-effectiveness, FWSCW is recognized for its low energy consumption and extended operational longevity when compared to other CW systems. The design of FWSCW is acknowledged for its simplicity and effectiveness in pollutant removal, as well as its capacity to provide a conducive environment for numerous habitats (Acero-Oliete et al. 2022; Canet-Martí et al. 2022; Nuamah et al. 2020; Shahid et al. 2018; Vivant et al. 2019; Vymazal and Březinová, 2015; Wu et al. 2015). Thus, this review addresses the performance of FWSCW in removing diverse pollutants and how design choices impacts this performance. In this section, an analysis and discussion were conducted on the existing literature regarding the performance of FWSCW in removing various pollutants and evaluating the impacts of design variables on their performance, as well as the pre-treatment applications.

Design impacts on FWSCWs removal performance

In this section, data was collected regarding the applied design variables and their linking to different pollutants removal efficiencies. Data pertaining to design and operational parameters (i.e., hydraulic residence time, hydraulic loading rate, water depth, system area, influent composition, and plant species) for FWSCWs performance were extracted and analyzed to demonstrate their critical importance in achieving sustainable and effective contaminant removal, Fig. (3). The performance of FWSCWs in removing nutrients, heavy metals, antibiotics, and pesticides, based on the most relevant studies, is presented in Tables SI 1, 2, 3, and 4. In this section, we analyze and evaluate the running conditions of hydraulic residence time (HRT), water depth, system area, and flow capacity that applied in FWSCWs different pollutants in order to assess their impact on pollutant removal performance.

HRT effect on FWSCWs removal performance

The hydraulic conditions of a FWSCWs system can significantly influence biogeochemical processes, microbial activity, and the system's overall efficiency in removing pollutants. HRT was highly variable in the studies we analyzed (Table 1). HRT may have a varied value based on the type of pollutant. HRTs for nutrients, antibiotics,

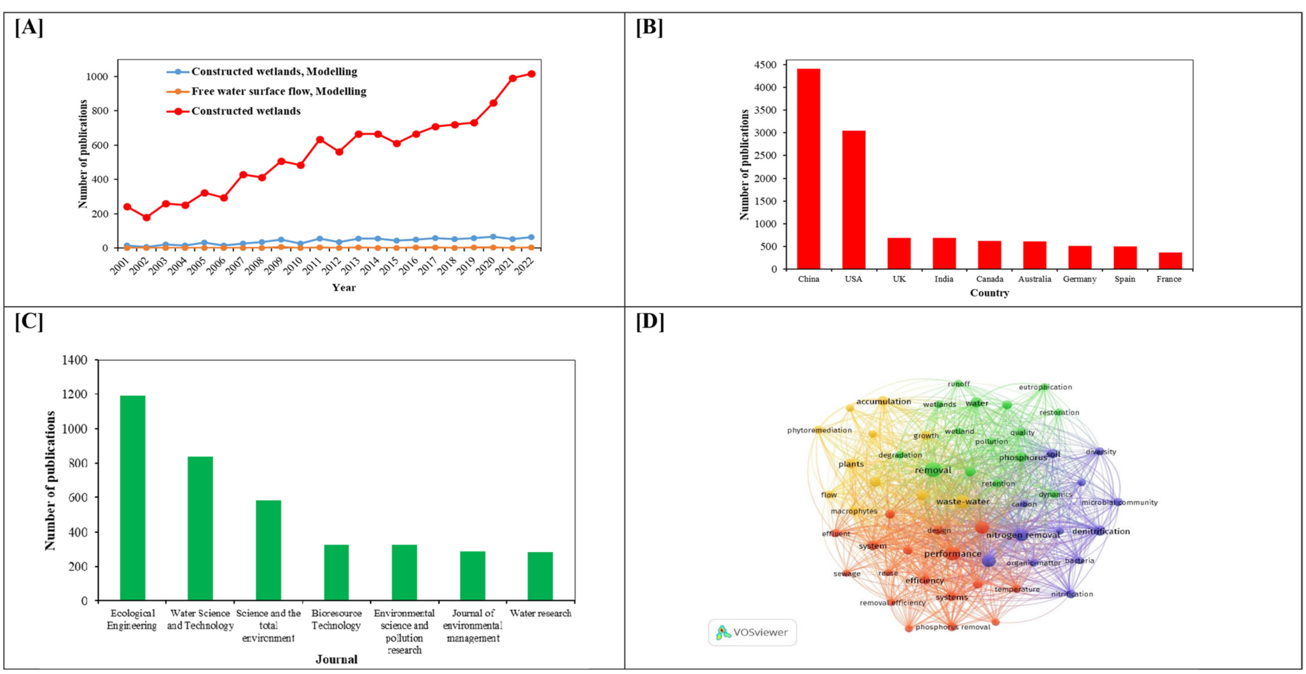

Fig. 2 Bibliometric analysis of existed literature regarding FWSCWs applications, (**a**) represents the number of studies from 2001 to 2022 regarding constructed wetlands (modelling), free water surface (modelling), and constructed wetlands. (**b**) represents number of publications in constructed wetlands according to countries. (**c**) represents number of publications by journal, and (**d**) represents the bibliometric analysis of most common 50 keywords used in the constructed wetlands field

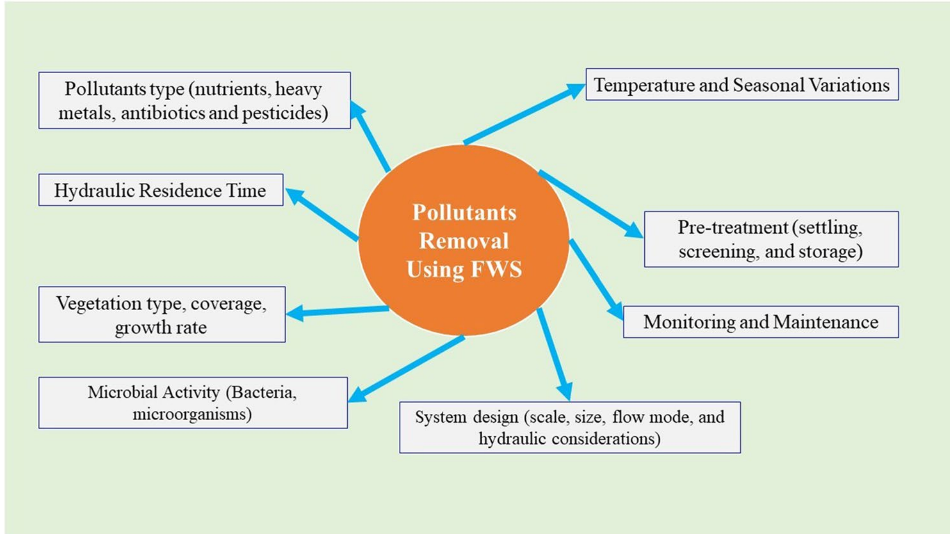

Fig. 3 The main factors influencing the pollutants removal through FWSCWs

and pesticides (average of 9.5, 11.8, and 9.3 days, respectively), tended to be longer and more variable than for heavy metals (average of 4.78 days). Ranges for all pollutants were large, with minimum HRTs < 1 day and maximums of 70 days (Table 1). Pollutant removal rates generally increased with increasing the value of HRT (Fig. 4e-f). Linear regression showed statistically significant relationships of HRT for nutrients, antibiotics, and pesticides ($p < 0.01$). While metals and HRT showed no significant relationship. However, the strength of all relationships was weak. Differences in experimental set up and operation among the reviewed studies could explain why stronger trends did not emerge – a more detailed statistical analysis could uncover potential relationships between the many interacting variables controlling pollutant removal. Generally, a longer HRT is expected to provide higher removal efficiencies as it allows wastewater to move slowly to the outlet, increasing the contact time among the wastewater, the rhizosphere, and microorganisms. However, in case of antibiotics, longer time can reduce treatment efficacy (Liu et al. 2019b). A longer time can also lead to a reverse action in plant uptake, causing plants to release pollutants back into the water. For example, Gaballah et al. (2021b) reported that a HRT of 3–5 days achieved higher nutrient removal compared to a HRT of 7 days.

Water depth effect on FWSCWs removal performance

Water depth is considered the primary design factor for CW systems for pollutant treatment, as it directly affects detention capacity, flow dynamics, and pollutant removal performance during operation (Vo et al. 2023). Similar to HRT, wetland depth was highly variable among the collected studies (ranging from 0.1 to > 1 m). Wetlands for removing nutrients are deeper on average (0.52 m) compared to wetlands for the other pollutants (average of 0.34–0.39 m) (Table 1). These data reveal subtle differences in the water depth used for different pollutant removal purposes, indicating that FWS design may need slight adjustments based on the type of pollutant.

There are no clear relationships between examined pollutants in water depth based on the data we found (Fig. 4a-d). However, pollutant removal has been shown to vary with water depth in some individual studies. This variation may be a result in differences between the system sizes and

Table 1 Summary of most effective design parameters for effective pollutants removal through FWSCWs

Pollutants	HRT (days)		Water depth (m)		Area (m^2)		Most utilized plants
	Mean ± SD	Range	Mean ± SD	Range	Mean ± SD	Range (low-high)	Range
Nutrients ($n = 15$)	9.50 ± 7.36	0.9 – 30	0.52 ± 0.33	0.1 – 1.45	15227.4 ± 34183.2	0.16-12500	*Rooted plants spp.*
Heavy metals ($n = 10$)	4.78 ± 3.58	0.11—12	0.39 ± 0.24	0.15 – 1.0	3942.3 ± 11832.9	0.18-43200	*Typha spp.*
Antibiotics ($n = 8$)	11.8 ± 21.1	0.82 – 70	0.39 ± 0.22	0.15 – 0.8	3006.6 ± 6780.2	0.23-2000	*Typha spp.*
Pesticides ($n = 5$)	9.30 ± 9.39	0.19—28	0.34 ± 0.28	0.1 – 0.8	18391.3 ± 44879	0.094-110000	*Floating spp.*

n refers to number of studies

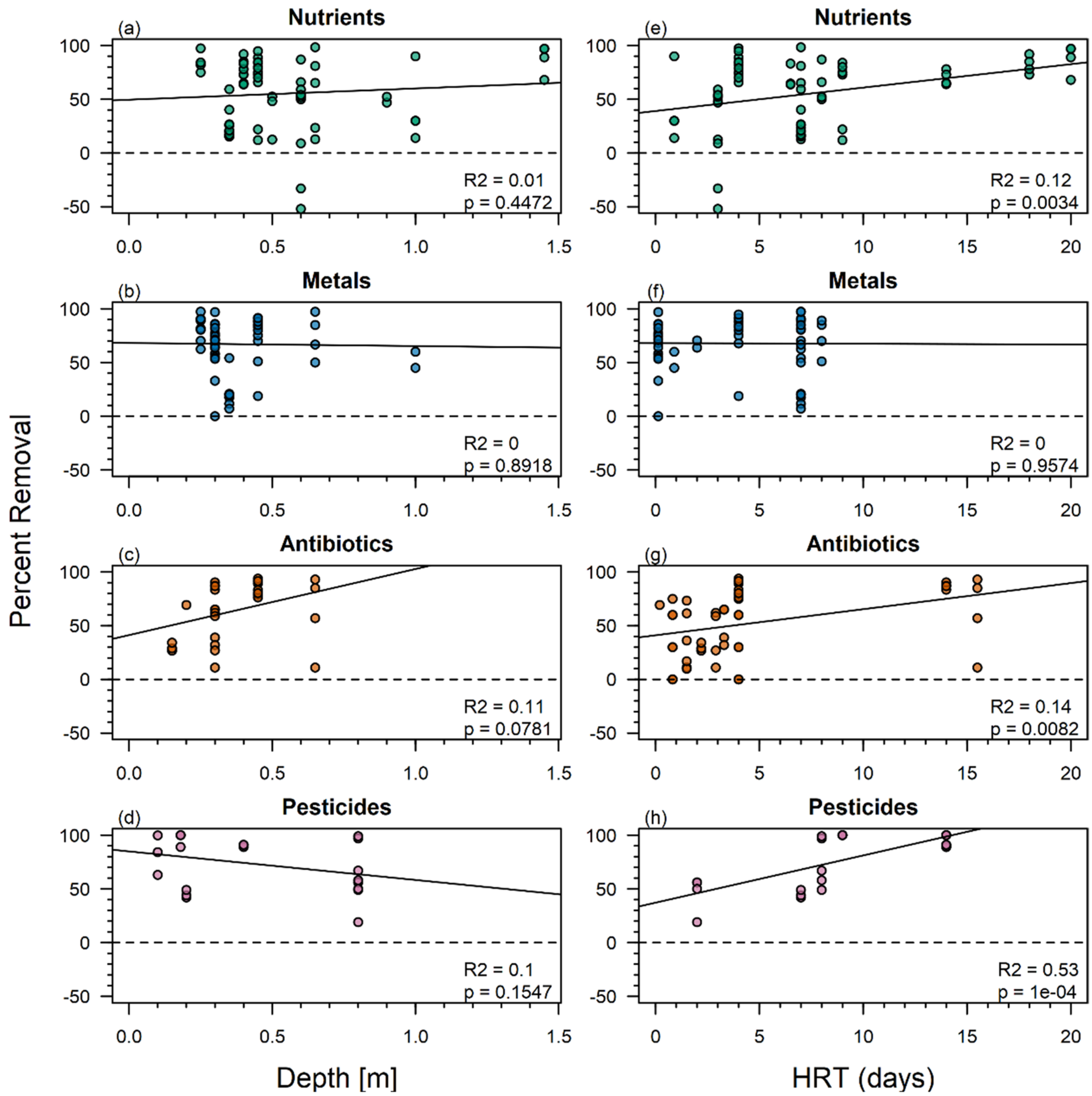

Fig. 4 Relationships between percent removal of the four pollutant categories and depth (**a-d**) and hydraulic retention time (**e–h**). Simple linear regression results are shown for each, including the R^2 value and p-value of the slope

pollutant type. According to Gaballah et al. (2021b, 2019), a water depth of 0.25 m performed better for nutrients and heavy metals compared to water depths of 0.15 m and 0.35 m when using different floating plants. This could be because shallow water depth can facilitate direct oxygen release by plant roots, which further assists in the biological removal of pollutants by microorganisms (Zhang et al. 2016).

FWS systems typically consist of basins or channels with suitable soil or another medium to support rooted vegetation. The shallow water depth reduces flow velocity and enhances the plant's capacity for pollutant uptake (Vymazal and Březinová 2015). However, excessively shallow water depth may limit the creation of different oxidation zones (aerobic/anaerobic), which are favorable for the removal of nitrogen compounds in FWS (Ferraz-Almeida et al. 2020). Nonetheless, it remains unclear at which water depth in FWS, the removal of pollutants is most efficient, as this can vary based on several factors, such as environmental conditions, system size, wastewater type, HRT and hydraulic loading rate (HLR), pollutant type and initial concentration, and measurement procedures. This suggests that the influence of water depth on the removal of different pollutants through FWS warrants further investigation.

System size effect on FWSCWs removal performance

The size of FWSCWs included in this review varied widely, ranging from 0.16 to 125,000 m^2. This wide range of system sizes suggests that FWS has been tested across different scales of application. As indicated in Tables SI 1, 2, 3, 4, and summarized in Table 1, the land area occupied by FWS was more extensive in the case of nutrient treatment, followed by heavy metals, while it was smaller for antibiotics and pesticides. These data demonstrate the research progress of FWS in relation to the removal of different pollutants, with FWS performance for antibiotics and pesticides still undergoing laboratory and pilot-scale investigations, with more full-scale operational systems for nutrients and heavy metals. According to Vymazal and Březinová (2015), the initial attempts to use wetland macrophytes for pesticide removal date back to as early as the 1970s, while CWs have been applied for pesticide removal in only the last decade. In the case of FWS, the system size for pesticide removal ranged from 0.094 to 23300 square meters. As reviewed by (Gaballah et al. 2022; Liu et al. 2019b), FWS systems typically have larger sizes compared to other CW systems but exhibit lower removal efficiencies in terms of antibiotics. This lower performance can be attributed to the fact that most large-scale FWS systems were constructed for purposes other than pollutant removal, with research primarily focused on monitoring system performance rather than conducting in-depth examinations of removal processes.

Flow capacity impact on FWSCWs removal performance

FWS systems have demonstrated high applicability for treating various wastewater types, with flow capacities ranging from 2 L to 21,500 m^3/day across system scales ranging from lab-scale to large scale (as indicated in Tables SI 1, 2, 3, and 4). These flow capacities were found to depend on the type of wastewater being treated. For example, high flow capacities were observed in FWSCWs systems designed to remove excessive amounts of nutrients from agricultural wastewaters. Conversely, FWS systems were designed with lower flow capacities when treating highly concentrated wastewater types like domestic wastewater.

Removal efficiency of different pollutants by FWSCWs

FWSCW have demonstrated a significant capacity to remove various pollutants, albeit with variations depending on the specific pollutant. This study reviews the efficacy of FWSCW in removing nutrients (i.e., TN, TP, NH_4-N, COD, BOD), heavy metals (i.e., Fe, Zn, and Ni), antibiotics (i.e., oxytetracycline, ciprofloxacin, doxycycline, sulfamethazine, and ofloxacin), and pesticides (i.e., Atrazine, S-Metolachlor, imidacloprid, lambda-cyhalothrin, diuron 3,4-dichloroanilin, Simazine, and Atrazine), Table (SI 1–4).

Removal efficiency of nutrients

Total nitrogen (TN), total phosphorus (TP), ammonium nitrogen (NH_4-N), and other water quality parameters such as chemical oxygen demand (COD) and biological oxygen demand (BOD) are the most frequently studied and reported parameters. Average removal rates were varied across the nutrients analyzed (51.6% for TN, 48.7% for TP, 54.4% for NH_4-N, 58.3% for COD, and 65.4% for BOD_5) (Table 2). Ranges of removal rates were large, indicating a variability in performance depending on the system scale, wastewater feed, retention time, and its initial concentration. For example, initial concentrations of TN ranged from 0.04 – 900 mg/L, and was largely a function of wastewater source (higher for domestic wastewater, and lower for agricultural runoff).

The diverse operational conditions of FWS have resulted in variable removal efficiencies for each parameter. For example, FWS systems treating landfill leachate removed 80.6, 45.4, 5.5, 70.0, 81.7, and 59.5% of initial BOD_5, COD, TP, Ammonia-N, TN, and total suspended solids (TSS), respectively (Bakhshoodeh et al. 2020). These values are somewhat higher than those analyzed in the current review. This difference can be attributed to the fact that this review has examined various wastewater sources rather than focusing on a single source. This finding underscores the importance of summarizing the state-of-the-art of existing literature in this regard, which can serve as a valuable resource for planning and designing FWS systems for the treatment of various wastewater sources.

Generally, nutrients can be effectively removed by FWSCWs as they are typically required for the growth of plants and microorganisms. Additionally, FWS provides favorable conditions for enhanced nutrient removal; for instance, ammonia nitrogen and other nitrogenous gases can be readily volatilized into the atmosphere under higher temperatures. However, the removal of TP is relatively low when compared to the removal of other pollutants. This is due to the fact that TP is challenging to remove biologically and is less readily taken up by plants (Kadlec and Wallace 2009; Vymazal 2018). In contrast, TP can be removed through physical–chemical processes and by adsorption to metals, suspended solids, and soils (Colares et al. 2020). Shen et al. (2022) found that approximately 86% of TP was adsorbed by the system bed media due to the high affinity of phosphorus for sorption processes. In this regard, lower water depth, shorter retention time, and lower flow capacity all promote greater TP adsorption. Gaballah et al. (2021b) reported that TP removal was higher at a water depth of 0.15 m than at water depths of 0.25 m and 0.35 m, and within a shorter retention time of 4 days compared to 7 days. TP removal can also be hindered in FWSCWs when flow capacity and initial TP concentration are high

(Keizer-Vlek et al. 2014; Palihakkara et al. 2018). Therefore, adjustments to FWSCWs design factors might have the potential to enhance TP removal. However, these conditions may be less effective for removal of nitrogen. Nitrate, in particular, may be removed most effectively by denitrification, which requires anoxic conditions that could release adsorbed phosphorus back into the water column. There is therefore a tradeoff between conditions favorable for removal of different nutrients that must be accounted for in wetland design and operation.

Removal efficiency of heavy metals

FWSCWs show variable performance for heavy metal removal (Table 2). We found that iron (Fe), zinc (Zn), and nickel (Ni) are the most frequently studied metals. The inflow concentrations of these metals ranged from 0.2 μg/L to 26.5 mg/L, with an average removal rate of 67.8%. The principal removal mechanisms for heavy metals in CWs include biological pathways, chemical precipitation and co-precipitation, binding to organic matter, sorption onto soil and plant root surfaces, plant uptake, and filtration of suspended solids by root and soil systems (Bakhshoodeh et al. 2020, 2017; Xu and Mills 2018). Given that FWSCWs offer a highly conducive biological environment, this can lead to enhanced removal of heavy metals. However, compared to other pollutants, the removal of heavy metals is more sensitive to HRT. Longer HRT, such as 15 days, has been shown to result in lower removal of metals like copper (Bhutiani et al. 2019). Similarly, higher water depth has been found to decrease the removal of nickel (González et al. 2015) and lead (Gaballah et al. 2021b). Additionally, high loading rates of metals can stress plant uptake and lead to metal accumulation in plant tissues, potentially resulting in the release of metals back into the system.

Table 2 Summary of pollutant removal performance of FWSCWs. Values shown are mean (range)

Pollutants	Initial concentration (mg/L)	Percent Removal (%)
Nutrients		
TN	132.5 (0.04 – 900)	51.6 (9.0 – 90.3)
TP	2.4 (0.05 – 12.5)	48.7 (-52 – 87)
NH_4-N	8.64 (0.21 – 28.76)	54.4 (-33 – 97.53)
COD	179.2 (25.65 – 600)	58.3 (15.3 – 85)
BOD5	54.6 (3.1 – 181.5)	65.4 (15.5 – 92)
Heavy metals	1.5 (2×10^{-4} – 26.5)	67.8 (0.0–97.3)
Antibiotics	3.5 (1.93×10^{-6} – 100)	54.71 (0 – 93.8)
Pesticides	0.002 (5.8×10^{-8} – 0.05)	72.85 (42 – 100)

Negative values refer to an increase in outflow concentration compared to inflow concentration, indicating a negative removal

Removal efficiency of antibiotics

The number of studies exploring antibiotics removal through various CWs configurations has significantly increased in the last decade (McCorquodale-Bauer et al. 2023). The main roles of different substrates in antibiotics removal were reviewed by (Cui et al. 2023). FWSCWs are the most widely applied CWs at a large scale compared to other CWs types, and their ability to remove antibiotics varies and still requires considerable attention. The most examined antibiotics in FWSCWs include oxytetracycline, ciprofloxacin, doxycycline, sulfamethazine, and ofloxacin, which are known for their high consumption rates in the animal livestock industry, and their fate has been monitored in the literature (Gaballah et al. 2021a, 2021c; Hawash et al. 2023).

Some studies have found FWS have a wide range of antibiotics removal rates (-67% to 100%, average 50.39%) (Liu et al. 2019b), while others suggest the removal of antibiotics by FWSCWs is negligible (He et al. 2018). In this review, we found an average antibiotic removal efficiency of 54.71 ± 27.9% (ranging from 0.0% to 93.8%), associated with different initial concentrations ranging from 0.00193 μg/L to 100 mg/L (Table 2). This removal performance is the lowest among examined pollutants (nutrients, metals, and pesticides) in the current work. This lower removal performance is consistent with the existing literature. Ilyas and van Hullebusch (2020) reported that FWS has the lowest removal performance for antibiotics and personal care products (PCPs) among other CWs types due to the limited coexistence of aerobic and anaerobic conditions. Although FWS systems provide some aeration due to the free water surface exposed to the atmosphere, the oxygen transfer rate is lower compared to systems with continuous aeration, such as subsurface flow constructed wetlands. This limited aeration can restrict the activity of aerobic microorganisms involved in the degradation of pharmaceuticals and PCPs. Moreover, antibiotics and PCPs are often complex chemical compounds with diverse structures and properties. Some of these compounds may require specific environmental conditions or microbial communities for efficient degradation. The dynamic and variable conditions within FWS systems may not always support the optimal degradation of these compounds. Additionally, FWS removal performance for antibiotics may be affected by the initial concentration of nutrients and other water quality parameters (Liu et al. 2019b).

Removal efficiency of pesticides

The performance of FWS for the removal of pesticides from agricultural runoff and drainage exhibit high variability (Vymazal and Březinová, 2015). Pesticides can be removed within a range of 20% to 90% through CWs (Tournebize et al. 2017). However, the removal and dissipation of pesticides are complicated due to the great diversity of their uses and properties, especially regarding their transport and elimination. Pesticides can be eliminated from wastewater through various processes, including transfer and transformation (Elsaesser et al. 2011; Mathon et al. 2019). In the studies we reviewed, pesticide inflow concentrations ranged from 0.058 ng/L to 50 μg/L. FWS demonstrated relatively higher removal performance compared to other pollutants examined in this review, with an average removal rate of 72.85% for 12 different pesticides (ranging from 42 to 100%) (Table 2). This relatively higher removal could be due to the prolonged time of systems applications, in addition to the low initial concentrations compared to other examined pollutants in this work.

Role of plants in FWSCWs

Plants can uptake nutrients as a source for their growth, antibiotics as a carbon source, and other pollutants as compounds of their feeding (Wang et al. 2017). There is increasing focus on plants role in the treatment process in CWs, especially their active role in supplying oxygen and root exudates and helping to maintain healthy microbial life (Masi et al. 2023; Rizzo et al. 2020). Plants can significantly influence the efficiency of CWs by creating suitable conditions for the removal of pollutants (Ji et al. 2022). The ability of plants to uptake and accumulate different pollutants in their tissues varies from one species to another. Additionally, the effectiveness of plants in CWs, particularly their adsorption sites and activity, may be limited by the initial concentration of pollutants (Liu et al. 2019b). Therefore, the selection of suitable plant species is essential for the effective removal of pollutants in CWs. Gaballah et al. (2022) reported that *Eichhornia crassipes*, a floating plant, and *Cyperus papyrus* and *Typha angustifolia*, emergent plants, are widely used in CWs in Egypt. *Phragmites australis* is commonly applied in CWs due to its various practical advantages, such as limiting the risk of clogging, and the species' longevity, high resistance to pollutants exposure, and effective pollutant removal (Rizzo et al. 2020). In particular, *Phragmites australis* has been extensively studied for its role in antibiotics removal in CWs (Gaballah et al. 2021a). Nuamah et al. (2020) highlighted popular emergent aquatic plant species commonly used for wastewater treatment, including *Scirpus spp., Phragmites spp., Typha spp., Juncus spp., Eleocharis spp., Iris spp.,* and *Carex spp*.

While there has been extensive research on the role of plants in floating treatment wetlands, their role in FWSCWs still requires considerable attention. Common plants that have demonstrated considerable pollutant removal performance in FWS are highlighted and discussed in this paper.For instance, *Typha angustifolia*, *Phragmites australis*, and *Eichhornia crassipes* are commonly used in Africa, Europe, and Asia for the removal of nutrients and heavy metals. *Typha angustifolia, Myriophyllum verticillatum*, and *Cyperus alternifolius* are commonly employed for antibiotics removal, while *Juncus effusus*, *Phragmites australis*, and *Eleocharis mutata* are utilized for pesticides removal, as illustrated in Table (S1-4). In this review, plants were categorized based on their use in FWS as follows: *Typha spp.* (*Typha latifolia, Typha domingensis*), *Phragmites spp.* (*Phragmites australis, Phragmites angustifolia*), floating *spp.* (*Eichhornia Crassipes, Pistia stratiotes, Azolla pinnata*), and other rooted plants spp. (e.g., *Cyperus papyrus, Cyperus giganteus, and Juncus effusus, C. tegetiformis*). The FWS performance in the presence of these plant categories is as follows: an average removal of 50.8%, 38.3%, 57.0%, and 57.0%, respectively for nutrients; 70.7%, 67.1%, 59.5%, and 64.8%, respectively for heavy metals; 67.1%, 46.1%, 45.5%, and 63.5%, respectively for antibiotics; and 56.5%, 57.3%, 92.4%, and 59.9%, respectively for pesticides, as shown in Fig. (5). From the collected data analysis, it was observed that FWS systems supported with *Typha spp.* showed slightly better performance for nutrients and metals,

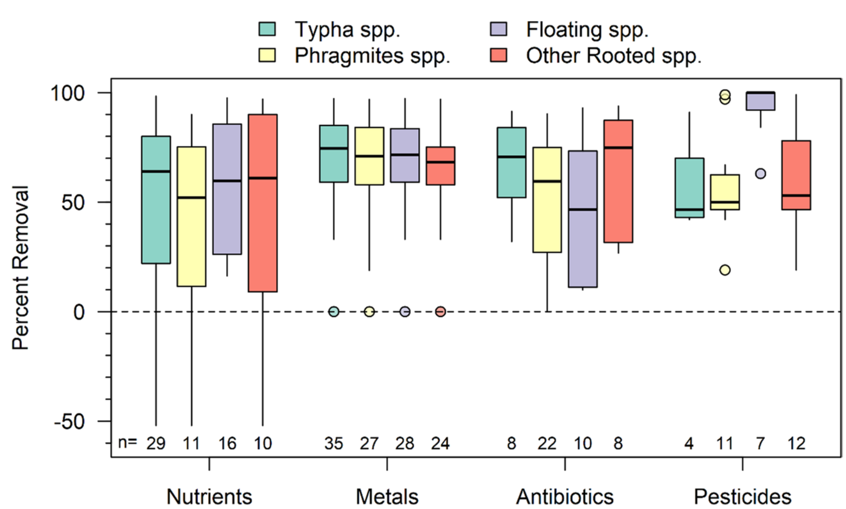

Fig. 5 Plant species applied in FWSCWs for different pollutants removal and their impacts on the removal process

while other rooted spp., had the best performance for antibiotics. This performance resulted from the efficient uptake mechanisms of these pollutants by such plants, regardless of their characteristics. On the other hand, the largest difference was observed for pesticides, whereas, floating spp., showed by far the best performance. This performance might be attributed to the fact that floating plants have larger contact areas with water compared to other plant types, which facilitates the uptake of pesticides, leading to their immobilization or detoxification. Another reason is that, many pesticides are hydrophobic, meaning they have low solubility in water and tend to adhere to surfaces. This property allows them to accumulate on the surfaces of floating plant leaves, which have a waxy cuticle that enhances pesticide retention (Vymazal and Březinová 2015). Overall, the ability of plants to uptake pollutants differs from one plant species to another and from one pollutant to another, resulting in different responses to various pollutant types. Hence, increasing attention to the role of plants in removing various pollutants is still warranted. In addition to future research should investigate how biomass dynamics, including production and harvesting of plants, affect the removal of these contaminants. Understanding the role of biomass can provide deeper insights into optimizing treatment processes for more effective removal of pesticides and antibiotics.

Pre-treatment impacts FWS's performance

Pre-treatment methods can significantly impact the performance of FWSCWs (Bosak et al. 2016). As FWSCWs have shown lower removal performance compared to other CWs, further assistance is needed through the application of pre-treatment steps. Pre-treatment methods are often employed to improve the quality of influent wastewater before it enters the wetland system. They can include sedimentation, aeration, screening, septic tanks, and other processes aimed at reducing the load of solids, organic matter, and contaminants in the wastewater (Abdelwahab et al. 2021). According to (de Campos and Soto 2024), the potential for improved pollutant removal lies in the integration of constructed wetlands (CWs) with conventional and advanced technologies in new configurations. For instance, Bosak et al. (2016) reported that the removal efficiency of nutrients can be significantly enhanced by applying pre-treatment methods such as sedimentation and aeration. Vymazal (2014) recommended the implementation of pre-treatment methods for effective and sustained performance of wetlands. Lei et al. (2022) reported that the removal of sulfamethoxazole, furosemide, mecoprop, and diclofenac was significantly enhanced with less accumulation in the plants after light pre-treatments (UVC and sunlight) method in mesocosm scale. Kamilya et al. (2022) recommended that pre-treatment systems, such as septic tank, hydrolysis acidification, coagulating sedimentation, grille, and UASB, can significantly reduce the quantity of suspended and organic matter entering into CWs, which may effectively reduce clogging of substrates. Overall, the different pollutant concentrations in the wastewater have an adverse effect on the effluent quality and the biotic component of the CW systems. Hence, it is necessary to reduce the effluent concentration by introducing a pre-treatment unit or by modifying the operating conditions of the CW systems.

FWS modelling approaches

Modeling of CWs is used for a variety of purposes, including predicting system performance, adjusting design parameters to optimizing systems performance, and ensuring compliance with environmental regulations and standards. Models are tools – and these tools are needed to better describe processes in CWs, compare similar systems and their behavior under different conditions, and predict and evaluate system performance (Meyer et al. 2015), Table (3). Pollutant removal in all CWs, including FWSCWs, is dependent on system hydraulics as well as a variety of physical and biochemical processes (e.g., adsorption, plant uptake, microbial metabolism, etc.). Modeling these complex, interacting processes is difficult, and many models take simplified approaches to predict CW performance.

CWs models vary in complexity depending on the specific modeling objectives and data available. Various classification systems for wetland models have been developed, either depending on the modeling approach or model objectives (Meyer et al. 2015). Broadly, these models can be separated into two groups: "black-box" or "process-based" models (Galanopoulos et al. 2013, Kumar and Zhao 2011). Black-box models use statistical approaches or simple rate-based equations to predict pollutant removal, without accounting for the specific removal process involved, Table (3). Process-based models, on the other hand, try to explicitly model these various removal processes, and often also include more physically realistic modeling of wetland hydrology and hydraulics (Stephenson and Sheridan 2021). Several studies have examined modeling of CWs (Meyer et al. 2015; Galanopoulos et al. 2013; Kumar and Zhao 2011; Stephenson and Sheridan 2021), but typically with a focus on a particular type of wetland or specific process. Most modeling studies focus on other CWs types, and there is a need to better understand how existing modeling tools can be applied to FWSCWs. In this section, we review modeling approaches (separated into black-box and process-based models) that have been applied to FWSCs.

Black-box models focus on predicting overall pollutant removal rather than focusing on specific removal processes.

Table 3 Applied models in FWSCWs for different pollutants prediction

Category	Model name	Purpose	Used parameters	Software	Validation	RMSE	R^2	Reference
Black-box models	Fuzzy logic model	prediction model for five-day biochemical oxygen demand (BOD) removal	Plant type, Temperature, HRT, depth, solar heat, system substrate, system shape, month, initial concentration	MATLAB	(1) experimental data from five pilot-scale FWS; and (2) an independent set of data from various FWS facilities in the literature	/	0.8221	(Kotti et al. 2013)
	QWASI	describe the fate and transport of pesticides in FWSCWs	HRT, initial concentration, water depth, surface area, rainfall, temperature, buried sediment, water inlet/outlet, plant type, system size	Simulation model	Model was validated using two wetlands systems	/	0.9	(Ramos et al. 2019)
	tanks-in-series model (TIS)	total nitrogen removal from agricultural runoff	precipitation, air temperature, water level, inflow and outflow volume, water balance, water depth,	Simulation model	Models were validated based on FWS wetland located in the experimental farm of the Canale Emilio Romagnolo Land Reclamation Consortium, in the village of Budrio, Italy	2.42	/	(Canet-Martí et al. 2022)
	First-order kinetics with non-zero background concentration					2.29	/	
	Monod kinetics					2.52	/	
	AQUASIM model	describing the basic physicochemical and biochemical processes	Biological factors, water temperature, water volume, plant biomass, pollutant yield, system size	AQUASIM	Model was validated using one year running time of pilot FWS unit	/		(Galanopoulos et al. 2013)
	biokinetic model	simulates TSS concentration	Inlet/outlet total suspended solids concentration, Temperature, Water depth, Vegetation cover, Maximum / minimum daily wind speed	SURFWET	The model sensitivity analysis using the Morris method and scaled elementary effects was performed	/	/	(Gargallo et al. 2018)
	Statistical Regress model	Predicting nutrients removal (BOD_5, NH_3, TN, TP)	Water depth, plant coverage, temperature, HRT	SAS	Pilot-scale FWS data	/	0.743, 0.933, 0.911, 0.824	(Gaballah et al. 2019)
	first-order reaction kinetics using plug flow reactor model	Prediction of removing antibiotics ciprofloxacin and tetracycline	HRT, initial concentration, plant density	/	Using mesocosm scale of FWS system	/	0.8	(Panja et al. 2021)

Table 3 (continued)

Category	Model name	Purpose	Used parameters	Software	Validation	RMSE	R^2	Reference
	The BOD-VART mode	simulate the effects of the root zone and the water column in BOD removal processes	Flow velocity, effective diffusion coefficient, decay rate of BOD5 in the water column, HRT, vegetation,	MATLAB	FWSCWs large scale system in Egypt	1.97	0.74	(Aboukila and Elhawary 2022)
	VART-BOD model	Simulate the effects of the root zone and the water column in BOD removal processes	Flow velocity, effective diffusion coefficient, decay rate of BOD5 in the water column, HRT, vegetation,	MATLAB	Gustine City wetland and Lake Manzala engineered wetland	0.41–8.7	0.73–0.99	(Deng et al. 2016)
	VART-TP model and VART-NH4 model	Two models were used for removal of total phosphorus and ammonium in free-water surface wetlands	flow velocity, decay rate of TP, and effective diffusion coefficient in the root zone, cross-section area, HRT, system size, temperature	MATLAB	The VART-TP model validated through data collected from the test cells of a CWs in Florida; The VART-NH4 model validated through data collected from Egypt	(4.45–17.5)-(3.58–7.63) µg TP/L, 2.26 mg NH4/L	0.91	(Aboukila and Deng 2018)
	Linear regression model	Phosphorus retention in surface-flow constructed wetlands targeting agricultural drainage water	HLR, HRT, seasonal variation	/	Three new FWSCWs in Denmark during three years validation	/	0.0 – 0.81	(Mendes et al. 2018)
	Tank-in-series (TIS) model	Ammonia Removal in FWSCWs Employing Synthetic Floating Islands	Water depth, plant density, HRT, HLR, system size	/	Data for mesocosms with mats and vegetation	0.88 mg N/L for ammoniacal nitrogen, and 0.63 mg N/L for total oxidized nitrogen	0.75	(Al Lami et al. 2021)
Process-based models	2-dimensional, depth-averaged numerical model	simulate the velocity field and the transport of a dissolved tracer under steady flow conditions	Water depth, system area, spatial vegetation patterns, plant density, first-order reaction, pollutant load, HRT	COMSOL	Model simulation and validation was done using a 100m long and 60m wide rectangular wetland	/	/	(Sabokrouhiyeh et al. 2020)
	Thin Films (DGT) and Biotic Ligand Model (BLM)	Prediction of Metal (Zn and Cu) Bioavailability and Toxicity with Diffusive Gradients	temperature, pH, dissolved metal concentrations (DCu and DZn), alkalinity, and DOC	DGTs analysis package	Observed data from pilot-scale FWS unit	/	0.8, 0.57	(Qin et al. 2022)

Root mean square error (RMSE), *DCu* means dissolved Cu, *DZn* means dissolved Zn, *DOC* means dissolved organic carbon

These models oversimplify complex wetland processes, and they are unlikely to be used to understand the degradation processes occurring in CWs. On the other hand, process-based numerical models are better at revealing the mechanisms of contaminant transformation and degradation in CWs (Langergraber 2011; Travaini-Lima et al. 2015; Yuan et al. 2020). These models are known for their more holistic approach, attempting to represent the entire ecosystem rather than focusing on very specific processes. Both categories of models have been used in the case of FWS, but black-box models are much more common. Therefore, in this review, the most recent models used for nutrients, heavy metals, antibiotics, and pesticides in FWS were discussed and reviewed.

Black-box models category

Regression models

This type of model is often used to determine if a significant relationship exists between the inlet and outlet concentrations of a particular pollutant through CWs. Various approaches have been used, but the equation follows the same general forms:

$$nonlinear : C_{out} = aC_{in}^{b}X_1^{c}X_2^{d} \ldots \quad (1)$$

Or

$$linear : C_{out} = a + bC_{in} + cX_1 + dX_2 + \ldots \quad (2)$$

where, C_{in} is inlet concentration, C_{out} is outlet concentration, a-d are regression coefficients, and Xn are any number of independent variables that may influence pollutant removal (for example, HRT, depth, HLR, etc.) (Kumar and Zhao 2011; Alias et al. 2021). Alias et al. (2021) applied Multiple Linear Regression Analysis (MLRA) model to predict the removal of BOD_5, COD, TP, TN, and TSS, with fitting R^2 of 0.50, 0.62, 0.029, 0.30, and 0.059, respectively. This MLRA model considered the HRT, water depth, and rainfall as main factors influencing the removal of mentioned parameters. Gaballah et al. (2019) applied a non-linear regression model to predict the removal of BOD_5, NH_3, TN, TP from pilot-scale of FWS, considering the design factors such as retention time, plant coverage, and water depth. Fitting R^2 of that model was 0.743, 0.933, 0.911, 0.824, respectively to the measured removal rates of BOD_5, NH_3, TN, TP.

Mendes et al. (2018) examined phosphorus retention in FWS treating agricultural drainage water, considering hydrological parameters such as HLR, phosphorus loading rates, nominal hydraulic time, discharge-weighted TP, specific TP retention, and TP retention efficiency. Allen et al. (2023) applied multiple Generalized Additive Models (GAM) predict the ammonium, phosphate, and iron (II) dynamics in the sediment porewater of a FWS under artificial aeration through the diffusive equilibrium in thin films technique. Nyieku et al. (2021) employed ordinary least squares regression models to predict the removal efficiency of important parameters (BOD, COD, oil and grease, total coliform bacteria, TP, and nitrate) in FWS using four key environmental variables: temperature, dissolved oxygen, pH, and oxidation reduction potential. Their R^2 values ranged from 0.013 to 0.587 for BOD, from 0.164 to 0.368 for COD, from 0.226 to 0.491 for oil and grease, from 0.055 to 0.137 for total coliform bacteria, from 0.051 to 0.343 for TP, and from 0.129 to 0.463 for nitrate. In summary, regression models are relatively easy to interpret as they provide insights into removal predictions related to the main influencing factors of the FWS system. They do not require complex algorithms or extensive computational resources. However, most regression models assume a linear relationship and may not account for all the factors that influence removal performance, which can result in less accurate predictions with low R^2 values, as evident in the studies mentioned above. Also, these models cannot be applied to other biological systems since they are only valid for the particular data they were fit with.

First-order models

First-order modeling is a simplified mathematical approach used in various fields, including physics, chemistry, engineering, economics, and ecology, to describe the behavior of systems by considering the rate of change of a single variable. This approach assumes the rate of change of a variable is directly proportional to its current value or difference from an equilibrium state. This model was first used to predict pollutant removal in wetlands in the mid-1980s (Kadlec and Wallace 2009; Ventura et al. 2022). A first order decay model has the following form:

$$\frac{C_o}{C_i} = e^{-K_T t} \quad (3)$$

where, Ci is initial pollutant concentration, Co is the pollutant concentration at time t, t = hydraulic residence time, day, K_T = temperature-dependent first-order reaction rate constant, day^{-1}, that can be calculated using the following equation:

$$K_T = K_{20}\theta^{(T-20)} \quad (4)$$

where, Θ is the modified Arrhenius temperature factor, dimensionless, K_{20} = rate constant at 20 °C, day^{-1}, T = water temperature, °C, and. This model is the most commonly applied in CWs in last two decades, and has been used for design and to predict the removal performances of most of the investigated pollutants. The focus has been mainly to determine the corresponding k_{20} for various pollutants. As summarized by (Gaballah et al. 2019; Kadlec and Wallace 2009; Kumar and Zhao 2011), K_{20} for FWS might be 0.026 day^{-1} for BOD_5, 0.011 day^{-1} for TP, 0.018 day^{-1} for TKN, 0.019 day^{-1} for $NH^+{}_4$-N, 0.005 day^{-1} for NO_3-N and 0.023 day^{-1} for TSS. There are many "k" values based on the temperature conditions have been reported by several researchers and found to be varied due to a variation in the experimental set-up and environmental conditions. It is worth noting that research still needed to draw conclusions for a unique 'k' value for the removal rates of different pollutants at a certain condition.

First order models neglect or assume the background concentrations to be constant for the predicted pollutants in the system, which is not simulating the reality due to spatial variability exhibition of these pollutants. This issue has encouraged researchers to improve this model by incorporating it with a tank in series (TIS)-model called "*P-k-C**" model considering the background concentration of the predicted pollutants. In this context, (Kadlec and Wallace 2009) has summarized the different values of background concentrations (C*) associated with different pollutants under different environmental conditions of FWS. Overall, first-order model is less used currently but it is still considered as an appropriate design equation for pollutant removal in CWs. First-order models are a valuable tool in the analysis of CWs due to their simplicity and ease of interpretation. However, they are most appropriate when the underlying processes are reasonably well-approximated as first-order reactions and when a more mechanistic approach is not required. Recent studies such as Gaballah et al. (2019) reported that first-order model was fitted well to the observed data from FWS system for nutrient removal. Panja et al. (2021) used first-order reaction kinetics (plug flow reactor (PFR model)) for predicting the removal of antibiotics ciprofloxacin (CIP) and tetracycline (TC), and nutrients, N and P, from secondary wastewater effluent. The results of this study showed that there was a general match between the experimental and predictive model data points through 7 days of residence time with 10 mg/L of initial concentration of CIP and TC. Another study conducted by Zhai et al. (2016) applied the first order kinetics for diclofenac removal prediction in FWS system, with R^2 of 0.614. However, no studies have been published applying first order equations for pesticides or metals.

Tank-in-series (TIS) model

There are several models were utilized to describe the required retention time for pollutants removal in real reactors such as continuous stirred tank (CSTR) assuming a perfect mixing and plug flow reactor (PFR) assuming no mixing (Kalam 2016). The TIS model is a widely used concept in environmental engineering and wastewater treatment to describe the hydraulic behavior and performance of flow-through systems, such as water treatment plants, chemical reactors, and wastewater treatment processes (Canet-Martí et al. 2022). The TIS model represents the system as a series of well-mixed tanks or compartments through which the influent flows, allowing engineers to analyze the behavior of the system and predict its efficiency. In the context of wastewater treatment, the TIS model is often used to study the removal of pollutants, chemical reactions, and the dispersion of substances within a treatment system. This model can be described through a gamma distribution with n = N and β = ti as shown in the following equation:

$$g(t) = \frac{1}{ti(N-1)}\left(\frac{t}{ti}\right)^{N-1}.exp^{\left(-\frac{t}{ti}\right)} \quad (5)$$

where, t represents detention time (d), t_i represents the mean detention time in one tank (d), N represents the number of tanks in the TIS model that may reflect the state of mixing or no mixing. Hence, a high number of tanks means a small degree of dispersion and thus PFR reactor is presented, N = 1 means CSTR is defined. The end result of this model is somewhat represented as a function of retention time in the wetland through a gamma (g) distribution. In this context, the first-order volumetric constant (d^{-1}) was integrated with TIS model to offer a better platform to accommodate distributed parameters during the pollutants movement through the wetland. For application of TIS model in FWS, (Al Lami et al. 2021) developed a conceptual model to represent ammonia nitrogen and total oxidized nitrogen since FWS system was assumed to behave as a CSTR with loss processes occurring via first-order kinetics with R^2 of 0.75.

A modified version of the TIS approach, called the relaxed TIS model, uses the following equation:

$$\frac{C_{out} - C^*}{C_{in} - C^*} = \left(1 + \left(\frac{k_t t}{Nh}\right)^{-N}\right) \quad (6)$$

where h is the wetland depth (m) and all the other terms have been described previously. This becomes the "relaxed" TIS model when N, kt, and C* are treated as model fitting parameters, rather than specified a priori (Merriman et al. 2017). This model can perform just as well as more complex process-based models for predicting nutrient removal in several constructed wetlands (Carleton and Montas 2010). It has also been successfully applied to predict removal of nutrients from constructed FWS wetlands receiving stormwater runoff (Merriman et al. 2017).

Monod models

The Monod model is a mathematical model used to describe the kinetics of microbial processes, particularly the growth of microorganisms and their consumption of organic matter and nutrients. As described by Kumar and Zhao (2011), Monod models have been used for a transition from first- to zero-order biological degradation kinetics due to increased pollutant loading. The Monod model is typically expressed with the following equation:

$$R = \mu \frac{S}{Ks + S} \quad (7)$$

where, R (mg/d) is the rate of the microbial process (e.g., microbial growth rate or substrate consumption rate), μ (mg/m^3.d) is the maximum specific growth rate of microorganisms and also represents zeroth-order volumetric rate constant ((defined as μ = dXdt1X, X represents the biomass concentration), S (mg/m^3) is the concentration of the pollutant (e.g., organic matter or nutrients), Ks is the half-saturation constant, representing the pollutant concentration at which the microbial rate is half of the maximum rate. The Monod model has been applied in CWs for pollutant removal due to its ability in helping optimize operational parameters, such as hydraulic retention time and influent characteristics, to enhance treatment efficiency. Kumar and Zhao (2011) reported that Monod model is an alternative explanation of "C*", which may prevent total decomposition of the pollutant within the given HRT when pollutant's concentration drop to near zero and then the Monod equation predicts a very low reaction rate. This feature makes the Monod model better at describing the variability of observed data than a first-order model. However, research is still on going for exploring the optimal μ values associated with higher fitting R^2. Aboukila and Elhawary (2022) applied the Monod model as part of the BOD- Variable Residence Time (VART) model to simulate the effects of the root zone and the water column on BOD removal processes in a FWS system in Lake Manzala, Egypt (R^2 of 0.74). In the BOD-VART model, several factors were included such as flow speed, system length, area, total simulation period, and other derivatives. The model was most sensitive to flow velocity, effective diffusion coefficient, and the decay rate of BOD_5 in the water column. Another study by (Deng et al. 2016) also applied the BOD- VART model, for simulation of BOD removal processes in FWS, incorporating biogeochemical processes to simulate various BOD removal mechanisms, including Monod kinetics of bacterial growth, mass exchange between water column and root layers, advection, dispersion, and diffusion. This model included parameters such as vegetated water column layer, advection-dominated upper root layer, and diffusion-dominated lower root layer and reported R^2 and RMSE values that vary in the ranges of 0.73–0.99 and 0.41–8.7 mg/L, respectively. Similar models were developed by (Aboukila and Deng 2018) (VART-TP and VART-NH_4) for simulating the removal processes of TP and NH_4^+ in FWS wetlands with a satisfactory agreement with TP and NH_4 at the system outlet at RMSE 7.63 μg/L and 0.06 mg/L, respectively.

Process-based models category

1D process-based models

Various process-based models have been developed that simulate wetland hydraulics in 1 dimension (e.g. plug flow or CSTR), but incorporates more sophisticated pollutant removal modeling. As an example, CWM1 is a biokinetic model that describes microbial dynamics and transformation and degradation processes mainly in subsurface flow constructed wetlands (Campa 2014; Langergraber 2011; Pálfy and Langergraber 2014; Yuan et al. 2020). This model was first applied by Langergraber et al. (2009) to describe biochemical transformation and degradation processes for organic matter, nitrogen, and sulfur in subsurface flow constructed wetlands using the HYDRUS Wetland Module software for verification. The model contains 59 parameters that describe the various processes occurring in CWs (Gargallo et al. 2018). Aragones et al. (2020) used CWM1 as a base to develop SURFWET – a biokinetic model applicable for FWSCWs. This model uses a simplified hydraulic formulation based on the principle of conservation of mass, consisting of a completely stirred tank reactor and includes both physical and biochemical processes involved in pollutant removal in wastewater (organic matter, nitrogen, phosphorus, suspended solids). It captures the interplay of the main agents on contaminant removal, including bacteria, macrophytes, and phytoplankton.

Gargallo et al. (2018) applied the CWM1 directly for suspended solids modeling in FWS wetlands. While most of the models described above focused on a particular removal process, CWM1 includes multiple processes and could be the best modeling tool for predicting biochemical transformation and degradation processes occurring in FWSCWs. However, since this model was initially developed for subsurface flow wetlands, further research is needed to determine its applicability to FWS wetlands.

Wang et al. (2012) developed a model that assumes the FWSCW behaves as a CSTR, but incorporates specific submodels for phosphorus, nitrogen, and carbon cycling as well as microbial metabolism and sedimentation processes. They validated their model on 1 year of field data from a FWS wetland in Taiwan, and showed good performance for all variables (R^2 of 0.514 – 0.826 for effluent DO, TP, TN, BOD5, and TSS concentrations). This wetland was treating domestic wastewater and had very high pollutant concentrations in both the influent and effluent.

2D process-based models

Many mechanistic models have been developed in the last three decades to describe wetland dynamics (Pasut et al. 2020). Recently, a two-dimensional (2D) mechanistic mathematical model has been applied to describe the main biochemical processes related to organics and nitrogen degradation in CWs (Yuan et al. 2020). A two-dimensional model is a mathematical and computational framework used in environmental engineering, hydrology, and fluid dynamics to simulate and analyze the behavior of water flow and the transport of solutes in a two-dimensional space (Sabokrouhiyeh et al. 2020). This type of model is particularly useful for understanding and predicting how water, and any substances it may carry, move and mix in rivers, lakes, estuaries, and other bodies of water (Kumar and Zhao 2011). Cancelli et al. (2019) reported that the 2D mechanistic model was developed to estimate the biochemical transformation and degradation of organic matter, nitrogen, and phosphorus species in CWs using numerical modeling. However, this 2D mechanistic model is multifaceted and, while it performs well for bulk influent and effluent properties, it does not provide partitioning and concentration estimates for specific chemicals and does not include vegetation-mediated processes of contaminant removal such as evapotranspiration.

Sabokrouhiyeh et al. (2020) developed a 2D mechanistic mathematical depth-averaged hydrodynamic and solute transport model to fill this gap by showing that the average stem density of plants is the main property of the spatial vegetation distribution affecting the concentration reduction efficiency and mass removal rate of FWSCWs, with high fitting with the measured data of pollutant removal processes. This model aimed to quantify the effectiveness of FWS wetlands with different vegetation patterns in reducing pollutant load and to identify the optimal vegetation distributions that maximize contaminant removal. Another study by (Zounemat-Kermani et al. 2015) used a numerical model of a two-dimensional depth-average hydrodynamic model through the Galerkin finite volume formulation and equations of the k–ε turbulence model to explore the effects of characteristic geometric features on HRT. This study reported that using the two-dimensional depth-average hydrodynamic model has resulted in simulating the appropriate HRT by introducing a new aspect ratio between inlet/outlet configurations of FWS. While process-based models explicitly incorporate the necessary hydraulic, physical, and biochemical processes occurring in wetlands, these models require significant input data (e.g., 40–60 input parameters; Gargallo et al. 2018). There is therefore a balance between the complexity (but potential higher accuracy) of these process based models versus the ease of use but potentially limited applicability of more black-box approaches. FWSCWs have received less modeling attention compared to other constructed wetland types. Additional research is needed in this area and could potentially produce an intermediate-complexity process-based model that incorporates the most important mechanisms with lower data demands compared to current approaches.

Conclusion

Protecting the environment from the excessive discharge of pollutants has received increased attention recently, particularly in the context of nature-based solutions like CWs. This review provides detailed information about the ability of FWSCWs to remove various pollutants, including nutrients, heavy metals, antibiotics, and pesticides, as well as the key design parameters influencing this process. FWSCWs systems exhibit disparities in their abilities to remove different pollutants. It has been observed that FWSCWs may be able to effectively remove pollutants by optimizing design parameters such as water depth, HRT, system size, plant species, and flow capacity. However, optimal parameters differ for the various pollutant and further research is necessary to define optimal conditions for different pollutants. Nevertheless, while progress in the performance of FWSCWs for removing nutrients may have reached a saturation point, their ability to remove antibiotics and pesticides suffers from a lack of studies. Furthermore, there is a notable lack of attention to modeling approaches aimed at optimizing FWSCWs' design parameters for enhanced removal performance, as opposed to merely focusing on performance prediction purposes. Given that FWSCWs are inherently complex systems with numerous variables, including hydraulic flow, plant growth, microbial activity, and pollutant removal processes, upgrading modeling to include the interactions among these variables can provide a clearer understanding of system performance. Moreover, progress in modeling the behavior and removal are limited to the simulation of only nutrient and organic pollutant load dynamics, while lacking an attention to antibiotics and pesticides.

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Declarations

Competing interests The authors declare no competing interests.

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