Wastewater Treatment Using Constructed Wetlands with Forced Flotation: Enhancing Phytoremediation through a Floating *Typha latifolia* Rhizosphere

Ricardo Enrique Macias-Jamaica[1,*], Edgar Omar Castrejón-González[2], Vicente Rico-Ramírez[2], Ximena Guillén-Almaraz[3], Cassandra Maldonado-Pedroza[3], and Martha Paulina Rodríguez-Peña[3]

[1]Institute for Mathematical and Computational Engineering, Pontificia Universidad Catolica de Chile, Santiago, Chile
[2]Departmento de Ingeniería Química, Tecnológico Nacional de México en Celaya, Celaya 38010, México
[3]School of Engineering and Sciences, Tecnologico de Monterrey, Monterrey 64849, México
Email: rmaciasj@estudiante.uc.cl (R.E.M.-J.); omar@iqcelaya.itc.mx (E.O.C.-G.); vicente@iqcelaya.itc.mx (V.R.-R.); a01781067@exatec.tec.mx (X.G.-A.); a01705683@exatec.tec.mx (C.M.-P.); a01782025@tec.mx (M.P.R.-P.)
*Corresponding author
Manuscript received December 3, 2024; revised January 7, 2025; accepted March 7, 2025; published April 24, 2025

Abstract—**This study evaluates the effectiveness of Constructed Wetlands with Forced Flotation (CWFF) for enhancing phytoremediation in wastewater treatment. The innovative CWFF design eliminates granular support media and utilizes a floating rhizosphere of Typha latifolia, facilitating direct interaction between contaminants and plant roots, thereby improving pollutant removal, degradation, and volatilization. Experiments were conducted under continuous flow conditions using both synthetic municipal wastewater (Chemical Oxygen Demand of 538 mg O_2/L) and high-strength industrial wastewater from a dairy industry (Chemical Oxygen Demand of 8,236 mg O_2/L). The CWFF system achieved significant removal efficiencies, including up to 99.77% reduction in Chemical Oxygen Demand and 99.64% reduction in Biochemical Oxygen Demand for industrial wastewater. The integration of aerobic, anoxic, and anaerobic zones facilitated comprehensive contaminant degradation, whereas the absence of granular substrates prevented clogging issues commonly found in traditional wetlands. These results highlight the high treatment capacity and operational flexibility of CWFF, showing its potential as a scalable and sustainable solution for addressing modern environmental challenges in wastewater management.**

Keywords—**industrial wastewater, macrophytes, organic pollution, continuous flow**

I. Introduction

The inadequate sanitation and management of industrial wastewater represent a critical global challenge with severe implications for public health and the environment [1]. It is estimated that 3.1% of all deaths worldwide are caused by unsafe or inadequate water, poor sanitation, and lack of hygiene [2, 3]. Globally, 46% of the population (3.6 billion people) lacks adequate sanitary facilities for the safe disposal of human waste and about 946 million people still practice open defecation [4]. Additionally, approximately 80% of wastewater returns to the environment without treatment or reuse, contributing to the contamination of water resources [4, 5]. At least 2 billion people use drinking water contaminated with faecal matter, increasing health risks for local populations [4]. The release of untreated wastewater leads to loss of biodiversity, ecosystem degradation, and heightened public health hazards, including the spread of diseases such as cholera, typhoid fever, tuberculosis, hepatitis, and dysentery [6, 7]. Moreover, the growing presence of heavy metals in wastewater, resulting from industrial growth and human activities, is concerning due to their non-biodegradable nature and potential carcinogenicity [8]. Many wastewater treatment facilities use outdated or inefficient technologies that cannot effectively remove contaminants, highlighting the importance of proper management to ensure the sustainability of business operations and meet the expectations of stakeholders who demand sustainable practices [9]. In México for example, it was estimated that, in the year 2000, 250 m^3/s of municipal wastewater were generated in urban centers, while in 2012, approximately 229.73 m^3/s were discharged; projections indicate that, by 2030, 9,200 million cubic meters of wastewater will be generated [10]. This scenario underscores the urgent need to assess and characterize wastewater quality to develop cost-effective and sustainable treatment strategies that minimize impacts on health and the environment [6, 9, 11].

Constructed wetlands (CWs), also known as artificial wetlands, have emerged as effective and sustainable systems for wastewater treatment replicating natural wetland processes to remove pollutants through physical, chemical and biological mechanisms [12–14]. These engineered systems utilize the unique properties of macrophytes and microbial communities to apply phytoremediation techniques, addressing the need for efficient and low-cost treatment methods, especially for persistent pollutants like trace metals [12, 14]. Due to the characteristics of trace metal pollutions (such as permanence and slow natural removal), it is necessary to find efficient and low-cost treatment methods for cleaning [14]. CWs are categorized into two principal types based on water flow: free water surface flow CWs (FWSF CWs) and subsurface flow CWs (SSF CWs), with SSF CWs further divided into vertical flow CWs (VFC Ws) and horizontal flow CWs (HF CWs), according to the direction of water flow [15, 16]. Additionally, CWs can operate under batch flow or continuous flow regimes. Batch systems retain water for a specific time period to allow for treatment processes; once this time elapses, the water is drained, and a new batch is introduced [17, 18]. In contrast, continuous-flow wetlands maintain a constant, uninterrupted flow through the media of the system, ensuring steady movement across the substrate or vegetation layer, which enhances contaminant removal efficiency by maintaining consistent contact with microbial and plant communities [19]. The removal of pollutants in CWs involves sedimentation, adsorption, and

doi: 10.18178/ijesd.2025.16.2.1519

biological uptake; physically, sedimentation allows suspended particles to settle due to gravity, enhancing pollutant clearance [20]. Chemically, adsorption processes are crucial for removing phosphorus and heavy metals, with materials like iron-rich cupola slag and zeolite media enhancing efficiency due to their high adsorption capacities [21]. Biologically, macrophytes provide extensive surface areas that support microbial communities which are essential for the stabilization of organic matter and enhancement of filtration efficiency [10]. Vegetation in CWs not only influences pollutant removal processes but also contributes to the performance of the system, with both conventional plants and those with economic value being utilized [10]. Previous studies have reported that plants such as *Typha latifolia*, *Pistia stratiotes*, *Carex aquatilis*, *Phragmites australis*, and *Alisma Plantago-aquatica* show considerable removal efficiencies for Chemical Oxygen Demand (COD), Total Nitrogen (TN), Total Phosphorous (TF) and some trace metals in wastewater [19]. Economically, CWs offer inherent advantages such as being cost-effective, and requiring minimal energy and low maintenance [13, 22]; for instance, constructed wetlands have a minimal power consumption of 3.9%, significantly reducing maintenance resources [23]. Additionally, the CO_2 emissions from conventional wastewater treatment plants are almost seven times higher than those from vertical subsurface flow CWs, highlighting their environmental benefits [22, 23]. Recent advances in eco-technology have underscored the potential of constructed wetlands with forced flotation (CWFF) as progressive, nature-based solutions that effectively address a wide array of chemical and biological contaminants, offering an economically and energetically favorable alternative for the treatment of open water systems [22, 24–26]. The overall performance of CWs is influenced by factors such as ambient temperature, hydraulic load, vegetation type, and media used, which collectively determine the ability of the system to adapt and to process efficiently diverse wastewater inputs [27]. This strategic design addresses limitations of traditional substrates, enhancing absorption capacities and facilitating water flow through essential oxygenation phases necessary for optimal contaminant degradation [25, 26].

Phytoremediation within Constructed Wetlands with Forced Flotation (CWFF) has emerged as a promising solution to address the challenges of high contaminant loads in wastewater [26]. This sustainable approach harnesses the innate abilities of aquatic macrophytes, such as *Typha latifolia*, and their symbiotic microbial communities to remove pollutants through adsorption, uptake, and transformation processes [28–31]. Specifically, *Typha latifolia* has been extensively documented for its robust growth in diverse environmental conditions, well-developed root architecture, and high tolerance to both organic and inorganic pollutants. Its rhizosphere supports dense microbial biofilms that enhance pollutant degradation, making *Typha latifolia* particularly effective in phytoremediation processes [25, 29]. The plant's ability to thrive in nutrient-rich or oxygen-limited waters, combined with their capacity for rapid biomass production, further underscore their suitability for continuous-flow wetlands. These characteristics allow *Typha latifolia* to keep consistent pollutant uptake and degradation rates, offering a resilient and adaptable platform for wastewater treatment. The presence of microbial biofilms in the rhizosphere enhances the degradation and stabilization of contaminants, making phytoremediation a dynamic and effective method [29, 31]. CWFF systems effectively leverage these biological processes to remove a wide array of contaminants, including nutrients, organic pollutants, solids, and pathogens, under varying load conditions [28]. The efficacy of this method is influenced by factors such as plant species selection, growth conditions, and environmental parameters like pH, light, and temperature [31, 32]. Recent studies have reported that CWFF can significantly reduce high loads of contaminants, offering a cost-effective and environmentally benign alternative to traditional wastewater treatment methods [28].

Nevertheless, although *Typha latifolia* has been commonly studied in conventional wetlands, often with emphasis on heavy metals uptake [14], relatively few studies have investigated the plant under a forced-flotation condition for high-strength organic pollution removal. Most conventional constructed wetlands also use granular media, which may clog and needs intensive maintenance. By contrast, our CWFF method totally avoids granular support, quickly optimizing contact between roots, microbial biofilms, and contaminants. This design improves the degradation of pollutants in aerobic and anoxic/anaerobic zones and extends the applications of *Typha latifolia* phytoremediation beyond removal of trace metals. This approach allows our results to make a strong case for using forced flotation (a proven but underutilized system) as a continuous flow, effective, scalable, and resilient biological treatment of high-strength effluents; specifically, our approach targets the removal and degradation of organic matter, making our research most relevant to novel effluents of modern wastewater technology.

In response to these challenges, in this study we present results obtained from our own prototype reactor to assess and compare the efficiency of Constructed Wetlands with Forced Flotation (CWFF) in removing organic matter, settleable solids, and total solids against established systems like Free Water Surface Flow Constructed Wetlands (FWSFCW) and Sub-Surface Flow Constructed Wetlands. Experiments are conducted under various hydraulic retention times using synthetic COPAS wastewater [33] and industrial wastewater with excessive organic matter; those experiments aim to demonstrate that the CWFF system can significantly surpass traditional methods. Additionally, the study evaluates pollutant removal in each segment of the prototype—comprising aerobic, anoxic, and anaerobic zones—and investigates the organic removal mechanisms occurring within the reactor. The experiments are performed in continuous mode, utilizing a total operational volume of 240 liters (63.4 gallons), encompassing both the treatment water volume and the rhizosphere volume occupied. This research seeks to underscore the potential enhancements in treatment efficacy offered by CWFF, emphasizing its adaptability to variable environmental conditions and its feasibility for scaling in diverse applications.

II. Literature Review

A. Overview of Traditional Constructed Wetlands (CWs)

Constructed Wetlands (CWs) have been developed as sustainable alternatives to conventional wastewater treatment methods, drawing inspiration from natural wetland ecosystems. The initial implementation of CWs began in the 1950s in Germany, with the first full-scale operational system in the 1960s [15]. These engineered systems aim to replicate the physical, chemical, and biological processes inherent in natural wetlands to remove pollutants such as degradable organic matter, nitrogen, and phosphorus from wastewater [15, 26, 28, 34].

The primary components of CWs include waterproof basin, filter materials, wetland plants, and inlet and outlet structures. Filter materials serve as a medium for microbial growth, which is crucial for the degradation of organic pollutants and the transformation of nitrogen compounds- The design and area required for CWs depend on the quality and quantity of the wastewater to be treated, as well as the root depth of the plants to ensure effective contact with the flowing water [15]. Additionally, the performance is significantly influenced by factors such as surface loading rates and residence time. Research indicates that the efficiency of these systems is not only determined by surface loading rates—calculated by dividing the daily or hourly flow (Q) by the gross surface area of the tank (A)—but also by the time the water remains within the system.

The flow Q through a CW can be described by the Eq. (1):

$$(SLR) = \frac{Q}{A} \tag{1}$$

where A is the surface area CW. Q/A is known as the surface loading rate (SRL) and is expressed as $\frac{m^3}{h \cdot m^2}$, $\frac{m}{h}$ or $\frac{mm}{s}$.

This relationship highlights the importance of both flow characteristics and the residence time for the effective settling of particles, which is influenced by their size, concentration and the turbulence within the system.

CWs are classified based on water flow patterns into FWSF CWs and SSF CWs [16, 29, 30]. Additionally, CWs can operate under batch flow or continuous flow regimes [17–19].

B. Mechanisms of Phytoremediation in CWs

Phytoremediation within CWs leverages the natural abilities of plants and their symbiotic microbial communities to remove, degrade, or stabilize contaminants in wastewater [26]. Phytoremediation mechanisms employed by aquatic macrophytes include rhizofiltration, phytoextraction, phytovolatilization, phytodegradation and phytotransformation [35]. These processes enable plants to absorb nutrients and contaminants from water, effectively reducing levels of nutrients, organic pollutants, solids, and pathogens under varying load conditions [26].

Aquatic plants utilize various physiological and morphological adaptations to remove contaminants through adsorption, uptake, and transformation processes [29–31]. The effectiveness of phytoremediation involves factors such as transpiration rates and root biochemistry. Environmental parameters like pH, light, and temperature also play significant roles in the efficiency of these processes [31, 32]. Moreover, the presence of microbial biofilms within the rhizosphere enhances the stability and degradation capacity of CWs, contributing to the dynamic nature of phytoremediation [29, 31].

C. Role of Macrophytes in Pollutant Removal

Macrophytes are integral to the functionality of CWs, significantly influencing pollutant removal processes and overall system performance [10, 36]. Both conventional plants and those with economic value are utilized in CWs to optimize treatment efficiency. Studies have shown that plants such as *Typha latifolia*, *Pistia stratiotes*, *Carex aquatilis*, *Phragmites australis*, and *Alisma plantago-aquatica* exhibit considerable removal efficiencies for trace metals (TMs) in wastewater, as illustrated in Fig. 1 [14].

Typha latifolia, in particular, has been identified as a potent hyper accumulator, demonstrating the ability to reduce chromium content by up to 96.7% in tannery wastewater treatment [37]. This species is highly productive, well-adapted to waterlogged conditions and anoxic soils, and contributes to the soil carbon pool [38]. Typha species are also excluder plants for metals like Co, Cu, and Pb, showing high tolerance to phytotoxic concentrations in sediments and tissues [39].

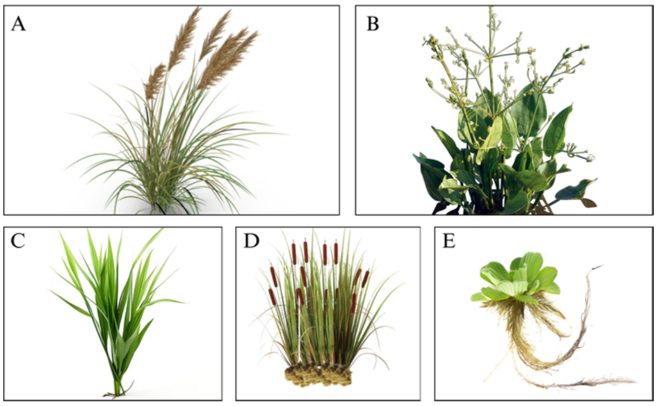

Fig. 1. A) *Phragmites australis*, B) *Alisma plantago-aquatica*, C) Carex aquatilis, D) *Typha latifolia*, E) *Pistia stratiotes.*

Floating macrophytes perform several roles in CWs, including stabilization, nutrient retention, enhancement of microbial communities, removal of toxic substances, and tolerance to complex wastewater effluents [37]. For instance, Typha latifolia and *Typha angustifolia* have been shown to contribute to nutrient removal from dairy wastewater, with plant uptake accounting for significant reductions in Total Kjeldahl Nitrogen (TKN), ammonium (NH_4^+), and Total Phosphorus (TP) [4].

D. Advances in CWFFs

Constructed Wetlands with Forced Flotation (CWFF) have emerged as an innovative natural method for treating surface water bodies and restoring ecological processes [26]. CWFF systems utilize floating beds that support plant growth and enhance the denitrification potential, thereby improving the overall efficiency of nitrogen removal [24]. These systems effectively address a wide array of chemical and biological contaminants, offering an economically and energetically favorable alternative to traditional wastewater treatment methods [22].

Within CWFFs, biofilms on aquatic plant roots play a pivotal role in detoxifying water by removing organic nutrients, heavy metals, and emerging pollutants such as antibiotics, pesticides and hormones [22]. Unlike traditional CWs that rely on substrates like gravel and sand (which may impede efficient nitrification and restrict the removal of certain contaminants), CWFFs utilize substrates that enhance absorption capacities and facilitate water flow through essential oxygenation phases (aerobic, anaerobic, and anoxic) necessary for optimal contaminant degradation [25, 26].

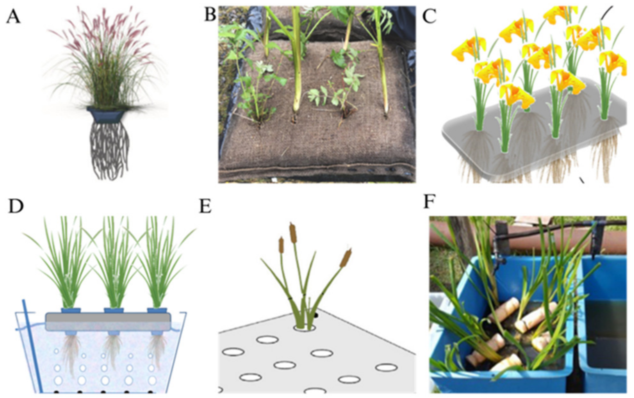

Fig. 2. Forced flotation mechanisms reported in the literature: A) E. Ntagia, *et al.* [22], B) M. I. Choudhury, *et al.* [24], C) G. A. Oliveira, *et al.* [40], D) G. A. Oliveira *et al.* [40], E) D. Arivukkarasu, *et al.* [26], and F) L. H. Bauer, *et al.* [41].

Field studies have demonstrated the effectiveness of CWFFs in various environmental conditions. For example, implementations in Sweden showed that strategic aeration supports macrophyte health and benefits treatment performance even in cooler temperatures and increasing hydraulic retention time during colder months benefits treatment performance [15, 24]. Additionally, integrating floating beds contributes to a circular economy by utilizing biomass post-harvest to alleviate local environmental pressures, with active harvesting strategies playing a crucial role in limiting re-pollution of water bodies (Fig. 2) [22].

E. Challenges and Future Directions

Despite the advantages of CWs and CWFFs, several challenges persist, particularly concerning system clogging and maintenance. Clogging can be physical, chemical, or biological, and it is influenced by factors such as substrate porosity, hydraulic load, oxygen supply conditions, organic loading, water depth and plant species. Addressing clogging is essential for improving the purification effect of CWs, and future research should focus on combining anti-clogging strategies with purification enhancements [42].

Understanding the correlation between treatment performance and hydraulic behavior is crucial for optimizing CW functionality [12]. Advancements in eco-technology, such as the development of CWFFs, offer promising solutions to these challenges. By enhancing absorption capacities and facilitating effective water flow, CWFFs address limitations associated with traditional substrates, leading to improved efficiency and sustainability in wastewater treatment [25, 26].

Future directions include further exploration of plant species with high removal efficiencies, optimization of operational parameters, and integration of CWs into broader environmental management strategies. Emphasizing the role of CWs in a circular economy framework (such as utilizing biomass post-harvest) can contribute to environmental sustainability and resource recovery [22].

III. Materials and Methods

A. Design and Implementation of the CWFF

The basis of this study is the development of an innovative Constructed Wetland with Forced Flotation (CWFF) system, engineered to enhance wastewater treatment under continuous flow conditions. Departing from traditional constructed wetlands, the CWFF integrates forced flotation techniques to improve the removal efficiency of organic and inorganic pollutants [5, 26].

Inspired by the dynamic wetland configuration proposed by Chang *et al.* [43], our CWFF prototype features a series of interconnected chambers that create a serpentine flow path, inducing sequential downflow and upflow movements. Wastewater enters through a single inlet, ensuring an even distribution of the influent load across the system. As the wastewater advances through each chamber, the contaminant levels progressively decrease due to the sustained microbial and phytoremediation processes. This configuration helps to prevent short-circuiting and dead zones, thereby promoting a more uniform interaction between the wastewater, the plant roots, and the treatment media. Additionally, a constant inflow rate was maintained to stabilize hydraulic conditions and ensure that the effluent moves uniformly across each chamber. As wastewater traverses moves through the chambers, it experiences varying redox conditions (transitioning through aerobic, anoxic, and anaerobic zones) which are crucial for facilitating a comprehensive range of biochemical reactions necessary for contaminant breakdown [24].

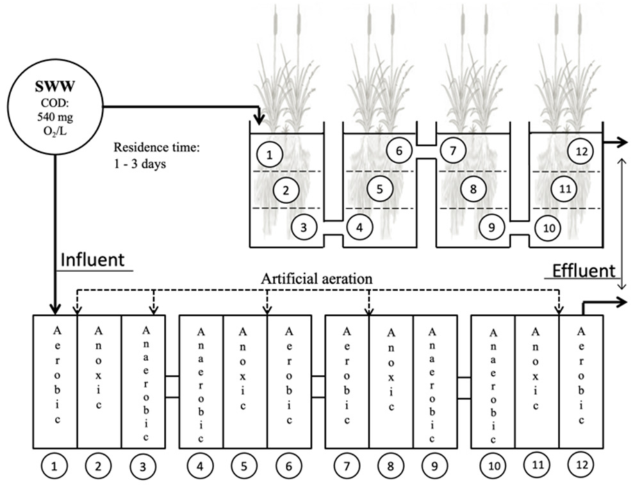

Fig. 3. Distribution of zones, in continuous flow.

Fig. 3 illustrates the schematic layout of the CWFF system, comprising twelve distinct zones. Each zone is meticulously designed to contribute uniquely to the overall treatment process, promoting a balanced and continuous flow throughout the system. This strategic segmentation enhances the degradation of complex pollutants and supports a diverse microbial ecosystem essential for effective biodegradation.

B. Adaptation of Typha Latifolia for the CWFF

A pivotal element of the CWFF system is the utilization of the macrophyte *Typha latifolia*. Traditionally an emergent plant thriving in soil-based or gravel substrates, *Typha latifolia* required significant adaptation to function effectively in the floating environment of the CWFF. We undertook a physiological conditioning process to acclimate the plants to grow without conventional substrates, enabling them to absorb nutrients directly from the water column while tolerating full sunlight exposure. This adaptation is crucial, as it allows the plants to maintain robust growth and metabolic activity within the CWFF, thereby enhancing pollutant removal through phytoremediation mechanisms [38, 39].

The *Typha latifolia* plants used in this study were collected from Xochimilco Park, in Mexico City (coordinates: 19.2974, –99.0945, where they are native. Well established 80 cm tall plants with most of the rhizosphere removed were used. They were subsequently introduced into the CWFF prototype in synthetic wastewater, which served as the growth medium for the first parameter. In this adaptation to forced flotation the plants established new roots and microbial biofilms almost immediately under continuous flow conditions enabling them to work effectively without soil or gravel support.

The adapted root systems of *Typha latifolia* provide extensive surface areas for microbial colonization, fostering symbiotic relationships that enhance the biological degradation of contaminants [5]. The interactions between the plant roots and the microbial communities facilitate the breakdown of organic matter, nutrients, and other pollutants present in the wastewater [37].

C. Selection and preparation of Wastewater Samples

To evaluate the performance of the CWFF system under realistic conditions, we utilized both synthetic and real wastewater samples. Initially, several synthetic wastewater formulations were considered [44, 45]; however, to closely replicate the characteristics of municipal wastewater and ensure consistency in our experiments, we adopted the COPAS synthetic wastewater recipe as described by Prieto *et al.* (2019) [33].

The COPAS formulation involves dissolving powdered cat food—comprising approximately 40% proteins, 17% fats, and 43% carbohydrates—in water to achieve a target Chemical Oxygen Demand (COD) of around 540 mg O_2/L. This composition effectively simulates the organic load found in urban wastewater, providing a consistent and reproducible medium for treatment studies. The use of COPAS offers multiple advantages: it reduces preparation time and costs; its particles rapidly release organic carbon and nitrogen, facilitating microbial metabolism; and it has been demonstrated to be highly biodegradable, producing about 60% of the theoretical methane yield after 45 days of anaerobic incubation [33].

For the subsequent phase of the study, untreated high-strength wastewater was fed directly from a dairy industry facility. This real wastewater presented a complex matrix of organic pollutants, allowing us to assess the CWFF's efficacy in treating industrial effluents under continuous flow conditions. It also enabled the evaluation of the effectiveness of the rhizosphere as a substantial biofilter and habitat for diverse bacterial communities within the CWFF system.

D. Experimental Setup and Operational Parameters

The CWFF system was constructed with a total operational volume of 240 liters (63.4 gallons), encompassing both the volume of water to be treated and the space occupied by the rhizosphere. The system was designed to operate under continuous flow conditions, with hydraulic retention times (HRTs) carefully adjusted to investigate their impact on treatment efficiency [6, 12]. Wastewater was introduced into the system at controlled flow rates to maintain steady-state conditions and ensure optimal interaction with the treatment media.

To evaluate the performance of the CWFF under varying conditions, three distinct experiments were conducted:

Experiment 1: The CWFF was tested using synthetic wastewater (SWW) prepared with a COD of 540 mg O_2/L. Six runs were performed at different HRTs of 12, 24, 36, 48, 60, and 70 hours. For each HRT, the system was operated continuously for at least 15 days to reach steady-state conditions before samples were collected. This allowed the microbial communities to acclimate to each specific HRT, ensuring reliable results [6, 12].

Experiment 2: To verify the reproducibility of the results from Experiment 1, the procedure was duplicated under identical conditions, with each HRT maintained for at least 15 days before sampling. This replication confirmed the consistency and reliability of the CWFF's performance data.

Experiment 3: The CWFF was tested with 160 liters of untreated high-strength dairy industry wastewater, characterized by a COD of 8,236 mg O_2/L, Total Solids (TS) of 13,424 mg/L, Suspended Solids (SS)| of 4,276 mg/L, pH of 5.08, and electrical conductivity of 590 μS/cm. Artificial aeration was introduced to maintain adequate oxygenation levels required for aerobic processes [5]. The system was operated continuously for at least 15 days before sampling to ensure steady-state conditions under the high organic load.

Throughout all experiments, samples were collected at various locations within the CWFF system corresponding to the different redox zones—aerobic, anoxic, and anaerobic. Key parameters such as COD, total solids, and settleable solids were monitored to evaluate pollutant removal efficiency in each segment [8, 14]. This approach provided a detailed assessment of the biological and physicochemical processes occurring within the system.

E. Hydrological and Biological Engineering

The CWFF system innovatively combines hydrological design with biological processes. Its forced flotation mechanism enhances contact between wastewater, macrophyte roots (*Typha latifolia*), and microbial communities, facilitating efficient pollutant degradation through phytoremediation and microbial activity [7, 34, 36]. Eliminating soil or gravel substrates overcomes limitations of traditional wetlands, such as clogging and large space requirements [37, 42]. This floating design offers flexibility and scalability, suitable for diverse settings, including areas with limited space.

The adjustable hydraulic retention times of the system and its capacity to handle varying organic loads make it adaptable for treating both municipal and industrial wastewater [5, 26]. Incorporating artificial aeration, when necessary, enhances oxygen transfer, supporting aerobic microbial processes essential for breaking down complex organic compounds [5].

In summary, the CWFF provides a sustainable and efficient approach to wastewater treatment, representing a viable alternative to conventional methods with significant potential for environmental management and pollution reduction [26].

F. Monitored Parameters

Considering the chemical analysis that is going to be performed to evaluate the efficiency of CWFF in removing the organic pollutants, COD, Biochemical Oxygen Demand (BOD_5), Total Suspended Solids (TSS) and TS were analyzed as well as pH and Electrical Conductivity (EC). This combination effectively captures organic loading and settling, as well as basic physicochemical conditions in the wastewater, in line with our research goal of testing the feasibility of forced flotation under high-strength organic conditions.

All analyses were performed following the Standard Methods for Examination of Water and Wastewater: a) COD was determined by the closed reflux colorimetric method (Standard Method 5220D), b) BOD_5 was determined using the 5-day BOD test (Standard Method 5210B), c) TSS and TS was determined using the gravimetric method (Standard Method 2540D), and d) pH and EC measuring devices were calibrated according to the manufacturer instructions and verified periodically for accurate results. Each parameter was measured in triplicate for every sample collected, ensuring the statistical reliability of the data.

For other phytoremediation studies, it has been shown that Typha latifolia has a large potential for heavy metal uptake; however, heavy metals were not analyzed in this study on purpose. We show that high-efficiency removal of organic pollutants can be achieved without granular media and with the new forced-flotation design, using high-strength wastewater from the dairy industry as the inflow. Such an approach opens further research interests over other trace metals and emerging pollutants, building from the findings reported here.

IV. Result and Discussion

A. Synthetic Wastewater

To evaluate the effectiveness of the Constructed Wetland with Forced Flotation (CWFF), both synthetic wastewater (SWW) and industrial wastewater were characterized for key parameters relevant to organic pollutant removal. Table 1 presents the average values of Chemical Oxygen Demand (COD), Biochemical Oxygen Demand over 5 days (BOD_5), Total Suspended Solids (TSS), Total Solids (TS), pH, and Electrical Conductivity (EC) for both wastewater types.

The SWW exhibited values similar to those of typical domestic wastewater in terms of COD, TSS, TS, pH, and EC [33]. The higher BOD_5 value indicates a greater proportion of readily biodegradable organic matter due to the use of cat food in the COPAS formulation [28]. A BOD_5/COD ratio greater than 0.5 (specifically 0.617) suggests that the SWW is highly amenable to biological treatment processes [5].

Table 1. Characterization of the used wastewater

Parameter	Synthetic wastewater Average value (mg/L)	Industrial wastewater Average value (mg/L)
COD	538	8,236
BOD_5	332	3,192
BOD_5/COD	0.617	0.387
TSS	455.5	4,276
TS	691.5	13,424
pH	7.45	5.08
E.C.	419	590

In contrast, the industrial wastewater from the dairy industry showed significantly elevated pollutant concentrations, with COD and TSS values approximately 15 times higher than those of the SWW. The high organic load (COD of 8,236 mg/L) presents a substantial challenge for treatment systems. The lower BOD_5/COD ratio of 0.387 indicates the presence of more complex, less biodegradable organic compounds, necessitating more robust treatment strategies [34].

B. Constructed Wetland in Forced Flotation (CWFF)

The CWFF system demonstrated remarkable adaptability and effectiveness in treating both SWW and industrial wastewater. The rhizosphere of *Typha latifolia* replaced traditional support media like gravel, addressing common issues such as clogging and maintenance [5, 40]. This design leverages the extensive root systems of the macrophytes to enhance microbial colonization and pollutant degradation [29, 31].

Fig. 4. A) System at the start of operations; B) system with 5 weeks of maturation; C) system with 4 months of maturation; and E) complete growth of the rhizosphere throughout the forced flotation container.

The unique CWFF design allows for both upward and downward water flow through interconnected polyethylene containers, promoting uniform distribution and contact between the wastewater and the plant roots. This configuration facilitates various redox condition (ranging from aerobic to anaerobic and anoxic zone) essential for the comprehensive breakdown of contaminants [24, 31]. In our CWFF design (Fig. 4), zones 1,6,7 y 12 mainly work under aerobic conditions through forced aeration and oxygen exchange on the surface, favoring oxidation of organic matter and addition of nitrification. However, these aerobic zones are highly energy-rich, so that, in the anoxic stages (zones 2, 5, 8 y 11), denitrification occurs due to the reduction of aerobic-nitrate to nitrogen gas. Lastly, zones 3, 4, 9 y 10 are anaerobic zones, which allow the degradation of larger compounds and sulphate reduction. Such proposed arrangement of individual redox conditions enables sequential biochemical transformations for thorough contaminant degradation.

Notably, *Typha latifolia* achieved growth heights of up to four meters within the CWFF system, surpassing typical growth observed in traditional constructed wetlands (Fig. 5) [37]. This robust growth indicates successful adaptation to the floating conditions and reflects the plants high capacity for nutrient uptake and biomass production under controlled experimental conditions.

C. Experiment 1 and 2: Synthetic Wastewater

Integrating the three oxygenation zones—aerobic, anoxic, and anaerobic—within the CWFF system significantly enhanced the removal of contaminants that are challenging to eliminate under aerobic conditions alone. The aerobic zones facilitated the oxidation of organic matter and the conversion of ammonium to nitrate through nitrification [17]. Subsequently, the anoxic zones enabled denitrification, transforming nitrate into nitrogen gas and preventing ion accumulation in the system. The anaerobic zones contributed to the reduction of sulfates to sulfides, aiding in the degradation of more complex and recalcitrant compounds.

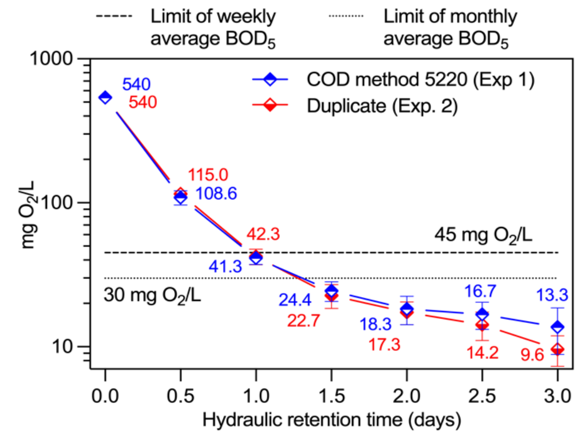

Fig. 5. COD for experiments 1 and 2.

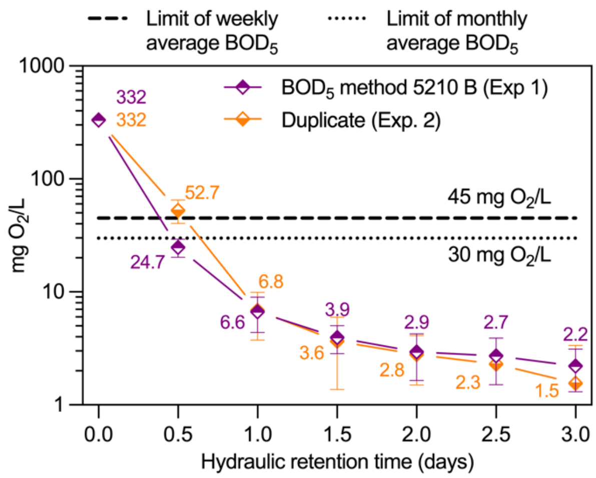

Fig. 6. BOD_5 for experiments 1 and 2.

This stratification of redox conditions within the CWFF created a dynamic environment that supports diverse microbial communities, each adapted to specific oxygen levels, thereby enhancing overall treatment efficiency [15,31]. The unrestricted transition between zones ensures that pollutants undergo multiple degradation pathways, maximizing removal rates.

Fig. 5 and Fig. 6 illustrate the levels of COD and BOD_5 in the effluent over a range of hydraulic residence times (HRTs) from 0.5 to 3 days (12 to 72 hours). The effluent quality is evaluated against the standards specified in 40 CFR Part 133: Secondary Treatment Regulation by the United States Environmental Protection Agency (EPA), which sets permissible limits for COD and BOD_5 in treated wastewater discharges [46]. The results indicate that BOD_5 concentrations remain well below the EPA permissible limit at all tested HRTs, demonstrating effective removal of biodegradable organic matter and a low residual load of such compounds in the effluent.

In the case of COD (Fig. 5), effluent values remain below the permissible limit for HRTs of 1.5 days and longer. At an HRT of 1 day, the BOD_5/COD ratio is 0.16, which is below the threshold value of 0.2. This low ratio suggests that the remaining organic matter consists of compounds with low biodegradability, a typical feature of industrial wastewater. Such conditions often necessitate the use of physicochemical treatment processes for effective removal. However, our experimental results demonstrate that, with a minimum HRT of 1.5 days, the CWFF system utilizing *Typha latifolia* effectively reduces COD levels below regulatory limits. This finding highlights the metabolic capacity of the plants and the efficiency of the CWFF system in degrading fewer biodegradable compounds, showing its potential for treating industrial wastewater through biological processes.

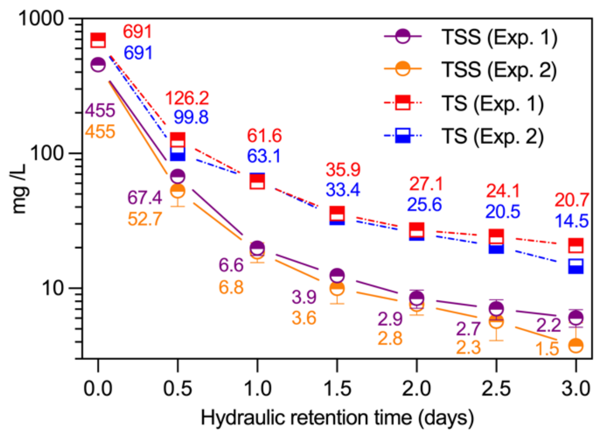

Fig. 7. TSS and TS for experiments 1 and 2.

Fig. 7 illustrates that the majority of TSS removal occurs within the initial 12% to 25% of the CWFF system. Within a hydraulic residence time of just one day, the system achieves approximately 95% of the TSS reduction, resulting in effluent concentrations below 20 mg/L. This high removal efficiency is primarily due to sedimentation and filtration processes enhanced by the dense vegetation of *Typha latifolia* within the system.

In contrast to conventional constructed wetlands where solids are trapped within substrate materials like gravel or sand, the absence of such substrates in our CWFF allows suspended solids to be directly intercepted by the extensive rhizosphere. The roots of *Typha latifolia* act as a natural filter, capturing solids which are then rapidly degraded by associated microorganisms or absorbed by the macrophytes themselves. This mechanism not only enhances TSS removal but also minimizes the risk of substrate clogging, a common issue in traditional systems [40, 42].

D. Experiment 3: Industrial Wastewater

An experiment was conducted to evaluate the efficiency of the CWFF system under industrial conditions, as show in Fig. 8. Specifically, high-strength wastewater with elevated organic content from a dairy industry was analyzed. During the experimental run, it was observed that fats present in the industrial wastewater adhered to the stems of the macrophytes (*Typha latifolia*); that was due to differences in static charge between the fats and the plant surfaces. This adhesion prevented the formation of a surface film (mirror effect) that could otherwise hinder the penetration of solar radiation into the water column. By preventing this film formation, solar radiation was able to penetrate the water, enhancing photosynthetic activity and supporting aerobic microbial processes.

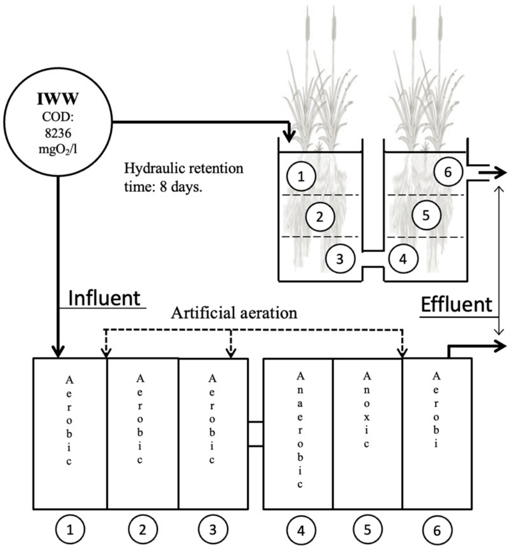

Fig. 8. Distribution of zones, experiment 3.

Additionally, the adhesion of fats to the macrophyte stems prevented the accumulation of these lipids within the rhizosphere, thereby avoiding potential clogging of the root zone. This maintenance of clear hydraulic pathways ensured unimpeded flow of nutrients and oxygen, facilitating their subsequent degradation by microorganisms and phytoremediation processes. The results indicate that the CWFF system effectively manages high-fat-content wastewater by leveraging the physical and biological properties of the macrophytes to maintain system functionality and enhance contaminant removal.

The experiment demonstrated that an influent with a high pollutant load, specifically a COD of 8,236 mg/L, was reduced to an average value of 130 mg/L, as shown in Fig. 9. This substantial reduction corresponds to a COD removal efficiency of 99.77% and suggests high microbial activity and an efficient filtration process within the rhizosphere of *Typha latifolia*.

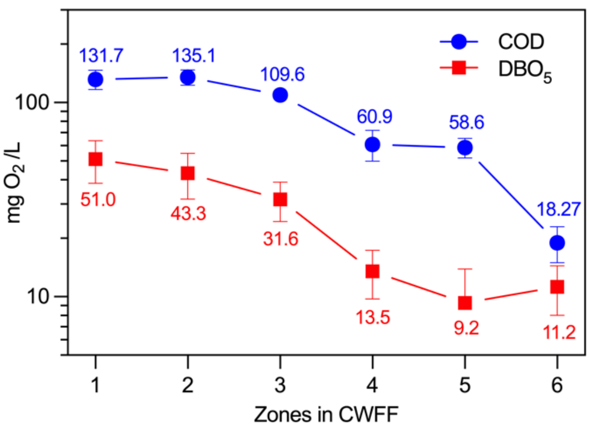

Fig. 9. COD and BOD_5 sampled in the 6 zones of CWFF in experiment 3.

Similarly, the system achieved a 99.64% removal of BOD_5, indicating effective degradation of biodegradable organic matter. Fig. 10 illustrates a significant decrease in the levels of Total Suspended Solids (TSS) and Total Solids (TS), further confirming the system efficiency in removing particulate matter.

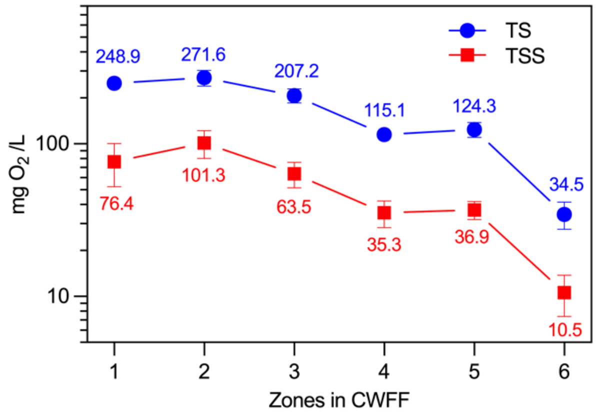

Fig. 10. TS and TSS sampled in the first 6 zones of CWFF.

It is important to note that in both Fig. 9 and Fig. 10, there is a pronounced change in the slope between zones 3 and 4. This change corresponds to the transition from downward to upward flow within the CWFF system, which enhances the rhizofiltration process and the degradation of organic contaminants. The upward flow increases contact between the wastewater and the macrophyte roots, facilitating greater pollutant uptake and microbial activity.

These results underscore the effectiveness of the CWFF system in treating high-strength industrial wastewater. The significant reductions in COD, BOD_5, TSS, and TS demonstrate the system capability to handle elevated pollutant loads. The enhanced performance between zones 3 and 4 highlights the critical role of flow configuration and rhizosphere processes in maximizing contaminant removal. Overall, the CWFF presents a promising solution for sustainable industrial wastewater treatment, combining efficient pollutant degradation with operational adaptability.

V. Conclusion

This study evaluated the efficacy of Constructed Wetlands with Forced Flotation (CWFF) for wastewater treatment, demonstrating that removing granular support media and implementing a forced floating rhizosphere significantly enhance phytoremediation processes. By utilizing the macrophyte *Typha latifolia* in a floating configuration, the CWFF system facilitates the removal, degradation, and volatilization of pollutants, allowing contaminants to come into closer contact with bacterial flora and enhancing microbial activity.

The experimental results showed that the CWFF system effectively treated both synthetic municipal wastewater and high-strength industrial wastewater from a dairy industry. Notably, the system achieved a 99.77% reduction in Chemical Oxygen Demand (COD) and a 99.64% reduction in Biochemical Oxygen Demand over 5 days (BOD_5) when treating industrial wastewater with an initial COD of 8,236 mg/L. The integration of aerobic, anoxic, and anaerobic zones within the CWFF created optimal conditions for a variety of biochemical processes, including nitrification, denitrification, and anaerobic degradation, leading to comprehensive contaminant removal.

The absence of granular substrates in the CWFF mitigated common issues associated with traditional constructed wetlands, such as clogging and maintenance challenges. The forced flotation design enhanced the interactions between wastewater, plant roots, and microbial communities, resulting in efficient filtration and degradation of organic matter, nutrients, and suspended solids. Additionally, the system adaptability to different hydraulic retention times (HRTs) demonstrated its operational flexibility, with optimal performance observed at HRTs between 24 and 60 hours.

Based on our findings, we conclude that forced flotation is a promising and sustainable technique for wastewater treatment. When paired with artificial aeration, the CWFF system enhances biodegradation processes and ensures viability under diverse environmental conditions. This approach offers a scalable and effective model for wastewater treatment across various scenarios, from municipal sewage to industrial effluents, highlighting its relevance in modern environmental engineering.

However, it should be emphasized that there are some limitations of CWFF technology. For example, systems of this type might need bigger plots of land, which can be difficult to come by in congested urban centers or in areas with scarce resources. Moreover, external variables like ambient temperature, necessary solar hours for crop growth, and influent water quality can substantially affect performance. Sometimes, additional remedies (e.g., artificial aeration or thermal insulation) are needed to achieve optimal conditions for microbial metabolic activity and plant growth. Tackling these issues necessarily implies more operational complexity or cost, which must be balanced with the advantages that CWFF brings in every local scenario.

In comparison with conventional systems such as activated sludge or physicochemical treatments, which usually involve higher energy demand, specific chemical reagents and trained personnel, CWFF presents a more sustainable approach. It minimizes dependence on external inputs, reduces risks of clogging and makes maintenance and operational cost simpler by taking advantage of natural degradation and absorption processes. Furthermore, the floating macrophyte concept reduces the carbon footprint of the system and can be integrated into the landscape aesthetically, simulating an aquatic garden. Altogether, these characteristics support CWFF as a green, sustainable treatment option in a wide variety of contexts.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

R.E.M. conducted the research; all authors analyzed the data; all authors wrote the paper; and all authors had approved the final version.

References

[1] M. A. Onu, O. O. Ayeleru, B. Oboirien *et al.*, "Challenges of wastewater generation and management in sub-saharan Africa: A review," *Environmental Challenges*, vol. 11, 100686, April 2023. https://doi.org/10.1016/j.envc.2023.100686

[2] R. Bi, C. Zhou, Y. Jia *et al.*, "Giving waterbodies the treatment they need: A critical review of the application of constructed floating wetlands," *Journal of Environmental Management*, vol. 238, pp. 484–498, May 2019. https://doi.org/10.1016/j.jenvman.2019.02.064

[3] J. Wolf, R. B. Johnston, A. Ambelu *et al.*, "Burden of disease attributable to unsafe drinking water, sanitation, and hygiene in domestic settings: A global analysis for selected adverse health outcomes," *The Lancet*, vol. 401, no. 10393, pp. 2060–2071, June 2023. https://doi.org/10.1016/S0140-6736(23)00458-0

[4] X. Li, X. Zhang, M. Zheng *et al.*, "Application of decentralized wastewater treatment technology in rural domestic wastewater treatment," *Sustainability*, vol. 16, no. 19, p. 8635, October 2024. https://doi.org/10.3390/su16198635

[5] V. Kumar, S. Agrawal, S. A. Bhat *et al.*, "Environmental impact, health hazards, and plant-microbes synergism in remediation of emerging contaminants," *Cleaner chemical engineering*, vol. 2, 100030, June 2022. https://doi.org/10.1016/j.clce.2022.100030

[6] Z. X. da Costa, F. C. Boogaard, V. Ferreira *et al.*, "Wastewater management strategy for resilient cities—case study: Challenges and opportunities for planning a sustainable Timor-Leste," *Land*, vol. 13, no. 6, pp. 799, May 2024. https://doi.org/10.3390/land13060799

[7] A. E. Turcios, R. Miglio, R. Vela *et al.*, "From natural habitats to successful application-role of halophytes in the treatment of saline wastewater in constructed wetlands with a focus on Latin America," *Environmental and Experimental Botany*, vol. 190, pp. 104583, October 2021. https://doi.org/10.1016/j.envexpbot.2021.104583

[8] N. A. Qasem, R. H. Mohammed, and D. U. Lawal, "Removal of heavy metal ions from wastewater: A comprehensive and critical review," *Npj Clean Water*, vol. 4, no. 1, pp. 1–15, July 2021. https://doi.org/10.1038/s41545-021-00127-0

[9] B. J. Singh, A. Chakraborty, and R. Sehgal, "A systematic review of industrial wastewater management: Evaluating challenges and enablers," *Journal of Environmental Management*, vol. 348, 119230, December 2023. https://doi.org/10.1016/j.jenvman.2023.119230

[10] J. A. F. Viveros, G. Martínez-Reséndiz, F. Zurita *et al.*, "Partially saturated vertical constructed wetlands and free-flow vertical constructed wetlands for pilot-scale municipal/swine wastewater treatment Using Heliconia Latispatha," *Water*, vol. 14, no. 23, p. 3860, November 2022. https://doi.org/10.3390/w14233860

[11] J. Matesun, L. Petrik, E. Musvoto *et al.*, "Limitations of wastewater treatment plants in removing trace anthropogenic biomarkers and future directions: A review," *Ecotoxicology and Environmental Safety*, vol. 281, 116610, August 2024. https://doi.org/10.1016/j.ecoenv.2024.116610

[12] N. N. Idris, L. H. Chua, Z. Mustaffa *et al.*, "A review study on the association between hydraulic performance and treatment effectiveness in free surface flow constructed wetlands," *Ecological Engineering*, vol. 203, 107258, June 2024. https://doi.org/10.1016/j.ecoleng.2024.107258

[13] A. Biswas, and S. Chakraborty, "Organics and coliform removal from low strength domestic wastewater using integrated constructed wetland-microbial fuel cell reactor with bioelectricity generation," *Journal of Cleaner Production*, vol. 408, 137204, July 2023. https://doi.org/10.1016/j.jclepro.2023.137204

[14] Z. Si, Y. Wang, X. Cao *et al.*, "Mechanism and performance of trace metal remove by continuous-flow constructed wetlands couple with a micro-electric field," *Water research*, vol. 164, 114937, November 2019. https://doi.org/10.1016/j.watres.2019.114937

[15] R. Kaur, A. Talan, B. Tiwari *et al.*, "Constructed wetlands for the removal of organic micro-pollutants," *Current developments in biotechnology and bioengineering*, Elsevier, 2020, ch. 5, pp. 87–140. https://doi.org/10.1016/B978-0-12-819594-9.00005-X

[16] L. Feng, Z. Gao, T. Hu, *et al.*, "Performance and mechanisms of biochar-based materials additive in constructed wetlands for enhancing wastewater treatment efficiency: A review," *Chemical Engineering Journal*, vol. 471, 144772, September 2023. https://doi.org/10.1016/j.cej.2023.144772

[17] T. Saeed, "A comparative performance assessment of the integrated upflow and surface flow-based constructed wetlands dosed with landfill leachate: Electrode coupling and input load variation," *Water*, vol. 16, no. 13, p. 1776, June 2024. https://doi.org/10.3390/w16131776

[18] M. Alateeqi, M. Khajah, M. Abu-Arabi *et al.*, "Greywater treatment using vertical subsurface flow constructed wetland system," *Journal of Engineering Research*, vol 11, no. 3, pp. 7–12, September 2023. https://doi.org/10.1016/j.jer.2023.100052

[19] A. Nema, K. D. Yadav, and R. A. Christian, "A small-scale study of plant orientation in treatment performance of vertical flow constructed wetland in continuous flow," *International Journal of Phytoremediation*, vol. 22, no. 8, pp. 849–856, January 2020. https://doi.org/10.1080/15226514.2020.1715918

[20] S. Kaura, A. Mathur, and A. Kalra, "Bacteria and Pollutants," *Modern Approaches in Waste Bioremediation: Environmental Microbiology*, Springer International Publishing, 2023, pp. 339–364. https://doi.org/10.1007/978-3-031-24086-7_16

[21] X. Wang, D. Cai, M. Ji *et al.*, "Isolation of heavy metal-immobilizing and plant growth-promoting bacteria and their potential in reducing Cd and Pb uptake in water spinach," *Science of the Total Environment*, vol. 819, 153242, May 2022. https://doi.org/10.1016/j.scitotenv.2022.153242

[22] E. Ntagia, K. Amulya, S. L. Le *et al.*, "Pilot and full scale applications of floating treatment wetlands for treating diffuse pollution," *Science of the Total Environment*, vol. 899, 165595, November 2023. https://doi.org/10.1016/j.scitotenv.2023.165595

[23] Y. Zhang, X. You, S. Huang *et al.*, "Knowledge atlas on the relationship between water management and constructed wetlands—A bibliometric analysis based on citeSpace," *Sustainability*, vol. 14, no. 14, p. 8288, July 2022. https://doi.org/10.3390/su14148288

[24] M. I. Choudhury, J. E. Nilsson, S. Hylander *et al.*, "Enhancing nitrogen removal through macrophyte harvest and installation of woodchips-based floating beds in surface-flow constructed wetlands," *Chemosphere*, vol. 359, 142284, July 2024. https://doi.org/10.1016/j.chemosphere.2024.142284

[25] N. Chand, S. Suthar, and K. Kumar, "Wastewater nutrients and coliforms removals in tidal flow constructed wetland: Effect of the plant (Typha) stand and biochar addition," *Journal of Water Process Engineering*, vol. 43, 102292, October 2021. https://doi.org/10.1016/j.jwpe.2021.102292

[26] D. Arivukkarasu and R. Sathyanathan, "Phytoremediation of domestic sewage using a floating wetland and assessing the pollutant removal effectiveness of four terrestrial plant species," *H_2Open J.*, vol. 6, no. 2, pp. 173–187, April 2023. https://doi.org/10.2166/h2oj.2023.032

[27] D. Parde, A. Patwa, A., Shukla *et al.*, "A review of constructed wetland on type, treatment and technology of wastewater," *Environmental Technology & Innovation*, vol. 21, 101261, February 2021. https://doi.org/10.1016/j.eti.2020.101261

[28] Z. U. R. Farooqi, M. M. Hussain, M. A. Ayub *et al.*, "Potentially toxic elements and phytoremediation: opportunities and challenges," *Phytoremediation*, pp. 19–36, 2022. https://doi.org/10.1016/B978-0-323-89874-4.00020-0

[29] L. Y. Kochi, P. L. Freitas, L. T. Maranho *et al.*, "Aquatic macrophytes in constructed wetlands: a fight against water pollution," *Sustainability*, vol. 12, no. 21, 9202, November 2020. https://doi.org/10.3390/su12219202

[30] D. B. Loureiro, L. D. Lario, M. S. Herrero *et al.*, "Potential of Salvinia biloba Raddi for removing atrazine and carbendazim from aquatic environments," *Environmental Science and Pollution Research*, vol. 30, no. 8, pp. 22089–22099, October 2022. https://doi.org/10.1007/s11356-022-23725-y

[31] R. Z. Marques, P. G. D. Oliveira, M. L. Barbato *et al.*, "Green Solutions for Antibiotic Pollution: Assessing the Phytoremediation Potential of Aquatic Macrophytes in Wastewater Treatment Plants," *Environmental Pollution*, vol. 357, 124376, September 2024. https://doi.org/10.1016/j.envpol.2024.124376

[32] M. T. Javed, K. Tanwir, M. S. Akram *et al.*, "Phytoremediation of cadmium-polluted water/sediment by aquatic macrophytes: Role of plant-induced pH changes," *Cadmium Toxicity and Tolerance in Plants*, pp. 495–529. Academic Press. https://doi.org/10.1016/B978-0-12-814864-8.00020-6

[33] A. L. Prieto, C. S. Criddle, and D. H. Yeh *et al*., "Complex organic particulate artificial sewage (COPAS) as surrogate wastewater in anaerobic assays," *Environmental Science: Water Research & Technology*, vol. 5, no. 10, pp. 661–1671, August 2019. https://doi.org/10.1039/C9EW00365G

[34] UN.DESA, The Sustainable Development Goals Report 2023: Special Edition, 2023.

[35] A. U. Khan, A. N. Khan, A. Waris *et al*., "Phytoremediation of pollutants from wastewater: A concise review," *Open Life Sciences*, vol. 17, no. 1, pp. 488–496, May 2022. https://doi.org/10.1515/biol-2022-0056

[36] UN.ESCAP, United Nations 2023 Water Conference Mid-term Review of the Water Action Decade: key messages from the United Nations Regional Commissions. https://hdl.handle.net/20.500.12870/5546.

[37] Z. F. Rizvi, M. Jamal, H. Parveen *et al.*, "Phytoremediation potential of Pistia stratiotes, Eichhornia crassipes, and *Typha latifolia* for chromium with stimulation of secondary metabolites," *Heliyon*, vol. 10, no. 7, April 2024. https://doi.org/10.1016/j.heliyon.2024.e29078

[38] A. B. Jensen, F. Eller, and B. K. Sorrell, "Comparative flooding tolerance of *Typha latifolia* and Phalaris arundinacea in wetland restoration: Insights from photosynthetic CO_2 response curves, photobiology and biomass allocation," *Heliyon*, vol. 10, no. 1, January 2025. https://doi.org/10.1016/j.heliyon.2023.e23657

[39] M. M. Nabuyanda, P. Kelderman, J. van Bruggen *et al*., "Distribution of the heavy metals Co, Cu, and Pb in sediments and Typha spp. and Phragmites mauritianus in three Zambian wetlands," *Journal of Environmental Management*, vol. 304, 114133, February 2022. https://doi.org/10.1016/j.jenvman.2021.114133

[40] G. A. Oliveira, G. S., Colares, C. A., Lutterbeck *et al.*, "Floating treatment wetlands in domestic wastewater treatment as a decentralized sanitation alternative," *Science of the Total Environment*, vol. 773, 145609, June 2021. https://doi.org/10.1016/j.scitotenv.2021.145609

[41] L. H. Bauer, A. Arenzon, N. D. Molle *et al.*, "Floating treatment wetland for nutrient removal and acute ecotoxicity improvement of untreated urban wastewater," *International Journal of Environmental Science and Technology*, vol. 18, no. 12, pp. 3697–3710, January 2021. https://doi.org/10.1007/s13762-020-03124-x

[42] H. Wang, L. Sheng, and J. Xu, "Clogging mechanisms of constructed wetlands: A critical review," *Journal of Cleaner Production*, vol. 295, 126455, May 2021. https://doi.org/10.1016/j.jclepro.2021.126455

[43] J. Chang, S. Wu, Y. Dai et al., "Treatment performance of integrated vertical-flow constructed wetland plots for domestic wastewater," *Ecological engineering*, vol. 44, pp. 152–159. https://doi.org/10.1016/j.ecoleng.2012.03.019

[44] B. Shrestha, R. Hernandez, D. L. B. Fortela *et al.*, "Formulation of a simulated wastewater influent composition for use in the research of technologies for managing wastewaters generated during manned long-term space exploration and other similar situations—literature-based composition development," *BioTech*, vol. 12, no. 1, p. 8, January 2023. https://doi.org/10.3390/biotech12010008

[45] E. O'Flaherty, and N. F. Gray, "A comparative analysis of the characteristics of a range of real and synthetic wastewaters," *Environmental Science and Pollution Research*, vol. 20, pp. 8813–8830, June 2013. https://doi.org/10.1007/s11356-013-1863-y

[46] United States Environmental Protection Agency (EPA), 2021, 40 CFR Part 133, Secondary Treatment Regulation.