THE ROLE OF PARTIAL SATURATION IN VERTICAL FLOW CONSTRUCTED WETLANDS (VFCW): MECHANISMS, TREATMENT PERFORMANCE AND FUTURE PERSPECTIVES

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ABSTRACT: Vertical flow constructed wetlands (VFCW) are a nature-based solution used to treat a variety of effluents, with a primary focus on the removal of organic matter and nutrients. Several operational modifications and strategies in VFCW have been studied to optimize treatment performance, including partial saturation of the support media. Partial saturation is a key factor for system performance, influencing microbial activity, oxygen availability, and pollutant removal, among other factors. This strategy creates environments with different oxygenation levels, which allow the development of different microorganisms that aid in removal and degradation of pollutants. Partial saturation allows for both aerobic and anaerobic zones withing the same unit, leading to more complete treatment and reducing area required. This article presents, in a clear and succinct manner, the aspects involved in the partial saturation of VFCW systems, its mechanisms and impacts on treatment, as well as results from worldwide studies and future perspectives.

KEYWORDS: Vertical Flow Constructed Wetlands; Partial Saturation; Nature-based Solutions; Wastewater Treatment Optimization; Nutrient Removal.

1 I INTRODUCTION

Constructed Wetlands (WC) are nature-based solutions that have been used for years to treat various types of effluents (VYMAZA, 2022). Among the WC types, Vertical Flow Constructed Wetlands (VFCW) stand out for their high efficiency in removing organic matter and pollutants. These systems involve the passage of wastewater through a porous medium (e.g. sand or gravel), which supports the growth of plants and the development of microbial communities essential for pollutant removal (SIRIWARDHANA et al., 2023).

With the advancement of technology, several construction and operational strategies have been developed to improve the performance and efficiency of pollutant removal. One of the strategies that has been gaining considerable attention is the partial saturation of the support medium. Nevertheless, any change in design and/or operational parameters of VFCWs, including the saturation level, can significantly influence their efficiency in treating wastewater (VIVEROS et al., 2022).

The saturation level refers to the height that wastewater occupies inside the VFCW, that is, the level at which the porous spaces within the medium are filled with liquid (VERA-PUERTO et al., 2021). This parameter plays a crucial role in determining the aerobic and anaerobic conditions within the unit, which, in turn, affect microbial activity, oxygen transfer, and the overall treatment performance (LIU et al., 2018; SAEED; HAQUE; KHAN, 2019; SAEED; SUN, 2017). Maintaining an optimal saturation level is essential to achieve high rates of organic matter degradation and nutrient removal, particularly nitrogen compounds. However, achieving an ideal saturation level is a challenge, given the various types of VFCW and other construction and operational factors.

Recent studies have highlighted the importance of understanding and optimizing saturation levels in VFCWs to enhance their performance (DATTA et al., 2022; LANGERGRABER; ŠIMŮNEK, 2018; ZUO et al., 2024). VFCWs that maintain partial saturation, achieve higher removal rates of organic matter compared to fully saturated systems (ZUO et al., 2024). The coexistence of aerobic and anaerobic zones, facilitated by controlled saturation levels, is essential for efficient nitrogen removal (NEGI et al., 2022; XIA et al., 2020).

Advancements in monitoring technologies and a deeper understanding of microbial ecology have further emphasized the significance of saturation levels (FAULWETTER et al., 2009; TANG et al., 2020; VERDUZO GARIBAY et al., 2021). The diversity and activity of microbial communities are strongly influenced by the saturation conditions, which impacts the overall treatment efficiency (LIU et al., 2018; XIA et al., 2020; ZUO et al., 2024). Moreover, the development of hybrid systems and automated control mechanisms presents new opportunities for optimizing saturation levels in VFCWs, thereby improving their performance and sustainability (DATTA et al., 2022).

This review article aims to explore the influence of saturation levels on the performance of VFCWs, focusing on the underlying mechanisms, treatment performance, and strategies for optimization. By examining recent research and case studies from different regions, this article provides a comprehensive understanding of how saturation levels can enhance the efficiency of VFCWs in various environmental settings.

2 I IMPACT OF SATURATION ZONE IN THE VFCWS SYSTEM

Partially Saturated Vertical Flow Constructed Wetlands (Figure 01) are designed to enhance the efficiency of wastewater treatment by utilizing both aerobic and anaerobic processes. Understanding the underlying mechanisms in these systems is crucial for optimizing their performance.

The saturation level in VFCWs is critical because it influences various biochemical processes that determine the overall treatment performance. The degree of saturation affects oxygen availability, microbial community structure, and plant development, all of which play essential roles in the system efficiency (AL-SAEDI; SMETTEM; SIDDIQUE, 2018; ZUO et al., 2024).

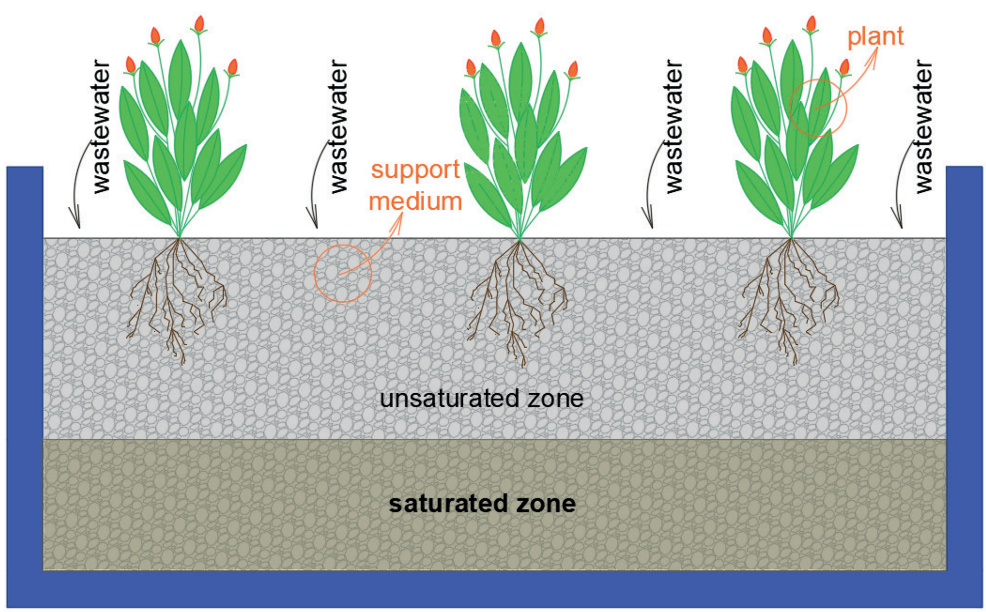

Figure 01. Representative schematic of a Partially Saturated Vertical Flow Constructed Wetland.

2.1 Oxygen level conditions

Using a saturation zone in a VFCW is an interesting strategy, as it allows for the same unit to have predominantly aerobic zones (upper, unsaturated part) and predominantly anerobic zones (saturated zone), in addition to a transition layer between these regions. This setup enables different microorganisms, processes and metabolic pathways to occur in a single system, enhancing pollutant removal.

2.1.1 Aerobic Zones

Partially saturated VFCWs maintain unsaturated zones where air can penetrate, facilitating aerobic microbial activity. This is crucial for the oxidation of organic matter and the nitrification process, where ammonium is converted to nitrate. However, it is important to note that the maintenance of the aerobic layer is directly linked to the feeding method of the unit. In VFCWs, wastewater is generally applied in batches, which is referred to as intermittent feeding (BASSANI et al., 2021).

Aerobic conditions in VFCWs are crucial for the efficient breakdown of organic pollutants, leading to high biochemical oxygen demand (BOD) and chemical oxygen demand (COD) removal rates (VIVEROS et al., 2022; XIA et al., 2020). Studies have shown that maintaining unsaturated conditions in VFCWs can significantly enhance aerobic microbial activity and organic matter decomposition (DATTA et al., 2022; PELISSARI et al., 2018; VIVEROS et al., 2022).

In partially saturated VFCWs, the presence of unsaturated zones allows oxygen diffusion, which is essential for aerobic microbial processes. These processes include the oxidation of organic matter and the nitrification process, where ammonium (NH_4^+) is converted to nitrate (NO_3^-). This process is crucial for nitrogen removal in wastewater.

2.1.2 Anaerobic Zones

In contrast, fully saturated zones in VFCWs favor anaerobic processes, such as denitrification (CABRED et al., 2019). Denitrification is a critical process for nitrogen removal, where nitrate is reduced to nitrogen gas (N_2) under anaerobic conditions. This process is facilitated by denitrifying bacteria, which thrive in the absence of oxygen. This dual environment, where both aerobic and anaerobic processes can occur, is essential for comprehensive nitrogen removal and the overall efficiency of VFCWs (CABRED et al., 2019; LÓPEZ et al., 2015; ROSENDO; DA PAZ; ROSENDO, 2022).

2.2 Microbial activity and diversity

Different saturation levels create a heterogeneous environment that supports a diverse microbial community. This diversity is beneficial for the breakdown of complex organic compounds and the transformation of nutrients. Studies using molecular techniques have demonstrated that microbial communities in VFCWs can adapt to varying saturation levels, optimizing the degradation of pollutants (ZUO et al., 2024).

In VFCWs, biofilms form on the surfaces of the substrate, plant roots, and other materials. The presence of both saturated and unsaturated zones in VFCWs promotes the development of biofilms with a wide range of microbial species, each adapted to different environmental conditions. This microbial diversity enhances the overall pollutant removal efficiency through synergistic interactions among different microbial populations (LAI et al., 2020a; PELISSARI et al., 2018).

2.3 Nutrient cycling

The dual environment, where both aerobic and anaerobic processes can occur in partially saturated VFCW, is essential for comprehensive nitrogen removal (XIA et al., 2020; ZUO et al., 2024). For example, nitrification (the conversion of ammonium to nitrate) occurs in aerobic zones, while denitrification (the reduction of nitrate to nitrogen gas) takes place in anaerobic zones (LAI et al., 2020a). This sequential process ensures effective nitrogen removal from the wastewater. Additionally, the diverse microbial communities in VFCWs can metabolize a wide range of organic compounds, further enhancing the treatment efficiency (KIM et al., 2015). Recent studies have highlighted the importance of maintaining a balance between aerobic and anaerobic conditions to optimize nutrient cycling and pollutant removal in VFCWs (LAI et al., 2020b; ZUO et al., 2024).

2.4 Plant development in VFCWs

The saturation zone in VFCWs significantly influences plant development. Plants play a crucial role in wetlands, absorbing nutrients for their metabolism and facilitating oxygen transfer (RAHI et al., 2020). Plants with roots submerged in a saturated environment, are capable of absorbing nutrients and metals for their leaves and stems (KADLEC; WALLACE, 2009).

Roots play a key role in nutrient cycling and pollutant uptake, and the saturation zone influences the availability of nutrients and pollutants in the root zone. The rhizosphere creates a very rich environment, with a large surface area for the development of biofilm, which in turn can diversify and specialize in the removal of specific pollutants, depending on the saturation. The saturation level influences the extent and nature of these biofilms, which are essential for pollutant degradation (RAHI et al., 2020). Plant root exudates release low-molecular-weight organic compounds into the rhizosphere, providing substrates that stimulate microbial growth and significantly enhance overall microbial activity in the system (SINGH; MUKERJI, 2006; STEINAUER; CHATZINOTAS; EISENHAUER, 2016; ZHALNINA et al., 2018).

3 I IMPACT OF SATURATION LEVEL ON VFCWS TREATMENT PERFORMANCE

The saturation level in Vertical Flow Constructed Wetlands (VFCWs) has a profound impact on the treatment performance of these systems. By influencing the balance between aerobic and anaerobic zones, the saturation level affects the removal of organic matter, nitrogen, phosphorus, and other pollutants. This section delves into the specific impacts of saturation levels on various aspects of treatment performance.

Partially saturated VFCWs enhance the removal of Biochemical Oxygen Demand (BOD) and Chemical Oxygen Demand (COD) due to the optimized conditions for both aerobic and anaerobic microbial processes. Research has shown that these systems can achieve higher efficiencies in organic matter degradation compared to fully saturated or fully unsaturated systems (SAEED; YADAV; MIAH, 2022a).

In aerobic zones, microorganisms utilize oxygen to break down organic pollutants into simpler compounds, reducing BOD and COD levels. Studies have demonstrated that partially saturated conditions significantly enhance aerobic microbial activity, leading to improved decomposition of organic matter (BASSANI et al., 2021; DATTA et al., 2022; VIVEROS et al., 2022). In fully saturated zones, anaerobic microorganisms contribute to the degradation of organic matter. This process not only complements aerobic degradation but also ensures the breakdown of compounds that are less biodegradable under aerobic conditions (CABRED et al., 2019)

The coexistence of aerobic and anaerobic zones fosters a synergistic environment where a wide range of organic pollutants can be degraded efficiently. This dual environment facilitates the breakdown of complex organic compounds into simpler, more biodegradable forms, improving overall BOD and COD removal (GOURDON et al., 2018; STEFANAKIS; AKRATOS; TSIHRINTZIS, 2014).

The combination of saturated and unsaturated regions in VFCWs play a crucial role in influencing the overall nitrogen removal efficiency. In the aerobic zones, nitrifying bacteria convert ammonium to nitrate, while in the anaerobic zones, denitrifying bacteria reduce nitrate to nitrogen gas (ZUO et al., 2024). This nitrogen cycle is essential for removing nitrogen compounds from wastewater. Partially saturated VFCWs have been shown to enhance nitrogen removal by creating suitable conditions for nitrification and denitrification processes, leading to improved total nitrogen (TN) removal efficiency (DATTA et al., 2022; ZUO et al., 2024).

Additionally, adjusting the saturated zone depth (SZD) in VFCWs can optimize the aerobic and anoxic regions, further enhancing organic matter and nitrogen removal. Specifically, VFCWs with a SZD of 0.51 m have demonstrated the best performance for TN removal through simultaneous nitrification and denitrification, achieving high TN removal efficiencies of 67.4–80.3% (LIU et al., 2018). Therefore, the balance between saturated and unsaturated regions in VFCWs is critical for maximizing nitrogen removal efficiency in wastewater treatment systems.

Saturation levels can also influence overall phosphorus removal efficiency. In VFCWs, phosphorus can be removed through adsorption onto the substrate material, precipitation, and uptake by plants (KIM et al., 2015). The saturation level affects the redox conditions within the unit, which in turn influences the solubility and availability of phosphorus compounds. Maintaining optimal saturation levels can enhance phosphorus removal by promoting favorable conditions for adsorption and plant uptake. Research has demonstrated that optimizing the saturation level can improve phosphorus removal efficiency in VFCWs (KIM et al., 2015; LIU et al., 2018; VERA-PUERTO et al., 2021).

4 I WORLDWIDE APPLICATIONS OF PARTIALLY SATURATED VERTICAL FLOW CONSTRUCTED WETLANDS

The VFCW technology is present in many regions of the globe, mainly in Europe, where it originated (KADLEC; WALLACE, 2009). Therefore, research is also developed in different regions, under different characteristics, such as climate.

In Europe, a French study on partially saturated VFCW to remove emerging contaminants and antibiotic resistance genes showed that, even at the beginning of operation, the system was able to achieve removal efficiency of over 65% for 22 compounds (TADIĆ et al., 2024). Furthermore, the saturation conditions can aid in the removal of some specific antibiotics (AYDIN; INCE; INCE, 2015). Also, research conducted in Germany demonstrated that optimizing the saturation level through intermittent aeration significantly enhanced the removal of BOD and TN (BOOG et al., 2014).

In South America, a study conducted in Brazil examined the performance of VFCWs treating restaurant wastewater under varying saturation levels. The researchers found that VFCWs with 0.25 m of saturation level achieve a removal efficiency of 95.34% for COD and 96.95% for TKN (CARVALHOJR. et al., 2018). Besides, a work about nitrogen transforming bacteria in VSFCW presents insights about the bacterial consortium in this type of CW system, measuring the varied abundance of ammonia-oxidizing bacteria (AOB) and nitrite-oxidizing bacteria (NOB) in different layers of wetland (PELISSARI et al., 2017). Furthermore, research in Chile evaluated the performance of unsaturated and partially saturated VFCWs for the treatment of rural wastewater. Total nitrogen removal was positively influenced in the second phase of the experiment, using partial saturation, reaching efficiencies close to 60% (VERA-PUERTO et al., 2021).

A North American study conducted in Canada, where the pilot system installation site reached –32 °C, shows an advantage of VFCW, especially partially saturated systems, is the resilience and adaptability of the system to different climates. Despite the extreme conditions, it was possible to achieve a removal efficiency greater than 85% for COD. One of the conclusions of the study was the importance of aeration for the removal of organic matter in saturated systems in places with intense cold, thus also avoiding freezing of the saturated layer (GREBENSHCHYKOVA et al., 2020). A study conducted in the United States using partially saturated VFCW brought an innovation: dosing hydrogen peroxide into the system. This addition aims to supplement dissolved oxygen levels and has been shown to benefit plant root development by increasing total nitrogen removal (DINAKAR; TAO; DALEY, 2020).

Asia has conducted very interesting studies on various types of partially saturated VFCW. A study in Bangladesh tested partially saturated and unsaturated systems of microbial fuel cell integrated tidal flow constructed wetlands for the co-treatment of different proportions of landfill leachate and municipal wastewater. The results of the study, which also evaluated different support media and hydraulic retention time, show that longer retention time favors treatment performance (SAEED; YADAV; MIAH, 2022b). In Japan, in a study by Song et al. (2009), the application of saturated and unsaturated VFCW for polishing traditional treatment effluent was studied, aiming at the removal of estrogen. The study highlighted the importance of the unsaturated region, where aerobic conditions favored the removal of the hormone. Studies like this are very important to direct future research on the application of partially saturated VFCW for different purposes (SONG et al., 2009).

In Africa, a study in Ivory Coast on saturated VFCW focused mainly on the difference between support media and the presence or absence of planted species. In the research, removal efficiencies of 98% were achieved for total suspended solids, 84% for ammoniacal nitrogen and 89.4% for Biochemical Oxygen Demand (KPANNIEU et al., 2023).

5 | RESEARCH OPPORTUNITIES

Operational strategy in partial saturated VFCW, requires a deeper understanding of its dynamics, including correlations with construction factors (such as support material and plants species), climate influence, and the role of the hydraulic and operational regime.

Further research, including robust monitoring, is essential to establish optimal parameters and expand the knowledge and application of VFCW systems through pilot or real-scale experiments.

5.1 Advanced monitoring

A significant challenge in research is the extensive monitoring of systems, involving substantial field and laboratory work. The use of automatic sensors can greatly ease the routine of sample collection and analysis. There are sensors capable of recording and sending data remotely and continuously on various parameters, such as: pH, temperature, dissolved oxygen, water level, and nitrogen compounds. Moreover, especially in real systems, it is important to record the hydraulic regime, with data on pulses per day and inflow. Real-time monitoring of this data enables a deeper understanding of system behavior and the potential for technical adjustments to enhance efficiency. Advanced sensors and monitoring systems to continuously track saturation levels and system performance can be used to optimize the operation and management of VFCWs, ensuring consistent treatment performance.

5.2 Microbial ecology

Understanding the microbial communities in each layer and region of VFCW systems is of great importance. More knowledge about microorganisms involved in the unsaturated and saturated layers at different depths is needed to elucidate their roles in the removal of different pollutants.

By understanding the microbial diversity in the support medium and rhizosphere, researchers can explore the mechanisms and activities inherent to the biofilm, and its response to different load and climate conditions, for example. Advanced molecular microbiology techniques, such as Metagenomics, Metatranscriptomics, and Metabolomics, allow a deep understanding of the genes expressed by microbial communities, as well as their metabolites, opening opportunities for studying metabolic pathways and pollutant degradation under different operational conditions. Studies on this topic could lead to the design of specialized systems for the removal of certain pollutants or to increase overall treatment efficiency.

5.3 Hybrid systems

Another interesting opportunity for research and technological innovation is developing hybrid systems that combine partially saturated VFCW with other technologies Depending on the effluent characteristics and treatment objectives, combining technologies can enable specific pollutant removal, further polishing of treated effluent, or pathogen inactivation, for example. These cater to the specific needs of each effluent generation site by installing new systems or optimizing existing treatments.

6 I CONCLUSION

This review underscores the critical role of saturation levels in optimizing the performance of Vertical Flow Constructed Wetlands (VFCWs). By strategically managing the saturation zones, it is possible to enhance the removal efficiency of organic matter, nitrogen, and phosphorus through the simultaneous facilitation of aerobic and anaerobic processes. The dual environment fostered by partial saturation supports diverse microbial communities that are essential for comprehensive pollutant removal.

The integration of advanced monitoring technologies, such as real-time sensors, and a deeper understanding of microbial ecology presents significant opportunities for refining VFCW design and operation. Future research should focus on exploring the effects of different saturation levels across various environmental conditions and effluent types. Moreover, the development of hybrid systems that combine VFCWs with other treatment technologies could further expand their applicability and effectiveness in wastewater treatment. The application of partial saturation in VFCWs are likely to play a crucial role in advancing sustainable and efficient wastewater treatment solutions globally.

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