A Review on the Development, Mechanism and the Applications of the Tidal Flow Constructed Wetland Systems

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Abstract

Wetlands are an assortment of water bodies that give an environment to aquatic and terrestrial species and act as a distinct ecosystem flooded by water, where this water cover may occur seasonally or permanently. These may vary depending on various reasons, such as; the differences in the soils, topography, climate, hydrology, water chemistry, vegetation, etc. Constructed wetlands are being constructed by humans for the purpose of wastewater treatment specifically. These can be classified based on various parameters including the characteristics of the wastewater components and the wetland system itself, where they differ in their performance as well. The treatment wetland system technology has been developed so far, in terms of treatment efficiency, various types of contaminant removal capability, and the usage of land. Hybrid technologies have been developed to enhance these performance terms. The current study focus on the development, mechanism, and applications of the tidal flow constructed wetland systems, which possess a rhythmic cycle of filling and draining and enhanced treatment performance. The findings of the studies done with regard to various constructed wetland systems could be integrated to further enhance the treatment efficiency of the tidal flow constructed wetland system, having critically considered the role of oxygen in the treatment mechanism.

Keywords: Constructed wetlands, Wastewater treatment, Tidal flow, Nitrification, Denitrification

I. INTRODUCTION

Wetlands can be considered as a variety of water bodies that provide a habitat for aquatic vegetation and possess a biofiltration capability. They can be either natural marsh and swamp environments or artificially constructed storage basins and ponds. Wetland systems are located in the places where the water table is normally lying near the soil surface or at places of a permanent shallow-water cover. Constructed wetlands for wastewater treatment, sometimes referred to as treatment wetlands, are manmade systems that use natural processes to remove contaminants from polluted water in a more regulated setting (Faulwetter *et al*., 2009; Vymazal, 2009).

There are numerous methods and strategies used in wastewater treatment using the constructed wetlands, thus making it difficult to distinguish each and every method. However, studies have shown that they can be categorized based on their loading pattern (continuous or intermittent flow), vegetation (rooted emergent, floating, or submerged macrophyte-based system), wastewater characteristics (municipal, agricultural or industrial), or soil hydraulics and materials (Borkar and Mahatme, 2015).

Kathe Seidel in the 1960s (Seidel, 1961) and Reinhold Kickuth in the 1970s have significantly contributed to the development of wastewater treatment technology using constructed wetlands (Du *et al*., 2014). By then the usage of constructed wetlands has been primarily employed for the treatment of typical tertiary and secondary domestic and municipal wastewater (Kivaisi, 2001). By the time the usage of constructed wetlands has been extended to purify the agricultural effluents (Zhao, Sun and Allen, 2004; Wood *et al*., 2008), tile drainage waters (Borin and Toccheto, 2007; Kynkäänniemi *et al*., 2013), acid mine drainage (Wieder, 1989), industrial effluents (Mbuligwe, 2005; Calheiros *et al*., 2007) and landfill leachates (Justin and Zupančič, 2009; Istenič *et al*., 2012). Table 1 represents the road map of CWs.

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Table 1: History of the development of CWs

Year	Innovation	Reference
1901	U.S. patent issued for the construction of distributed vertical flow, a fluctuating water level, and aeration of the wastewater.	(Monjeau, 1901)
1953	Vegetation-based designs for the improvement of inland waterways that suffered from overfertilization, pollution from sewage, and siltation.	(Seidel, 1953)
1952-1956	Research on the use of wetland plants for sanitation purposes. Also pointed out that "There are many questions about these systems and many limitations.	(Vymazal, 2011)
1970	Following a series of national conferences aimed at the use of wetlands for wastewater treatment in the United States.	(Brinson, 1984; Greeson *et al*, 1979)
1980	International exchange of knowledge by organizing conferences in various countries. Europe was mostly focused on Horizontal Flow CWs.	(Geller *et al*, 1992)
1985	The first two Horizontal Flow (HF) CWs were built in the United Kingdom and by the end of 1987 more than 20 HF CWs were designed.	(Cooper and Boon, 1987)
1990	The European Guidelines for constructed wetlands were introduced.	(Cooper, 1990)
1997	Austria accepted constructed wetlands as a certified technology by issuing official guidelines.	(Austrian Standards International, 1997)
1999	Denmark accepted constructed wetlands as a certified technology by issuing official guidelines.	(Danish Environmental Protection Agency, 1999)
2000	Australia and US EPA accepted constructed wetlands as a certified technology by issuing official guidelines.	(Sinclair, 2000; Queensland Department of Natural Resources, Brisbane, Australia, 2000; U.S. Environmental Protection Agency, 2000)
2000	The International Water Association issued its "Scientific and Technical Report" on the performance, design, and operation of constructed wetlands.	(Kadlec *et al*, 2000)
2000 - 2003	Increased demand for ammonia-N removal from sewage has resulted in the more frequent use of hybrid constructed wetlands, which are better suited to meet this goal than a single CW unit.	(Mander *et al.*, 2003; Brix, Koottatep and Laugesen, 2007)
2005	Built wetlands have been used to treat not only municipal wastewater but also effluent from tanneries, wineries, compost leachate, and shrimp aquaculture.	(Calheiros, Rangel and Castro, 2007; Kucuk, Sengul, and Kapdan, 2004; Grismer, Carr and Shepherd, 2003; Masi *et al*, 2002; Reeb and Werckmann, 2005; Lin *et al.*, 2005)
2005	The tidal flow CWs have been developed.	(Cooper, Griffin and Cooper, 2005)
2008	Numerical models of different complexities have been developed for describing various processes in subsurface flow CWs.	(Rousseau, Vanrolleghem and De Pauw, 2004; Langergraber, 2008)

Contaminant removal in constructed wetlands is complicated and reliant on a number of mechanisms such as; sedimentation, filtration, precipitation, volatilization, adsorption, plant uptake, and a range of microbiological activities (Vymazal, 2007; Kadlec and Wallace, 2008; Faulwetter *et al.,* 2009).

Constructed wetlands have traditionally been used to remove suspended solids and organic matter, and they have shown to be effective in achieving these aims (Dordio and Carvalho, 2013; Vymazal, 2009). Advanced wastewater treatment in terms of total nitrogen (TN) removal has become a mandatory requirement across the world to prevent the eutrophication of aquatic bodies (Wendling *et al*., 2013).

However, none of the traditionally constructed wetlands such as; Surface flow constructed wetlands, Horizontal subsurface flow constructed wetlands, or Vertical subsurface flow constructed wetlands can remove TN effectively on their own, as they lack the ability to provide alternate aerobic and anoxic conditions for the subsequent nitrification/denitrification processes (Kadlec and Wallace, 2008; Vymazal, 2007, 2011). As an example, Surface flow constructed wetlands and

Horizontal subsurface flow constructed wetlands do provide favorable circumstances for denitrification, but nitrification is impeded by the lack of oxygen transfer. Conversely, the Vertical subsurface flow constructed wetlands, generate an aerobic environment that promotes nitrification while preventing denitrification (Vymazal, 2007). As a result, advanced process designs, such as hybrid or staged systems (Cooper *et al*., 2005; Cui *et al*., 2012; Seo *et al*., 2008; Vymazal, 2007), are becoming an unavoidable trend in the future development of constructed wetlands to accomplish successful TN removal (Vymazal, 2009).

Hence, the technology of wastewater treatment in constructed wetlands proceeded so far could be summarized as; Combining various types of constructed wetlands in hybrid systems to improve treatment performance; particularly for nitrogen, treatment of specific compounds present in wastewaters, search for suitable media with high capacity for phosphorus removal in subsurface flow constructed wetlands, identification of bacteria that assist in the treatment processes and the displaying of the pollution removal and the hydraulics of the various types of constructed wetlands (Zhi *et al*., 2015).

Further, the hybrid constructed wetlands have been demanded as a more suited approach in lieu of the single constructed wetlands in response to the necessity of removing the ammonia-N from sewage. Extra capital investment and a set of complex operating procedures are required by the hybrid systems of constructed wetlands and the Tidal flow constructed wetlands have been presented as an inclusive and cost-effective modification of enhanced removal of nitrogen, ammonium (NH_4^+), and TN (Zhi *et al*., 2015).

In this review, the mechanism, applications, and efficiency of the tidal flow wetland system are described with regard to the other wetland treatment designs.

II. DISCUSSION

Tidal flow constructed wetlands provide a rhythmic sequential cycle of a "filled/wet" phase and a "drained/dry" phase that enhances both nitrification and denitrification in a single reactor, reducing the costs of extra land use and initial capital (Borkar and Mahatme, 2015).

Tidal flow constructed wetlands are a somewhat new innovation that uses a new oxygen transfer operational strategy (Wu *et al*., 2014). They produce a musical successive pattern of a flood/wet stage and a channel/dry stage, which increments both the nitrification and denitrification in a single reactor. High TN removal rates were accomplished in Tidal flow constructed wetlands when the C/N proportions were higher than 10. Various researches have shown a restricted denitrification process in Tidal flow constructed wetlands, resulting in the accumulation of NO_3^--N and NO_2^--N because of the degradation of organic matter during the aerobic stage. The flood and drain (F/D) pattern of Tidal flow constructed wetlands is a critical parameter influencing the hydraulic loading rate (HLR) and aerobic/anoxic conditions for greatest nitrogen removal (Wu *et al*., 2015).

In tidal flow constructed wetland systems, the wastewater is fed to the aeration pipes at the bottom of the bed. It then percolates upward, flooding the surface. The pump is turned off when the surface is entirely inundated, and the wastewater is retained in the bed, in contact with the microorganisms growing on the medium. After a certain amount of time has passed, the wastewater is drained downward, air diffuses into the spaces in the bed, and the treatment cycle is complete after the water has drained from the bed (Cooper *et al*., 2005).

Ammonium removal in constructed wetlands is complicated, including a variety of sequential or concurrent physical, chemical, and biological interactions inside the substrates (Vymazal, 2007). The process of biological nitrification-denitrification is widely recognized as the most common method of ammonium removal. However, nitrification frequently comes before denitrification and is a rate-limiting phase in most classical constructed wetlands due to the lack of oxygen supply (Maltais-Landry *et al*., 2009; Hu *et al*., 2014). Accordingly, oxygen in wetland beds is significant for nitrification and ought to be expanded. In most horizontal subsurface flow constructed wetlands, oxygen transport to saturated media is restricted, with just a little amount of net delivery through macrophyte roots (1–8 $gm^{-2}d^{-1}$) (Kadlec and Wallace, 2008; Garcia *et al*., 2010). Artificially aerated constructed wetlands can enhance the oxygen transfer rate to 160 $gm^{-2}d^{-1}$ by compressing air from the atmosphere into the wetland bed through a blower

(Kadlec and Wallace, 2008). Therefore, the removal of nutrients could be enhanced and the required area would also be reduced significantly. However, this extra aeration could consume a lot of energy and the air diffusers could get dirt quickly leading to malfunctioning, hence their cleaning mechanism plus their replacement systems have to be decided carefully (Wu *et al.*, 2014).

Tidal flow constructed wetlands are consistently loaded up with wastewater and the drained, going about as uninvolved siphons that repel and draw air from the atmosphere into grids (Sun *et al.,* 2006). Subsequently, the oxygen transfer rate comes to up to 450 $gm^{-2}d^{-1}$ (Wu *et al.*, 2012). Also, the treatment limit of ammonium and organic matter fundamentally improves (Hu *et al.*, 2014). By Fick's law, the half-time of oxygen diffusion from the air-water interface across thin biofilms, which is less than 100 µm is on the order of a second or less. In this way, the diffusion benefits the oxygen transfer in the drained phase to quickly nitrify adsorbed ammonium ions (McBride and Tanner, 1999). In the next flood cycle, nitrate (NO_3^-) anions as a result of ammonium oxidation are desorbed into bulk water. And they fill in as terminal electron acceptors for denitrification utilizing the organic carbon in the feeding water (Wu *et al.,* 2015).

However, it should be noted that for the treatment wetlands, oxygen is a vital natural parameter that controls nitrification and biodegradation of organic materials. Especially, when constructed wetlands are utilized to treat high-strength wastewaters, the oxygen transfer limitations act as a crucial factor affecting the performance of the treatment process (Wu *et al.*, 2011). Accordingly, another tidal flow operation approach; also named the fill-and-drain operation has been proposed. Here, as the constructed wetland is being filled and drained, its bed of it is being saturated sporadically and when the air draws into the aggregate oxygenates the biofilms (Jiang et al. 2014). Hence, the operation has been researched as a method of improving treatment efficiency in various studies (Zhao, Sun and Allen, 2004; Jiang *et al.*, 2014).

A study done on the oxygen transfer capacity and the removal of NH_4^+-N and organic matter utilizing a laboratory scale tidal flow constructed wetland has reported that the maximum removal of BOD, NH_4^+-N, and TN for various pollutant loadings (BOD loading 174–330 g/m^2/day) was 91, 82, and 43 %, respectively (Wu *et al.*, 2011). Sun *et al.* (2006) studied a pilot-scale constructed wetland for high-strength piggery wastewater treatment utilizing tidal flow operation, where the study concluded of the system that shows a cleaning impact, and the removal efficiencies of COD, BOD, TSS, NH_4^+-N, and TP were 80, 82, 78, 58, and 45%, respectively. This is significantly higher than the ordinary subsurface flow systems. However, the performance of removal utilizing this methodology relies upon many factors such as; flood channel proportions, C/N proportion, and substrate qualities. Another study has covered the impact of utilizing various medium arrangements in tidal flow constructed wetlands by treating the wastewater emitted from a pig farm and the outcomes exhibited that utilizing coarse substrates in the upper layer of the constructed wetland system could enhance the removal of organic matter and suspended solids due to the minimized effect of clogging (Sun *et al.*, 2006). Furthermore, another study has explored the impact of various flooded/drained (F/D) time proportions on nitrogen transformations in tidal flow constructed wetlands, where it has been indicated that the extended drained periods and shorter flooded periods have shown a positive impact on the nitrification in the wetlands, whilst the F/D time proportions had a little impact on the Phosphorous removal (Chang *et al.*, 2014; Zhi and Ji, 2014) has revealed that high COD (83–95 %), NH_4^+- N (63–80 %), and TN (50–82 %) removal efficiencies were accomplished in a tidal flow constructed wetland under the C/N ratios ranging from 2 to 12. They further reveal that a C/N ratio of greater than 6 (>6) is needed to achieve complete denitrification.

Apart from these promising results, further full-scale and real-world research are being needed to receive a better understanding of the tidal flow operation and its practicability in applications.

Added to that, the construction solid waste (solid waste generated from the construction fields/materials) -based tidal flow constructed wetland system would facilitate a high rate removal of Phosphorous, ammoniacal-nitrogen and organic matter from the domestic. Also, this strategy would enable us to utilize construction solid waste as a useful material. Hence, the construction solid waste could be used as the main substrate material in the constructed wetland systems and the usage of coal ash-based construction solid waste particularly would yield benefits in reusing and disposal of the construction solid waste, while stepping to an improved Phosphorous removal out of the domestic wastewater. Sorption in the construction of solid waste-based media has been suggested to be the main mechanism of Phosphorous removal. This usage eases the pressure on construction solid waste management and disposal. TCOD and NH4+ -N removal performance could be enhanced in a significant manner through the increased oxygen supply capacity via the tidal flow operation strategy (Yang *et al*., 2012).

The removal of COD, BOD, N, and P from rejected water of a municipal wastewater treatment plant utilizing a new alum sludge-based multi-stage vertical subsurface flow constructed wetland system has been investigated, where the results indicate that a critical decrease of up to 99.5% of P-input through the reject water recycling to the principle wastewater treatment stream can be accomplished by utilizing such alum sludge-based constructed wetland. The alum sludge has shown that it contains a few metal ions that identify with P-metal adsorption and precipitation. Particularly, the aluminum ion is the predominant constituent in the alum sludge. And it could potentially contribute to adsorption and chemical precipitation of P onto the alum sludge. Different studies show different results on the reported Phosphorous adsorption capacity of the alum sludge, as per their experimental method and the other conditions. However, a range of 1.1 to 150.0 mg-P/g-sludge could be observed in the results of the studies (Kim *et al*., 2002; Dayton and Basta, 2005; Novak and Watts, 2005; DeWolfe, 2006). A recent study has employed an Irish alum sludge as the wetland media, and its long-term lab-scale operation has depicted a strong association with phosphorousimmobilization. Also, the lifetime of the constructed wetland for Phosphorous adsorption saturation has been estimated to be 9-40 years (Zhao *et al*. 2011)

A novel tidal vertical flow constructed wetland has been developed to treat secondary effluent with low COD/ total nitrogen (C/N) ratio raw sewage as a carbon source. The tidal zone has been described by the presence of unclassified Xanthomonadaceae, Nitrospira, and Rhodanobacter, while Candidatus Brocadia and Denitratisoma, which includes anammox and denitrification, dominated the community composition in the saturated zone. These outcomes have additionally been affirmed by the relating functional genes (amoA, nxrA, nirS, and anammox). Hence, the halfway denitrification-anammox (PDN/AMX) and denitrification were proposed as the significant pathways identified with nitrogen removal (Zhan *et al.,* 2020).

The purification limit of a research center scale tidal flow reed bed system with final effluent recirculation at a proportion of 1:1 has been investigated. The normal removal efficiencies obtained for COD, BOD_5, SS, NH_4^+-N, and P have been 77%, 78%, 66%, 62%, and 38%, respectively (Zhao, Sun and Allen, 2004).

The beneficial effect of effluent recirculation on the performance of wetlands, particularly on the removal of inorganic nitrogen, has been reported in the literature. Kantawanichkul *et al.* (2001) investigated the effect of varying the recirculation ratio (recirculation flow rate: feed flow rate) in a vertical flow wetland system treating pig farm wastewater from 0:1 to 2:1. The optimum ratio was discovered to be 1:1, which allowed the system to achieve the highest nitrogen removal, 93 percent Total Nitrogen. A column-scale trial of a tidal flow constructed wetland system treating diluted piggery wastewater resulted in significant removal of organic matter, ammoniacal nitrogen, and suspended solids. Recirculating final effluent at a 1:1 ratio improved pollutant removal percentages (Sun, Zhao and Allen, 2005).

Accomplishing viable total nitrogen (TN) removal can be considered one of the major challenges faced by constructed wetlands. Including multiple tides in a single-stage tidal flow constructed wetland has been proposed in addressing this issue (Hu, Zhao and Rymszewicz, 2014). This has resulted in a very high value of 85% (average) on TN removal under a high nitrogen loading rate (NLR) of around 28 gNm^{-2}/day. This makes this system an optimum advanced wastewater treatment method for peri-urban and rural communities. This method has also, shown greater adaptability to tidal flow constructed wetlands. However, the contact/rest plan on the bed should be optimized as per the adsorption/nitrification kinetics. These findings will provide a new foundation for the design and modeling of nitrogen removal in tidal flow-constructed wetlands.

III. CONCLUSION

Oxygen is the crucial factor for continuous nitrification and denitrification processes. Conventional wetland systems do not have proper oxygen transferring processes via the substrate and wetland water. Tidal flow constructed wetlands possess special flow cycles, which proceed with the fill and drain. Oxygen can fill into the system during the drain cycle. The "Fill" part of the cycle enhances nitrification, while the "drain" part accounts for the enhancement of the denitrification. By combining and integrating various treatment technologies, followed by the particular specifications to the substrate and wetland water, Nitrogen and Phosphorous removal rates could be developed.

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