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Review

Vertical-horizontal subsurface flow hybrid constructed wetlands for municipal wastewater treatment in developing countries: A review

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The use of low-cost on-site wastewater treatment technologies, including constructed wetlands (CWs), is wide spread. Despite the purported high performance of vertical-horizontal subsurface flow (V-H SSF) hybrid CWs, data on implementation and performance in developing countries is scarce. Here, the design, operation and performance of V-H SSF hybrid CWs for treatment of municipal sewage in an effort to encourage and direct future research and assist technology choice were reviewed. Literature reveals that successful performance of V-H SSF hybrid CWs depends mainly on system design and is independent of mode of feeding. Moreover, performance and final effluent quality is high for biological oxygen demand (BOD), chemical oxygen demand (COD) and total suspended solids (TSS) which are all reduced by over 80%. Despite high removal of ammonium-nitrogen (NH_4^+-N), concentration in the final effluent remains above desired levels, which is attributed to the design of V-H SSF hybrid CWs based on BOD as a parameter of choice, rather than nitrogen. It was argued that further research on performance of V-H SSF hybrid CWs based on designs that consider both nitrogen in the form of NH_4^+-N and BOD and assessment under different climatic conditions, is essential prior to mass implementation of this technology in developing countries.

Key words: Hybrid constructed wetlands, municipal wastewater, pollutant removal.

INTRODUCTION

Pollution of surface water resources due to municipal discharge is a major environmental challenge due to enrichment of these systems with pollutants thus, posing a threat to aquatic ecosystems and public health (Edokpayi et al., 2017; Balthazard-Accou et al., 2019). In Africa for instance, most sewages are not subjected to treatment mainly due to the current state of disrepair of deployed wastewater treatment plants (WWTPs) and poor appreciation of the associated technologies. In many developing countries, centralized conventional WWTPs are the currently preferred choice by engineers, planners, and decision makers and the reason; these are the most tried and tested technologies (Tsagarakis et al., 2003). The major drawbacks of this implementation strategy are high construction costs, chemical and energy demands, in addition to the requirement for high skilled

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and non-skilled personnel for operation and maintenance. This has, in part, resulted in failure of WWTPs and discharge of effluent that does not always conform to national and international guidelines, and in most instances is blamed on insufficient funding for municipalities to meet day-to-day running costs (Bakir, 2001).

To overcome the high costs associated with establishment of wastewater treatment infrastructure in developing countries, there is a shift away from construction of centralized WWTPs to decentralized natural, low-cost wastewater treatment technologies including CWs, waste stabilization ponds (WSPs), bio-filtration (BF) and integrated algae pond systems (IAPS) to mention a few. These systems are typically passive and utilize natural processes that depend mainly on the interaction of bacteria and algae and/or macrophytes powered by sunlight as a major source of energy (Mahmood et al., 2013). When these biochemical and physical processes occur in a more natural environment rather than tank reactors, the resulting system consumes less energy, is more reliable, and requires less operation and maintenance and hence the overall cost is lower (Makopondo et al., 2020). Among the decentralized wastewater treatment technologies, WSPs are the most widely adopted technology for the treatment of both domestic and municipal wastewater in tropical and subtropical regions. Unfortunately, many of these systems perform below the required standard especially concerning nitrogen (Mburu et al., 2013), which is attributed mainly to improper operation and maintenance (Magayane and Mwanuzi, 2006). Moreover, the performance of WSPs is dependent upon the prevailing climatic conditions, which is disadvantageous in high rainfall regions, and open systems pose a risk to public health, as they can be breeding grounds for mosquitoes in malaria prone countries. Furthermore, passive treatment processes with exposed anaerobic ponds such as WSP systems are also considered major contributors to greenhouse gas emissions (Coggins et al., 2019). For this reason, there is a growing interest in evaluating alternative wastewater treatment technologies with less environmental impact that consistently produce a quality effluent for discharge particularly regarding nitrogen.

This review focuses on CWs as an alternative passive wastewater treatment technology for application in developing countries. Most other studies address the general performance of different types of hybrid CWs (Vymazal, 2013) and their potential for adoption in developing countries (Mthembu et al., 2013). However, one of the major aims of wastewater treatment is protection of the integrity of aquatic and public health through production of a quality effluent that meets discharge standards and, at the lowest possible cost. Despite the different types of hybrid CWs reported in the literature, the most popular hybrid system used for treatment of both domestic and industrial wastewater is the vertical-horizontal subsurface flow (V-H SSF) hybrid CW (Lavrnic et al., 2020). The major objective of V-H SSF hybrid CWs is to maximize nitrogen removal through nitrification (in the VSSF) and denitrification (in the HSSF) processes (Vymazal, 2013, 2017). While application of CWs is regarded as a potential and novel biotechnology for wastewater treatment, information about their performance and factors influencing the quality of treated water from these systems especially in the tropics is scarce (Mburu et al., 2012). Furthermore, Avellán et al. (2019) emphasize that policy and decision makers who might have an influence on choice of an appropriate wastewater treatment technology and/or process system often lack the necessary information. In an effort to reduce this knowledge gap, this review therefore seeks to contribute to the body of information about effluent quality and performance with attention to single stage V-H SSF hybrid CWs in sewage treatment. Additionally, factors affecting performance and effluent quality of SSF CWs in general are also surveyed with particular attention to design consideration, influence of mode of operation and type of macrophyte used.

CONSTRUCTED WETLANDS FOR WASTEWATER TREATMENT

Constructed wetlands for wastewater treatment are engineered systems planned, designed and constructed to imitate natural wetland systems utilizing natural wetland processes including wetland plants, soil, and associated microorganisms to remove contaminants from wastewater in a controlled environment (Vymazal and Kröpfelová, 2008). This remedial technology is a low cost and environmentally friendly sanitation alternative to conventional methods and recommended for on-site wastewater treatment in small communities to meet required effluent discharge standards (Rousseau et al., 2004; Massoud et al., 2009). Furthermore, it is recognized as dependable for the treatment of different types of wastewaters including municipal and domestic Chang et al., 2012), mine drainage (Sheridan et al., 2013), agricultural runoff (Tyler et al., 2012), landfill leachate (Białowiec et al., 2012) and abattoir wastewater (Odong et al., 2013) to mention a few. Invented in the middle of the 20th century (Vymazal, 2008), CW technology has potential in developing countries in particular those located in warm tropical and sub-tropical regions which favour high biological activity and productivity, and thus better treatment performance (Zhang et al., 2015).

Constructed wetlands are preferred to conventional WWTPs due to simplicity of operation and maintenance costs (Puigagut et al., 2007; Dhir, 2013), and low energy demand (Álvarez and Bécares, 2008). Unlike WSPs and mechanized WWTPs, CWs offer other ecosystem services when operated on a commercial scale. These include: the provision of habitat to wildlife such as fish,

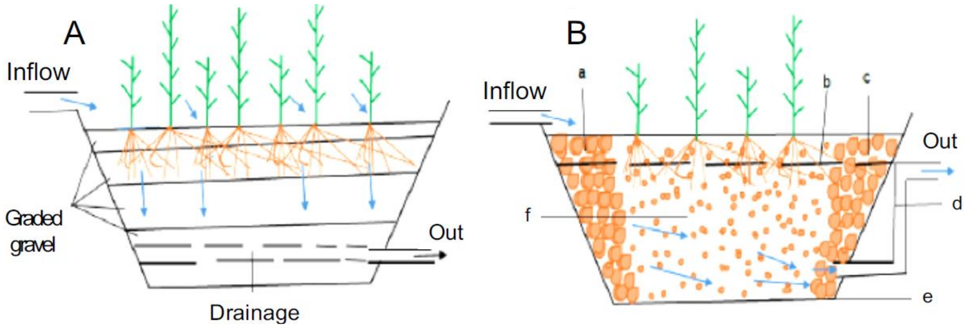

Figure 1. Diagrammatic representation of a typical subsurface flow (SSF) constructed wetland (CW) system. A) Vertical subsurface flow (VSSF) constructed wetland (CW); and, B) Horizontal subsurface flow (HSSF) constructed wetland (CW). Distribution (a) and collection zones (c) filled with large gravel; water level in the filtration bed (b); outlet structure (d) for maintaining the water level in the wetland; impermeable liner (e) such as Polyvinyl chloride and filtration zone (f), mainly gravel.
Source: Vymazal (2007).

birds, amphibians and reptiles (Lee et al., 2009), flood control, provision of educational and recreational opportunities when designed and built at schools, hospitals or even in municipal parks, provision of water for reuse and a visually attractive and functional landscape (Shutes, 2001; Lee et al., 2009; Stefanakis, 2020). Even so, like any other natural system, CWs are a biologically complex ecosystem with various components that interact non-linearly (Banzhaf and Boyd, 2012), and a better understanding of their effective performance is therefore required.

Categories of constructed wetlands

According to Kadlec and Knight (1996), CWs are categorized as either subsurface flow (SSF) or free water surface (FWS) systems depending on the type of flow. The former is further differentiated into vertical subsurface flow (VSSF) and horizontal subsurface flow (HSSF) CWs (Figure 1). A single stage CW either as vertical or horizontal subsurface flow system is preferred to FWS due to many environmental benefits. Thus, SSF conditions prevent odours and the breeding of mosquitoes especially in tropical regions. The bottleneck for SSF systems is however, the requirement of large land area (Zapater-Pereyra et al., 2014) and capital investment, which usually contributes significantly to the cost of the treatment media needed (Kadlec and Knight, 1996).

Horizontal subsurface flow CWs are designed so that wastewater continuously flows horizontally below ground through the substrate and effluent is then collected on the opposite side (Brix, 1994). The transfer of oxygen in this system is limited due to the fact that opportunities for contact between air and water are limited. Despite the fact that plants transport some oxygen from the atmosphere to the proximate roots, thereby creating some aerobic zones, the main part of the bed remains anaerobic (Vymazal, 2005). Nonetheless, there has been a growing interest in achieving completely nitrified conditions, which are seldom attained in the HSSF due mainly to insufficient oxygen supply (Vymazal, 2005).

In contrast to a HSSF system, wastewater is dosed onto the entire surface of the VSSF wetland system from above using a mechanical dosing system, allowing it to flow vertically through the treatment medium (sand or gravel bed) and discharge at the base (Brix and Arias, 2005). The bed is usually allowed to dry until the next dose of wastewater is applied, which allows diffusion of oxygen into the adjacent environment. The next dose traps air and this together with the aeration caused by the rapid dosing into the beds, leads to good oxygen transfer and hence nitrification (Brix and Arias, 2005). Aerobic conditions and direction of flow path are therefore two important features that differentiate VSSF from HSSF CW. The higher availability of oxygen in the VSSF CW increases nitrification thereby facilitating conversion of ammonium to oxidized nitrogen (Vymazal, 2007, 2013).

Phosphorus removal in VSSF CW is very similar to that of HSSF CW since the mechanisms are mainly physical and include adsorption to the substratum and plant root surface and/or precipitation with ions such as calcium, alluminium, and iron present in the rooting medium, and neither is influenced by oxygen concentration (Brix et al., 2001; Arias et al., 2001). It has therefore been proposed that, to improve phosphorous retention in CWs, treatment media with higher phosphorus adsorption capacities, higher calcium, iron or alluminium contents, larger particle surface areas, and appropriate hydraulic conductivities should be used (Vymazal et al., 1998).

Despite the higher removal of nitrogen by VSSF than HSSF CWs, the choice of application of CW type depends on the treatment objective. For example, where guidelines exist for receiving waters sensitive to eutrophication, nutrients, especially nitrogen, must be reduced to the required discharge limit and hence, a VSSF is recommended. In contrast, where wastewater is to be reused for agriculture, aquaculture, or even recreation (such as swimming), pathogenic microorganisms, helminths, BOD_5 and TSS are the target components for remediation. In this case, a HSSF CW is more suitable (Vymazal, 2005).

In the past two decades, intensive research has been carried out on the performance of SSF CW for treatment of domestic wastewater, especially in sub-Saharan Africa (Mashauri et al., 2000; Keffala and Ghrabi, 2005; Abidi et al., 2009) and accordingly, SSF CWs have proved efficient in the removal of BOD_5, COD, TSS, and pathogenic microorganisms. Despite the high performance of SSF CWs, it has been reported that independent systems in operation with either HSSF or VSSF show difficulty in reducing nitrogen to the levels required for discharge into surface water courses (Molle et al., 2008). Although some authors have reported a reduction in NH_4^+-N in the final effluent from HSSF CW (Vymazal, 2005), others have observed an increase (Mburu et al., 2013), which was attributed to prevailing anaerobic conditions. Likewise, the removal of oxidized forms of nitrogen is considered a bottleneck for many VSSF systems since the prevailing aerobic conditions in the system lead to production of nitrates (Molle et al., 2008).

To improve total nitrogen removal, studies have thus focused on using hybrid constructed wetlands. A hybrid constructed wetland system is defined as a combination of different types of CWs aimed at achieving higher treatment efficiency than a single CW, and particularly for nitrogen (Vymazal, 2013). This is due to the fact that single-stage CWs, which are a popular method adopted for removal of nitrogen and other pollutants from domestic wastewater, hardly achieve high removal of TN due to the inability to simultaneously provide both aerobic and anaerobic conditions (Tuncsiper, 2009). Among the hybrid CWs, a combination of VSSF and HSSF is a popularly adopted system for wastewater treatment (Vymazal, 2013); that exploits the uniqueness of each system (Tuncsiper, 2009). First, wastewater is treated in a VSSF CW, in which the aerobic environment makes nitrification possible, to convert the main part of nitrogen into nitrate. The effluent is then passed into and treated by a HSSF CW where the anoxic environment facilitates denitrification, converting nitrate to nitrogen gas (Tuncsiper, 2009). Despite insufficient data on the performance of hybrid CWs, Vymazal (2013) established that V-H SSF hybrid CWs are slightly better at ammonia removal than H-V SSF or multi-stage V-H SSF hybrid CWs.

Nitrogen removal from wastewater is important for health and protection of aquatic ecosystems especially in areas where discharge limits for NH_4^+-N and NO_3^--N into surface waters exist. In South Africa for example, NH_4^+-N and NO_3^--N limits are ≤ 6 and ≤ 15 mg/L, respectively for disposal of treated wastewater into a water resource that is not a listed water resource and to irrigation of any land up to 2 ML on any given day (DWS, 2013). In water resource areas where effluent cannot be reused in agriculture and must be discharged into a fragile watercourse, nitrogen removal is therefore paramount, and adoption of a V-H SSF hybrid CW could be essential.

Earlier, authors particularly Vymazal (2008, 2013) presented a detailed history of V-H SSF CW. Our analysis reveals that, whereas a few pilot scale V-H SSF hybrid CWs are reported in the literature for sub-Saharan Africa, there appears to be a deficiency in information on the full-scale application of the technology on the continent of Africa. Stagnation in the implementation of the V-H SSF CW technology in developing countries could be attributed to the fact that aid programs from developed countries tend to favour more overt technologies that have commercial spin-off to donors (Denny, 1997). Added to this is the fact that engineers and decision makers tend to prefer tried and tested technologies rather than the risk that may be associated with newer technologies (Verburg et al., 2006).

PERFORMANCE OF V-H SSF HYBRID CW FOR DOMESTIC WASTEWATER TREATMENT

Hybrid CWs involving the use of combined VSSF and HSSF CWs to maximize removal of contaminants from wastewater have been used widely to attain high removal efficiency, particularly for nitrogen (Vymazal, 2005, 2013). These CWs have been successfully used for domestic wastewater treatment particularly in small communities and in remote areas. Domestic wastewater originating from toilets, bathing, sinks and laundry is the major source of organic matter, TSS, the soluble nutrients NO_3^-, PO_4^{3-}, NO_2^-, NH_4^+, the particulate nutrients TP and TN, indicator organisms (e.g. *Escherichia coli*), pathogenic organisms like *Salmonella* and *Shigella* species and other organic contaminants (Sayadi et al., 2012). Many authors have documented the effluent quality and performance of V-HSSF hybrid CWs and results from these studies are summarized in Table 1 and, an overall evaluation of the surveyed hybrid CWs is as shown in Figure 2.

The survey shows that there is a paucity of data regarding the performance of hybrid systems on the African continent. Out of the sixteen surveyed hybrids, only three were reported from Africa and these were from one country (Tunisia). The effluent quality and performance of the surveyed V-HSSF hybrid CWs appears to be very high with regards to BOD_5: 19 ± 7.5 mg/L (92 ± 2% removal); COD: 74.0 ± 1.5.7 mg/L (86 ± 2% removal); TSS: 8.0 ± 1.8 mg/L (94 ± 2% removal); and TP: 3.0 ± 0.8 mg/L (64 ± 4% removal). Despite the

Table 1. Effluent quality and performance of single stage V-H hybrid constructed wetlands for sewage treatment from 2000-2014.

Example by country	Water quality parameter						Macrophyte species	Area (m^2)	Reference
	BOD$_5$	**COD**	**TSS**	**TP**	**TN**	**NH_4^+-N**			
Belgium									
Quality (mg.L^{-1})	5.8	43	5	2.9	27	*i*	*P. australis*	2250	Lesage et al. (2007)
Removal (%)	92	81	90	45	43	*i*			
Quality (mg.L^{-1})	4	47	4.8	3.4	*i*	*i*	*P. australis*	2250	Lesage (2006)
Removal (%)	92	81	95	32	*i*	*i*			
Quality (mg.L^{-1})	9	49	4.3	3.4	26	*i*	*P. australis*	1080	Lesage (2006)
Removal (%)	96	90	98	47	53	*i*			
Quality (mg.L^{-1})	10.3	57	15	4.3	23	*i*	*P. australis*	660	Lesage (2006)
Removal (%)	93	84	87	38	60	*i*			
Estonia									
Quality (mg.L^{-1})	5.5	*i*	5.8	0.4	19	9.1	*P. australis*	432	Öövel et al. (2007)
Removal (%)	94	*i*	87	91	70	84			
Tunisia									
Quality (mg.L^{-1})	*i*	*i*	*i*	*i*	*i*	30	*Typha* spp., *P. australis*	1.8	Abidi et al. (2009)
Removal (%)	*i*	*i*	*i*	*i*	*i*	19			
Quality (mg.L^{-1})	30	134	18	7.2	*i*	47	*Typha* spp., *P. australis*	1.8	Keffala and Ghrabi (2005)
Removal (%)	93	90	98	77	*i*	19			
Quality (mg.L^{-1})	*i*	*i*	*i*	*i*	*i*	*i*	*P. australis, Typha* spp.	327	Kouki et al. (2009)
Removal (%)	93	89	98	72	*i*	*i*			
Spain									
Quality (mg.L^{-1})	24	71	3.6	*i*	*i*	11	*P. australis, Scirpus* spp.	0.88	Herrera Melián et al. (2010)
Removal (%)	85	74	95	*i*	*i*	91			
Quality (mg.L^{-1})	66	172	16.2	8.8	26	40	*Typha latifolia*	450	Vera et al. (2010)
Removal (%)	84	77	95	35	43	51			
China									
Quality (mg.L^{-1})	*i*	21	3.2	0.4	*i*	2.2	*P. australis*	3716	Zhai et al. (2011)
Removal (%)	*i*	84	97	85	*i*	80			
Quality (mg.L^{-1})	*i*	26	7.2	0.9	*i*	5.3	*Cyperus alternifolius*	1400	Zhai et al. (2011)
Removal (%)	*i*	90	85	77	*i*	84			
Quality (mg.L^{-1})	*i*	28	1.6	0.6	14	6.2	*Cyperus alternifolius*	4459	Zhai et al. (2011)
Removal (%)	*i*	84	99	68	65	72			
Italy									
Quality (mg.L^{-1})	*i*	36	*i*	0.2	17	11.4	*P. australis*	6.75	Foladori et al. (2012)
Removal (%)	*i*	94	*i*	98	78	80			
Brazil									
Quality (mg.L^{-1})	*i*	29	*i*	4	*i*	5.6	*Typha* spp., *Zizaniopsis bonariensis*	110	Phillipi et al. (2010)
Removal (%)	*i*	95	*i*	69	*i*	89			

Table 1. Contd.

Mexico									
Quality (mg.L^{-1})	*i*	*i*	*i*	12	102	19	*Z. aethiopica*	3.66	Zurita and White (2014)
Removal (%)	*i*	*i*	*i*	0	26	85			

i= not indicated.
Source: Vymazal (2013).

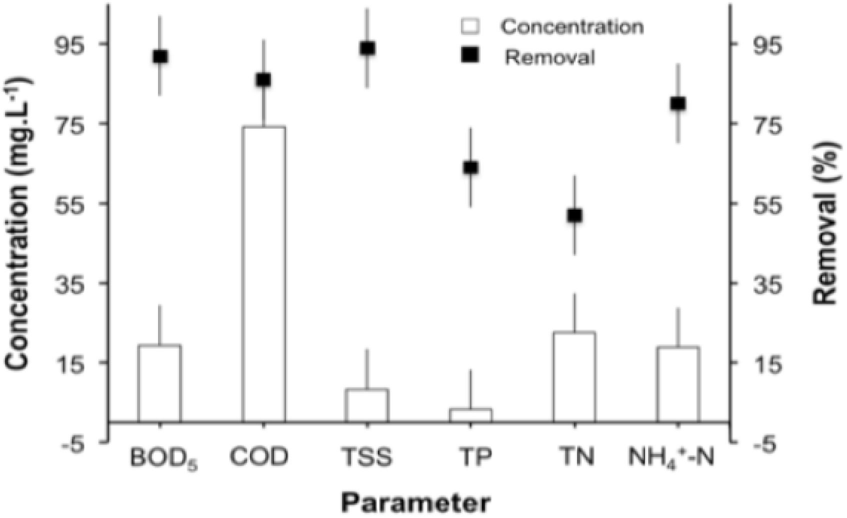

Figure 2. Surveyed data on effluent quality and pollutant removal efficiency of hybrid CW treating municipal sewage.

high removal of nitrogen species (NH_4^+-N and TN), the effluent quality from the surveyed systems is low at 19.0 ± 6.2 mg/L and 23 ± 2.1 mg/L for NH_4^+-N and TN, respectively. Some factors that could be contributing to poor effluent nitrogen concentration in the surveyed CWs are discussed subsequently.

FACTORS AFFECTING PERFORMANCE OF CONSTRUCTED WETLANDS AND EFFLUENT QUALITY

Several factors influence performance of a CW including design and construction, hydraulic and organic loading rate, operation, maintenance, media type and size, macrophyte, hydrology and environmental variables, particularly temperature (Varma et al., 2021). Literature on the influence of some of these factors on performance of CWs has been discussed in detail by others and includes construction (UN Habitant, 2008), hydraulic loading rate (HLR) and hydraulic retention time (HRT) (Chazarenc et al., 2007) and environmental variables (Varma et al., 2021) among others. Here, the influence of design, mode of operation and vegetation on performance of CWs are considered in more detail.

Design and size determination

Proper design and construction are a major consideration for successful deployment and performance of a CW. The components of a well-designed CW include a primary treatment unit and the various wetland compartments; the wetland itself, comprising substrate/ treatment media, vegetation, and micro-organisms (Steiner et al., 1989). The primary treatment unit is important for reducing heavy solids and organic load, and may require installation of an Imhoff tank or septic tank for individual households or a primary sedimentation tank or stabilization pond(s) for small communities (Korkusuz, 2004). Primary treatment units have the associated problem of sludge accumulation and may require desludging from time to time. However, this may be overcome by incorporating a fermentation pit in the primary treatment unit for accelerated anaerobic digestion with the added benefit of methane generation for use in energy derivation (Rose et al., 2002). A properly designed and constructed primary treatment unit for a CW should be able to remove up to 60% of influent BOD at 20°C (Magayane and Mwanuzi, 2006) and it is estimated, that inclusion of a fermentation pit will yield methane equivalent to 30% of the influent organic carbon

(Green et al., 1995).

Primary treatment is followed by secondary treatment, in this case the CW, and performance is dependent not only on efficient removal of organic matter and suspended solids from the primary treatment unit, but also optimum design. The latter, is to attain better nutrient removal while mitigating operational problems. Hence, optimum performance of a CW depends on using an appropriate area for a given hydraulic and organic load (or population) as smaller areas for large flows result in lower treatment efficiency. As a consequence of this requirement, different methods have been proposed for sizing the effective area of a CW including, the population equivalent (PE) method, pollutant loading method, and non-mechanistic models.

Non-mechanistic models have been widely adopted for sizing the effective area required for a SSF CW. Literature shows that by employing the equation described by Kickuth (1977) and Reeds et al. (1995), in which BOD is the design parameter, the required area for SSF systems for domestic wastewater treatment can be estimated. The bottleneck of using non-mechanistic models for CW area estimation is that BOD, which is widely used as a target pollutant in the design, results in under estimation of the area. Hence, this method is suitable for organic matter and TSS removal but not appropriate for nutrient removal (Vymazal, 2005). Thus, and as pointed out by Huang et al. (2000), nitrogen removal from a SSF CW is an important design criterion despite the fact that it has not been fully explored. Until now, no information on performance of SSF flow CWs designed for nitrogen removal has been available, and it is not clear if designs based on nitrogen will allow CW to meet organic matter effluent standards. Thus, the need to evaluate performance of CWs designed based on nitrogen removal.

Mode of operation versus macrophyte selection

The mode of operation of a CW greatly influences the redox potential and consequently the performance of the CW (Faulwetter et al., 2009). Mode of operation is thus categorized as either batch, intermittent or continuous feeding.

During batch feeding, the CW is fed wastewater in doses for a specific time period and then allowed to drain completely until the next dose is applied (Caselles-Osorio and Garcia, 2007). This mode of operation results in variation of redox potential with time in the wetland. Typically, redox potential declines when wastewater is dosed and this is then followed by a gradual increase in redox condition as pollutants are removed (Allen et al., 2002). This variation in redox condition may select for a microbial community that is adapted to changes in redox and nutrient conditions (Stein et al., 2003). Stein and Kakizawa (2005) reported that operating a CW under batch feeding promotes better oxidizing conditions and hence better nitrogen and organic matter removal.

Intermittent feeding is closely related to batch operation but differs slightly in a way that the CW does not completely drain before the next dose is applied. This allows the wetland to accumulate more dissolved oxygen (DO) which enhances mineralization of organic compounds particularly in the VSSF systems (Knowles et al., 2011). According to Knowles et al. (2011), problems associated with clogging of HSSF CW may also be overcome by intermittent operation where re-aeration of the subsurface may occurs. Studies have shown that intermittently fed CW perform better than continuously fed systems in terms of nitrogen and organic matter removal (Caselles-Osorio and Garcia, 2007) since, like batch feeding, intermittent feeding creates temporal and spatial variation in redox potential throughout the whole length of the wetland (Headley et al., 2005). Additionally, it may also increase oxygenation, which will reduce or eliminate the development of anaerobic zones within biofilms and minimize release of volatile fatty acids and ammonia.

The simplest and most common mode of operating a CW is by continuous flow (Faulwetter et al., 2009). However, there is debate by some authors over its use in CWs. Stein et al. (2003) for instance claim that, the major limitation of this mode of operating CWs is that it lowers DO concentration and consequently, reduces removal efficiency of some pollutants that require aerobic conditions for their elimination such as NH_4^+-N. In contrast, Toet et al. (2005) suggested that pollutant removal in CWs depends largely upon hydraulic retention time (HRT) and hydraulic loading rate (HLR) regardless of the mode of feeding. The HRT and HLR affect the time of contact between pollutants and the microbial population within the CW system. It has been revealed that operating a CW for longer HRT results in higher redox potentials and thus greater pollutant removal. Headley et al. (2005) for instance, reported redox potentials in the range of -92 to +103 mV when the HRT was 10.1 days and -109 to +186 mV when the HRT was 16.1 days, under intermittent operation of the wetland.

However, in our view, effluent quality from CWs especially concerning NH_4^+-N may be influenced by several factors; especially macrophyte species other than the mode of wastewater feed and flow. For instance, under intermittent operation, Zurita and White (2014) operated a hybrid CW planted with *Zantedeschia aethiopica* at a hydraulic loading rate (HLR) of 0.28 m/d with influent NH_4^+-N concentration of 128.2 mg/L. They reported effluent NH_4^+-N concentration of 19 mg/L (85% removal) from their system. In contrast, at a much lower HLR (0.08 m/d) and influent NH_4^+-N concentration (37 mg/L), Keffala and Ghrabi (2005) reported effluent NH_4^+-N concentration of 30 mg/L (19% removal) from a V-H hybrid system, planted with *Typha* species and *Phragmites australis* in the vertical and horizontal systems, respectively. Surprisingly, Herrera-Melián et al. (2010) were able to achieve an effluent NH_4^+-N concentration of 11 mg/L (91%) from a continuously operated hybrid system planted with *P. australis* and *Scirpus* species in the vertical and horizontal systems, respectively at 0.4 m/d with an influent NH_4^+-N of 122 mg/L.

In as much as the review by Brisson and Chazarenc (2009) on the effect of macrophyte species selection on pollutant removal in SSF CWs revealed that macrophyte species selection does not influence the effluent quality from CWs, based on results obtained by Zurita and White (2014), Keffala and Ghrabi (2005) and Herrera-Melián et al. (2010), we argue that if nitrogen is the target pollutant for removal especially in hybrid systems, it could be important to pay more attention to the macrophyte species used particularly in the HSSF CW than the mode of feeding. Hence, the difference in the NH_4^+-N effluent quality reported by Zurita and White (2014) and Keffala and Ghrabi (2005) under intermittent feeding based on the type of macrophyte used can be explained in two ways: (1) wetland plants have been reported to dispatch oxygen to the vicinity of the root system that is responsible for oxidation of ammonium (Brix, 1994); and status and health of the root system which may impact ammonia removal directly. While different plants do appear to show differences in oxygen released into the rhizosphere, to date, there is little information regarding oxygen release rates among CW plants. This is surprising as oxygen release rates could be important in selecting plant species for use in CWs in particular to target specific pollutants and especially nitrogen. Among the macrophytes, *P. australis* is the most studied. Using different methods, several studies have reported oxygen release rates from *Phragmites*. Brix (1990) and Gries et al. (1990) for instance reported oxygen release of up to 5-12, 0.02 and 1-2 g/m^2.d, respectively. Unfortunately, there is little or no information regarding oxygen release rates of *Z. aethiopica.* An earlier study on the use of this ornamental species in HSSF CWs by Belmont and Metcalfe (2003) however, showed considerable reduction in the influent ammonium concentration indicating that *Z. aethiopica* has a positive effect on ammonium removal. While SSF CWs are known to be anaerobic/anoxic, throughout the course of their study, however, Belmont and Metcalfe (2003) observed an increase in the effluent oxygen concentration that could be linked to the high oxygen release rates from the test species, *Z. aethiopica.* Although it may require further investigation, *Z. aethiopica* could have higher oxygen release rates than *P. australis*, which may account for the significant difference in the ammonium removal reported by Zurita and White (2014) and Keffala and Ghrabi (2005). (2) Bezbaruah and Zhang (2004) reported lower oxygen release rates in the range 0.00021-0.00155 and 0.00083-0.00288 g/m^2.d from brown and white roots of *Scirpus*, respectively than reported for *Phragmites*. Whereas firm, fleshy white roots are a sign of plant health, root rot typically manifests as the presence of soft, brown roots and may be the outcome of anoxic conditions within the rhizosphere caused by water logging or the result of fungal infection. In response, a pathogen-induced response occurs in which plants mount a defense that includes the production of secondary products (e.g. alkaloids) but if weak, leads to organ senescence and death. The lower NH_4^+-N concentration reported by Herrera-Melián et al. (2010) in a continuously operated hybrid CW than in intermittently operated hybrids reported by either Keffala and Ghrabi (2005) or Zurita and White (2014) could thus, be attributed to the difference in root function and/or alkaloid concentration of the macrophyte. It has been reported that some wetland macrophytes for example *P. australis* contain high concentrations of alkaloids especially N,N-dimethyltryptamines (DMT) in their rhizomes (Khan et al., 2012). During the treatment process, these alkaloids may be released as extracellular polymeric substances (EPS) containing nitrogenous compounds. It can therefore be hypothesized that the alkaloid concentration in the three different macrophytes follows the order *P. australis* > *Z. aethiopica*> *Scirpus* species.

Therefore, future study should aim at investigating the physiology and mechanisms of the different macrophyte species that go beyond a comparison in pollutant removal efficiency, such that unique species are selected for use in CWs depending on the treatment objective. Despite the simplicity of operation associated with continuous in comparison to intermittent fed CWs, there is insufficient data regarding performance of V-H SSF hybrid CW operated continuously and the resulting effluent quality. Feeding the wetland intermittently requires energy input, which may not be available or supplied reliably in developing countries but may be achieved using innovative and appropriate engineering. Nevertheless, research into performance of these systems under continuous feeding is essential if they are to be implemented in rural communities or developing countries where energy supply is unreliable.

CONCLUSION

This review shows that a combined VSSF with HSSF is a widely recognized and adopted hybrid system for the treatment of domestic wastewater. Despite the high removal efficiency of the V-HSSF hybrid CWs in reducing BOD_5, COD, TSS, TP and NH_4^+-N, water quality concerning nitrogen is low. The latter is attributed to design limitations as most systems are designed based solely on BOD as a target pollutant and not nitrogen. This overview of the current state of the technology also reveals that there is insufficient published information regarding the performance of V-HSSF hybrid CW systems in developing countries particularly in sub-

Saharan Africa. Out of the sixteen surveyed hybrids, only three were reported from Africa (Northern Africa). Further study is therefore required to shed light on final water quality and performance of systems designed on the basis of nitrogen removal and, operating under different climatic conditions.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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