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A Mini-Review on the Use of Constructed Wetland Systems for Water Treatment in Developing Countries

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ABSTRACT

The predominant scarcity of water globally has necessitated the invention of non-conventional resources to bridge the clean freshwater demand gap. Even in areas where there is access to water, inadequate quality and sanitation are pervasive problems, especially in developing countries. Resolving these intricate water-related problems, which emanate from population increase, the rise of urbanization and industrialization has not been realized using modern cost-, energy- and water-intensive technologies. In light of these challenges, wastewater treatment is a viable solution to supplement limited water resources. Of the available eco-technologies used in wastewater treatment for reuse, constructed wetlands (CWs) have proved to be the most effective. In this review, CWs are confirmed as reliable and low-cost green technologies with high effectiveness in wastewater treatment compared to conventional technologies. Therefore, their application among rural communities of developing countries is practical and highly advisable.

INTRODUCTION

The world is currently sharing a recurrent problem of water scarcity where available natural water sources cannot meet the demand adequately (Suhad et al. 2018). According to Scheierling et al. (2011), more than 67 % of the globe will have a water shortage state in 2025 and 50 % will experience high water stress by 2030. The World Water Assessment Programme (WWAP) (2015) agreed with these projections claiming that they will result from increased water demand at all production levels and at least 40 % of the world will likely be water scarce by 2030. Other drivers of water scarcity include a high population growth rate, expansion of agricultural and industrial activities, climate change, and global warming. These drivers result in a sharp rise in wastewater generation trends. Wastewater contains pollutants such as biochemical and chemical oxygen demand, microbes, heavy metals, non-biodegradable organics, and particles that deteriorate water quality once it is released into freshwater resources making the resources unsustainable for aquatic life, irrigation, and potability (Suhad et al. 2018). Due to the soaring water scarcity situation, researchers are exploring the use of non-conventional sources to meet the ever-rising demand. Wastewater has been identified as a feasible alternative (Noori et al. 2014, Zhang et al. 2014, Almuktar & Scholz 2015, Gorgoglione & Torretta 2018). The reuse of wastewater, however must be taken up with caution considering its characteristic pollutants whose unregulated environmental release is risky to ecological health. This consideration necessitates wastewater treatment before reuse.

The use of constructed wetlands (CWs) serves as a promising and innovative solution for cost-effective and sustainable treatment of wastewater particularly in developing countries where conventional wastewater treatment infrastructure is limited due to financial constraints (Zhang et al. 2014). The countries in addition experience water scarcity owing to the rising population and economic growth. CWs are ecological technologies and engineered systems for wastewater treatment that incorporate physical, chemical, and biological processes to decontaminate water in natural wetland environs. Constructed wetlands have been successfully used to cleanse wastewater off suspended solids, heavy metals, nutrients, and organic compounds (Zhang et al. 2014, Gorgoglione & Torretta 2018, Suhad et al. 2018). The preference to use CWs is associated with their high removal efficacy, great potential to reuse nutrients and water, simplicity of operation, and cost efficiency (Almuktar & Scholz 2015). Despite these successes, there have been limited studies focusing on the use of CWs in developing countries whose water status is dire due to the aforementioned drivers. This review study, therefore, focuses on the use of ecological technology in wastewater treatment, the various types of CWs, and their effectiveness in cleansing wastewater with a particular focus on developing countries.

CONSTRUCTED WETLANDS IN DEVELOPING COUNTRIES

The adoption of CWs in wastewater treatment for developing countries is on a rising trend due to its low energy requirements and ability to recycle large volumes fast according to Vymazal (2011). The technology has been used in developing countries to treat agricultural runoff (Yang et al. 2008), landfill leachate (Nahlik & Mitsch 2006), laboratory waste (Meutia 2001), and hospital wastewater (Shrestha et al. 2001), wastewater from sugar factories (Bojcevska & Tonderski 2007). In addition, CWs treat storm-water runoff (Sim et al. 2008, Avila et al. 2013), wastewater produced from oil processing (Ji et al. 2007), sludge effluent (Ahmed et al. 2008), lake and river water (Li et al. 2009, Tang et al. 2009). Domestic water (Zhai et al. 2011, Mburu et al. 2013), industrial wastewater (Chen et al. 2006, Maine et al. 2007), and agricultural wastewater (He et al. 2006, Zhang et al. 2014) have been treated using this ecological technique too.

Concerning the performance of CWs, their effectiveness in developing countries is favored by the warm subtropical and tropical climates of the regions, where these technologies are better performers compared to temperate regions (Kivaisi 2001, Zhang et al. 2014). In tropical regions unlike temperate regions, plant growth and microbial activity occur throughout the year, which are favorable prerequisites to CWs effectiveness (Kaseva 2004). Zhang et al. (2012) agreed with these sentiments claiming that tropical wetlands are exposed to direct sunlight and have higher temperatures year round, favor plant growth, and reduced microbial degradation time, which are important factors in wastewater treatment via CWs.

TYPES OF CWS AND THEIR TREATMENT EFFICIENCY

Constructed wetlands are classified into three; subsurface flow (SSF), free water surface (FWS), and hybrid CWs (Zhang et al. 2014). SSF CWs are further classified into horizontal and vertical systems. The selection of a particular type of CW depends on the treatment goals, available area, cost, geographic location, and target pollutants for treatment (Horner et al. 2012).

Free Water Surface Systems

The FWS systems are arranged with channels and tanks that are artificially or naturally waterproofed and where the water level remains constant above the medium surface and the depth ranges between 0.3 and 0.6 m (Gorgoglione & Torretta 2018). Flow in the system originates from an inlet area to an outlet in a region with low flow velocity, low water depth, and plant bodies. Small channels that mimic the plug flow reactor help in standardizing flow. According to Vymazal (2011), FWS systems ensure wastewater encounters biologically active surfaces to enhance its hydraulic retention time and prevent hydraulic short-circuit formation. FWS systems remove suspended solids through sedimentation and filtration as well as organics via microbial degradation. Removal efficacy for pathogens, chemical and biological oxygen demand (COD, BOD), and total suspended solids (TSS) is above 70% while nitrogen removal efficacy ranges between 40 and 50 % (Kadlec & Wallace 2008). At slow rates, FWS systems can remove phosphorous from wastewater at an efficacy rate of 40 to 90% (Vymazal 2011). A summary of the applications of FWS systems in decontaminating wastewater pollutants and their specific effectiveness in named developing countries is shown in Table 1. The results show varied removal efficacies based on individual studies and the pollutant being removed.

Subsurface Flow Systems

Subsurface flow (SSF) CWs are designed as horizontal (HSSF) or vertical (VSSF) where wastewater flows through a permeable medium (Vymazal 2011). In horizontal systems, wastewater flows towards the granular material horizontally and encounters anaerobic, anoxic, and aerobic conditions in the subsurface. The latter occurs near rhizomes and roots of plants that release oxygen to the substrate. Anoxic zones are rich with aerobic microbes, which transfer oxygen to the filter bed from the atmosphere. The redox conditions enable wastewater decontamination. Vertical CWs use a distribution system to feed wastewater to the entire surface and passes the media vertically (Zhang et al. 2014). The effluent introduction is discontinuous, unlike the horizontal systems where there is a continuous flow. Some of the studies demonstrating the effectiveness of SSF systems in developing countries, contaminants treated and plant species used are summarized in Table 2. Plant species in both vertical and horizontal systems enable purification by enhancing microbial activity at the rhizosphere and via oxygen release to the atmosphere from the root system to the surrounding environment (Gorgoglione & Torretta 2018).

From the comparisons of HSSF and VSSF, the former offers good conditions for denitrification though such systems have limited ability to denitrify ammonia. In VSSF systems, NH_3-N can be removed but denitrification barely occurs. The two systems have a moderate ability to remove total nitrogen (TN) while HSSF had better removal efficacy for total phosphorous (TP) compared to VSSF (Zhang et al.

Table 1: Application of FWS systems in decontaminating wastewater contaminants and their effectiveness in named developing countries.

Study Characteristics	Type of Wastewater	TSS	BOD	COD	NH_4-N	NO_3-N	TN	TP	Plant species	References
Petchaburi, Thailand	Municipal waste-									
Effluent level	water	40.4	12.7	-	51.8	-	-	2.2	*Typha angustifolia*	Klomjek & Nitisoravut 2005
% removal Efficacy		46.5	74.3	-	75.4	-	-	44.9		
Liaohe, China	Oil-based wastewa-									
Effluent level	ter	-	3.9	77	-	-	9.7	0.53	*Phragmites australis*	Ji et al. 2007
% removal Efficacy		-	88	80	-	-	10.2	18.5		
El Salvador										
Effluent level	Municipal waste-	-	20.1	72.8	0.54	-	6.08	1.86	*T. angustifolia*	Katsenovich et al. 2009
% removal Efficacy	water	-	80.8	65.2	94.75	-	58.59	66.5		
Shanghai, China										
Effluent level	Polluted river water	30	7.7	32	-	-	6.15	0.32	*P. australis*	Li et al. 2009
% removal efficacy		70	15.4	17.9	-	-	83.4	96		
Nyanza, Kenya	Wastewater from								*Echinochloa pyramidalis*	Bojcevska & Tonderski 2007
Effluent level	sugar factories	11	-	-	2.9	-	-	4.1	*Cyperus papyrus*	
% removal efficacy		76	-	-	36	-	-	29		
Putrajaya, Malaysia	Stormwater									
Effluent level		-	-	-	-	0.96	-	0.06	*Lepironia articulate*	Sim et al. 2008
% removal efficacy		-	-	-	-	70.7	-	84.3	*Phragmites karka*	
Peradeniya, Sri-Lanka	Municipal waste-								*Scirpusgrossus*	
Effluent level	water	45.8	19.2	-	3.4	0.9	-	1.36	*T. angustifolia*	Jinadasa et al. 2006
% removal efficacy		71.9	68.2	-	74.4	50	-	19		

*All effluent levels are in $mg.L^{-1}$

Table 2: Application of HSSF systems in decontaminating wastewater contaminants and their effectiveness in named developing countries.

Study Characteristics	Type of Wastewater	TSS	BOD	COD	NH_4-N	NO_3-N	TN	TP	Plant species	References
Taihu, Zhejing, China										
Effluent Level	Polluted lake water	-	-	4.23	1.16	0.37	2.29	0.052	*T. angustifolia*	Li et al. 2008
% removal efficacy		-	-	39.6	32	65.3	52.1	65.7		
Shatian, China	Municipal waste-									
Effluent Level	water	7.92	7.68	33.9	-	-	9.11	0.56	*P. australis*	Saeed et al. 2012
% removal efficacy		86.78	86.4	76.72	-	-	44.93	81.7		
Jiaonan, China	Municipal waste-									
Effluent level	water	30	11	125	-	-	63.8	2.98	-	Song et al. 2009
% removal efficacy		57.1	66.7	60.9	-	-	11.1	-	-	
Egypt										Abdel-Shafy et al. 2009
Effluent level	Greywater	8.9	29.1	58	-	-	4.6	1.7		
% removal efficacy		82.2	70.3	65.9	-	-	36	32.4	*P. australis*	
Effluent level	Blackwater	9	25	67	-	-	39.6	9.3		
% removal efficacy		89	86.4	83.5	-	-	69.3	56.2		
Juja, Kenya	Municipal waste-									
Effluent levels	water	25.5	28.9	91	19	1.1	-	0.8	*Cyperus papyrus*	Mburu et al. 2013
% removal efficacy		75.27	60.73	42.76	26.36	-	-	42.86		
Ocotian, Jalisco	Municipal waste-								*Anthurium andreanum*	Zurita et al. 2011
Effluent level	water	10.4	25.4	59.4	-	-	13.5	5	*Strelitzia reginae*	
% removal efficacy		81.66	77.94	76.32	-	-	52.78	40.24		
Dar es Salaam, Tanzania										
Effluent levels	Municipal sludge	-	-	41.8	15.86	0.83	-	-	*P. mauritianus*	Kaseva 2004
% removal efficacy		-	-	60.7	23.01	44.3	-	-	*Typha latifolia*	
Mother Dairy Plant, India										
Effluent level		12	4	55	-	-	7.5	1.5	*P. australis*	Ahmed et al. 2008
% removal efficacy		81	90	72	-	-	67	75		
Peradeniya, Sri Lanka									*Hydrilla verticillata*	Tanaka et al. 2013
Effluent levels		47.3	18.6	105.9	4.1	0.7	-	8.03	*Scirpus grossus*	
% removal efficacies	Municipal waste-	65.8	65.7	40.8	74.8	38.8	-	61.2		
El Salvador	water									
Effluent levels		32.13	62.8	147.13	-	-	12.04	2.61	*P. australis*	Katsenovich et al. 2009
% removal efficacies		84.15	22	56.2	-	-	39.3	-		
Can Tho, Vietnam										
% removal efficacies		93	83	84	91	-	84	99	*P. vallatoria*	Trang et al. 2010

*All effluent levels are in $mg.L^{-1}$

Table 3: Application of HSSF systems in decontaminating wastewater contaminants and their effectiveness in named developing countries.

Study Characteristics	Type of Wastewater	TSS	BOD	COD	NH_4-N	NO_3-N	TN	TP	Plant species	References
Kampala, Uganda										
Effluent level	Municipal wastewater	-	-	-	7.1	0.09	16.1	2.6	*C. papyrus*	Kyambadde et al. 2004
% removal efficacy		-	-	-	75.43	60.87	72.48	83.23		
Jalisco, Mexico										
Effluent level		21.9	20.8	49.5	-	-	14.6	4.2	*Anthurium andreanum*	Zurita et al. 2011
% removal efficacy		61.56	81.94	80.32	-	-	49.38	50.14	*Strelitzia reginae*	
Wuhan, China										
Effluent level		-	-	115.5	22.59	0.34	25.6	1.42	*Canna indica*	Chang et al. 2012
% removal efficacy		-	-	59.9	-	79.52	15	52	*Typha orientalis*	
Beijing, China										
Effluent level		302.4	11.8	-	30.7	-	-	5	*Salix babylonica*	Wu et al. 2011
% removal efficacy		97	96	-	90	-	-	88		
Wuxi, China	Livestock wastewater									
Effluent level		96	61.8	-	32.9	-	41.3	23.6	*P. communis*	He et al. 2006
% removal efficacy		77.1	81.3	-	61.7	-	66.6	48.9	*P. typhia*	
Taihu, China	Polluted lake water									
Effluent level		-	-	4.25	0.89	0.5	2.37	0.05	*T. angustifolia*	Li et al. 2008
% removal efficacies		-	-	40.4	45.9	62.9	51.6	51.6		
Tianjin, China										
Effluent level	Polluted river water	-	-	68.9	1.7	-	2.6	0.2	*T. latifolia*	Tang et al. 2009
% removal efficacies		-	-	35	71.3	-	64.9	61.2		
Longdao, Beijing										
Effluent level		10.9	6.9	38.3	18.5	-	18.5	1.59	*P. australis*	Chen et al. 2008
% removal efficacies		92.6	90.5	73.5	10.5	-	10.6	30.6	*Zizania aquatica*	

*All effluent levels are in $mg.L^{-1}$

2014). A higher potential overall is evident in HSSF systems since their design incorporates substrate flooding and consistent redox potential in the bed, unlike VSSF which has intermittent feeding of wastewater resulting in oxygenation of the bed and subsequent desorption and release of some pollutants such as phosphorous (Vymazal 2011).

Hybrid Systems

The subsurface and free water surface CWs cannot achieve the total removal of some pollutants such as TN. In a hybrid system, the various systems (surface and subsurface) are combined to optimize their advantages in a series of different types of CW systems (Vymazal 2011). Hybrid systems use VSSF to remove suspended solids and organics as well as offer nitrification environs while HSSF enables denitrification and further removal of TSS and organics. A summary of the application of hybrid CWs to treat wastewater and their effectiveness in some developing countries is summarized in Table 4. An analysis of the hybrid system results showed higher efficacy in wastewater treatment compared to the surface and subsurface systems though results differed based on the design characteristics of individual studies.

DISCUSSION

The findings of this review confirm that CWs are promising technologies for the treatment of various types of wastewater including greywater, blackwater, laboratory, hospital, lake, and river water (Gorgoglione & Torretta 2018). HSSF systems have longer life cycles that lead to humic acid formation, which is effective for nitrogen and phosphorous removal through redox reactions. VSSF systems are good nitrifiers due to adequate oxygen supply, require simple hydraulics, and only require a small setup area. FWS CWs are green spaces for communities in addition to having a high capacity to remove water pollutants such as TSS, BOD, and COD while hybrid systems have a combination of these advantages. The effectiveness of these systems in wastewater pollutant removal depends on a number of factors apart from the individual type. These include temperature, vegetation type, hydrologic regime, and pollutant loading (Kadlec & Wallace 2008, Trang et al. 2010). At a low hydraulic loading rate and high hydraulic retention time, the movement of wastewater is slower, which allows for its prolonged interaction with microorganisms and rhizosphere and ultimately,

Table 4: Application of HSSF systems in decontaminating wastewater contaminants and their effectiveness in named developing countries.

Study Characteristics	Type of Wastewater	TSS	BOD	COD	NH_4-N	NO_3-N	TN	TP	Plant species	References
Chiang Mai, Thailand	UASB effluent									
Effluent level		3	10	57	7	-	77	0.3	*Scirpus grossus Linn*	Kantawanichkul et al. 2003
% removal efficacy		99	98	95	98	-	79	99		
Santa Fe, Mexico	Municipal waste-									
Effluent Level	water	20	33	100	-	-	31	15	*T. latifolia*	Rivas et al. 2011
% removal efficacy		79	52	68	-	-	-	14	*P. australis*	
Kathmandu, Nepal	Greywater									Shrestha et al. 2001
Effluent level		2.6	5.2	29.1	0.5	-	-	2	*P. karka*	
% removal efficacy		97	97	93	96	-	-	35		
Jakarta, Indonesia	Laboratory waste-									
Effluent level	water	-	-	1.2	0.06	0.65	3.04	0.6	*Lemma sp.*	Meutia 2001
% removal efficacy		-	-	97.7	97.2	85.96	65.66	37.33	*Typha sp.*	
Bogota, Columbia	Municipal waste-									
Effluent level	water	10	28	-	9	-	15	3	*Typha sp.*	Arias & Brown 2009
% removal efficacy		96.9	92.26	-	62.5	-	63.4	40		
Turkey										
Effluent level		-	-	-	3.2	0.3	4.6	-	*P. australis*	Tuncsiper 2009
% removal efficacy		-	-	-	91.2	88.8	91.3	-	*Iris australis*	
Kathmandu, Nepal	Hospital wastewater									
Effluent level		2.8	3.3	20.2	1.6	-	-	4.2	*P. karka*	Shrestha et al. 2001
% removal efficacy		92.3	97.	93.8	95.2	-	-	46.6		
Lugu, China										
Effluent level	Municipal waste-	3.2	-	21	2.2	-	-	0.45	*Cyperus alternifolius*	Zhai et al. 2011
% removal efficacy	water	96.6	-	84.1	79.6	-	-	84.5		

*All effluent levels are in $mg.L^{-1}$ and UASB refers to up-flow anaerobic sludge bracket reactor.

better contaminant removal (Ranieri et al. 2013). Planted CWs are better performers unlike unplanted ones because their rhizosphere enhances the growth and activity of microbes by providing carbon from root exudates (Vymazal 2011). In tropical compared to temperate regions where plant growth occurs throughout the year and microbial activity is enhanced, CWs are more effective in contaminant removal. High temperatures of the tropics enhance biotic activity, which is a prerequisite for contaminant removal in CWs. Different macrophytes have varied abilities to take up nutrients and contaminants and the selection of an appropriate species is an essential consideration in designing CW systems. Zhang et al. (2014) also noted that CW systems are cost sensitive and space intensive and hence the need to optimize essential factors using hybrid systems to reduce the costs and at the same time, obtain the best results for wastewater treatment. Compared to conventional wastewater treatment plants, CWs have low operation and maintenance costs but require ample and affordable land space (Gorgoglione & Torretta 2018).

CONCLUSION

Constructed wetlands are promising ecological technologies whose emergence in developing countries is a viable, cost-effective, and suitable solution for wastewater treatment and use as an alternative water source to natural water sources that are scarce. They have been used in the treatment of greywater, blackwater, polluted river, and lake water among other types of wastewaters effectively. This review shows various CWs including VSSF, HSSF, FWS, and hybrid systems being useful in decontaminating pollutants such as TN, TP, COD, BOD, and TSS among others at different efficacy rates and based on the designs of the systems. Individual systems can be optimized by manipulation of design variables such as pollutant loading, vegetation species used, temperature, and hydrologic regimes of the CWs while availing enough space for such systems at reduced costs. Therefore, the use of CWs in developing countries is a promising step toward water security.

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