REVIEW PAPER ON HORIZONTAL SUBSURFACE FLOW CONSTRUCTED WETLANDS: POTENTIAL FOR THEIR USE IN CLIMATE CHANGE MITIGATION AND TREATMENT OF WASTEWATER

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Abstract. The combination of rapid urbanization and industrialization expansion increased waste volumes. Most of the wastewaters generated from either domestic or industrial sources are still discharged without adequate treatment processes, and impact on the environment and public health. The objective of this paper was to provide a comprehensive literature review on the application of horizontal subsurface flow constructed wetlands in treating a variety of wastewaters, discussing its feasibility in pollutant removal efficiency and additional benefit in climate change mitigation through carbon sequestration. The following results were obtained: 98%, 96%, 85%, 90%, 92%, 88% for BOD5, COD, TSS, TN, NH_4 –N, PO_43- respectively in Kenya; 98.46% and 98.55% for COD and BOD5 in Indonesia; and ranges from 94-99.9%, 91.7-97.9% and 99.99% for BOD5, COD and TFC respectively in Costa Rica. Whereas in Ethiopia, the HSSFCW achieved the following abatement efficiencies: COD ranges from 58 to 80%, BOD ranges from 66 to 77%, TKN ranges from 46-61%, sulfates ranges from 53 to 82%, and $NH_4 – N$ range from 64 to 82.5% for tannery wastewater treatment. For domestic wastewater treatment; 99.3%, 89%, 855, 84.05%, 77.3%, 99% and 94.5% were achieved for BOD5, COD, TSS, TN, PO_4^3-, TP, Sulfate, and TFC, respectively. In addition to improving water quality, CWs have a CSP. For example, CWs showed CO_2 equivalent of 4119.54 g C/m²/yr CSP (carbon sequestration potential) which is 15118.7118 g CO_2. The methane equivalent to this amount of carbon sequestration is 604.748472 g/m²/yr. Generally, research results indicated that constructed wetlands are efficient wastewater treatment techniques and should be encouraged for wastewater management as a strategy to reduce wastewater pollution. However, constructed wetland performance efficiency sustainability is affected by the operational conditions of HSSFCW including plant species, media/substrate types, water depth, hydraulic loading, and hydraulic retention time and feeding mode.
Key words: *carbon sequestration potential, horizontal subsurface flow, climate mitigation, wastewater, constructed wetland, performance evaluation, and greenhouse gases, carbon cycle*

Introduction

Globally, wetland ecosystems are more and more being used for the treatment and disposal of wastewater because they have been known as low-cost and operative treatment schemes (Brix et al., 2001). Their potential to advance the quality of water from inflow to outflow has been recognized (Donald, 1989) Constructed wetland schemes use a conglomerate of biological physical, and chemical parameters. The combination of rapid urbanization and industrialization expansion increased waste

Engida et al.: Review paper on horizontal subsurface flow constructed wetlands: potential for their use in climate change mitigation
and treatment of wastewater
- 1052 -

volumes. Most of the wastewater generated from either domestic or industrial sources are discharged still without adequate treatment processes. The discharging of untreated or partially treated wastewater by cities and industries causes an impact on the environment and public health resulting in the contaminated downstream water supplies becoming unfit for drinking, irrigation and recreational activities (Birhanu and Seyoum, 2007), due to the presence of nutrients, heavy metals, toxic organic pollutants and pathogens. Research reported by Bahri et al. (2008) also agreed that untreated wastewaters discharged into the freshwater bodies change the quality of freshwater. Besides deteriorating the freshwater bodies, the farmland soil characteristics are also changed due to using contaminated river waters or direct use of wastewater for irrigation. According to Bayrau et al. (2008) surveyed results in the case of Ethiopia outbreaks of waterborne diseases in addition to eutrophication of surface water and farmland resources are common.

The use of constructed wetlands for wastewater management is becoming more and more popular all over the world. This is due to its efficient wastewater management ability with cost-effective option in both developed and developing countries. Most of these systems are easy to operate, require low maintenance, and have low investment cost (Ballesteros et al., 2016; Langergraber, 2013). Today horizontal subsurface flow CWs (Constructed wetlands) are quite commonly used in many developed countries such as Germany, UK, France, Denmark, Australia, Poland and Italy. Constructed wetlands are also appropriate for developing countries but they are rarely investigated and implemented (Prasad et al., 2016). Water body deterioration is becoming a serious issue in developing countries due to indiscriminate discharge of wastewaters and lack of comprehensive management techniques. In developing countries constructed wetlands (CWs) are used to treat a wide variety of wastewaters such as domestic, municipal, industrial, landfill leachate as well as agricultural and highway runoff (Tilak et al., 2016). Wetland technologies are a reliable onsite wastewater treatment technology and work with a higher rate of biological activity which enables conversion of many of the pollutants that are contained in the wastewater into non-toxic byproducts and serve as secondary or tertiary treatment level that meets the regulatory standards. CWs have shown to successfully control macro (organic material, nutrients and pathogens) pollutants and provide high quality water used for irrigation, recreational and other reuse purposes. Generally, this technology serves as an active and low-cost alternative technology for the treatment of wastewater all over the world (Mustafa, 2013).

Treatment wetlands are technologies that are able to remove nutrients, toxic metals, organic pollutants, emerging contaminants and pathogenic organisms effectively (Belmont et al., 2009; Chen et al., 2012). Their effective pollutant removal is associated with several mechanisms involved in the constructed wetland systems. These are sedimentation, filtration, volatilization, adsorption, plant uptake and bacterial activity (Chazarenc et al., 2009; Ballesteros et al., 2016; Langergraber, 2013). The mechanisms of treatment in constructed wetland are complex processes which can happen simultaneously or sequentially involving microbial degradation, plant uptake, sorption, sedimentation, filtration and precipitation. In designing the good wetland, the main biological component in the CW is aquatic plants (macrophytes). However, it is important in determining the appropriate plant species that can survive in the wastewater environment, because only suitable plant species can treat a high concentration of pollutant in the waste water (Prasad et al., 2016). The selection of media type is also very important, because clogging problems are observed in subsurface flow constructed wetlands and linked hydraulic

retention time and hydraulic conductivity. Therefore, adequate selection of granular media could decrease the estimated wetland area and improve the removal efficiencies (Lopez-Lopez et al., 2015). The vegetation biomass from the constructed wetlands can provide economic importance to communities by harvesting it for biogas production, animal feed, fiber for paper making and compost (Lakshman, 1987).

They also have an important role in carbon sequestration (CS) and reports indicated that the highest CSP (carbon sequestration potential) was recorded for Typha latifolia (741.02 g m^{-2}/yr) followed by Phragmites australis (740.5 g m^{-2}/yr) and the lowest for Carexsp (137.37 g m^{-2}/yr) from wetlands (Maqubool et al., 2013). Generally, CW can provide economical on-site wastewater treatment that is both effective and aesthetically pleasing (El-Gohary, 2008), and become a popular subject among many community leaders, health officials, and home owners. However, in developing countries the use of CWs is certainly lower in comparison to their use in Europe or the United States, despite the enormous potential and the great necessity of these countries to implement low-cost treatment for better wastewater management strategy to achieve the required standards (Belmont et al., 2004; Zurita et al., 2006, 2008). In order to establish the performance of constructed wetland systems under different conditions various research studies have been carried out to investigate constructed wetland systems in the removal of pathogens, organic matter and nutrients. To date however, very limited research works on the performance of CW, especially under tropical conditions have been reported. Therefore, the purpose of this review paper was to provide a comprehensive literature review on the application of horizontal subsurface flow constructed wetlands in treating a variety of wastewaters, and to discuss its feasibility in pollutant removal efficiency and additional benefit in climate change mitigation through carbon sequestration.

Objective

This systematic review was aimed to assess and to provide a comprehensive literature review on the application of horizontal subsurface flow constructed wetlands in treating a variety of wastewaters, and to discuss its feasibility in pollutant removal efficiency and additional benefit in climate change mitigation through carbon sequestration.

Method

This review paper was written using searching key phrases "HSSF (Horizontal Sub Surface Flow) practice in the world", "Factors affecting treatment efficiency and "benefits and limitation of Constructed wetland" in springer link, science direct, library genesis, jester, and www.nap.org searching web pages. From these search results, peer reviewed journals and review papers were used. The interpretation of the result of each document was done using bar graphs, lines and scatter plot in a Microsoft Excel. In view of the current demand of this review, the performance assessment assignment employed a range of tools to gather and analyze data from secondary sources. The review approach considered and used specific indicator parameters that are important for the environment. The parameters used include: Total suspended solids (TSS), Total phosphors (TP), Total Kjeldahl nitrogen (TKN), Biological oxygen demand (BOD), Chemical oxygen demand (COD) and NH$_4$-N (ammonia nitrogen).

Engida et al.: Review paper on horizontal subsurface flow constructed wetlands: potential for their use in climate change mitigation
and treatment of wastewater
- 1054 -

Constructed wetland historical background

Natural wetlands are usually found between water bodies and terrestrial areas. These systems naturally screen and collect pollutants such as silt and nutrients as they migrate towards water bodies. Natural wetlands were historically used as wastewater discharge sites (Kadlec, 2003). This system is still used for wastewater treatment under controlled conditions and the use of constructed wetlands has increased significantly. The purposeful construction and study of wetlands to treat wastewater was started at the Max Plank Institute in 1952 by Seidel (Vymazal, 2011).

Research in this area has accelerated since 1985 because of the simplicity of the systems regarding mechanical operation, biological complexity and high level of treatment. The other attractive advantage for developing countries is that construction may be completed using local materials and labor. The first full scale horizontal flow constructed wetland was constructed and used in the Netherlands in the 1975 but vertical flow wetlands dated back to the time of Seidel (Kadlec, 2008). Horizontal subsurface flow constructed wetland is the most widely used technology in Europe. This technology is designed typically in a rectangular bed form, and contains planted macrophytes and lined with an impermeable membrane or made from concrete. Mechanically raw or pretreated wastewater is fed in at the inlet and passes slowly through the filtration medium under the subsurface of the bed in a horizontal path until it reaches the outlet zone before discharging via level control arrangement at the outlet (Vymazal, 2005).

Constructed wetland classification

General classifications

Constructed wetlands for wastewater treatment are typically classified into two types according to the wetland hydrology, i.e. free water surface (FWS) constructed wetland and subsurface flow (SSF) constructed wetlands (Saeed and Sun, 2012).

In the FWS system, the water flowing through the system is exposed to the atmosphere, while in the SSF system, water is designed to flow through a granular media, without coming into contact with the atmosphere. FWS wetlands can be subdivided into four categories based on their dominant type of vegetation: emergent macrophyte, free floating macrophyte, free floating leaved macrophyte and submerged macrophyte. However, the subsurface flow wetlands (which by definition must be planted with emergent macrophytes) can be sub-classified according to their flow patterns: horizontal or vertical (Vymazal and Kröpfelová, 2008).

Surface flow systems are further subdivided based on the type of macrophytes that grow on them as free floating macrophytes (e.g. duck weed and water hyacinth), submerged macrophytes, free floating leaved macrophytes and floating mat macrophytes. FWS systems are similar to natural wetlands, with shallow flow of wastewater over saturated substrate. Whereas, in SSF systems, wastewater flows horizontally or vertically through the substrate which supports the growth of plants, and based on the flow direction, SSF constructed wetland is divided further into horizontal flow (HF) and vertical flow (VF) systems. A combination of various wetland systems was also introduced for the treatment of wastewater, and this design generally consisted of two stages of several parallel constructed wetlands in series, such as VF-HF CWs, HF-VF CWs, HF-FWS, CWs, and FWS-HF, CWs (Vymazal, 2013). In addition, the multiple-

Engida et al.: Review paper on horizontal subsurface flow constructed wetlands: potential for their use in climate change mitigation
and treatment of wastewater
- 1055 -

stage constructed wetlands that were comprised of more than three stages were used (Kadlec, 2008). In the recent years, enhanced artificial constructed wetlands such as artificial aerated CWs, baffled flow CWs, Hybrid towers CWs, step feeding CWs and circular flow corridor CWs have been proposed to enhance the performance of the system for wastewater treatment (Wu et al., 2014). According to Haberl (1999) design configurations of constructed wetlands are classified on the basis of the following parameters, as illustrated in *Figure 1*.
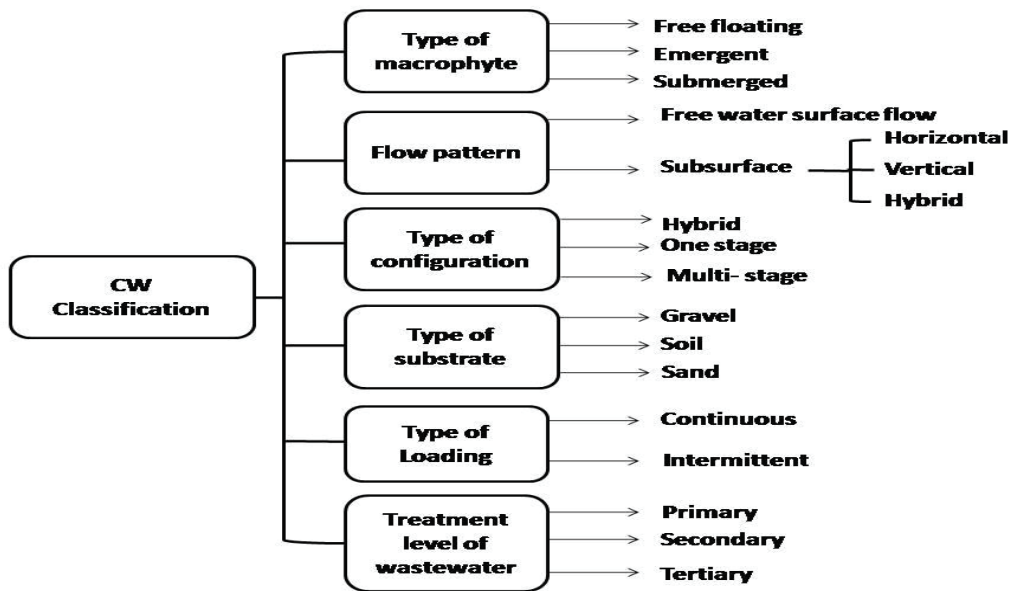

Figure 1. Classification and types of constructed wetland systems. Performance evaluation of constructed wetlands (Haberl, 1999)

Performance evaluation of constructed wetlands

Constructed wetlands are considered as natural treatment processes to stabilize, sequester, accumulate, degrade, metabolize and mineralize pollutants. They are used for a wide range of wastewater treatment such as municipal, domestic, agricultural, industrial, acid mine drainage, petroleum refinery wastes, compost and landfill leachates, and storm wastewaters (Vymazal, 2005). The treatment system involves macrophytes, substrates and microorganisms able to improve the water quality for reuse purposes. Macrophytes and Medias are an active component of horizontal subsurface flow constructed wetland (Vymazal, 2011). The selection of media type is also very important, because clogging problems are observed in subsurface flow constructed wetlands and linked hydraulic retention time and hydraulic conductivity (Lopez-Lopez et al., 2015).

Wastewater treatment is accomplished through the integrated combination of physical, biological and chemical interactions among biotic and abiotic components of the ecosystem and macrophytes cultivated in constructed wetlands make one of the basic components in the treatment process.

They influence plant microorganism's wastewater interactions by providing microbial attachment sites, sufficient wastewater residence time, trapping and settlement of suspended wastewater components as a result of resistance to hydraulic flow, surface area for pollutant adsorption, uptake and storage in plant tissue and diffusion of oxygen from aerial parts to the rhizosphere (Kyambadde et al., 2005). Wetlands remove metals using a

Engida et al.: Review paper on horizontal subsurface flow constructed wetlands: potential for their use in climate change mitigation
and treatment of wastewater
- 1056 -

variety of processes such as filtration of solids, sorption onto organic matter, oxidation and hydrolysis, formation of carbonates, formation of insoluble sulfides, binding to iron and manganese oxides, reduction to immobile forms by bacterial activity, and uptake by plants and bacteria. Metal removal rates in both surface flow and subsurface flow wetlands can be high, but can vary greatly depending upon the influent concentrations and the mass-loading rate (Vymazal, 2005).

A study conducted in Kenya to assess the effectiveness of CW in treating domestic wastewater showed that the removal of BOD5, TSS, COD, TN, NH4-N and Orthophosphate were highly effective with a removal value of 98%, 85%, 96%, 90%, 92%, and 88%, respectively (Nyakango, 1999). This was mainly because this wetland consists of a combination of an SF system followed by three SSF wetland cells in a series adjacent to it. A case study conducted in Italy, to assess the treatment performance of an SSF CW by Pucci et al. (2000) showed high removal efficiencies for COD (93%), TSS (81%), hygienic parameters (TC 99%, FC 99.7%), but relatively low for nitrate (55%), total nitrogen (50%) and ammonium (30%), and very low for total phosphorus (20%). This is mainly due to poor nitrification and denitrification in the system. There is substantial evidence in the design of CW that a number of cells in series can consistently produce a higher quality effluent. Because this process minimizes the short-circuiting effects of any one unit and maximizes the contact area in the subsequent cell (Gearheart, 2004).

Constructed wetland contaminant removal mechanisms

Nitrogen removal mechanisms in wetland are nitrification in aerobic zone, de-nitrification in anaerobic zones which release N_2 and N_2O gases, plant uptake, sedimentation, decomposition, ammonia volatilization, and accumulation of organic nitrogen in gravels because of redox potential of hydric sediment conditions (*Fig. 2*).
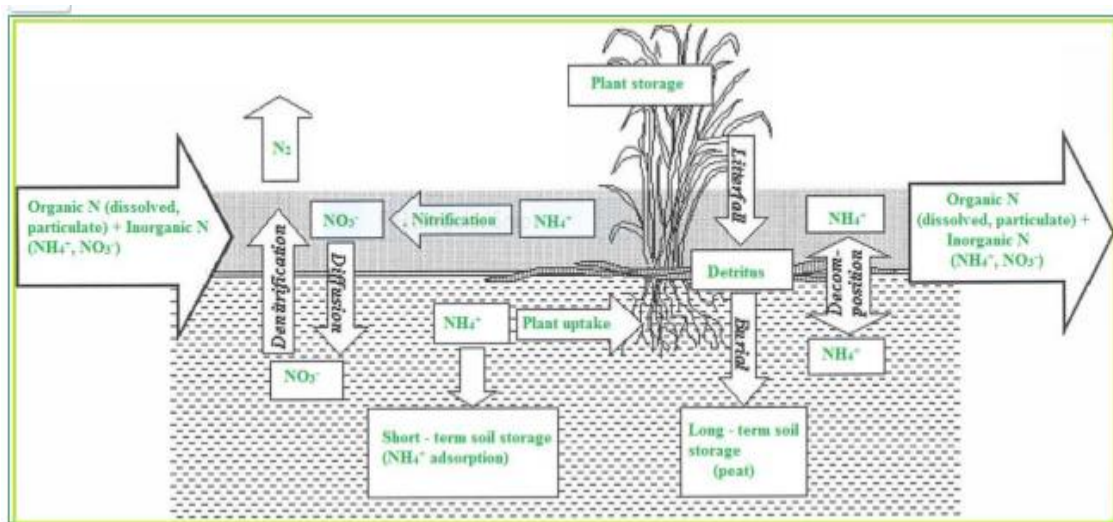

Figure 2. Nitrogen removal processes in wetland (Vymazal and Kröpfelová, 2008)

The fate of phosphorus is quite different in wetland soils, since there are no mechanisms comparable to de-nitrification as phosphorus has no gaseous phase.

Engida et al.: Review paper on horizontal subsurface flow constructed wetlands: potential for their use in climate change mitigation
and treatment of wastewater
- 1057 -

Consequently, plant uptake, sorption, decomposition and long-term storage occur, and then phosphorus tends to accumulate in wetlands. Precipitation of phosphate minerals can provide a significant sink for phosphorus in wetlands with large stores or inputs of iron and aluminum or calcium (*Fig. 3*) (Vymazal and Kröpfelová, 2008).
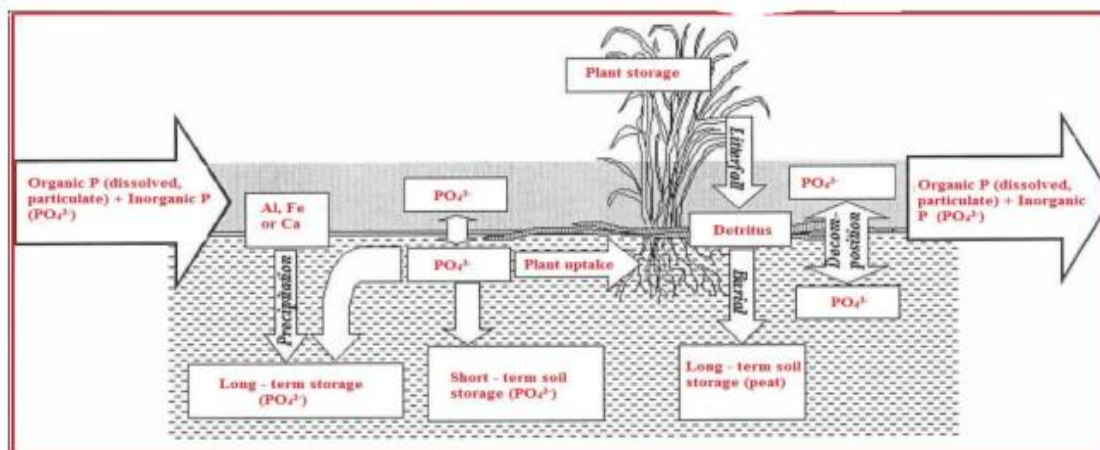

Figure 3. Phosphorus removal mechanisms (Vymazal and Kröpfelová, 2008)

The wetland treatment mechanism is a dynamic process acting wastewater purification under the cooperation of emergent macrophytes, substrates and attached microorganisms. In general, in constructed wetlands it is important to study biomass accumulation and nutrient flux in order to understand the dynamics of nutrients.The carbon cycle in wetlands has been investigated to understand the linkage between biomass generation and carbon sequestration (Kayranli et al., 2010). Wastewater treatment may also serve as a carbon sequestration offset (Rosso and Stenstrom, 2008). Wetland ecosystems are acting as a net carbon emission and sequestration systems depending on the time scale and hydrology operational strategies (Whiting et al., 2001), and as a component of a larger system treating wastewater (Rosso and Stenstrom, 2008). Constructed wetlands are passive natural processes and avoid carbon emission equivalent of 1.3 Mt C/yr for every 1.0 MGD as compared to conventional high rate treatment facilities such as activated sludge. There are many mechanisms for the capture and release of carbon in a wetland (*Fig. 4*). Pathways for the release of carbon in the constructed wetland system are slow decomposition, respiration, and physical removal. Photosynthesis is the process whereby a plant transforms atmospheric carbon in the form of CO_2 into the carbon of the plant tissue or biomass. The process of plant respiration releases some CO_2 to the atmosphere as a byproduct of cellular growth. In addition to respiration, plants release carbon as a byproduct of decomposition in the form of CO_2 and CH_4 (Burke, 2011).

Factors affecting the performance of constructed wetlands

Temperature

This is a key environmental factor that determines the activity of nitrifying bacteria and the de-nitrification potential in treatment wetlands (Langergraber, 2013). Nitrogen removal by biological means is most efficient at 20-25 °C and temperatures above this

Engida et al.: Review paper on horizontal subsurface flow constructed wetlands: potential for their use in climate change mitigation
and treatment of wastewater
- 1058 -

affect both microbial activity and oxygen diffusion rates in the constructed wetlands. The microbial nitrification and de-nitrification activities can decrease considerably at water temperatures below 15 °C or above 30 °C, and most microbial communities for nitrogen removal function at temperatures greater than 15 °C (Kuschk et al., 2003). Literature revealed that the activity of de- nitrifying bacteria in constructed wetland sediments is generally more robust in spring and summer than in autumn and winter and the overall removal rate of nitrate is higher in the summer than in winter (Oostrom, 1994). De-nitrification is commonly believed to cease at temperatures below 15 °C, but some studies have demonstrated de-nitrification activity at 14 °C or lower temperatures. Richardson et al. (2004) reported that the optimum temperature range for nitrification is 30-40 °C in soils and the optimal ammonification is carried out at 40-60 °C at the optimal pH between 6.5 and 8.5. At low temperature, nitrification is insufficient to prevent a net increase in ammonia concentration due to ammonification (Akratos and Tsihrintzis, 2007).
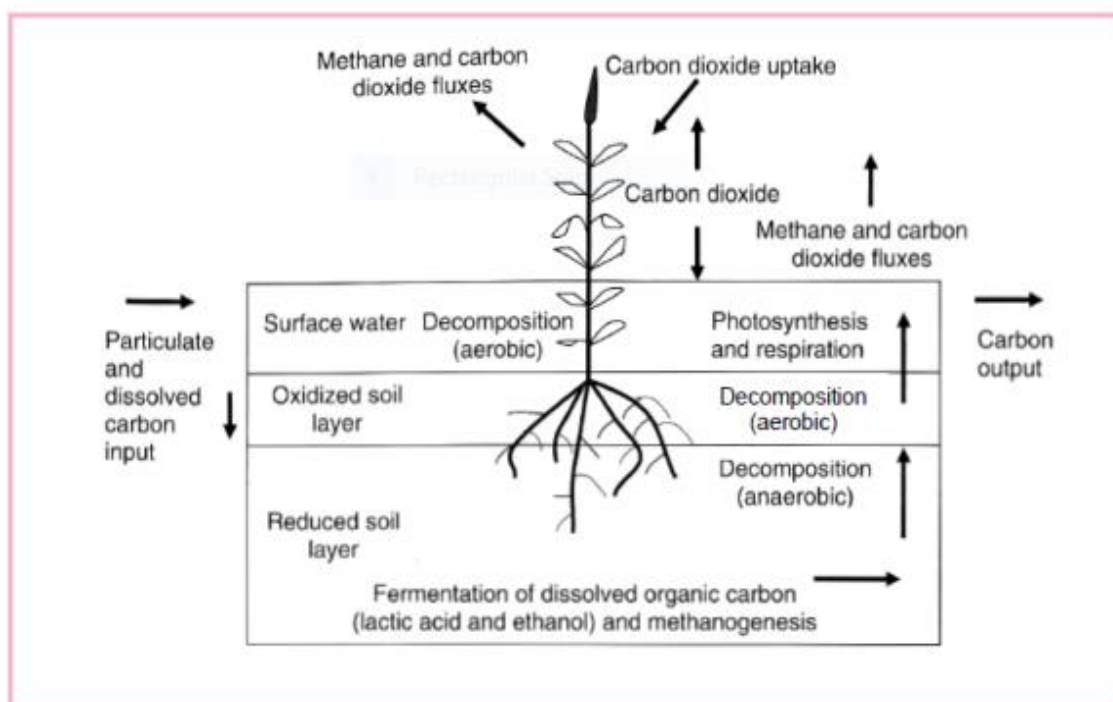

Figure 4. The carbon cycle (Kayranli, 2010)

HRT

The high purification efficiency of constructed wetlands can be achieved by choosing suitable growth media. Particle size, surface nature, bulk porosity and pore spaces of the growth media are important factors in selection of media type for wastewater treatment. Growth media provide not only physical support for plant growth but also additional sites for biofilm growth and the adsorption of nutrients, heavy metals and promote the sedimentation and filtration of pollutants. In general, the inconsistent treatment efficiency of constructed wetlands depends on the type of feeding mode, the plant types and type of media used (Abdelhakeem et al., 2016). According to Huang et al. (2000) explanation, ammonium and total Kjeldhal Nitrogen (TKN) concentrations in treated effluent decreased diagrammatically with increased wastewater retention time. In most

Engida et al.: Review paper on horizontal subsurface flow constructed wetlands: potential for their use in climate change mitigation
and treatment of wastewater
- 1059 -

wetland systems, efficient nitrogen removal requires longer retention time compared with organic matter (COD and BOD) removal efficiency. Accordingly, nitrogen removal efficiency varies greatly with flow conditions and HRT (Taylor et al., 2006).

In subsurface constructed wetlands, media perform the function of rooting material for macrophytes surface for microbial biofilm growth, screen organic and inorganic suspended matter, and distribute inflow and collect outflow water (U.S. EPA, 1993). Keeping the water level below the surface of the bed, this reduces the risk of human contact with pathogens, and reduces the opportunities for breeding vector organisms such as mosquitoes. Media can also provide adsorption sites for phosphorus (Kadlec, 2003). According to this researcher, potentially active industrial byproduct substrates include blast furnace slag, crushed rock, fly ash, and crushed concrete, burnt oil shale, iron ochre and wood chips. The microorganisms responsible for the degradation of pollutants are located at the surface of the media and the smaller sized media has a larger surface area than the coarser media (Vymazal and Kröpfelová, 2008).

Well graded media (containing all gravel sizes in the selected range) is better than poorly graded media as it offers greater pore space and provides good removal of particulate matter. In general, the substrate alone also provides significant wastewater treatment, but vegetation further improves treatment efficiency (Abdelhakeem et al., 2016). Therefore, the high purification efficiency of constructed wetlands can be achieved by choosing suitable growth media.

Types of plant species

Plants are often grown in gravel beds to stimulate uptake and create suitable conditions for the oxidation of the substrate, thereby improving the ability of the system to treat the wastewater and create aesthetic value, exhibit several properties which enhance wastewater treatment processes and thus, make them an essential component of the treatment wetland. These properties influence wastewater treatment through physical effects such as filtration, provision of surface area for the growth and attachment of microorganisms and regulation of undesirable water temperature as well as surplus algal growth. Macrophytes are the main biological component of wetlands and their presence has been hypothesized to play a key role in wastewater remediation (Luckeydoo et al., 2002). Macrophytes are also play an important role in wastewater treatment through uptake of nutrients, surface bed stabilization and other mechanisms (Kadlec, 2008). Wetland plants must survive the potentially toxic effects of the effluent and enhance the treatment process of wetlands in several ways such as filtering wastes, regulating flow, providing surface area for microbiological treatment, providing shed and controlling algae growth, contributing oxygen to the cells, taking up and storing some metals and nutrients from the wastewater (Kyambadde et al., 2005).

Metabolically, plants take up pollutants; produce organic carbon and oxygen, thereby improve the water to varying extents. They are not only assimilating pollutants directly into their tissues, but also act as catalysts for purification reactions by increasing the environmental diversity in the rhizosphere, promoting a variety of chemical and biological reactions that enhance purification. Several studies have shown that plants enhance treatment efficiency by providing a favorable environment for the development of microbial populations and by oxygenating the system. The roots of macrophytes provide surface areas for microbial growth and aerobic zones in constructed wetlands. The root facilitates various physical and biochemical processes caused by the relationship of plants, microbial communities, soil and contaminants. Wetland systems with

vegetation typically remove greater amounts of total nitrogen than non-vegetated systems (Taylor et al., 2006). Nutrient removal by the emergent plants is achieved by two processes: absorption of the plant itself and microorganism activity around the rhizome (Cooper and Boon, 1987). In general, the main role of macrophytes in constructed wetlands is to promote microbial growth with the media surfaces, and to assist the permeation velocity of the wastewater for pollutant treatment efficiency (*Table 1*).

Table 1. *Pollutant removal processes in surface flow constructed wetland (Tousignant and Fankhauser, 1999)*

Pollutant type	Removal process
Organic material (COD and BOD)	Particular organic matter is removed by settling and filtration then converted to soluble BOD Soluble organic matter is fixed by biofilms and degraded by attached bacteria in the biofilm on stems, roots sand particles etc.
Suspended solids (TSS)	Filtration Decomposition by bacteria during long retention time
Nitrogen	Nitrification and de-nitrification in biofilm Plant and microbial uptake
Phosphorus	Adsorption (retention in the media) Precipitation with Ca, AL or Fe
Pathogens	Filtration, adsorption, predation (feeding) by protozoa Die-off due to long retention times
Heavy metals	Precipitation and adsorption Plant uptake
Organic contaminates	Adsorption by biofilm and clay particles Decomposition due to long retention time and by bacteria

Other factors

Other important factors are wetland depth, pH, and DO. The nitrification and denitrification process depend upon water pH, the presence or depletion of dissolved oxygen, hydraulic loading rate, and the hydrological period of the wetland. At low DO concentration, nitrification occurs in the aerobic zone but denitrification occurs in the anoxic zone (Kadlec, 2008). The biofilm may improve the denitrification; because of algae provide a desirable carbon source for denitrifies (Mariñelarena and Di Giorgi, 2001). In general, in order to maintain and improve nitrogen removal and water quality in constructed wetlands, attention should be given to factors that promote the growth rate of macrophytes and bacteria, such as planting depth, harvesting time, optimization of temperature, pH, DO and HRT.

Performance efficiency of horizontal sub surface flow constructed wetland (HSSFCW): a case in other countries

This section presents different macrophytes used for treatment of wastewater in constructed wetland and their effectiveness in treating wastewater pollutants. The focus of each case study is according to parameters related to the overall constructed wetland design, macrophyte species, hydraulic loading rates and the efficiency of pollutant removal. In order to evaluate the performance efficiency of a CW unit, the percentage of concentration reduction and mass removal is reported. The wetland effluent is being

irrigated on vegetation, nutrient levels in the effluent do not need to be as strict as for direct discharge into a water course (Tousignant and Fankhauser, 1999). These systems are highly effective at improving water quality have many benefits such as habitat creation and low-cost operations (Kadlec, 2008). According to Mustafa (2013), the monitoring of horizontal flow constructed wetland indicates that the general performance of the system was good and it successfully reduced pollutants even under fluctuating pollutant loading resulting from power breakdown. The average reduction of BOD concentration over the treatment periods was 50% with mean effluent concentration of 34 mg/L. Whereas, the average removal efficiency of the treatment system for COD, TSS, ammonia–nitrogen, orthophosphate and fecal coliform were 44%, 78%, 49%, 52% and 98% with mean effluent concentrations of 68.3 mg/L, 45 mg/L, 9.7 mg/L, 3.7 mg/L and 3.0 x 10^3 CFU (Colony-forming units)/100 ml respectively.

In general, the monitoring of horizontal flow constructed wetland indicates that it was good and successful in reducing pollutants from wastewater up to the required standards even under fluctuating pollutant loading. The outcomes revealed that if constructed wetlands are properly planned and operated, they can be used as secondary or tertiary treatment level under local conditions and finally delivers high value water that can be used for landscape irrigation and also for other helpful uses. The COD removal efficiency of HSSFCW even at low concentration which might be due to high degradation rate in the wastewater collection systems and in settling tank before entering the CWs. In overall, the results obtained in Indonesia, Thailand, and Costa Rica revealed that, the local macrophytes and local natural substrates can perform successfully in the treatment of domestic wastewater (*Table 2*). The organic contaminants and pathogens can be removed successfully, therefore, the treated water can be used safely for irrigation, fishery or out-door uses. In addition, the treated water can replace a part of the fresh water need supplied from the pipe distribution systems and be potential to protect surface and ground water reduces from the pollutants. Moreover, the use of macrophyte creates a green space in a single house yard or green public views for neighborhood (Qomariyah et al., 2017).

Table 2. *The effective removal of pollutants in CWs with local macrophytes and natural substrates (Qomariyah et al., 2017)*

Type and size of CW	Type plant	Type of substrate	Country	Removal efficiency (%)
HSSFCW (1.7 x 0.7 x 0.7 m)	C. papyrus	Sand & gravel	Indonesia	BOD=98.55% COD=98.46% TSS=88 – 96% Detergent=99.86%
HSSFCW (2 x 1 x 1 m)	Canna & Helicona	Gravel	Thailand	BOD=94-99.9% COD=42-83% TSS=88%-96% TN=4 – 37% TP=6 – 35%
HSSFCW (14 x 1.2 x 0.6 m)	Coix lacrymajodi	Crushed rock	Costa Rica	BOD=94-99.9% COD=91.7-97.9% FC=99.99%

Engida et al.: Review paper on horizontal subsurface flow constructed wetlands: potential for their use in climate change mitigation
and treatment of wastewater
- 1062 -

The performance efficiency of subsurface flow constructed wetland in Italy done by Pucci et al. (2000) indicates that it has high removal efficiency for COD (93%), TSS (81%) and total coliform (99%), but relatively less removal for nitrates (55%), total nitrogen (50%), ammonium (30%) and total phosphorus (20%). This is mainly due to poor nitrification and denitrification in the treatment system. A study done in Kenya also revealed that the effectiveness of the constructed wetland in treating domestic wastewater and indicated a removal efficiency of 98%, 85%, 96%, 90%, 92% and 88% for BOD5, TSS, COD, TN, NH4–N and PO4 respectively (Nyakango, 1999). This achievement was due to the wetland design which consists of a combination of a surface flow system followed by three subsurface flow wetlands in a series adjacent to it.

The removal efficiency of constructed wetlands varies with hydraulic retention time, hydraulic loading, wetland design, temperature, substrate and vegetation. Although considerable number of reports has contributed to our understanding of the physical, chemical and biological processes that facilitate the removal process, inconsistence results suggest that further studies are required to optimize the system functioning. For example, many scholars show that, a wetland scheme with vegetation has advanced efficiency of removal than that without plants (Bwire et al., 2011) although others did not notice any significant change between planted and unplanted systems (Baldizon et al., 2002). Similarly, the percentages of nutrient (nitrates/nitrites and phosphates) removal obtained in the planted constructed wetland cell were higher than the averaged percentages of nutrient removal rates in the unplanted cell.

Thus, the average nitrate/nitrite percentage removal was 58.1% for planted cells and 21.6% for unplanted cell while the phosphate percentage removal averaged 40.1% for planted cells and 5.2% for unplanted cell (Mairi et al., 2012). Bacteria may be reduced by sedimentation, chemical reactions, natural die-off and predation by zooplankton, nematodes, lytic bacteria and attacks by bacteriophages (Denny, 1997). The role of plants related to the treatment of wastewater is the physical effects brought about by the presence of the plants. The macrophytes alleviate the surface of the beds, offer good condition for physical filtration and deliver enormous surface area for attached microbial growth (Brix and Schierup, 1989). Furthermore, macrophytes reduce the velocity of wastewater into the wetland system and also supply oxygen at the root zone which is used by aerobic microbes, thereby enhancing purification process of wastewater in addition to purification done by anaerobic microbes (Watson et al., 1989).

The performance efficiency of different constructed wetland systems that contain different HRT, substrate, plant species and wastewater type were reviewed in order to regulate the performance of constructed wetland parts in elimination of contaminants. The influent and effluent concentrations including percentage removal were summarized in *Table 3*.

Table 3. HSSFCW percentage abatement in different locations planted with Phragmites australis

Location	BOD$_5$	COD	TSS	TN	NH$_4$	TP	Reference
Egypt	93	91	92	60	57	63	Puigagut, 2007
Spain	74.2	66	87.8	56.5	45.7	45	Barbera, 2009
Italy	74	60	89	35	-	57	Kotti, 2010
Greece	76	64	-	55	43	48	El Hamouri, 2007

Engida et al.: Review paper on horizontal subsurface flow constructed wetlands: potential for their use in climate change mitigation
and treatment of wastewater
- 1063 -

As indicated in *Table 4,* the nitrogen removal in constructed wetlands depends upon system design, environmental chemistry (roots, plants, water and sediments), plant uptake, available carbon and material type. The mean removal efficiency of the planted (reeds) and unplanted constructed wetlands during the three months of warm and cold study periods are indicated in *Figure 5*. In general, proper performance and high removal at the first treatment unit (septic tank) increases the efficiency of the treatment plant (Farzadkia et al., 2015).

Table 4. *Treatment efficiency of HSSFCW in different countries*

Type of waste water	Type of media	Plant type	HLRL/D	HRT/D	Removal efficiency	Country	Reference
Domestic	Soil	P. karka	1	9	COD 44% BOD 50% TSS 78% NH_3 49% Po_4 52% FC 98%	Pakistan	Mustafa, 2013
Domestic	Gravel	P. mauritianus	2	12	BOD 76% NO_3 58.1 Po_4 40.1 FC 93.9%	Tanzania	Mairi, 2012
		Unplanted			BOD 48% NH_3 21.6% Po_4 5.2% FC 58.7		
Raw domestic	Tezontile rock	Z. aethiopica	200	3	COD 64% BOD 80.6 TSS 80.1 Org-N 54.9% NO_3 53.6 NH_4 19.6%	Mexico	Zurita et al., 2014
		C. papyrus			TP 4.8% FC 92%		
Raw domestic	Gravel (10-15 mm)	C. zizanoides	40	0.92	TSS 90.2% TN 59.4% NH_4 51.8%	San midi Ganzaria	Maucieri et al., 2014
		M. giagnteus			TSS 81.2% TN 45.7% NH_4 40%		
		P. australis			TSS 90.3% TN 57.2% NH_4 54.3%		
Domestic	Gravel (5 cm), peat (35 cm)	P. australis	0.27	22.6	BOD 96.4 COD 84.6 TSS 94.8% TN 79.5% NH_4-N 98.8% TP 83.7%	Spain	Andero-martiuer et al., 2016

HLR = hydraulic loading rate, HRT = hydraulic retention time

Engida et al.: Review paper on horizontal subsurface flow constructed wetlands: potential for their use in climate change mitigation
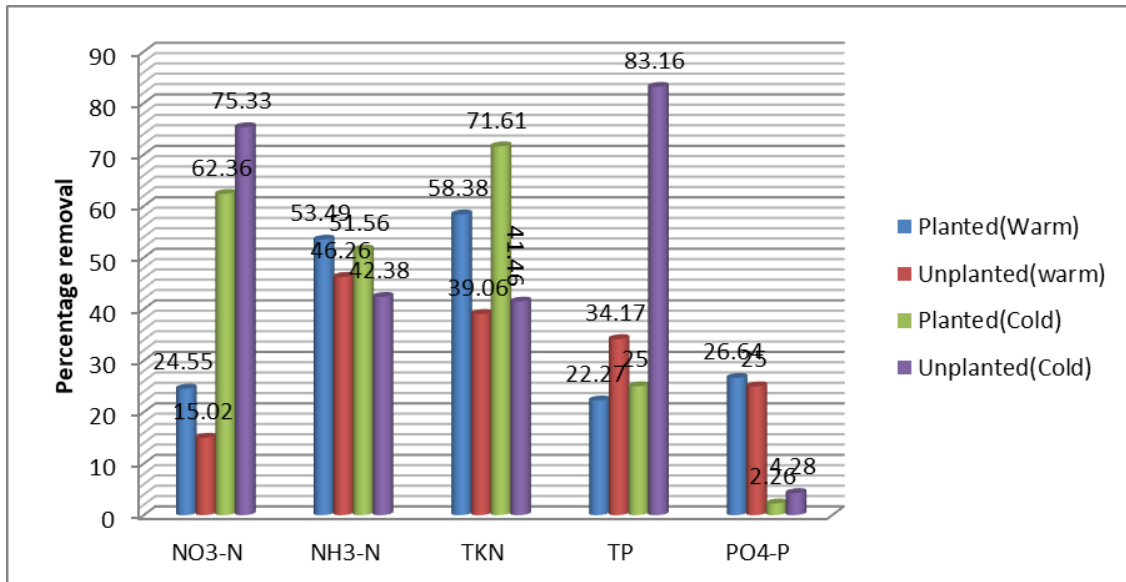and treatment of wastewater
- 1064 -

Figure 5. *Effect of vegetation, climate and media on nutrient removal (Farzadkia et al., 2015)*

The mean influent concentration of COD, TSS, NH4–N, NO3–N and PO4–P in January were 144, 54, 96, 2.76 and 3.62 mg/L, respectively. The effluent concentrations after treating with constructed wetland were 64, 8, 62, 1.69 and 3.55 mg/L, respectively. The mean percentage removal reductions for COD, TSS, NH4–N, NO3–N and PO4–P in this month were 55%, 85%, 35%, 39% and 2%, respectively. The mean influent concentrations of these pollutants in February were 192, 38, 63, 2.91 and 4.12 mg/L, respectively. The mean effluent concentrations were 64, 4, 28, 2.33 and 1.05 mg/L, respectively. The mean percentage removal efficiency of the wetland was reached 66%, 89%, 55%, 20%, and 75% for COD, TSS, NH4–N, NO3–N and PO4–P, respectively. In hydrologic comparison in the constructed wetland indicated that the COD, TSS, NH4–N, NO3–N and PO4-P reductions were considerably greater in February compared to January. This was due to the lower HLR and greater HRT in February compared to January. The major mechanisms of TSS and COD removals in constructed wetlands are sedimentation, filtration and physical entrapment in the void pores of the sand and gravel medias. The higher HRT also allows for greater physical settling of suspended particles, which reduces the TSS and the higher residence time allows wetland plants to uptake nutrients effectively thereby decreasing the effluent concentrations (Tilak et al., 2016). The nitrogen content of Pistia stratiotes, Typha latifolia and Lemon grass in the subsurface flow constructed wetland were 37.4 g/kg, 27.1 g/kg and 15.8 g/kg, respectively.

The phosphorus accumulation capacity of these plant species were also 8.4 g/kg, 2.96 g/kg and 2.29 g/kg, respectively for Pistia stratiotes, Typha latifolia and Lemon grass in the constructed wetland (*Fig. 6*) (Tilak et al., 2016). Subsurface flow constructed wetlands are good in utilizing pollutants in a symbiotic relation between aquatic plants and microorganisms in the media and the plant root system. Composite organic compounds confined in wastewater will be used up by plants as a nutrient, while the root structure of the aquatic plants will yield oxygen that can be used as energy or catalyst for a sequence of metabolic courses for heterotrophic aerobic microorganisms. Plants that are usually used include Cyperus alternifolus, Canna indica,

Engida et al.: Review paper on horizontal subsurface flow constructed wetlands: potential for their use in climate change mitigation
and treatment of wastewater
- 1065 -

Phragmites australis, Typha spp., Scirpus spp., etc. these plants reduce the concentration of BOD, COD, ammonia, nitrites, phosphorus and bacterial contaminants (Wijaya et al., 2016).
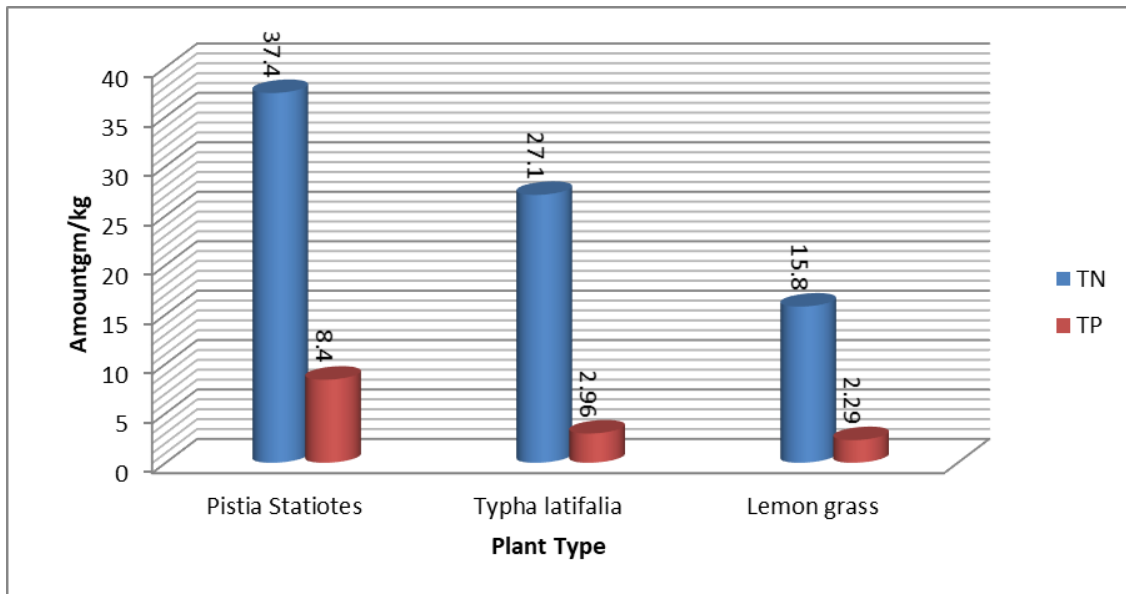

Figure 6. Nutrient accumulation in the wetland plants (Tilak et al., 2016)

The removal of nutrients from constructed wetlands are also dependent on the media types. The accumulation of total nitrogen and phosphorus in the constructed wetland media was also investigated by Tilak et al. (2016) as indicated in *Figure 7*.
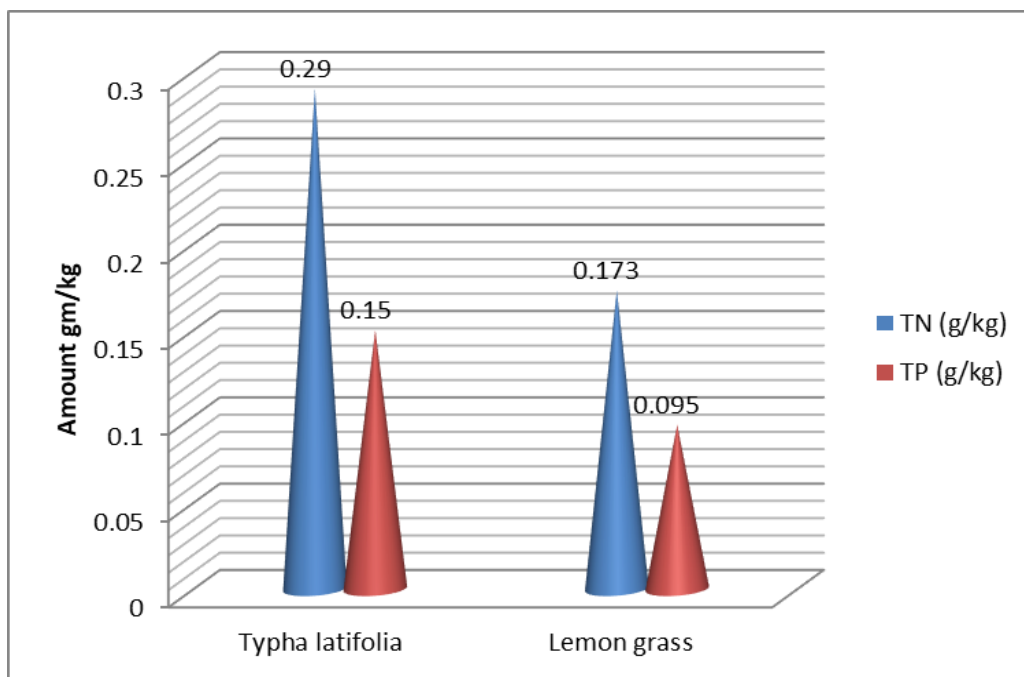

Figure 7. Nutrient accumulation in sand media (Tilak et al., 2016)

The effect of vegetation on the organic matter removal was better than (i.e., 5 to 15%) those of the unplanted. In general, the organic removal results suggest that control treatment influences wetland performance more than the type of macrophytes. The TSS removal efficiencies varied from 35 to 76% in both dry and nortes season. The organic matter (COD and BOD) removal showed similar pattern to that of TSS, which was varied from 36 to 68% and 28 to 69% for COD and BOD, respectively in the dry season, and whereas for the nortes season, they varied from 40 to 78% for COD and 49 to 74% for BOD. The nutrient removal efficiencies ranged from 47 to 66% and 59 to 79% for TN, 53 to 67% and 50 to 75% for $NH_4 +$ and 69 to 84% and 60 to 75% for NO_3- respectively for dry and nortes seasons. In general, the performance efficiency of the horizontal subsurface flow constructed wetland in organic matter, nutrient and pathogens were shown in *Figures 8* and *9*. The overall result clearly indicates that HRT is a key factor in the removal of a wide variety of contaminants (COD, BOD, TSS, TN, $NH_4 + NO_3$ - and TP) in horizontal subsurface flow constructed wetland treating swine wastewater. According to the findings, the Typha latifolia and Eleocharis interstincta are the most suitable macrophyte species to be used for the treatment of piggery wastewater. In spite of the fact that high contaminant concentrations in wastewater may have masked the macrophytes; contributing to the overall treatment efficiency of HSSFCW, vegetated beds usually provide better effluent quality than unplanted beds (Puigagut et al., 2007).

The above graph indicates that the local macrophytes and natural substrate can perform successfully in the treatment of domestic wastewater. The results demonstrated that removals of organics (COD and BOD) are high in the horizontal subsurface flow constructed wetlands. The treatment efficiency of BOD nan COD ranged between 76 and 99.4% and 76 and 8.46%, respectively except COD removal studied results in Thailand which varied between 42 and 83%.
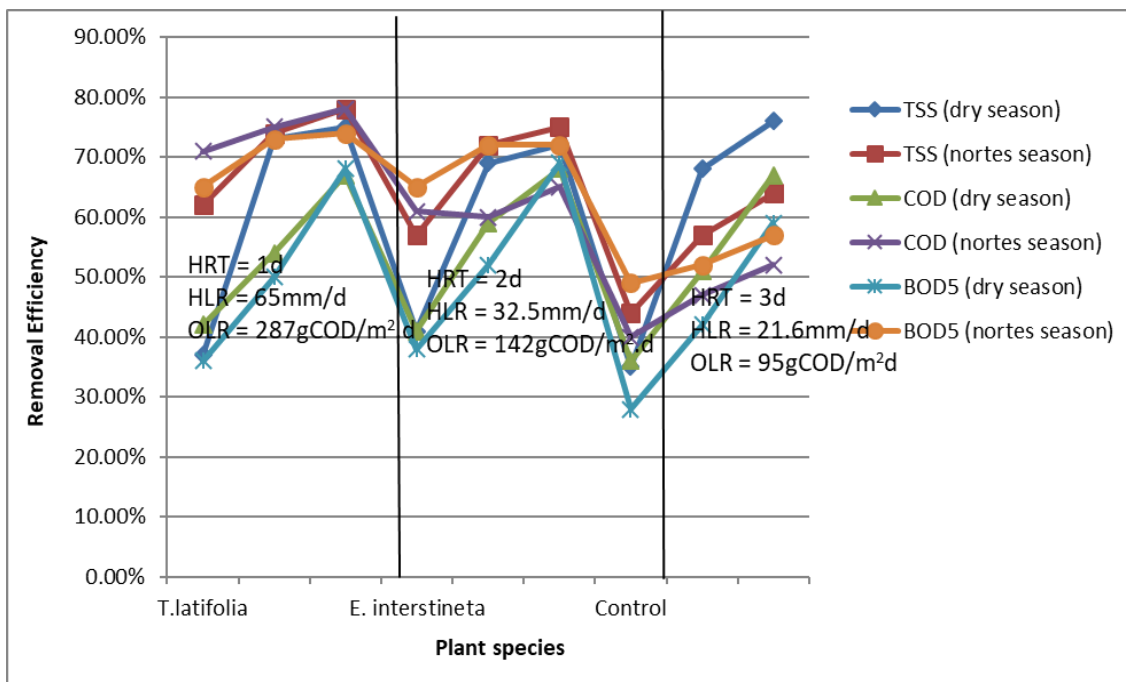

Figure 8. COD, BOD and TSS removal efficiency of HSSFCW at different seasons (Puigagut et al., 2007)
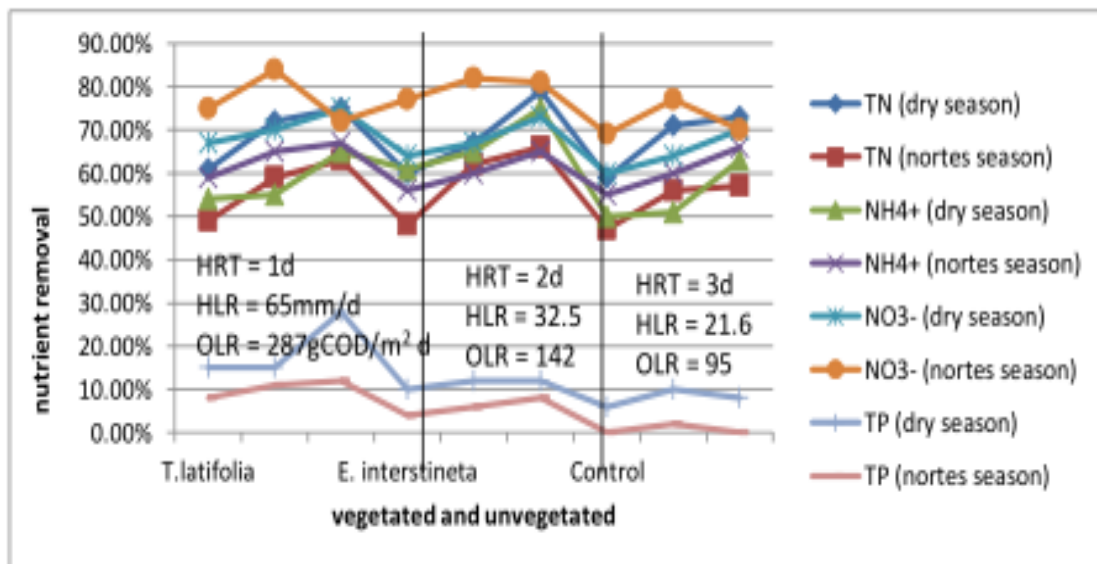
Engida et al.: Review paper on horizontal subsurface flow constructed wetlands: potential for their use in climate change mitigation
and treatment of wastewater
- 1067 -

Figure 9. *Influence of plant species and HRT on nutrient removal efficiency of HSSFCW (Gonzalez et al., 2009)*

Performance efficiency of HSSFCW: a case in Ethiopia

In Ethiopia, environmental degradation within and downstream of cities has multiple consequences for public health, in particular through the use of untreated wastewater in irrigated agriculture. Significant wastewater treatment efforts are done by Addis Ababa Water Supply and Sewerage Authority (AAWSSA), but it remained limited. Due to the combination of poor sanitation and undulating topography, almost all wastewaters generated in the city finds its way through a dense network of streams into Akaki Rivers (Little and Great Akaki rivers). Several factories also discharge their untreated effluents into the rivers. Wastewater collection and treatment are limited and treated wastewater is also discharged into the same river. Discharges from industry, domestic, and agricultures can cause an impact on environmental condition in river and coastal waters. Eutrophication is an accelerated growth of algae on higher forms of plant life caused by the enrichment of water by nutrients, especially compounds of nitrogen and/or phosphorus and inducing an undesirable disturbance to the balance of organisms present in the water and to the quality of the water concerned. Eutrophication of fresh water ecosystem is one of the most prevalent environmental problems responsible for water quality degradation on a world-wide scale. At present hardly any infrastructure is available for the effective treatment of sewage in developing countries.

Municipal sewerage and the extent of domestic and industrial wastewater treatment are inadequate in most urban situations. When there is a municipal sewerage network in place, the coverage is usually incomplete and the treatment level is insufficient. Even when treatment facilities exist, poor maintenance and operation often results in failing treatment processes, causing pollution of the effluent receiving surface waters. The risk of water borne diseases may actually increase in developing countries as a result of the introduction of a conventional sewerage scheme, since it is usually not accompanied by effective end-of-pipe treatment (UNEP/GPA, 2004). Untreated effluent contains high concentrations of salts, total suspended solids, chemical oxygen

Engida et al.: Review paper on horizontal subsurface flow constructed wetlands: potential for their use in climate change mitigation
and treatment of wastewater
- 1068 -

demand, nitrogen and phosphorous and toxic compounds, such as heavy metals and chlorinated organic compounds. Industrial effluents can seep into the aquifer and pollute groundwater or where it is discharged without proper treatment can affect the physico-chemical properties of the receiving water and consequently its biota (Kambole, 2003).

All this unregulated discharge of wastewater undermines biological diversity, natural resilience and has a significant impact on macro-invertebrates composition due to the water quality deterioration (Beyene et al., 2009). Addis Ababa City Rivers are highly affected by pollution of heavy metals, pathogens, organic compounds, synthetic chemicals, micro-plastics and nutrients (Aregawi, 2014). Study reports indicated that the city water bodies and surrounding agricultural soils are contaminated with heavy metals such as Hg, As, Pb, Sb, Ni, Sr, and Cd (Elias and Yohannes, 2017), which are extremely toxic even at low concentrations and cause gastrointestinal, skin, nerve damage, lung damage, cancer, nervous, immune system, and kidney damage, brain damage, liver damage, and etc. (Kassa, 2012). Beside these, water, soil and air pollution due to industrial and domestic waste discharges cause peculiar diseases. Study and literature report showed that most people found in Akaki Kality industrial zone are affected by peculiar diseases such as cough (76.5%), diarrhea (58.8%), typhoid (51%), typhus (45.1%), gastrointestinal (39.2%), skin problem (29.4%), asthma (33.3%), and bronchitis (3.9%) (Aregawi, 2014; Elias and Yohannes, 2017). This may be due to long term intake of food that contains high levels of heavy metals and pathogens, and contact with sediments containing heavy metals and pathogens, posing risks to human health (Itanna, 2002; Bekele, 2008) To protect water bodies from pollution, serious waste management implementation should be conducted. The main challenge mentioned by researchers is selecting the appropriate wastewater treatment techniques. Therefore, locally available effective pollution control systems are very important based on the country's economy. For this problem, constructed wetlands can be a good alternative options.

In Ethiopia, Terfie and Asfaw (2004) conducted a research on five pilot scale subsurface flows constructed wetlands; four units vegetated with Cyprus altenifolius, Typha domingensis, Phragmites karka and Borassus aethiopum and the fifth left as unvegetated (control). The performance efficiency of each cells in removing organic matter (COD & BOD5), ammonium and total nitrogen including total chromium under the 5-day hydraulic retention time and hydraulic loading of 120 L/day showed promising results. The wastewater analysis indicated that COD reduction by 58-80% for an inlet organic loading rate (OLR) ranged from 2202-8100 mg/L and BOD5 reduction by 66-77% for an inlet OLR ranged from 650-1950 mg/L. The removal of inorganic substances such as nitrates, sulfates, sulfides, total nitrogen and ammonia-nitrogen ranged from 30-57%, 82-92.4%, 53-82%, 46-61% and 64-82.5%, respectively (*Table 5*). Similarly, Kassa and Mengistou (2014) tested pilot scale HSSFCWs efficiency in treating domestic wastewater in vegetated and unvegetated conditions at HLR and HRT of 7 day and 26 L/day HLR. The results showed that the nutrient removal efficiency of HSSFCW was significantly higher in the planted species than in the unplanted treatment system. The average removal efficiency of orthophosphate in the treatment beds was 84.05% for C. papyrus, 65.29% for P. Karaka and 50.20% for the unplanted. She proved that the average removal efficiency of planted cells was higher than unplanted due to the macrophytes role to accumulate high biomass and remove nutrients.

Engida et al.: Review paper on horizontal subsurface flow constructed wetlands: potential for their use in climate change mitigation
and treatment of wastewater
- 1069 -

Table 5. *Pollutant removal efficiency of HSSFCW in Ethiopia*

Types of waste water	Media type	Plant type	HLR (L/d)	HRT (day)	Removal efficiency (%)	Standards (EEPA, 2000)	Reference
Domestic	Gravel (40-80 mm) (20-30 mm)	C. papyrus	17.7	2.16	COD = 89.4. BOD = 97.8. TSS = 83.9. TN = 53.9. NH$_4$ = 24.8. NO$_3$ = 82.4. TP = 16.5. PO$_4$ = 22.3		Genet, 2007
		C. alternifolia			COD = 87.3. BOD = 97.7. TSS = 82.3. TN = 54.8. NH$_4$ = 24.6. NO$_3$ = 78. TP = 12.5. PO$_4$ = 16.2		
		P. canariensis			COD = 89.6. BOD = 98.1. TSS = 83.2. TN = 57. NH$_4$ = 23. NO$_3$ = 81. TP = 18.1. PO$_4$ = 23.4		
Tannery	Clay (15 cm and gravel 45 cm)	C. alternifolius	120	5	COD = 64.8. BOD = 67.5. TN = 46. NH$_4$ = 64.8	BOD=80% (200) COD = 500 TSS = 50% NH$_4^+$=30% TN = 80% (60%) TP = 8% (10)	Terfie and Asfaw, 2014
		T. domingensis			COD = 56.6. BOD = 66. TN = 46.7. NH$_4$ = 53		
		B. aerthiopium			COD = 58 BOD = 66 TN = 58 NH$_4$ = 80		
		P. karka			COD = 81. BOD = 64. TN = 61. NH$_4$ = 82.5		
		Unplanted			COD = 89.4. BOD = 64. TN = 40.3. NH$_4$ = 62.7		
Domestic	Gravel (20-30 mm)	P. karka	26	7	NO$_3$-N = 58.3%. PO$_4$-P = 65.3%		Kassa and Mengistu, 2014
		P. Cyprus			NO$_3$-N = 56.4%. PO$_4$-P = 50.2%		
		Unplanted			NO$_3$-N = 36.1%. PO$_4$-P = 50.2%		
Domestic	Gravel (8-16 mm)	P. australis	18	6	BOD$_5$ = 82. TSS = 78.3. TN = 27		Ayano, 2013
		Unplanted	18	6	BOD$_5$ = 82. TSS = 78.3. TN = 27		

Jehovah Witnesses Branch Office (JWBO) full scale HSSFCW performance was evaluated by Birhanu (2007) and the result showed average removal efficiency of the constructed wetland system for BOD5, COD, TSS, ammonium, nitrate, total nitrogen, orthophosphate, total phosphorus, sulfate, sulfide and total coliform was 99.3%, 89%, 85%, 28.1%, 64%, 61.5%, 28%, 22.7%, 77.3%, 99% and 94.5%, respectively. The individual cells removal efficiency indicated that the wetland planted with Cyprus papyrus showed higher removal efficiency for nitrate (82.4%), ammonium (24.8%), total nitrogen (54.8%), orthophosphate (23.5%), and total suspended solids (83.9%) as compared to the other wetland systems. In the same regard, wetland cells planted with Phoenix canariensis showed higher removal efficiency for total phosphorus (17%), sulfide (99%), BOD5 (98%), COD (90%) and total coliform (94%). Whereas, the other wetland cells planted with Cyprus alternifolia showed higher removal efficiency only for sulfate ion (82.2%). The performance efficiency results indicated that, this wetland system has excellent removal capability for BOD5, COD, TSS, sulfate, sulfide and total coliform bacteria. However, since the HRT of the constructed wetland system (2.16

days), the nutrient (nitrogen and phosphorus) removal efficiency was low. The organic matter removal efficiency of JWBO CW investigated by Brhanu (2007) was similar to that of the study done in the USA: i.e., BOD5 (93%) (USEPA, 1993); in Kenya: BOD5 (98%), COD (96%) and TSS (85%) (Nyakango, 1999); in Northern Alabama: BOD5 (85%) (Kathleen, 2000); and in Italy: COD (93%) and TSS (81%) (Pucci, 2000). The higher removal of the planted treatment beds may be due to a combined biochemical reaction mechanism favored by plants, substrates and microorganisms. The most important effects of the macrophytes in relation to the wastewater treatment processes are the physical effects of the plant tissues that give rise to filtration effect and provide surface area for attached microorganisms. In addition to this, the media and macrophytes roots in SSF may provide a greater number of small surfaces, pores, and crevices which create the opportunity for the availability of a vast number of organic matter utilizing microorganisms adapted to the aerobic and anaerobic environment of wetland ecosystems which facilitate the organic matter removal process of CW more effectively (USEPA, 1993; Michael, 2006). On the other hand, the effectiveness may be associated with the presence of easily biodegradable organic matters in domestic wastewater by biological decomposition process within a short HRT (Reddy, 1991). According to Ayano' (2013) demonstration on the performance efficiency of horizontal subsurface flow constructed wetland at deferent depth with the same media type (gravel, 8-16 mm), wetland area and different hydraulic loading rate of 18 L/m^2/day and 36 L/m^2/day for depths 25 cm and 50 cm in planted and unplanted conditions, showed no significant difference in removal of pollutants at the same HLR. The removal of BOD5 and TSS were not different between planted and unplanted beds. However, areal and volumetric rates for planted beds were significantly greater than the unplanted beds for TKN. Unplanted beds may be more anaerobic than planted beds to favor reducing bacteria. Garcia et al. (2004) reported that the removal of HSSFCW increased with decreasing depth and attributed high oxidation reduction potential which is responsible for increasing nitrification. The result showed that constructed wetlands are successful in removal of nutrients from domestic wastewater.

Heavy metal removal efficiency of HSSFCW

The toxicity nature of most heavy metals

Recently there has been an increase in the river pollution trend in Addis Ababa and other cities, due to the discharge of untreated wastewater from the industries and municipal wastes. Constructed wetlands have a good potential for the removal of heavy metals from wastewater (Sahu, 2014). According to Sahu report, the horizontal subsurface flow constructed wetland reduced the concentration of Hg, Cr, Fe and Ni from the initial concentrations by 43%, 54%, 46% and 49%, respectively. The potential heavy metal remediation of HSSFCW planted with Phragmites australis was investigated by Bahre (2013) and achieved high removal efficiency of 99.33%, 93.67%, 89.24%, 96.14% and 98.33%, respectively for Fe, Mn, Pb, Cu and Zn at hydraulic loading rate of 22 L d^{-1} and hydraulic retention time of 28th days. In the same regard, the unplanted unit showed removal efficiency of 98.43%, 91.66%, 85.01%, 90.70% and 85.19% for Fe, Mn, Pb, Cu and Zn, respectively at the same conditions. The result indicates that uptake on roots for Pb and Cu was higher than the uptakes by plant leaves and stems. The soil media heavy metals accumulation also showed the highest adsorption capacity for the analyzed heavy metals from the planted and control systems.

This demonstrates that horizontal subsurface flow constructed wetland planted with Phragmites australis and red ash gravel can remove heavy metals from leachate.

This result is similar to the reported metal removal efficiency of subsurface flow constructed planted with S globulosus and E. sexangulare in treating leachates, which were 81.33% and 94.19%, respectively for Cu and Pb; while 86.91% and 95.88% removal in E. sexangular, respectively for Cu and Pb (Mohamed and Baskar, 2018). This finding also agrees with the result of Refidah (2002) who reported the removal efficiency of surface flow constructed planted with S. sumantresisana in treating leachate; which was 89%, 90% and 89%, respectively for Fe, Zn and Mn. The analysis of results showed that up to 99.3% of chromium was reduced from tannery wastewater for an inlet average Cr loading rate of 40 mg/L (Amenu, 2015). Similar values were reported by Terfie and Assfaw (2014) of total chromium in HSSFCW beds. The plant parts analysis on the accumulation of chromium showed similar results, more Cr was accumulated in root parts of the plants than in the shoot. This indicates that constructed wetland is a cost effective and environmentally friendly treatment method in removal of not only organic maters, nutrients and pathogens, but also heavy metals, and hence it can be used as an alternative treatment method for developing countries (*Table 6*).

Table 6. *Heavy metal removal efficiency of HSSFCW in Ethiopia*

Types of waste water	Media type	Plant type	HLR (L/d)	HRT (day)	Removal efficiency (%)	Standards (EEPA, 2000)	Reference
Leachates	Redish gravel (40-80 mm) (15-25 mm)	P. australis	22	28	Fe = 99.33. Mn = 93.6. Pb = 89.24. Cu = 96.14. Zn = 98.33		Bahre, 2008
		Unplanted			Fe = 99.33. Mn = 93.6. Pb = 89.24. Cu = 96.14. Zn = 98.33		
Tannery	Clay (15 cm and gravel 45 cm)	C. alternifolius	120	5	Cr = 35.84	Pb = 0.5 Ni = 2 Cu = 2 Hg = 0.001 Zn = 5 Cr = 2	Terfie and Asfaw, 2014
		T. domingensis			Cr = 48.68		
		B. aerthiopium			Cr = 26.96		
		P. karka			Cr = 30.26		
		Unplanted			Cr = 59.6 for clay, 38.15 for Gravel		
Syntatic	-	-	48.6	9	Cr = 51. Ni = 47 Fe = 45. Hg = 43		Sahu, 2014

Heavy metals in plant tissues and substrate media

The probable recognized biological processes for metal removal in wetlands are plant uptake and adsorption on the substrate media. The Pb and Cu uptake ability of P. australis by its roots may be due to the localized properties of the root, mainly predominated rhizofiltration mechanisms to accumulate heavy metals (Zhu et al., 1999). Similarly, Kadlec and Wallace (2009) reported that plants can accumulate higher concentrations of metals in their roots. This may be due to the slow mobility of metal transport from the root to shoot. In the same case, substrate media is also one of the important factors for the removal of heavy metals. *Figures 10* and *11* indicate the role of substrate media for Pb and Cu removal from leachate. However, the retention time and the type of media have an effect on the treatment of wetland (Knox et al., 2004). Since media provides a viable

condition for maximum removal of pollutants, due to its diverse treatment mechanisms including sedimentation, adsorption, precipitation and microbial interaction (USEPA, 1993). In general, the control HSSFCW showed the higher removal efficiency of Pb and Cu than the planted wetland. Similar finding was observed in the removal of chromium from tannery wastewater (Terfie and Assfaw, 2014). This may be due to chemical precipitation and sorption of metals on substrate media.
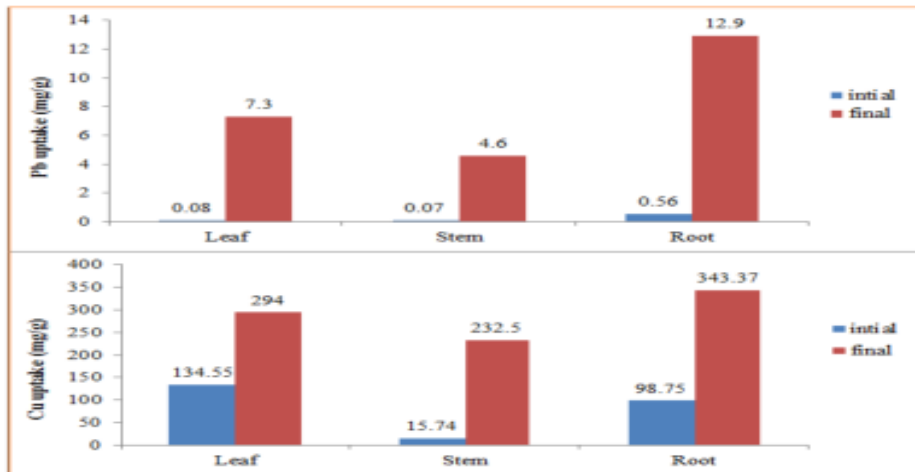

Figure 10. Pb and Cu uptake of different parts of P. australis in CW (Knox et al., 2004)
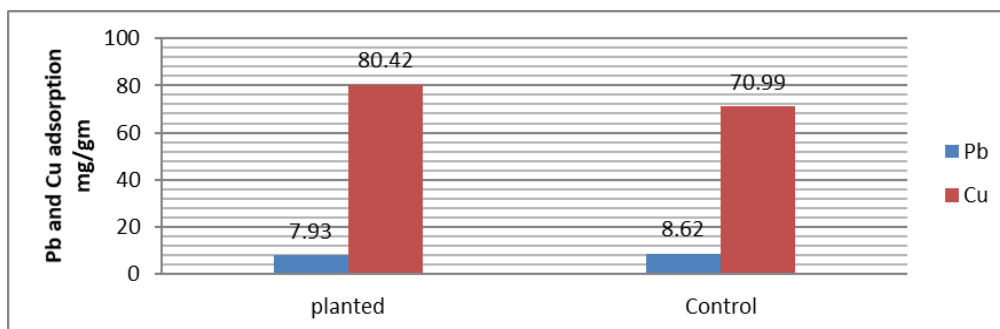

Figure 11. Pb and Cu adsorption in planted and control CW beds (substrate media, red ash gravel) (Knox et al., 2004)

Terfie and Assfaw (2014) investigation data indicates clearly the fate of total chromium in the horizontal subsurface flow constructed wetland (*Fig. 12a*). Whereas Kassa and Mengistou (2014) investigated data on the fate of total phosphorus is under question mark, where the fate of TP is in a constructed wetland (*Fig. 12b*).

However, the removal efficiency of heavy metals is dependent on the HRT, flow rate (Q) and pH. Sahu (2014) determined the effect of HRT on the reduction of different heavy metals. The treatment efficiency was observed increased as HRT increases from 1 to 7 days at a flow rate of 8 cm^3/min (*Fig. 13*). As *Fig. 13* showed the maximum removal of 54%, 49%, 46% and 43% were obtained respectively for Cr, Ni, Fe and Hg at 7 days HRT. The effect of HRT on the removal of heavy metals was also determined by Bahre (2013) and presented in *Figure 14*.

Engida et al.: Review paper on horizontal subsurface flow constructed wetlands: potential for their use in climate change mitigation
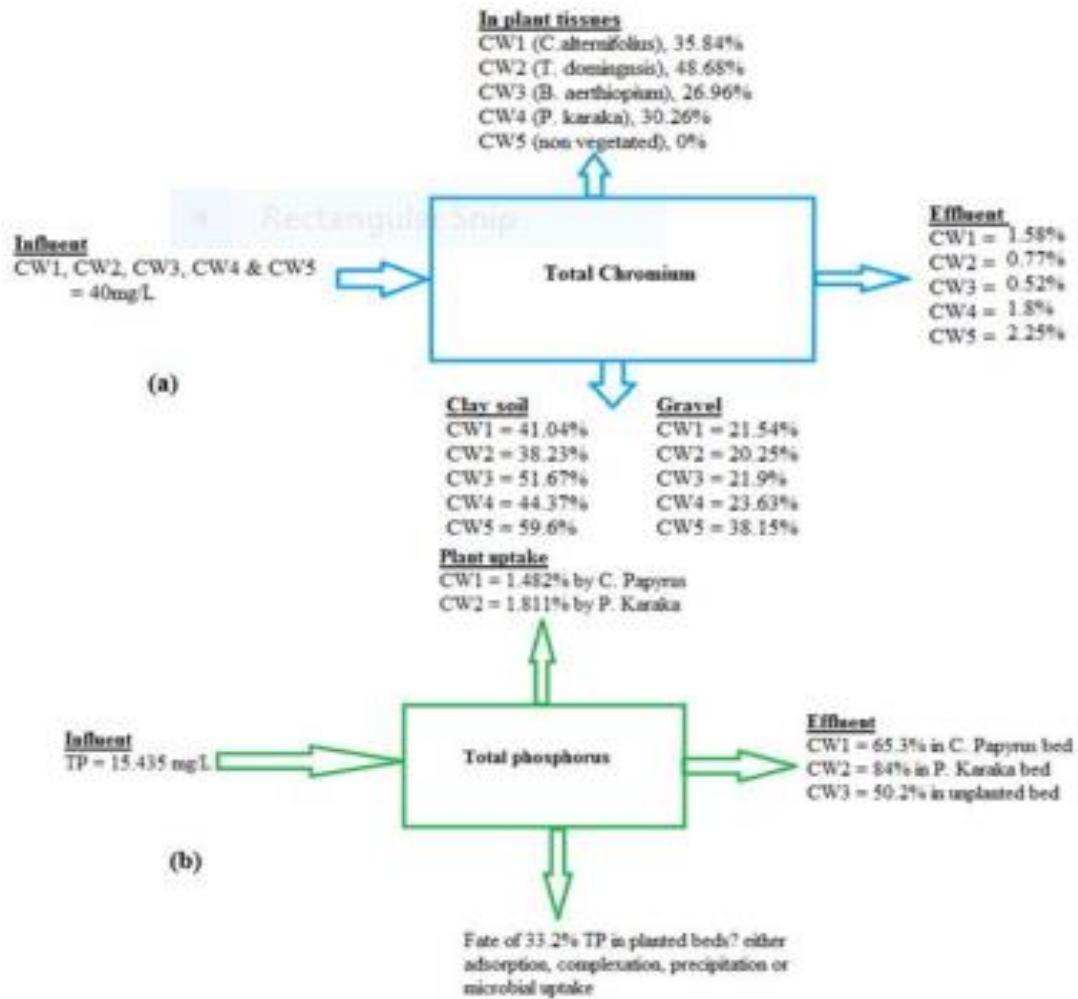and treatment of wastewater
- 1073 -

Figure 12. a *Mass balance of chromium.* **b** *Mass balance of TP in HSSFCWs (Kassa and Mengistou, 2014)*
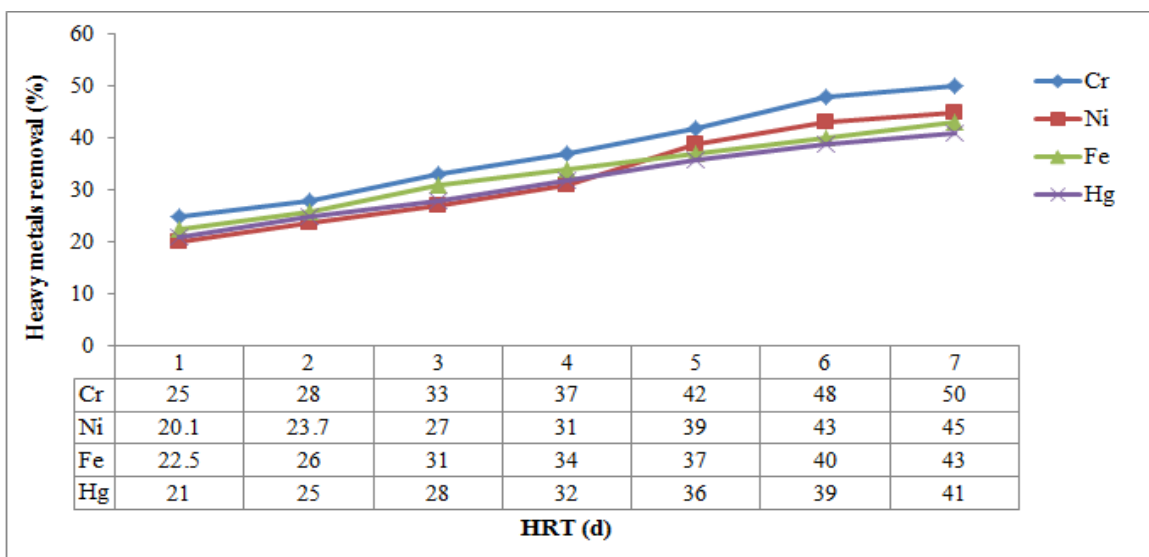
Figure 13. *Effect of HRT on heavy metals removal from HSSFCW (Bahre, 2013)*

Engida et al.: Review paper on horizontal subsurface flow constructed wetlands: potential for their use in climate change mitigation
and treatment of wastewater
- 1074 -

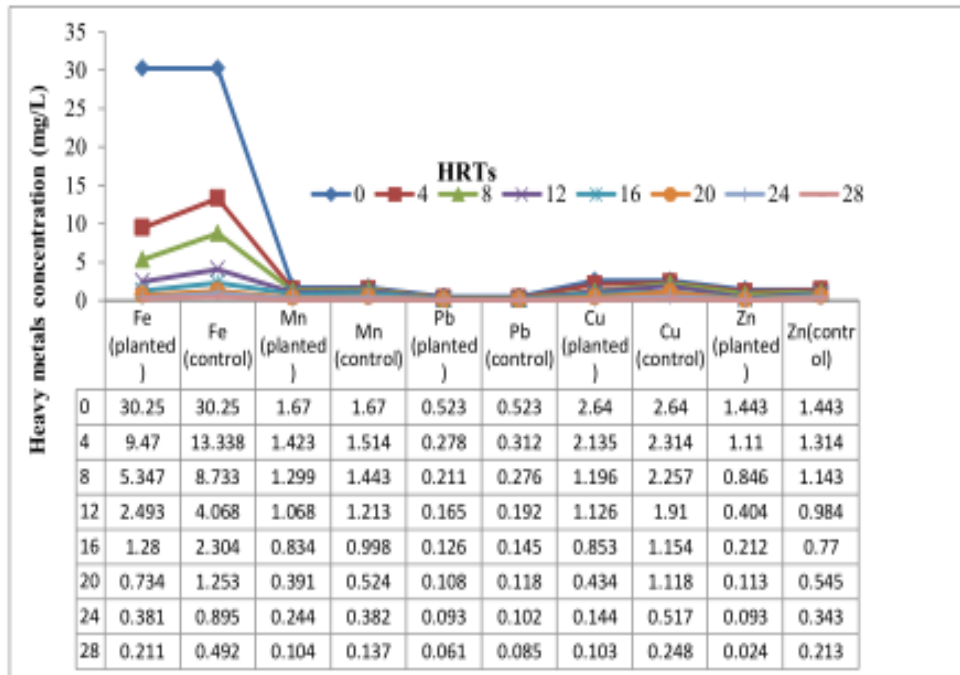|	Fe (planted)	Fe (control)	Mn (planted)	Mn (control)	Pb (planted)	Pb (control)	Cu (planted)	Cu (control)	Zn (planted)	Zn (control)
0	30.25	30.25	1.67	1.67	0.523	0.523	2.64	2.64	1.443	1.443
4	9.47	13.338	1.423	1.514	0.278	0.312	2.135	2.314	1.11	1.314
8	5.347	8.733	1.299	1.443	0.211	0.276	1.196	2.257	0.846	1.143
12	2.493	4.068	1.068	1.213	0.165	0.192	1.126	1.91	0.404	0.984
16	1.28	2.304	0.834	0.998	0.126	0.145	0.853	1.154	0.212	0.77
20	0.734	1.253	0.391	0.524	0.108	0.118	0.434	1.118	0.113	0.545
24	0.381	0.895	0.244	0.382	0.093	0.102	0.144	0.517	0.093	0.343
28	0.211	0.492	0.104	0.137	0.061	0.085	0.103	0.248	0.024	0.213

Figure 14. Effect of vegetation and HRT on the removal efficiency of heavy metals (Bahre, 2013)

Factors affecting the performance efficiency of constructed wetlands

Vegetation and HRT

The TSS removal efficiency of planted and unplanted constructed wetland at different HRT was significantly different. The initial TSS concentration was 106 mg/L. Some while after treatment under CW were reduced to 35.4 and 19.7 mg/L at 2 and 4 days HRT with a removal efficiency of 66.7% and 81.5%, respectively in the vegetated one. Whereas, for the unplanted CW, TSS were reduced to 62.3 and 49.8 mg/L for 2 and 4 days HRT with total removal efficiency of 41.5% and 53.2%, respectively. The planted CW had higher results in TSS removal than the unplanted one (*Fig. 15*). Increase of HRT resulted in better TSS removal efficiency even for the non-vegetated CW. The efficiency of BOD5 removal was 52% and 73.4% at HRT of 2 and 4 days in the planted beds. Constructed wetland without plantation removed only 20-35% BOD5 from the influent.

Constructed wetland planted with Canna indica L. gave higher BOD$_5$ removal efficiency than non-vegetated CW. The BOD5 removal also increased at higher HRT (i.e., almost half BOD5 removed at 4 days HRT) than shorter HRT (i.e. 2 days HRT). TKN removal in the vegetated CW also gave the maximum removal efficiency compared to the non-vegetated CW. This removal efficiency of TKN may be associated with addition of plant activity. CW planted with Canna indica L. removed TKN for 45.3% for 2 days HRT and 69.6% for 4 days HRT. TKN removal efficiency had increased at increasing HRT (Panrare et al., 2015). This TKN removal of the CW technique may be due to volatilization, plant uptake and bacterial assimilation (Vymazal, 2007). The vegetated CW at 4HRT also gave the highest phosphate removal efficiency (77.7%). This phosphate removal in CW could be normally by plant and bacterial uptake, adsorption at the media and sedimentation. The effect of vegetation and HRT on the performance efficiency of constructed wetland is indicated in *Figure 15*.
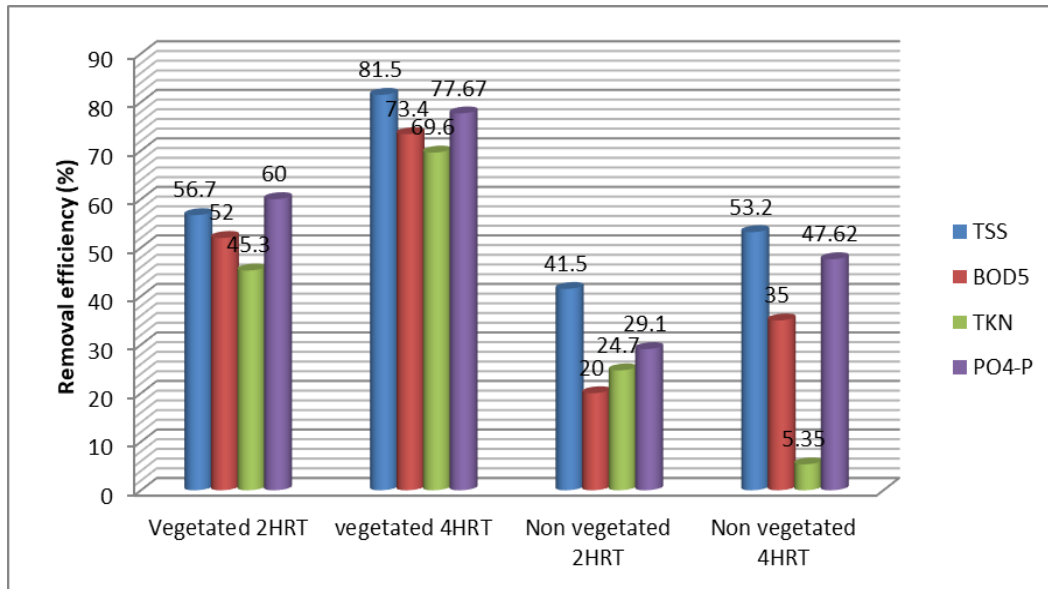
Engida et al.: Review paper on horizontal subsurface flow constructed wetlands: potential for their use in climate change mitigation
and treatment of wastewater
- 1075 -

Figure 15. *Effect of vegetation and HRT on pollutant removal efficiency of CW*

Plant species

Plants used in constructed wetlands play a major role in absorbing nutrients from wastewater. Some of the most important plant species with nutrient absorbing ability is summarized in *Table 7*.

Table 7. *Nutrient absorption capacity of macrophytes (Brix, 1994)*

Media type		*Cyperus alternifolus*	*Typha latifolia*	*Eichornia crassipes*	*Pistia stratoites*	*Potamogeton pectinatus*	*Certophylum demersum*
Absorption capacity kg/ha/h	N	1100	1000	2400	900	500	100
	P	50	180	350	40	40	10

Media type

The level of permeability and hydraulic conductivity of the media is very influential on the retention time of wastewater, in which the retention time is enough to give a chance to contact between microorganisms in wastewater and oxygen released by plant roots. The main function of the media in the constructed wetland is to provide places for plants to grow, microbial attachment for pollutant transformation process, and nutrient absorption (Dadan, 2016). The performance of subsurface flow constructed wetland based treatment can be shown in *Table 8*.

Microorganisms

Preferably heterotrophic aerobic microorganisms are present due to faster processing ability than anaerobic types. The oxygen content in the media will be supplied by plant roots, which is a byproduct of the process of photosynthesis of plants with the help of sunlight (Dadan et al., 2016).

Engida et al.: Review paper on horizontal subsurface flow constructed wetlands: potential for their use in climate change mitigation
and treatment of wastewater
- 1076 -

Temperature

The temperature of wastewater affects the activity of microorganisms and plants, furthermore it will affect the performance of processing (Dadan et al., 2016).

Table 8. Performance of SSFCW media (Khiatuddin, 2003)

Media type		Gravel	Soil	Sand	Clay
Percentage of removal efficiency (%)	BOD	55-96	62_85	96	92
	SS	51_98	49_85	94	91
	Coloforms	99	-	100	

Constructed wetland as climate change mitigation

Constructed wetlands are increasingly widespread for wastewater treatment in small communities and households where in addition to the fundamental purifying function, they also have decorative function that imposes the choice of plants characterized by high functional, amenity, and aesthetic values (Ghermandi et al., 2010). Constructed wetlands carbon cycles contribute to the global greenhouse gases (GHGs) balance through their CO_2 and CH_4 emissions. In particular, they can act as CO_2 sinks by photosynthetic CO_2 assimilation from the atmosphere or as a source of CO_2 through bed respiration (Barbera et al., 2009) and organic matter decomposition (Brix et al., 2001). The rate of carbon decomposition in constructed wetlands depends on the redox chemistry of the soil, the bioavailability of organic carbon and temperature. For example, in summer season, oxygen diffusion to the topsoil can reduce methanogenesis and stimulate methane oxidation (Grünfeld and Brix, 1999). However, an increase in temperature can decrease dissolved oxygen in deeper subsoil and enhance methane production. All biochemical reactions increase as temperature increases C and N turnover in constructed wetlands causing high variations in GHG emissions in different regions. Due to this more data and investigation are needed on constructed wetland types for better extrapolation of GHG emissions. Hence, organizing more information on nutrient removal efficiency and GHG emissions across CW in different CW types is necessary for better management. Emissions of GHG in CWs can vary across CW types, e.g., surface flow or subsurface flow (*Tables 9* and *10*).

Generally, methane emissions are higher in surface flow CWs (SFCWs) than subsurface flow constructed wetlands (*Table 9*), but may vary with season. Nitrous oxide and carbon dioxide emissions are higher in VSSFCWs than in HSSFCWs and SFCWs. Aquatic plants play an important role in GHG production and transport to the atmosphere by releasing GHG through their interconnected internal gas lacunas. Emergent plants can transport atmospheric oxygen to the rooting zone and contribute to increase the N_2O and CO_2 production and methane consumption (Brix, 1989). Release of low molecular weight organic matter that is labile in nature is more likely to produce GHGs than stable forms. A fluctuating water table in CWs has significant impacts on GHG dynamics (Mander, 2011). In aerobic and anaerobic conditions, incomplete nitrification and denitrification increase N_2O emissions (Healy et al., 2007). In general, assessment of GHG emissions in various types of CWs which are vegetated or unvegetated *is necessary in the light of the national and global GHG budgets.*

Engida et al.: Review paper on horizontal subsurface flow constructed wetlands: potential for their use in climate change mitigation
and treatment of wastewater
- 1077 -

Table 9. Nitrous oxide emission from various CW types (m g m^{-2} d^{-1})

CW type	Type of WW	N$_2$O emission (m g m^{-2} d^{-1})	Reference
Surface flow	Municipal	2	Johansson, 2003
SF	Dairy	16.8	Van der Zaag, 2010
SF	Municipal	0.01	Søvik, 2006
SF	Agri runoff	0.4	Søvik, 2006
SF	Municipal	4	Søvik, 2006
All SF		4.642	
Horizontal sub surface flow	Domestic	8.6	Mander, 2005
HSSF	Municipal	7.1	Søvik, 2006
HSSF	Domestic	0.17	Liu et al., 2009
HSSF	Dairy	9.5	Van der Zaag, 2010)
HSSF	Domestic	0.17	Mander, 2011
All HSSF		5.108	
Vertical sub surface flow	Domestic	4.6	Mander, 2008
VSSF	Domestic	11	Mander, 2005
VSSF	Domestic	1.44	Mander, 2011
VSSF	Domestic	0.005	Gui et al., 2007
VSSF	Municipal	15	Søvik, 2006
All VSSF		6.409	

Table 10. Carbon dioxide and methane emission from various CW types (m g m^{-2} d^{-1})

CW type	Type of WW	CO$_2$ emission	CH$_4$ emission	Reference
SF	Dairy	4250	223	Van der Zaag, 2010
SF	Municipal	1200	29	Søvik, 2006
SF	Agri runoff	3200	350	Søvik, 2006
SF	Municipal	1400	72	Søvik, 2006
ALL SF		2512.5	168.5	
HSSF	Domestic	5.33	0.001	Garcia, 2005
HSSF	Dairy	3475	118	Van der Zaag, 2010
HSSF	Domestic	600	0.48	Mander, 2011
HSSF	Municipal	3800	340	Søvik, 2006
ALL HSSF		1970.1	114.6	
VSSF	Municipal	2662	33.5	Mander, 2008
VSSF	Domestic	1080	3.36	Mander, 2011
VSSF	Municipal	8400	110	Søvik, 2006
VSSF	Municipal	22000	140	Søvik, 2006
ALL VSSF		8535.5	71.72	

Even if constructed wetlands are contributors of GHG, on the other hand, constructed wetlands present an important opportunity for carbon sequestration and greenhouse gas offsets by virtue of their potential for restoration using known and innovative land management methods. Because constructed wetlands are inherently highly productive and accumulate large below-ground stocks of organic carbon. Wetlands are major carbon sinks. While vegetation traps atmospheric carbon dioxide in wetlands and other ecosystems alike, the net-sink of wetlands is attributed to low decomposition rates in anaerobic zones. Recently, constructed wetlands used for wastewater treatment and

Engida et al.: Review paper on horizontal subsurface flow constructed wetlands: potential for their use in climate change mitigation
and treatment of wastewater
- 1078 -

protecting wetland bodies clearly represent an immediate and large opportunity for enhancing carbon sequestration (Kanungo et al., 2017). The percentage of organic carbon (OC%) content of the 15 emergent macrophytes varied between 34.97 to 50.92, 34.98 to 52.04, 34.96 to 52.01 and 34.91 to 50.94. similarly, biomass (g/m ^{2}) ranged from 104 to 687, 16 to 1382, 141 to 1493 and 122 to 635. The carbon sequestration potential (CSP) was determined by multiplying the OC in per gram of dry weight to the biomass of that species (Wang et al., 2011) and the total CSP of all the emergent macrophytes was obtained by the summation of individual CSP of all species. Based on this calculation, the highest CSP was recorded for Typha latifolia followed by Phragmites australis and the lowest for Carexsp. (*Fig. 16*) which exhibited from the highest carbon content of 53.62% which was greater than the 44% value reported by Wang et al. (2011) for Typha orientalis.
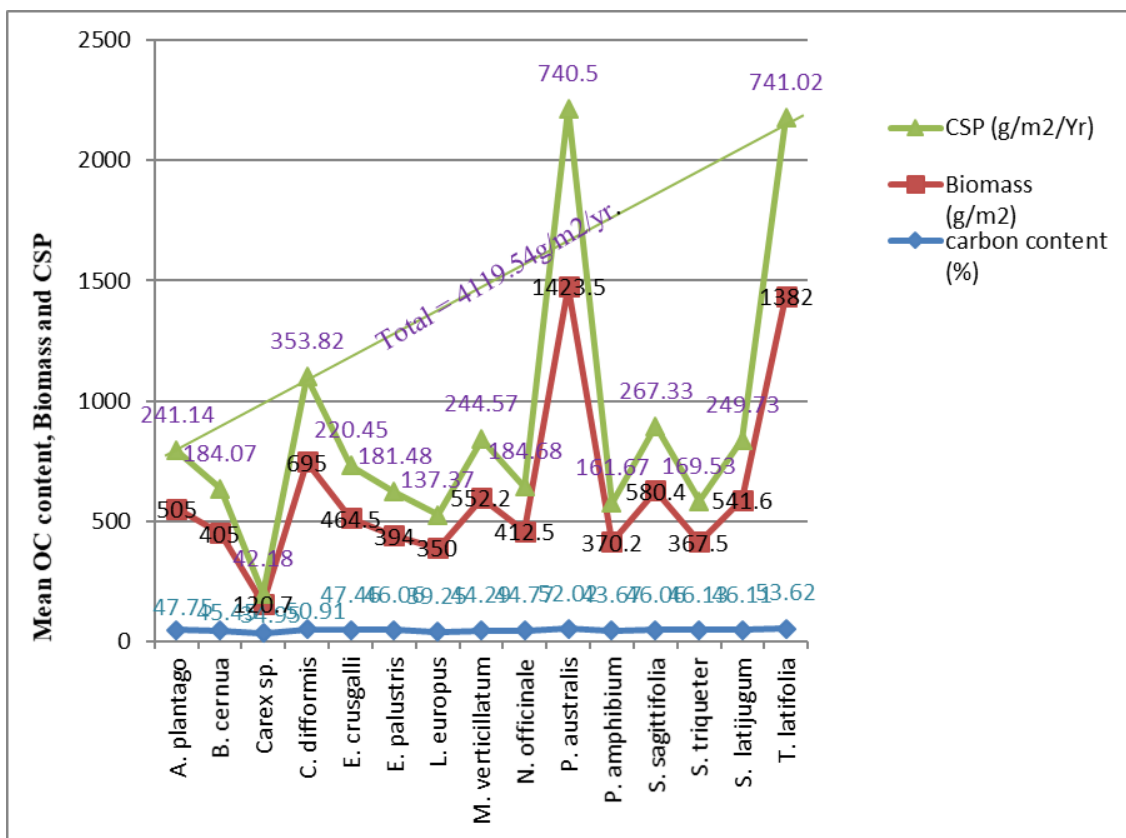

Figure 16. *Mean carbon content, biomass and carbon sequestration of macrophytes (Mitsch et al., 2015)*

Wang also reported 44.7%, 44.1% and 41.8% of carbon for Phragmites communis, Cyprus malaccensis, and Eleocharis dulcis, respectively which is lower than the values of Phragmites australis, Cyperus difformis, and Eleocharis palustris, respectively obtained by Khan and Maqubool (2014). These macrophytes species carbon content and hence their CSP was higher when compared with other reported results for Scirpus lacustris (44.12%), Eleocharis palustris (43%) (Fernández-Aláez et al., 1999); Phragmites australis (29.2%) and Myriophyllum salsugineum (15.8%) (Piola et al., 2008). Furthermore, Costa and Henry (2010) observed the highest carbon content for E.

azurea (43.7%), Myriophyllum aquaticum (43%), Cyperus esculentus (41.6%) and Polygonumspectable (38%). Assuming 4119.54 gC/m^2/yr as the rate of carbon sequestered in each year in this system, the limit for carbon emissions can be calculated to determine the point at which the system offsets carbon emission. To compare the physical sequestration and the gaseous emissions both are converted to carbon dioxide equivalents (CO$_2$e) (Forster et al., 2007). The CO$_2$e allows the comparison of different masses and gases as they relate to their greenhouse warming potential. Methane has 25 times the potential as CO$_2$. Each gram of carbon is equivalent to 3.67 g of CO$_2$. The CO$_2$ equivalent of 4119.54 gC/m^2/yr. is 15118.7118 g CO$_2$. The methane equivalent to this amount of carbon sequestration is 604.748472 g/m^2/yr. Constructed wetlands showing methane emission values less than 1,600 kg/ha/yr are considered as potential for carbon sequestration (Kayranli et al., 2010). Based on this argue, the above treatment plant has a carbon sequestration potential.

Constructed wetlands are purposely constructed in order to reduce input of nutrients and organic pollutants to water bodies. When these systems are used for wastewater treatment, microbial processes and gas dynamics are likely to be altered. With increased inputs of nutrients and organic pollutants, there is an increase in greenhouse gases production due to decomposition processes. Constructed wetlands therefore, can be sources of important greenhouse gases. The average CH$_4$, N$_2$O and CO$_2$ fluxes for surface flow constructed wetland were 2.9, 1.05, and 15.2 mg/m^2/h, respectively. Whereas the average higher fluxes were found from free water surface constructed wetland with average CH$_4$, N$_2$O and CO$_2$ fluxes at 5.9, 1.8, and 29.6 mg/m^2/h, respectively, corresponding to the average global warming potential (GWP) of 392 mg CO$_2$ equivalents/m^2/h and 698 mg CO$_2$ equivalents/m^2/h, respectively for SSFCW and FWSCW (*Fig. 17*) (Chuersuwan et al., 2014).
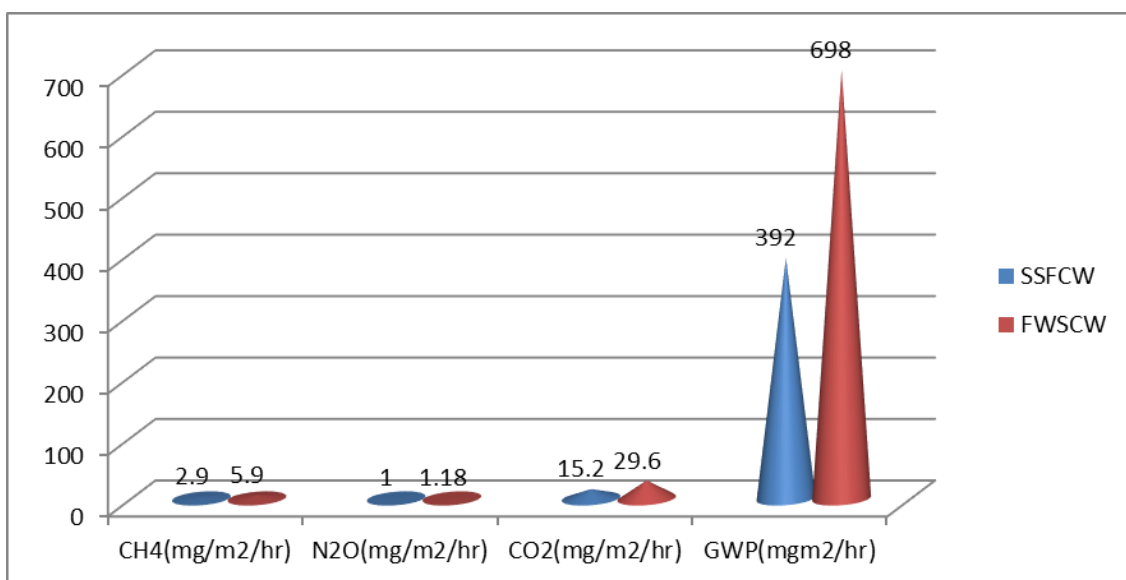

Figure 17. Comparison of greenhouse gas emissions and GWP of free water and subsurface flow CWs (Chuersuwan et al., 2014)

In another study by Maucieri et al. (2014), the comparison of vegetated and unvegetated horizontal subsurface flow constructed wetland effect on the CO$_2$ (eq)

Engida et al.: Review paper on horizontal subsurface flow constructed wetlands: potential for their use in climate change mitigation
and treatment of wastewater
- 1080 -

balance showed a significant difference. The average CO_2 emission of the whole monitored period were 15.5, 15.1, and 3.6 g m^{-2} d^{-1} for Arundox donax L. Phragmites australis and unvegetated beds, respectively. Whereas, cumulative estimated CH_4 emissions during the study period were 159.5, 134.1 and 114.5 g m^{-2} d^{-1} for A. donax, P. australis and unvegetated beds, respectively. CO_2 (eq) balance showed that the two vegetated beds act as CO_2 (eq) sinks, while the unvegetated bed act as CO_2 (eq) source. Considering only the above-ground plant biomass in the CO_2 (eq) budgets, P. australis and A. donax determined uptakes of 1.3 and 8.35 kg CO_2 m^{-2} d^{-1}, respectively, and generally the plant biomass carbon content and the bed biomass yield in the vegetated cell fixed 11.61 and 27.03 kgCO_2 (eq) m^{-2} d^{-1}, respectively for P. australis and A. donax, showing a positive balance, while the unvegetated bed had a negative balance (*Fig. 18*). Carbon dioxide and methane emissions and carbon budgets in a horizontal subsurface flow pilot constructed wetland with vegetated with C. papyrus and Chrysopogon zizanoids Roberty and Mischantus giagnteus, showed higher biomass accumulation in M. giganteus (7.4 kg m^{-2}) followed by C. zizanoids (5.3 kg m^{-2}) and C. papyrus (1.8 kg m^{-2}).
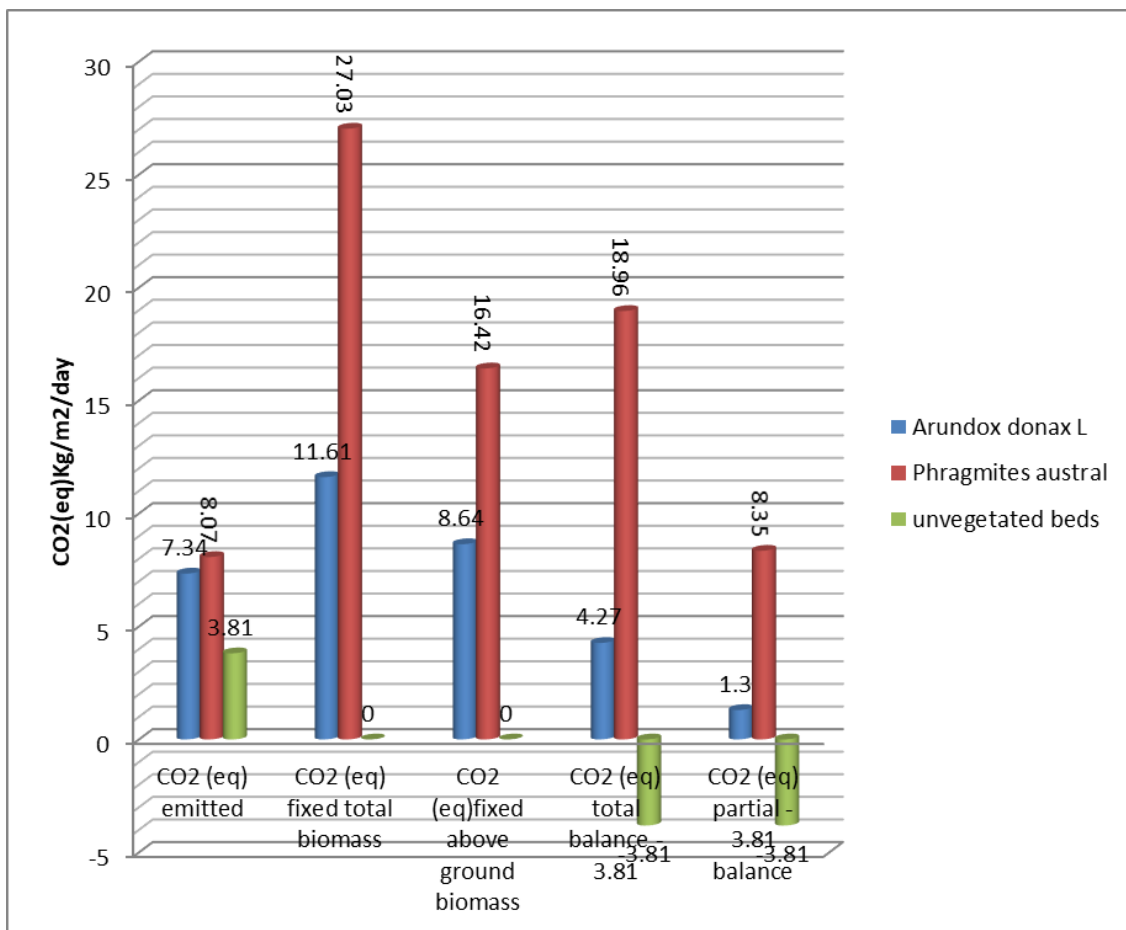

Figure 18. HSSFCW beds carbon dioxide equivalent balance (Maucieri et al., 2014)

The cumulative CO_2 emissions by C. papyrus and C. zizanoids during the 1-year monitoring period showed similar trends with final volumes of about 775 and 1074 g m^{-2}, respectively, whereas M. giganteus emitted 3,395 g m^{-2}. Cumulative methane emission

Engida et al.: Review paper on horizontal subsurface flow constructed wetlands: potential for their use in climate change mitigation
and treatment of wastewater
- 1081 -

showed the greatest methane emission for C. zizanoids bed with 240.3 g m^{-2} followed by C. papyrus (12 g m^{-2}) and M. giganteus. The organic carbon abatement determined the carbon flux in the atmosphere. Gas fluxes were influenced both by plant species and monitored months with average carbon emitted to carbon removed ratio for C. zizanoids, C. papyrus and M. giganteus of 0.3, 0.5 and 0.9, respectively. The growing season carbon balances were positive for all vegetated beds with the highest carbon sequestered in the bed with M. giganteus (4.26 kg m^{-2}) followed by C. zizanoids (3.78 kg m^{-2}) and C. papyrus (1.89 kg m^{-2}) in *Figure 19*.
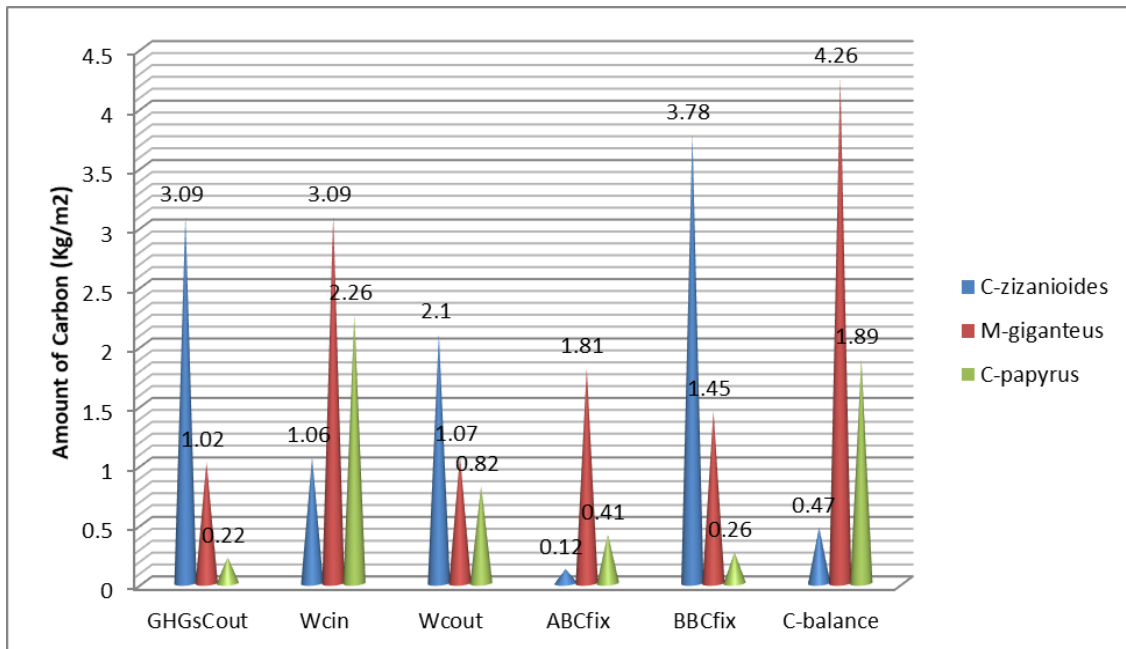

Figure 19. Carbon balance in HSSFCW

Conclusion

The reviewed results showed that the HSSFCWs perform good removal efficiencies for organic matter and SS under low C:N:P loading conditions. Nowadays, the strategies of treating domestic and municipal wastewaters by decentralized way become common in rural and urban areas using constructed wetland technologies. Besides this, constructed wetlands are accepted as a reliable wastewater technology as post treatment of effluents. Because they are low cost, easily operated and maintained and have a strong prospective for application in developing countries.

Most research investigation results revealed that use of a subsurface horizontal flow phytoremediation treatment system is a promising natural technology in the treatment of municipal or industrial wastewater. Because, CW treatment system was found to comply with WHO (1989) standards for treated effluent reuse. Globally, the following abatement efficiencies were achieved by HSSFCW treatment system: 98%, 96%, 85%, 90%, 92%, 88% for BOD5, COD, TSS, TN, NH$_4$–N, PO$_4^{3-}$, respectively in Kenya; 98.46% and 98.55% for COD and BOD5 in Indonesia; and ranges from 94-99.9%, 91.7-97.9% and 99.99% for BOD$_5$, COD and TFC, respectively in Costa Rica. Whereas in Ethiopia, the HSSFCW achieved the following abatement efficiencies: COD ranges from 58 to 80%, BOD ranges from 66 to 77%, TKN ranges from 46 to 61%, sulfates ranges from 53 to

Engida et al.: Review paper on horizontal subsurface flow constructed wetlands: potential for their use in climate change mitigation
and treatment of wastewater
- 1082 -

82%, and NH_4–N ranges from 64 to 82.5% for tannery wastewater treatment. For domestic wastewater treatment; 99.3%, 89%, 855, 84.05%, 77.3%, 99% and 94.5% were determined for BOD_5, COD, TSS, TN, PO_4^3-TP, Sulfate, and TFC, respectively.

The pollutant removal efficiencies and greenhouse gas emissions from the CWs increased with the rise in temperature. The HSSF CWs had the highest tendency to emit CH_4 and thus global warming potential of CWs, and the combined CWs by way of contrast showed low global warming potential. Due to the climate demonstrative of CW and periodic changes, further study to observe the seasonal fluctuations of CH_4 and N_2O emission is necessary. CWs have been found to be potential sinks of Carbon in terms of organic carbon. We face several significant questions regarding the potential for carbon sequestration in wetlands. Constructed wetlands can be managed as net carbon sinks over time. From the Reviewed results point of view, the net carbon gain and the biomass was comparatively higher, carbon storage in biomass and reduced CO_2 emissions. For example, the City of Arcata sequesters carbon in all three treatment units at a rate equivalent of 80,000 kg CO_2/yr. Most research investigation results revealed that horizontal subsurface flow constructed wetlands have been successfully employed to abate key contaminants from wastewater and able to meet the required standard discharge limits.

However, constructed wetland performance efficiency sustainability is affected by the operational conditions of HSSFCW including plant species, media/substrate types, water depth, hydraulic loading, and hydraulic retention time and feeding mode. Though the Total Carbon value at the CW is particularly beneficial for the growth of emergent macrophyte. CWs can be used to treat the wastewater from an industry or community development and also provide an additional benefit as green belts around the industries or the community development. By adopting these Biological CW treatment systems, we can not only achieve our plan of carbon emission reduction but also generate huge amount of savings and earn carbon credits too to ensure a Clean Development Mechanism.

Recommendations

In this paper, encouraging reviewed results were obtained on the role of HSSF CWs on the performance of climate mitigation and wastewater treatment. Based on this review, recommendations for the educational community and user of the technology are suggested. In order to obtain refined results for further long-term research on the performance of the wetlands with respect to all parameters using advanced sized wetland is essential. Besides, further analysis of carbon sequestration potential for climate mitigation and nitrification potential using the HSSF constructed wetlands is recommended for better results. For the user of the technology it can be chosen for application and their construction cost is evidently cheaper. However, evapotranspiration was peak and overstated during dry seasons in planted beds. Furthermore; it is worthwhile to use HSSFCW as one part of the treatment system to reduce GHG emission effect and infection before applying wastewater to recycle in irrigation.

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