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Constructed wetlands: an approach for wastewater treatment

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ABSTRACT

Constructed wetlands (CWs) have a great potential for the treatment of wastewater. These systems consist of beds or channels which have been planted with helophytes (water loving plants), which rely upon physical, chemical and biological processes to remove contaminants from wastewater. CWs are generally classified into two categories: surface-flow and subsurface-flow. Both the systems are capable of removing nitrogen, phosphorus, biochemical oxygen demand, chemical oxygen demand, total suspended solids, metals and pathogens from different types of domestic and industrial wastewaters. This paper provides a review of the mechanism of removal of contaminants from wastewaters in the root zone of constructed wetlands which includes both aerobic and anaerobic microbiological conversions, sedimentation, mineralization, chemical transformations, physicochemical adsorption, chemical precipitation and ion exchange. This technology act as a natural and low cost treatment facility for wastewaters of different origin.

Introduction

Constructed wetlands (CWs) are simple and low cost wastewater treatment systems that use natural processes utilizing shallow (usually less than 1 m deep) beds or channels, helophytes, substrate (soil, sand and gravels) and a variety of microorganisms to improve wastewater quality (EPA, 2004). CWs are capable to reduce contaminants including inorganic matter, organic matter, toxic compounds, metals and pathogens from different wastewaters. Reduction or removal of contaminants is accomplished by diverse treatment mechanisms including sedimentation, filtration, chemical precipitation, adsorption, microbial interactions and uptake or transformation by helophytes (Watson et al., 1989). All these processes takes place simultaneously and are difficult to understand. Incoming nutrients support the growth of helophytes, which convert the inorganic chemicals into organic materials and forms the basis of CW food chain (Brix, 1993). Microorganism's play a main role in biochemical transformation of contaminants (Hoppe et al., 1988; Madigan et al., 1997) and their capability in removing toxic organic compounds added to wetlands has been reported (Pitter and Chudoba, 1990; Kadlec and Knight, 1996; Reddy and D'Angelo, 1997; Suyama et al., 1998; Kivaisi, 2001). CWs are less expensive and have low maintenance cost than traditional wastewater treatment systems. Additionally these systems have more aesthetic appearance than traditional wastewater treatment systems (Kadlec et al., 2000; Haberl et al., 2003; Langergraber, 2008). On the basis of wastewater flow, the CWs are subdivided into two types: (i) surface flow (SF) or free water surface flow wetlands, in which wastewater is flowing horizontally over the wetland substrate. A wide variety of submerged and floating plants have been used in SF CWs (ii) sub-surface flow (SSF), in which the wastewater flows horizontally or vertically through highly permeable substrate (gravel, rock or soil). The plant species generally used in SSF CWs includes common reed (Phragmitis australis), cattail (Typha spps.), bulrush (schoenoplestus) and canna indica. The treatment efficiency of these systems mainly depends on the wetland design, hydraulic loading rate (HLR), type of contaminant, microbial interactions and the climatic factors. For best treatment efficiency these systems require a low hydraulic loading rate and a long hydraulic retention time.

In the last several decades, these systems have been constructed to treat the wastewaters originated from different sources for quality improvement. CWs are used for treating various wastewater types i.e. domestic wastewater (Cooper et al.,1997), acid mine drainage (Kleinmann and Girts, 1987), agricultural wastewaters (DuBowry and Reves,1994; Rivera et al., 1997), landfill leachate (Masbough et al., 2005), urban storm-water (EPA,1995) and industrial wastewater including paper and pulp (Abira et al., 2005), food processing (Gasiunas et al. 2005; Mantovi et al. 2007), petrochemical industry (Yang and Hu, 2005) chemical (Sands et al., 2000), textile (Mbuligwe, 2005) and tannery (Calheiros et al., 2007). Both the systems (surface flow and sub-surface flow) are capable of removing nitrogen, phosphorus, biochemical oxygen demand, chemical oxygen demand, suspended solids, metals and pathogens from different types of domestic and industrial wastewaters. In CWs, nitrogen removal efficiency ranges from 25 to 85% depends on the type of system (U.S. EPA, 1988). Sinicrope et al. (1992) and Noller et al. (1994) reported the removal of cadmium, lead, silver and zinc by filtration in CW. The removal efficiency was reported to be 75–99.7% cadmium, 26% lead, 75.9% silver and 66.7% zinc. In Iran, a SSF CW of 150 m2 was tested for treatment of domestic wastewater. At an organic loading of 200 kg/ha/day, the removal efficiencies for COD, BOD, TSS, N, P and fecal coliform bacteria were obtained 86%, 90%, 89%, 34%, 56%, and 99% respectively (Badkoubi, et al.,1998). Wastewater of the pulp and paper industry contains a number of toxic compounds that may cause deleterious environmental impacts upon direct discharge to receiving waters. Some of the compounds known to impart toxicity are chlorinated organic compounds which include; di, tri, tetra chlorophenols, chloroguaiacols, tetrachlorodibenzo-p-dioxins (TCDD) and furans (TCDF) (Xie et al., 2005). It has been observed that these

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toxic organic compounds can be easily degraded by the CW systems to meet increasingly stringent discharge limits. Choudhary et al. (2010) evaluated the effectiveness of subsurface flow constructed wetlands for the treatment of pulp and paper mill effluent.

In this paper, we try to summarize the different physical, chemical and biological interactions that occur in constructed wetlands for the treatment of wastewaters.

Surface flow constructed wetlands

A surface flow (SF) wetland consists of a shallow basin (<1m), soil or other medium to support the roots of helophytes and the water control structure that maintains a shallow depth of water (0.2-0.4 m). In this system wastewater surface is above the substrate as shown in Figure 1. In SF CWs, the near surface layer is aerobic while the deeper waters and substrate are usually anaerobic. Wetlands built to treat mine drainage and agricultural runoff, are usually SF wetlands. These systems are generally used in North America (Reed et al., 1995). The advantages of SF CWs are that their capital and operating costs is low (EPA, 1995; EPA, 2000; DeBusk, 1999) but they generally have a lower contaminant removal efficiency compare to SSF (Lee et al.,2009).

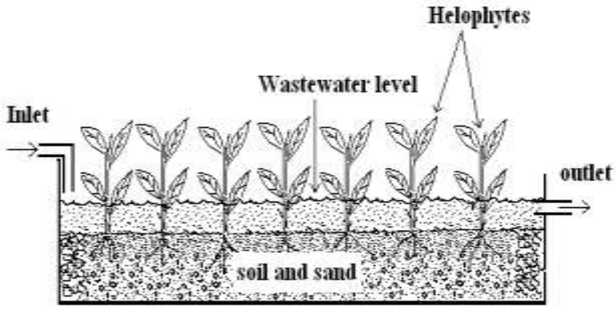

Figure 1: Surface flow constructed wetland

Subsurface flow constructed wetlands

A subsurface flow (SSF) wetland consists of a sealed basin with a porous substrate of rock, gravel and soil or combination of these. The water level is designed to remain below the top of the substrate as show in Figure 2. The wastewater is forced vertically into the sediments by gravity. SSF wetlands have most frequently been used to reduce biochemical oxygen demand, chemical oxygen demand, suspended solids, metals, nitrogen, phosphorus and pathogens from domestic and industrial wastewaters (EPA, 2000; Khatiwada and Polprasert, 1999; Sirianuntapiboon and Jitvimolnimit, 2007). These systems are very popular in Europe and South Africa (Lee et al., 2009). SSF CWs are further subdivided into two types: horizontal flow (HF) and vertical flow (VF), according to the flow direction of wastewater. Recently the combination of horizontal flow and vertical flow CWs has been used, named as hybrid systems, for the wastewater treatment. These hybrid systems act more efficiently to improve wastewater quality. SSF CWs are more efficient on an areal basis as compare to SF systems (Kadlec, 2009).

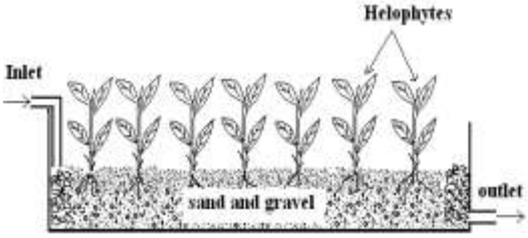

Figure 2: Subsurface flow constructed wetland

Mechanism of treatment

The two main mechanisms operative in most of the CWs are liquid/solid separations and constituent transformations (EPA, 2000). Separations typically include gravity separation, filtration, absorption, adsorption, ion exchange, stripping, and leaching. Transformations may be chemical, including oxidation/reduction reactions, flocculation, acid/ base reactions, precipitation and biochemical reactions occurring under aerobic or anaerobic conditions facilitated by root zone environment. Both separations and transformations may lead to contaminant removal in wetlands. The overall processes taking place in CWs for the removal of contaminants are divided into three categories i.e. physical, chemical and biological which are summarized in the Table 1.

The efficiency of CWs to remove the contaminants from the wastewater mainly depends on the root zone interactions between soil, contaminants, helophyte roots and a variety of microorganisms. The soil is the main supporting material for plant and microbial growth. It was observed that fine gravel promotes greater growth of plants and therefore increases the amount of contaminants removal (Garcia et al., 2005). Helophytes are directly involved in the uptake of nutrients and in direct degradation of pollutants by releasing oxygen in the rote zone. That imparts microbial activity and gives aerobic degradation of pollutants. The main factors which influence the uptake of xenobiotics (organic pollutants) by the plants are the compounds' concentration, physicochemical characteristics such as the octanol–water partition coefficient (log K_{OW}), acidity constant (pKa), etc. (Stottmeister et al., 2003; Wenzel et al., 1999). Sandermann (1992) divides the metabolism of contaminants in plants into three phases i.e. transformation, conjugation and compartmentation. The main characteristic of CWs is that their functions are largely regulated by microorganisms and their metabolism. Microorganisms include bacteria, yeasts, fungi, protozoa and algae. These play a central role in biogeochemical transformation of nutrients (Hoppe et al., 1998; Madigan et al., 1997). It has been reported by several workers that microorganisms are also capable of removing toxic organic compounds by aerobic or anaerobic degradation processes (Pitter and Chudoba, 1990; Kadlec and Knight, 1996, Reddy and D'Angelo, 1997; Suyama et al., 1998). Respiration and fermentation are the major mechanisms by which microorganisms break down organic pollutants into harmless substances such as carbon dioxide (CO_2), nitrogen gas (N_2) and water (H_2O) (Faulwetter et al., 2009). In summary microbial activity (EPA, 2000; Stottmeister et al., 2003):

1. Involved in the recycling of nutrients.
2. Alters the reduction/oxidation conditions of the substrate.
3. Transforms a variety of inorganic and organic compounds.

Some microbial transformations are aerobic (in the presence free oxygen) while others are anaerobic (in the absence of free oxygen). Microbes are capable of degrading most of organic pollutants, but the rate of degradation varies considerably, depending on chemical and structural properties of the organic compound, and the chemical and physical environment in the soil.

Suspended solids removal

Suspended solids removal is very effective in SF constructed wetlands. The predominant physical mechanisms for suspended solids removal are flocculation/ sedimentation and filtration (EPA, 2000; Kadlec, 2009). Suspended matter in wastewater may contain different types of contaminants, such as nutrients, heavy metals and organic compounds (Debusk, 1999). The surface forces are also responsible for the reduction of suspended solids include Vander Waal's force of attractions and electric forces, which may be attractive or repulsive depending on the surface charges (Metcalf and Eddy, 1991).

Nitrogen removal

As we know that high concentration of nitrogen in the domestic and industrial wastewater causes a very serious problem of eutrophication in wastewater receiving bodies. On the other hand a variety of inorganic and organic nitrogen forms that is essential for all living organisms. Nitrogen may be removed from wastewaters by several processes in CWs like adsorption, volatilization, plant adsorption & uptake, ammonification and nitrification-denitrification complex are the most important removal pathways around the root zone. The inorganic forms of nitrogen present in wastewater are ammonium (NH_4^+), nitrite (NO_2^-) and nitrate (NO_3^-). All these inorganic form of nitrogen are significantly removed by the plant uptake at low hydraulic loading rates. In CWs helophytes converts inorganic nitrogen forms into organic compounds that serve as building blocks for cells and tissues. Various helophyte species differ in their favored forms of nitrogen absorbed, depending on the forms available in the substrate (Lambers et al., 1998). Kantawanichkul et al. (2009) have reported an average nitrogen uptake by helophytes of 0.8 ± 0.25 g m^{-2} d^{-1} for *Cyperus* and 0.12 ± 0.06 g m^{-2} d^{-1} for *Typha*. But at higher loading rates the removal of nitrogen mainly depends on the microbial interactions (Tanner et al., 2002). It has been well established that the major process responsible for nitrogen removal during wastewater treatment in wetlands is nitrification-denitrification complex mediated by the microorganisms (Gersberg et al., 1983; Reddy et al., 1989).

Nitrification is the oxidation of ammonium to nitrate mediated by nitrifying bacteria. This process is only operational under aerobic conditions and is divided into two steps: first is the conversion of ammonium to nitrite by *Nitrosomonas* bacteria and second is conversion of nitrite to nitrate by *Nitrobacter* bacteria. In this process the nitrifying bacteria drive energy from the oxidation of ammonia and nitrite while carbon dioxide is used as carbon source (Vymazal, 2007). The overall reactions for these two steps are:

$$NH_4^+ + 1.5O_2 \rightarrow NO_2^- + H_2O + 2H^+ \quad (1)$$

$$NO_2^- + 0.5O_2 \rightarrow NO_3^- \quad (2)$$

Lee et al. (2009) summarizes that nitrification is influenced by temperature, pH value, alkalinity of the water, inorganic carbon source, moisture, microbial population, and concentrations of ammonium-N and dissolved oxygen.

Denitrification is an anaerobic decomposition process in which organic matter is broken down by microorganisms (such as *Pseudomonas, Micrococcus and Bacillus*) using nitrate in stead of oxygen as an electron acceptor. The process occurs in two steps: first nitrate is reduced to nitrous oxide, which is subsequently further reduced to atmospheric nitrogen (Verhoeven and Meuleman, 1999). Denitrification is illustrated by following equation (Hauck, 1984):

$$2NO_3^- \rightarrow 2NO_2^- \rightarrow 2NO \rightarrow N_2O \rightarrow N_2 \quad (3)$$

Denitrification contributes to 60 -70% of the total nitrogen removal in CWs (Spieles and Mitsch, 2000; Reddy and D'Angelo, 1997). The rate of denitrification is influenced by many factors such as nitrate concentration, microbial flora, type and quality of organic carbon source, hydroperiods, different plant species residues, the absence of O_2, redox potential, soil moisture, temperature, pH value, presence of denitrifiers, soil type, water level, and the presence of overlying water (Sirivedhin and Gray, 2006; Vymazal, 1995, Bastviken et al., 2005).

Ammonification is a complex biochemical process in which organic N is biologically converted into ammonia by several intermediate steps. This process takes place more rapidly than nitrification in the aerobic zones of the substrate. Ammonification rates are influenced by pH, temperature, carbon to nitrogen (C/N) ratio, available nutrients and conditions of substrate (Reddy and Patrick, 1984). In CWs, the adsorption of ionized ammonia takes place through cation exchange reaction with substrate. This process of nitrogen removal is limited to SSF CWs where the contact between substrate and wastewater is efficient. On the other hand volatilization may be a significant route for the removal of nitrogen in the form of ammonia (Vymazal, 2007).

Phosphorous removal

CW provides the conditions for the interconversion of all forms of phosphorus. Phosphorus occurs in both organic and inorganic forms in different wastewaters. Dissolved organic phosphorus and insoluble forms of organic and inorganic phosphorus are generally not biologically available until transformed into soluble inorganic forms. Soluble reactive phosphorus is taken up by helophytes and converted to tissue phosphorus or may become sorbed to CW substrate. Phosphorus uptake by helophytes is usually highest during the beginning of the growing season, before maximum growth rate is attained (Vymazal, 1995). Most phosphate is removed from wastewater through sediment retention. Phosphorus transformations in wetlands are: peat/soil accretion, adsorption/desorption, precipitation/ dissolution, plant/microbial uptake, fragmentation, leaching and mineralization (Vymazal, 2007). Richardson and Marshall (1986) found that soil adsorption control long-term phosphorus sequestration in wetlands (Richardson and Marshall, 1986). Adsorption refers to movement of soluble inorganic P from soil pore water to soil mineral surfaces, where it accumulates without penetrating the soil surface. Precipitation can refer to the reaction of phosphate ions with metallic cations such as Fe, Al, Ca or Mg, forming amorphous or poorly crystalline solids. A variety of cations can precipitate phosphate under certain conditions. Some important mineral precipitates in the wetland environment are: Apatite, Hydroxylapatite, Variscite, Strengite, Vivianite and Wavellite (Reddy and D'Angelo, 1994).

BOD and COD removal

The removal of BOD and COD is believed to occur rapidly through settling and entrapment of particulate matter in the void spaces in the gravel or rock media (EPA, 1993). Removal of BOD in CWs is mainly due to aerobic microbial degradation and sedimentation/filtration processes (Watson et al., 1989). Soluble organic compounds are removed by the microbial growth on the media surfaces and attached to the roots and rhizomes of plants. Organic matter contains approximately 45 to 50% carbon (C), which is utilized by a wide array of microorganisms as a source of energy (DeBusk, 1999). For this purpose oxygen is supplied by the helophytes in the root zone to convert organic carbon to carbon dioxide. Soluble organic matter may also be removed by a number of separation processes including adsorption/absorption (the movement of contaminants from one phase to another). The degree of sorption and its rate are dependent on the characteristics of both the organic matter and the solid surface (helophytes, substrate and litter) (EPA, 2000). Biochemical conversions are important mechanisms to degradable organic matter in wetlands. They may account for removal of some organic constituents by virtue of mineralization or gasification and the production of organic matter through synthesis of new biomass. The decomposers (bacteria and fungi) in CWs play the main role of the removal of organic matter by way of mineralization and gasification. They are also responsible for the synthesis of biomass and the production of organic metabolic end products. In addition to this, phytovolatilization is also an important phenomenon for the removal of contaminants. Some wetland plants also take up contaminants through the root system and transfer them to the atmosphere via their transpiration stream (Hong et al., 2001; Ma and Burken, 2003). Hydrophilic compounds such as acetone (Grove and Stein, 2005) and phenol (Polprasert and Dan, 1996) are directly removed by the process of volatilization/phytovolatilization.

Metal removal

The main mechanism for the removal of metal from industrial wastewater in constructed wetlands includes (Stottmeister et al., 2003; Debusk, 1999):

1. Filtration and sedimentation
2. Precipitation
3. Adsorption
4. Uptake by the helophytes and microorganisms

Filtration and sedimentation are the main process in removal of heavy metals from waste water in CWs. Sinicrope et al. (1992) and Noller et al. (1994) reported the removal of cadmium, lead, silver and zinc by filtration (Sinicrope et al., 1992; Noller et al.,1994). The removal efficiency was reported to be 75–99.7% cadmium, 26% lead, 75.9% silver and 66.7% zinc. Sedimentation is a physical process after other mechanisms aggregate heavy metals into particles large enough to sink (Walker and Hurl, 2002).

Precipitation depends on the solubility product (Ksp) of the metal, pH of the wastewater, concentration of metal ions and relevant anions. When the values of the concentration of cations and anions are such that their product exceeds Ksp, precipitation takes place (Sheoran and Sheoran, 2006). Heavy metals in this way are removed from wastewater and trapped in the wetland sediments. Heavy metals in CWs may be adsorbed to soil or sediment, or may be chelated or complexed with organic matter. In addition to adsorption of heavy metals, oxide formation is also an important mechanism for metal removed from wastewater (Weider and Lang, 1986).

Biological removal is also an important pathway for heavy metal removal in the CWs; it includes plant and microbial uptake. The rate of metal removal by plants varies widely, depending on plant growth rate, plant species and concentration of the heavy metals in the wastewater (Sheoran and Sheoran, 2006). Maximum concentration of metals in plants was observed in roots. Barley et al. (2005) also reported the highest metal concentrations in the roots of wetland plants (Barley et al., 2005).

Some helophytes are known to accumulate a relatively high amount of heavy metals in their biomass. Such helophytes are called 'hyperaccumulators (Stottmeister et al., 2003). Microorganisms also provide a measurable amount of heavy metal storage and uptake (Hallberg and Johnson, 2005a). Sobolewski (1999) reported the reduction of metals to non-mobile forms by microbial activity in CWs (Sobolewski, 1999).

Pathogens removal

CW systems have excellent pathogen removal capability as reported in different studies (Stottmeister et al., 2003; Gersberg et al., 1987; Ottova et al., 1997). These systems act as biofilter through a combination of physical, chemical and biological processes which all participates in the reduction of the number of pathogens (Brix, 1993).

Physical factors include aggregation, filtration, sedimentation and exposure ultra-violet ray. Chemical factors include adsorption, oxidative damage, and exposure to toxins given off by other microorganisms and plants (Gersberg et al., 1989b). Biological mechanisms include natural death, ingestion by nematodes, protozoans, lytic bacteria and bacteriophages attacks (Ottova et al., 1997). Kadlec and Knight (1996) reported the elimination of coliforms (more than 90%) and streptococci (more than 80%) in various systems of constructed wetlands (Kadlec and Knight, 1996). Neralla et al. (2000) reported the reduction in fecal coliform populations up to 99% by CW (Neralla et al., 2000).

Conclusion

Constructed wetlands have a great potential to treat contaminated wastewater from different origins. With careful designing and planning, a CW can efficiently remove variety of inorganic, organic and biological contaminants from domestic and industrial wastewaters.

Helophytes and microorganisms are the active agents in the treatment process. The cost for design and construction can be considerably lower than other conventional wastewater treatment options. These systems also enhance the aesthetic value of the local environment. Although this paper deals with the study of mechanism of several contaminants removal in CWs but still a long-term investigation is required.

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Table 1: Contaminant removal mechanisms in constructed wetlands

Parameters	Physical	Chemical	Biological
Suspended solids	Sedimentation Filtration		Biodegradation
Biochemical oxygen demand	Sedimentation	Oxidation Reduction	Biodegradation
Chemical oxygen demand	Sedimentation	Oxidation Reduction	Biodegradation Phytodegradation Phytovolatilization Plant uptake
Nitrogenous Compounds	Sedimentation Volatilization	Adsorption	Bio-denitrification- nitrification Plant uptake
Phosphoric Compounds	Sedimentation	Adsorption Precipitation	Microbial uptake Plant uptake
Metals	Sedimentation Filtration	Adsorption Precipitation	Plant uptake
Pathogens	Filtration UV ray action	Adsorption Oxidation	Natural death Exposure to natural toxins Bacteriophage attack