Wastewater Treatment Using Constructed Wetland

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Constructed wetlands (CW) is an environmentally friendly technique for removing pollutants from wastewater and has been applied to municipal wastewater, petroleum refinery wastewater, agriculture drainage, acid mine drainage, etc.

Keywords: constructed wetland ; wastewater ; plants ; microorganisms

1. Introduction

In the last decade, environmental awareness has increased, and the treatment of environmental pollution and contamination has become the main agenda of concerned governmental bodies around the world. Usually, a suitable environmental remediation method for a certain type of waste is selected based on the effectiveness of the degradation process and the cost of the method [1][2][3]. More importantly, the environmental impact of the selected method is of special concern because in some remediation methods the daughter product of the degradation process is more toxic than the original contaminant. Scientists and researchers believe that there is no single universal remediation method suitable for all types of contaminants and all sources; instead, an effective remediation program may involve the collective implementation of two or more methods [1][2]. Wetlands are one of the effective remediation technologies that now attract environmentalists for the treatment of wastewater contaminants [2]. Mother Nature, through natural wetlands, removes contaminants from water resources through different natural processes including biodegradation, sorption, phytostabilization, phytoextraction, and rhizofiltration [2][4][5][6][7]. Constructed wetlands are developed to mimic the natural processes in removing/degrading contaminants in wastewater [8][9]. Municipal wastewater, industrial wastewater (particularly petroleum refinery and sour-water treatment wastewater products), agriculture wastewater, stormwater, textile wastewater, landfill leachates, mining drainage, etc., are examples of contaminated wastewater that can be treated using wetlands [10][11][12]. Constructed wetlands use natural processes in degrading contamination; therefore, it is an environmentally friendly remediation method with minimum adverse environmental impact [13]. CW is designed to treat wastewater from different sources similar to common effluent treatment plants [14].

Wetlands are generally defined by the saturation of soil for a long enough period for anaerobic conditions to develop. There are various types of wetlands including natural fresh and salt-water wetlands and constructed wetlands [2]. Wetlands constructed for remediation of contaminants integrate complicated inclusive processes that involve water, substrate (soil), plants, animals, microorganisms, and the environment. Constructed wetlands implemented various remediation methods including biodegradation, phytoremediation, and natural attenuation [15]. The main processes that occur in wetlands include physical processes such as filtration and sedimentation, chemical processes such as adsorption and precipitation, and biological processes such as biodegradation and plant assimilation [16].

The vast majority of the wetlands are characterized by a high density of vascular plants. High-density vegetation results in slowing the water flow, creating microenvironments, and providing sorption sites for contaminants and attachments sites for microorganisms [5]. As the plants die and fall in the water, the parts of the plants above the water create additional sorption and exchange sites. In addition, plant debris is a suitable source of organic carbon and nutrients (nitrogen and phosphorous) for microorganism metabolism. The oxygen concentration is very low in wetlands due to soil saturation conditions. Therefore, the vegetation in wetlands is limited to species (vascular plants) that can grow at low oxygen concentrations [5].

Microorganisms play a dominant role in the contaminant degradation process and in the transformation of the contamination between the environment and the plant. Usually, a microbial consortium is involved in contaminant degradation and the transformation processes [9]. There are specific degradation pathways for each microorganism to degrade a specific contaminant. The success of the process of contaminant degradation relies on the existence of microorganisms that are required for the degradation process and suitable environmental conditions [17][18].

Constructed wetlands have been used all around the world for the treatment of wastewater. For instance, CWs have been used in Europe since the second half of the last century; the first country to use CWs in Europe was Germany [16]. Many other countries including the United Kingdom, Austria, Slovenia, Switzerland, and Denmark have CWs in operation. Some countries in Africa have been using CWs, such as South Africa, Tanzania, Kenya, and Seychelles. Some statistics show that the cost of subsurface CWs in Africa for wastewater treatment is around US $5 per person compared to mechanical wastewater treatment (i.e., activated sludge system), which costs around US $50 per person [16][17]. A recent study showed that the total cost (including operation, maintenance, and disposal of sludge) of wastewater treatment varies between €0.30 to €0.88 per m^3 [19]. In China, there are more than 400 CWs [20].

Constructed wetlands are characterized by very slow water flow and shallow water depth. The slow water flow results in a long retention time that facilitates the settlement of the sediment and increases the contact time between the wastewater and the components of the wetland [21]. Thus, in the design, it is critical to choose a suitable flow velocity to provide enough time for microorganisms to degrade the contaminants. The components of the constructed wetland affect the degradation processes. For instance, the number of sorption sites in the soil and the substrate control the bioavailability and degradation process [21]. There are two schools of thought concerning bioavailability; some scientists believe that bacteria can degrade contaminants without the need for the contaminants to be desorbed [21]. On the other hand, some researchers believe that the contaminants need to be desorbed first before bacteria can degrade them. Some types of bacterial strains are capable of producing biosurfactants to facilitate the desorption process [22]. Therefore, for constructed wetlands, understanding the capabilities of the available microorganism consortium is essential for a successful treatment process.

2. Wetland Treatment Systems

Generally, constructed wetlands can be classified according to different criteria such as hydrology (surface-flow and subsurface-flow), macrophyte types (free-floating, emergent, and submerged), and flow path (horizontal or vertical) [23]. As mentioned before, there are many types of constructed wetlands including surface flow (SF) wetlands, subsurface flow (SSF) wetlands, and hybrid systems, which encompass surface and subsurface flow wetlands [24]. The hybrid system is a multistage system in which the treatment is performed in different units that are designed for specific functions. For instance, for wastewater treatment, some units are designed to promote aerobic reactions, while other units are designed for anaerobic conditions. A wetland equipped with an air pump connected to a subsurface network of air distribution pipes is called aerated CW [25]. The air bubbles introduced by the air pump can increase the oxygen transfer rate in horizontal flow (HF) or vertical flow (VF) type wetlands and effectively creates aerobic conditions. The estimated oxygen consumption rate in CW could be 250 g of $O_2/m^2/d$ with air flow rate and distribution to be ≥0.6 $m^3/m^2/h$ and 30 cm × 30 cm, respectively. Mechanically aerated wetlands can provide higher oxygen transfer rates (more than 1 $m^3/m^2/h$). The aerated wetland has improved nitrification/denitrification capacity as well as better biogeochemical conditions in the wetland subsurface and the plants [25][26].

In the literature, scientists and engineers use various terms to describe wetlands. For instance, in free-surface flow (FSF) the surface of the wastewater flow is above the soil (substrate in the CWs) [2][3][4]. Alternatively, some scientists use the term SF surface flow to denote the FSF. Additionally, the term SSF is used for a sub-surface flow system in which the wastewater flows horizontally or vertically such that the water level is below the ground surface. The abbreviation HSSF is used for horizontal subsurface flow or alternatively SSHF subsurface horizontal flow [2][4][5][13]. The terms VSSF and SSVF are used for the vertical subsurface flow or subsurface vertical flow, respectively. Sometimes the abbreviation of the constructed wetlands CWs is added to the above-mentioned terms. For example, CWs is added to HF to become HFCWs [1][22]. In an attempt to unify the terms used in the literature, this article will use the following abbreviations: SF for surface flow, VSSF for vertical subsurface flow, and HSSF for horizontal subsurface flow.

3. Microorganisms Used in the Wetland

The design of wetland components includes the substrate (the soil matrix), the hydrology (water flow and water control structures), and the plants. However, important components of wetlands such as communities of microbes and invertebrates are developed naturally [27][28]. Bacteria play a dominant role in contaminant degradation and in the transformation of contaminants between the environment and the plant. Different types of heterotrophic and autotrophic bacteria contribute to contaminant degradation. Heterotrophic bacteria utilize organic carbon for their metabolism; therefore, they are active in the degradation of organic pollutants such as petroleum hydrocarbon. On the other hand, autotrophic bacteria use carbon dioxide for cell growth [29].

In aerobic digestion, the organic pollutant serves as electron donor and oxygen serves as electron acceptor. In this process, the pollutant is decomposed to CO_2 through a certain pathway, which involves the production of daughter products of the original contaminant [30][31][32]. It is very important to mention that in some cases some daughter products of these processes are more toxic than the original pollutant. Therefore, it is very important to ensure that degradation happens at the end of the processes (i.e., produce CO_2 and H_2O). The shallow surface of the surface flow constructed wetlands and the top layers of the subsurface flow constructed wetlands provide a suitable environment (i.e., oxygen concentration) for aerobic degradation of contaminants [30].

In anaerobic digestion, the organic pollutant serves as electron donor and CO_2 serves as electron acceptor. Some other chemical compounds serve as electron acceptors including nitrate, nitrite, sulphate, and carbonate. In denitrification, nitrate and nitrite serve as electron acceptors, and the organic pollutant serves as the electron donor [13][30]. **Table 1** shows various types of bacteria that contribute to nitrification and denitrification processes

Table 1. Bacterial strains involved in nitrification and denitrification in constructed wetlands.

Bacteria	Porous Media	Process	Reference	
1	***Pseudomonas falva* WD-3**	**Brown soil (0–4 mm diameter), Sludge (5–10 mm diameter) and Gravel (40–50 mm diameter)**	**Denitrification**	[33]
2	***Alcaligenes faecalis strain WT14***	**Sediments**	**Heterotrophic nitrification and aerobic denitrification**	[34]
3	***Albidiferax***	**Rough sand (1–2 mm diameter), gravel (10–20 mm diameter) and Gravel (30–50 mm diameter)**	**Nitrification**	[35]
4	***Candidatus Nitrosotenuis***	**Quartz sand (5–10 mm diameter), activated carbon (2–5 mm diameter) and Cobble (15–30 mm diameter)**	**Nitrification**	[36]
5	***Nitrosomonas***	**Quartz sand (5–10 mm diameter), activated carbon (2–5 mm diameter) and Cobble (15–30 mm diameter)**	**Nitrification**	[36]
6	***Nitrosopumilus***	**Quartz sand (5–10 mm diameter), activated carbon (2–5 mm diameter) and Cobble (15–30 mm diameter)**	**Nitrification**	[36]

The metabolism of each type of bacteria is optimum under specific environmental conditions including pH, temperature, oxygen concentration, and sunlight. In general, pH around 6–7 is suitable for most types of bacteria. A temperature around 28–30 is suitable for most types of bacteria. However, thermophilic bacterial strains survive under very high temperatures, such as *Sulfolobus Solfataricus*, *Bacillus licheniformis,* and *Thermomonas hydrothermalis* [28].

The temperature has an effect on the microbial activity in the wetlands; therefore, the temperature can directly affect the success of the treatment process. Low temperatures slow down the microbial activities, while very high temperatures have detrimental effects on the microorganisms. Sorption and sedimentation processes are also affected by the temperature. Temperature directly affects the concentration of dissolved oxygen in the water and the oxidation-reduction potential. High temperatures cause low dissolved oxygen environments. Temperatures between 20 and 30 °C are suitable for the growth of plants as well as bacterial growth [11][30].

There are several aspects concerning microorganisms in enhancing the outcome of constructed wetlands through prolonging the survival of the microorganisms or improving bacterial viability and persistence in the wastewater environment. This can be divided into two main factors: the wetland environment and the characteristics of microorganisms. Survival and persistence of bacteria in the wetlands are affected by changes in soil pH, nutrients, electron acceptors, osmotic stress, temperature (cold or hot weather), UV exposure, and chemicals [37]. In addition to the wetland environment, the characteristics of the microorganisms play a significant role in their existence; for example, some bacteria form biofilms that protect themselves from external stresses. Another mechanism for bacteria to survive is to produce spores [38]. In the event of severe weather and nutrient deprivation, bacteria will die, eventually producing endospores that have a very hard shell and protect them [39]. Typically, under extremely poor living conditions, endospores are in a state of dormancy (sleeping condition); once the environmental conditions improve, the spore will germinate and outgrow [1].

Alga contributes to the removal of contaminants in constructed wetlands. For instance, *Chlorella Vulgaris* and *Scenedesmus obliquus* strains can remove selenium from river water when treated with a wetlands system by volatilization and accumulation [40]. Plants and microorganisms can contribute to the volatilization of selenium. The volatilization of selenium has been approved to be dependent on nutrients (N and P). Previous studies showed that the volatilization of selenium is more sensitive to an increase in P than the increase in N [41].

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