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CONSTRUCTED WETLAND SYSTEMS TO REMOVE NUTRIENTS FROM WASTEWATERS

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Abstract
Constructed wetlands are man-made systems imitating the structures and functions of natural wetlands. Although it seems to be a simple treatment system, constructed wetlands include complex and integrated processes among the ecological phases surrounding microorganisms, animals, plants and aquatic environment. For a successful design and operation, these ecological processes should be well-comprehended. These systems are used for treatment of various wastewater sources including domestic, industrial wastewaters, feedlot and agricultural runoff waters. Besides organic matter constructed wetland systems are successfully operated for nitrogen and phosphorus removal from wastewaters. Nitrification/denitrification and plant uptake are the primary processes for nitrogen removal. Phosphorus removal is realized through the processes of adsorption, desorption, precipitation, filtration and plant uptake. In these systems, aquatic plants support treatment processes through oxygen supply to filter beds and up taking some nutrients; soil, sand-gravel etc. substrate materials support the treatments processes through adsorption and filtration. For efficient nutrient (nitrogen and phosphorus) removal, planted constructed wetland systems should be used and appropriate adsorbent substrate materials should be placed in wetland basins. In this study, nutrient removal mechanisms of constructed wetland systems were presented, and recommendations were provided for more efficient removal of nutrients.

Keywords: Constructed wetlands, nutrient, treatment, Turkey

1. INTRODUCTION

Natural wetlands are natural habitats or ecosystems saturated seasonally or permanently and the bottom of them is covered with hydric soils to support emergent plants. Natural wetlands include marshes, swamps, bogs and mangroves (Figure 1). These aquatic environments with emergent plants provide a shelter for various wildlife creatures, especially for migratory birds. Besides shelter, natural wetlands also serve an ambient for water purification and treatment. Several benefits of the wetlands could be summarized as follows (CBD, 2015):

- Environmental benefits
    - Provides natural water regulation and purification processes. Wetlands trap sediments, decreasing the transport of sediments to downstream deposits and maintaining natural environmental flows.
    - Combats extremely dry and extremely wet weather conditions, for example flood control and drought mitigation.
    - Promotes very productive ecosystems and provide habitats to diverse species.

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  - Provides carbon storage and sequestration (certain wetlands, such as peatlands), which is vital for climate change mitigation.
  - Protects low-lying coastal communities against storms and flooding from the sea, and stabilize the shoreline soils, reducing the risk of erosion.

- Socio-economic benefits
  - Regulates capacity. Sediment regulation, in particular, can play an important role in dam operations and hydropower production.
  - Provides aesthetic and recreational value for local populations.
  - Creates new income possibilities for local communities, for example through tourism or fishing activities.

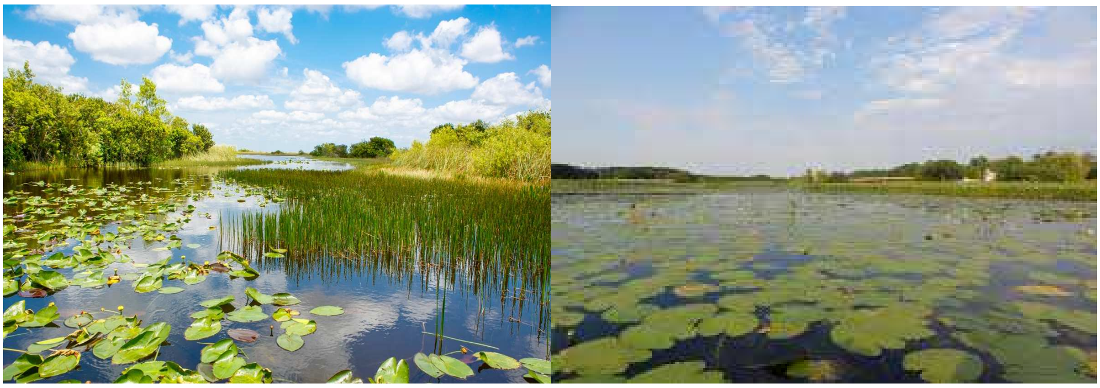

Figure 1. Natural wetlands (Source: https://japan.wetlands.org/)

Just because of water purification benefits of the natural wetlands, researchers focused on constructed wetlands through imitating natural processes for wastewater treatment purposes (Figure 2). Constructed wetlands, so called as natural treatment systems, are generally constructed for wastewater treatment purposes especially in rural sections. These systems are man-made systems constructed as to imitate the on-going processes in natural wetlands (Gokalp and Kanarya, 2018).

In this study, initially a brief information was provided about constructed wetlands, then nutrient removal mechanisms of constructed wetland systems were presented, and recommendations were provided for more efficient removal of nutrients with different substrate materials in constructed wetlands.

2. CONSTRUCTED WETLANDS

Constructed wetlands are used in wastewater treatments for domestic effluents, industrial effluents, processing water effluents, mine drainage water and similar other polluted effluents. Constructed wetlands have several advantages over the conventional treatment systems. The primary advantage is their low costs and easy construction. They require quite low or even zero-energy for operation and have significantly lower operational costs than the conventional ones. Constructed wetlands are environment-friendly systems and provide habitat for various wetland plants and organisms. Beside these advantages, they have also some disadvantages. They require larger construction areas than regular and conventional treatment systems to treat the same capacity wastewater influent. The system performance is less stable, dominantly depend on wastewater characteristics and can easily be altered by changing climate conditions (Gokalp and Tas, 2018a).

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Constructed wetland systems are composed of a wetland basin, inlet, outlet, diver level control structures and piping installations. A basin of about 1 m deep is excavated based on the population to be served or the wastewater influent quantity. In case of considering the population to be served, ideally 5 m^2 basin area is allocated per person, but generally 3-5 m^2 basin area is allocated in most cases. Then the basin is covered either with a synthetic liner or compacted clay layer to prevent leakage from the bottom. About 20 cm soil layer is placed over the impervious bottom to provide a rooting medium for aquatic plants. This soil layer is overlaid with graded substrate materials (sand, gravel and similar granular material) (Figure 2). Inlet and outlet sections are constructed with coarser material for easy flow of influent and effluent. An adjustable outlet pipe is installed at the outlet section of the system to control hydraulic gradient and hydraulic retention time. A slope of 0.01 m/m is provided over the basin floor to allow gravitation flow of wastewater throughout the system (Gokalp and Tas, 2018b).

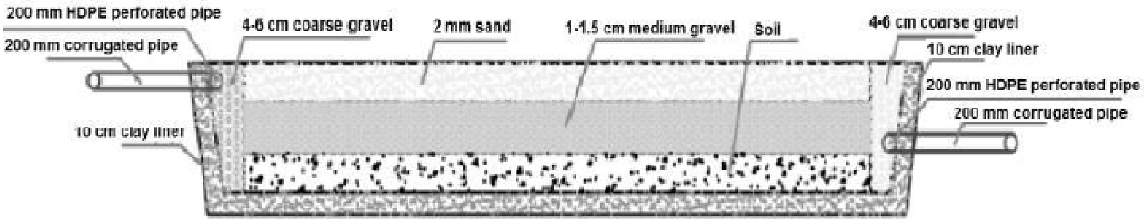

Figure 2. Constructed wetland cross-section (Gokalp and Kanarya, 2018)

3. NUTRIENT REMOVAL FROM WASTEWATERS

A constructed wetland system is a reasonable option for treating wastewater by simulating natural wetlands. This system has been found to be able to remove various pollutants and nutrients from wastewater (Hammer, 1989) and has also been successfully used to treat wastewater with high concentrations of nutrients (Tanner et al.,1995). However, a wide range of nutrient removal instances in constructed wetlands has been reported, with many wetlands failing to meet relevant environmental standards, particularly for nitrogen and phosphorous in polluted water bodies (Greenway, 2005). Variances among studies may be related to differences in macrophyte species and density, media, wastewater type, retention times, loading rates, climatic condition, temperature, design and size of the setups (Tanner, 2001).

3.1. PHOSPHORUS

The removal of phosphorus (P) from domestic wastewater is primarily to reduce the potential for eutrophication in receiving waters. Most P-removal technologies have been developed for use at larger wastewater treatment plants that have rigorous operation and monitoring systems. Smaller treatment plants often do not have these luxuries, there is a concern that P releases from small treatment systems may have greater environmental impact. Here P-removal technologies were reviewed with the goal of determining which treatment options are amenable to small-scale applications. Significant progress has been made in developing some technologies for small-scale application, namely sorptive media. Different phosphorus sources in wastewater and potential treatment processes are presented in Figure 3 (Bunce et al., 2018).

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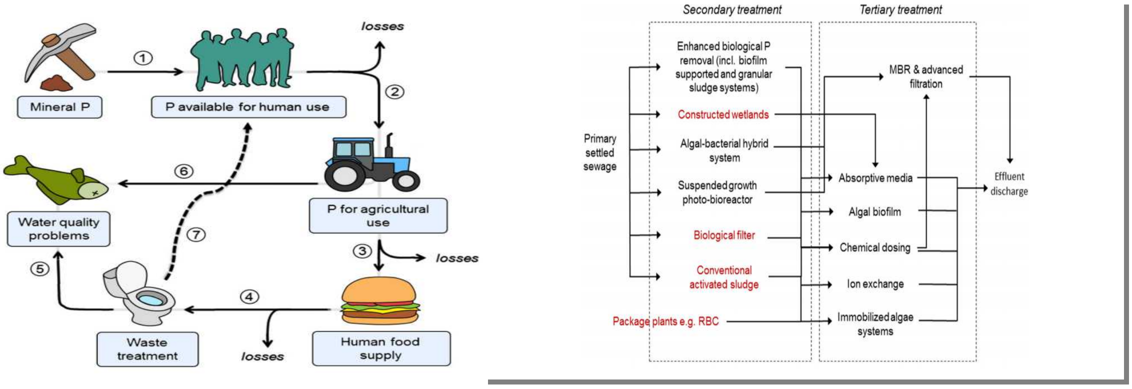

Figure 3. Phosphorus sources and treatment processes (Bunce et al., 2018)

In recent years, much work has been done to improve P removal in filter systems using active media. In contrast to traditional filtration systems, reactive media filters rely on P-sorption properties of certain materials to remove P in a targeted manner from wastewater, rather than using filter media solely for attachment of biomass. Absorptive media are manufactured from either, natural products (e.g., apatite, bauxite or limestone), industrial waste products (e.g., fly ash or steel slag) or man-made products (e.g., FiltraliteTM). There are several commercially available products of which the most widely studied ones are zeolite and pumice stone.

P is removed by filter media by the process of sorption or by direct precipitation. Briefly, this involves the movement of inorganic P from the wastewater to the surface or body of reactive components (e.g., calcium or iron) contained in the media, where is accumulates. The P removal capacity is therefore, dependent on the mineral content of the media. Early work on P removal by sorptive media focused on the use of locally sourced sands and gravel. More recently, the development of a wide variety of natural or man-made materials has advanced the potential for the application of this technology at small-scale (Bunce et al., 2008).

Much work has focused on reducing the footprint and enhancing the functionality of processes that include P sorption mechanisms, such as in constructed wetlands, a treatment option with potential for P-removal at smaller scales. Constructed wetlands are favorable as P uptake can be achieved through microbial and plant uptake, in addition to adsorption by media. While the removal of P in wetlands without the use of absorptive media is restricted to 40–60%, such systems are fairly well understood and flexibility in configurations means that they may be suitable for a wide range of applications, being able to achieve the simultaneous removal of multiple contaminants (beyond just P).

The advantages of “adsorptive” wetlands include the potential for low operational maintenance, an “aesthetically” pleasing planted wetland, and the ability of such systems to also reduce biological oxygen demand (BOD) and ammonium levels. Therefore, wetlands constructed with sorptive filter media can provide a holistic treatment solution with the removal of multiple contaminants by a combination of precipitation, microbial activity and plant uptake. In such systems, appropriate pre-treatment will also allow for a longer lifetime of the filter media, by decreasing the risk of clogging and allowing one to use finer reactive filter media with higher sorption capacity.

3.2. NITROGEN

Nitrogen has a complex biogeochemical cycle with multiple biotic/abiotic transformations involving seven valence states (+5 to -3). The compounds include a variety of inorganic and organic

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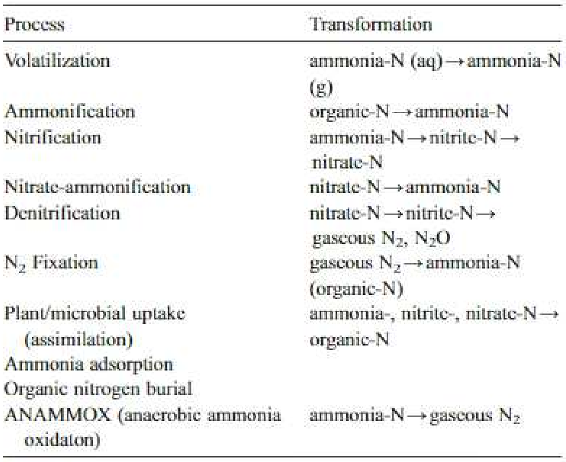
nitrogen forms that are essential for all biological life. The most important in-organic form of nitrogen in wetlands are ammonium (NH^{4+}), nitrite (NO^{2-}) and nitrate (NO^{3-}). Gaseous nitrogen may exist as dinitrogen (N_2), nitrous oxide (N_2O), nitric oxide (NO_2 and N_2O_4) and ammonia (NH_3).
Nitrogen transformations in wetlands. The major nitrogen transformations in wetlands are presented in Table 1. The various forms of nitrogen are continually involved in chemical transformations from inorganic to organic compounds and back from organic to inorganic. Some of these processes require energy (typically derived from an organic carbon source) to proceed, and others release energy, which is used by organisms for growth and survival. All of these transformations are necessary for wetland ecosystems to function successfully, and most chemical changes are controlled through the production of enzymes and catalysts by the living organisms they benefit.

Nitrification the first anoxic oxidation process to occur after oxygen depletion is the reduction of nitrate to molecular nitrogen or ammonia. The reduction of nitrate is per-formed by two different groups of nitrate-reducing bacteria: the denitrifying bacteria which produce $N_2O$and N_2 as major reduction products and the nitrate-ammonifying bacteria which produce NH^{4+} as the major end product of the reduction of nitrate. In sediments and soils, both denitrification and nitrate-ammonification are observed (Keeney et al., 1972). Different numbers of electrons are used in the reduction of one molecule of nitrate in both nitrate-reducing system: 5 in the case of denitrification and 8 in the case of nitrate-ammonification. Therefore, more organic matter can be oxidized per molecule of nitrate by nitrate-ammonifying bacteria than denitrifying bacteria. In addition, nitrate reduction is generally performed by fermentative bacteria that are not dependent on the presence of nitrate for growth under anaerobic conditions. So, nitrate-ammonifying bacteria may be favored by nitrate-limited conditions (Laanbroek, 1990). Al-though dissimilatory nitrate reduction seems to be more energy efficient than denitrification, Van Oostrom and Russell (1994) only found a 5% contribution of the first process to the nitrate removal.

Table 1. Nitrogen transformations in constructed wetlands (Vymazal and Kropfelova, 2009)



Process	Transformation
Volatilization	ammonia-N (aq) → ammonia-N (g)
Ammonification	organic-N → ammonia-N
Nitrification	ammonia-N → nitrite-N → nitrate-N
Nitrate-ammonification	nitrate-N → ammonia-N
Denitrification	nitrate-N → nitrite-N → gaseous N_2, N_2O
N_2 Fixation	gaseous N_2 → ammonia-N (organic-N)
Plant/microbial uptake (assimilation)	ammonia-, nitrite-, nitrate-N → organic-N
Ammonia adsorption	
Organic nitrogen burial	
ANAMMOX (anaerobic ammonia oxidaton)	ammonia-N → gaseous N_2

Denitrification is most commonly defined as the process in which nitrate is converted into dinitrogen via intermediates nitrite, nitric oxide and nitrous oxide (Hauck, 1984). From a biochemical viewpoint, denitrification is a bacterial process in which nitrogen oxides (in ionic and gaseous forms) serve as terminal electron acceptors for respiratory electron transport. Electrons are carried from an electron-donating substrate (usually, but not exclusively, organic compounds) through several carrier systems to a more oxidized N form. The resultant free energy is conserved in

ATP, following phosphorylation, and is used by the denitrifying organisms to support respiration (Jetten et al., 1997).

4. SUBSTRATE MATERIALS TO REMOVE NUTRIENTS FROM WASTEWATERS

In the gravel systems, the main P-removal mechanisms are adsorption and precipitation reactions with Ca, Al, and Fe but also, like in all media, biological assimilation and plant uptake can play a remarkable role. Tanner et al. (1999) showed that over 5 years, P accumulation decreased, and substratum P-sorption capacity became saturated. Mann and Bavor (1993) described testing the phosphorus removal efficiency gravel based constructed wetland system in a 2-year study in which removal ranged from −40% to 40%. Korkusuz et al. (2005) showed that many substrates in subsurface constructed wetlands (e.g. pea gravel, crushed stones, sand, etc.) usually do not contain high concentrations of Ca, Al, Mg and Fe, and thus the removal of phosphate is, generally, low and varies widely among systems due to the different materials used.

For domestic wastewater treatment in Turkey, vertical subsurface flow constructed wetlands showed TP removal efficiency for gravel wetland cells of only 4%. He et al. (2007) reported TP removal during a 14-weeks experiment in a gravel wetland from 6.8% to 54%, on average 22.44%. In pilot-scale units containing medium gravel obtained from a quarry, Akratos and Tsihrintzis (2007) found greater removal efficiency for fine gravel (89%), followed by medium gravel with cattail (67%) and cobbles (57%). The removal efficiencies of the other two units were significantly lower (medium gravel with reed 28.2%; medium gravel alone 43.9%). PO_4^{3-} and TP removal efficiency was predominantly affected by porous media size and type.

In sand or gravel substrates, phosphorus is bound to the media mainly as a consequence of adsorption and precipitation reactions with calcium (Ca), aluminum (Al) and iron (Fe). At pH levels greater than 6, the reactions are a combination of physical adsorption to iron and aluminum oxides and precipitation as sparingly soluble calcium phosphates. At lower pH levels, precipitation as iron and aluminum phosphates (strengite, variscite) becomes increasingly important (Gerritse, 1993). The capacity of filter media to remove P may therefore be dependent on the contents of these minerals in the substrate. This hypothesis is supported by the observation that P-removal has been found to be particularly efficient in constructed reed beds containing ferruginous sand (Netter, 1992). However, P-removal efficiency is often high initially and then decreases after some time as the P-sorption capacity of the sand is exhausted (Ciupa, 1996). Arias et al. (2001) found that the P-removal capacity of some sands would be used up after only a few months in full-scale systems, whereas that of others would persist up to several years.

The most important characteristic of the sands that determined their P-removal capacity was their Ca content. In situations where the wastewater to be treated is more acid, the contents of Fe and Al may be more important, as the precipitation reactions with these ions are favored at lower pH levels (Stumm and Morgan, 1981). Pant et al. (2001) showed that some local sands from Canada with elevated contents of Fe, Al and P have high P sorption capacity. Sand filters are also known as efficient units for complex wastewater purification (BOD, COD, NH_4-N, and also in some cases PO_4-P and fecal coliforms). Long-term purification, however, has only been demonstrated in a few studies (Mander et al., 2003).

Zeolite is a hydrated aluminum-silicate mineral in which the aluminum and silicon polyhedral are linked by the sharing of oxygen atoms. Drizo et al. (1999) described that zeolite achieved an adsorption maximum of 0.462 kg^{-1}. Chen et al. (2006) has found the maximum P retention for different zeolites at different pH ranges, defined by Langmuir adsorption, to be only 0.01–0.05 g P kg^{-1}.

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Coals are composed of aluminum silicate clays, carbonates, sulphides, chlorides and quartz that are oxidized at high temperatures (>1500 °C), which melts almost all of the inorganic components with the exception of quartz. Coal fly ash is an inorganic waste product from coal combustion, consisting mainly of spherical glassy particles of silica (SiO_2), alumina (Al_2O_3) and iron oxides. Fly ashes are widely used on agricultural land to improve the physical and chemical properties of soil.

In addition, fly ashes are used in effluent treatment to remove various pollutants (COD, suspended solids, organic components, chrome dye, heavy metals, phenolic compounds, fluoride and also P. Chen et al. (2006) found that high Ca, medium Ca and low Ca fly ashes from coal-using power plants in China showed retention at different pH ranges to be up to 42.6 g P kg^{-1}. He et al. (2007) described retention capacity as defined by Langmuir as being up to 29.5 g P kg^{-1}, while the initial pH in slurry was alkaline (9.7–11.6). He et al. (2007) studied constructed wetlands for the treatment of low-concentration polluted eutrophic landscape river water with a three-stage system filled with fly ash. The TP adsorbed by the last 7 m of the fly ash stage was about 83%.

5. CONCLUSION

Constructed wetland systems are used for treatment of wastewater effluents coming from domestic, industrial and agricultural sources. Besides organic matter, constructed wetland systems are successfully operated for nitrogen and phosphorus removal from wastewaters. Nitrification/denitrification and plant uptake are the primary processes for nitrogen removal. Phosphorus removal is realized through the processes of adsorption, desorption, precipitation, filtration and plant uptake. Plants used in these systems support treatment processes through oxygen supply to filter beds and up taking some nutrients. Various type of substrate materials are used in these systems including soil, sand, gravel, pumice, zeolite, fly ash and some other waste materials. Each one of them has different nutrient removal performance. Thus, several researches are conducted on various other substrate materials or on mixtures of these materials. The follow-up research on filter materials for phosphorus retention should focus on their hydraulic parameters combined with the analysis how to avoid the possible clogging. Likewise, more attention should be given to investigate obvious constraints such as poor hydraulic conductivity, low surface area, or high content of undesirable contaminants such as heavy metals.

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