A Review on the Control of Agricultural Non-Point Source Pollution through Wetlands

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Abstract: Understanding the sources and the impacts of agricultural non-point source pollution (NPSP) will be essential to implementing more sustainable practices and systems. Constructed wetlands have become a popular topic in mitigating NPSP, especially the removal of nitrogen (N) and phosphorus (P). This review examined the performance of constructed wetlands in N and P removals through various published peer-reviewed articles. The performance of constructed wetlands in removing pollutants varies among different countries. The N and P removal mechanisms were also discussed in this article, such as the denitrification and P adsorption processes. Additionally, this paper explored the impact factors influencing the performance of constructed wetlands, including temperature, hydraulic residence time, vegetation, and input concentrations. In general, constructed wetlands would be more effective in regions with higher temperatures and vegetation with larger root biomass. Future studies should focus more on improving the performance of constructed wetlands in colder areas, and other more detailed parameters, such as specific beneficial microorganisms, should be researched.

1. Introduction

The agricultural production in China has dramatically risen with fertilizers and pesticides (Yi et al., 2020; Tao et al., 2020; Xia et al., 2020; Liu et al., 2019; Wang et al., 2015). However, there has also been an increase in agricultural non-point source pollution (NPSP) due to the excessive use of pesticides and fertilizers (Yi et al., 2020; Tao et al., 2020; Xia et al., 2020; Liu et al., 2019; Wang et al., 2015). The previous research showed that two-thirds of global pollution was caused by NPSP (Otero et al., 2011; O'Geen et al., 2010; Bowes et al., 2005; Boesch et al., 2001). Among those, 68% to 83% of the pollutants generated under agricultural scenarios (O'Geen et al., 2010; Bowes et al., 2005). It has been reported that there were some sources for NPSP, including precipitation, manure, aquaculture, land runoff, atmospheric deposition, or hydrologic modification (Yi et al., 2020; Otero et al., 2011; O'Geen et al., 2010; *National Management Measures for the Control of Nonpoint Pollution from Agriculture*, 2003).

NPSP derived from agriculture can cause the deterioration of the quality of surface water and groundwater due to the inorganic pollutants released from NPSP, especially nitrogen (N) and phosphorus (P) (Xia et al., 2020; Yi et al., 2020; O'Geen et al., 2010). Some studies showed that approximately 52% and 54% of the total loading of nitrogen (TN) and phosphorus (TP) was attributed to agricultural NPSP in Taihu Lake Basin, China, and about 24% TN and 71% TP caused by NPSP were found in Italy (Tao et al., 2020; Xia et al., 2020; Yi et al., 2020). Excessive N and P accumulation from non-point source water released directly into the water bodies can result in the eutrophication of lakes, rivers, and groundwater, limiting estuaries and oceans (Xia et al., 2020; Yi et al., 2020; Cha et al., 2012; O'Geen et al., 2010; Diaz and Rosenberg, 2008; Boesch et al., 2001). Overabundance N and P deposition from agricultural runoff in the Mississippi-Ohio-Missouri River basin has been identified as a significant source of hypoxia in the Gulf of Mexico (Batson et al., 2012; O'Geen et al., 2010; Diaz and Rosenberg, 2008). The excessive portion of N and P in the groundwater system could also negatively affect public health (Dowd et al., 2008). It has been reported that nitrate in drinking water can cause methemoglobinemia in infants (Panneerselvam et al., 2021), and a high level of phosphate

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can cause digestive problems (Nieder et al., 2018). Thus, it is necessary to control NPSP and decrease the accumulation of N and P to improve water quality and protect public health.

Some programs aiming to address NPSP have been created by the US Environmental Protection Agency (EPA): National Estuary Program, Pesticides Program, and Coastal Nonpoint Pollution Control Program (Xia et al., 2020; *National Management Measures for the Control of Nonpoint Pollution from Agriculture*, 2003). The previous studies also presented some strategies and technologies used to control NPSP: best management practices (BMPs) and low impact development facilities -- including vegetated filter strips, infiltration trenches, permeable surfaces, and others (Lee et al., 2020; Li et al., 2019; Sobotkova et al., 2018; Cha et al., 2012; Liu et al., 2008). In addition, there are several studies show that N and P accumulation can be reduced through source control, process control, and end treatment, including the management of pesticides and fertilizer use, conservation tillage practices, and ecological ditches (Xia et al., 2020; Chilundo et al., 2018; Wu et al., 2013; Diaz and Rosenberg, 2008; Peigné et al., 2007). Xia et al. (2020) pointed out that although there were many existing technologies in controlling NPSP, the performance of a single method would not be optimal. Other papers also concluded that it was difficult to implement most technologies due to economic pressure, social barriers, and actual environmental conditions (Yi et al., 2020; Wang et al., 2015; Wu et al., 2013; Brauer et al., 2009). Thus, it is necessary to find a more efficient technology to control NPSP with low costs. Recently, the constructed wetland has been reported to be a promising technology to treat NPS (Yi et al., 2020; Xia et al., 2020; Li et al., 2019; Zheng et al., 2016). The costs of constructed wetlands are relatively low compared to other BMP methods, and wetlands are efficient in removing NPSP pollutants (Lee et al., 2020; Yi et al., 2020; O'Geen et al., 2010; Zedler, 2003).

Constructed wetland systems were first designed by K. Seidel as a conventional tertiary and secondary life/urban wastewater treatment (Yi et al., 2020; Vymazal, 2009; Kivaisi, 2001). Constructed wetlands have been extensively utilized in recent years in various nations to treat agricultural NPSP, rural household sewage, and animal waste (Yi et al., 2020). Studies have shown that constructed wetlands can effectively reduce N and P accumulation in the surface water and groundwater (Lee et al., 2020; Yi et al., 2020; O'Geen et al., 2010; Zedler, 2003). The wetlands can capture stormwater runoff and treat it naturally via filtration, sedimentation, and microbiological processes (Lee et al., 2020; Yi et al., 2020; O'Geen et al., 2010; Zedler, 2003). Another outstanding advantage of constructed wetlands is the cost. Research showed that constructed wetlands had a lower operating price than traditional sewage treatment facilities and produced effluent with better quality than conventional sewage treatment plants (Yi et al., 2020; Liu et al., 2019; Kivaisi, 2001). Studies have shown that the performance of wetlands for the control of NPSP was dependent on the types of wetlands (O'Geen et al., 2010; Tanner et al., 2005). Wetlands with smaller surface areas can remove up to 15% of pollutants, while wetlands with relatively larger surface areas will have a much better performance, with the removal efficiency of up to 98% (Díaz et al., 2012; Moreno-Mateos et al., 2010; Bastviken et al., 2009). Other studies also pointed out some other factors influencing the performance of constructed wetlands, including the substrates of wetlands, the condition of climate and surrounding vegetation, the size and shape of wetlands, and other factors (Yi et al., 2020; Wang et al., 2015; O'Geen et al., 2010; Diaz and Rosenberg, 2008).

Even though much research has been reported, few papers reviewed the use of wetlands with a comprehensive understanding of the performance, mechanism, and impact factors. Thus, this review aims to summarize the up-to-date knowledge of constructed wetlands in the control of NPSP. The study will focus mainly on the performance, mechanism, and impact factors of the wetlands. The aim is to elucidate the underlying reasons for removal discrepancies between various kinds of constructed wetlands, explain the mechanisms, and investigate the connection between affecting variables and the removal efficiency of N and P. Finally, some future work and prospects to improve constructed wetland system performance for NPSP treatment have been pointed out.

2. Treatment Performance

Treatment effectiveness, which is strongly correlated with ecological and economic advantages, is one of the most critical properties of constructed wetlands for NPSP management (Lee et al., 2020; Liu et al., 2019). Table 1 shows the treatment performance of constructed wetlands for the control of NPSP reported by several studies (Bastviken et al., 2009; Beutel et al., 2009; Chyan et al., 2016; Gunes et al., 2012; Koskiaho et al., 2003; Li et al., 2019; Moreno-Mateos et al., 2010; Pedescoll et al., 2016, 2013; Zhang et al., 2014; Zheng et al., 2016; Díaz et al., 2012). From Table 1, it shows that N and P removal efficiency ranges from 17.5% to 98% and from 13.3% to 69%, respectively, through using different types of constructed wetlands for the control of NPSP. Díaz et al. (2012) found that the wetland with a hydraulic residence time of 20 days and an area of 173 hectares presented the best performance in removing both N and P, obtaining 98% and 69% removal rate of N and P, respectively. On the other hand, the constructed wetland in Taiwan, China, had the lowest N and P removal rate of 17.5% and 13.3% for N and P, respectively (Chyan et al., 2016). Since the wetland area in Taiwan, China was only 0.00012 ha, one possible explanation of the difference in removal rate could be the area of the wetlands. A more effective removal rate can be achieved by larger wetland areas, such as the wetlands in Central Valley, California with an area of 173 hectares (Díaz et al., 2012).

Furthermore, from Table 1, Koskiaho et al. (2003) showed that the N removal rate was 0% and the P removal rate was -20%. The mean temperature of the study site Finland was -9.8°C to 16.5°C. Also, when the mean annual temperature was -12.2°C to 14.4°C, the removal rate of N in Sweden was 3% to 15% (Bastviken et al., 2009). N and P removal rates increased from 22% to 98% and from -20% to 69%, respectively, as the temperature increased from 3°C to 34°C (Díaz et al., 2012; Koskiaho et al., 2003). Higher temperatures positively affect the performance of wetlands by accelerating the absorbing processes of vegetation or microorganisms of the pollutants (Chyan et al., 2016; Wang et al., 2015; Zheng et al., 2016). Thus, to achieve an optimal performance of constructed wetlands, higher temperatures are needed. Future studies can focus more on maintaining the treatment performance of wetlands in areas with a lower average temperature or with larger temperature differences.

In some studies, the removal performance of P was better than that of N (Gunes et al., 2012; Koskiaho et al., 2003; Li et al., 2008; Zheng et al., 2016). Most of the constructed wetlands were in Mediterranean climate zones, and some others were in Monsoon climate zones (Gunes et al., 2012; Koskiaho et al., 2003; Li et al., 2008; Zheng et al., 2016). In other studies, the removal performance of N was better than that of P (Chyan et al., 2016; Díaz et al., 2012; Pedescoll et al., 2016, 2013; Zhang et al., 2014). Compared to the data of the studies in Table 1, smaller artificial wetlands in a milder climate zone tended to have a better performance in reducing P (Gunes et al., 2012; Koskiaho et al., 2003; Li et al., 2008; Zheng et al., 2016). For example, the wetland in Xi’an, China, and in Garip Village, Turkey, with an area of 0.068 hectares, and 0.284 hectares, respectively, performed better in reducing P than in reducing N (Gunes et al., 2012; Zheng et al., 2016). Other artificial wetlands with larger areas and longer hydraulic residence time tended to perform better in reducing N (Chyan et al., 2016; Díaz et al., 2012; Pedescoll et al., 2016, 2013; Zhang et al., 2014). However, Li et al. (2008) found that longer hydraulic residence time might not improve performance in removing N than P.

Table.1. Removal performance of different scales of wetlands published in previous studies

Sources	Location	Climate zone	Average temperature (°C)	Hydraulic residence Time (d)	Area (ha) depth (cm)	N removal efficiency (%)	P removal efficiency (%)	COD removal efficiency (%)	BOD removal efficiency (%)
(Maxwell et al., 2017)	Mackinaw River watershed, Illinois	Humid continental	5.1 - 15.5	-	3.5 200	18.5 - 44.5	-	-	-
(Chyan et al., 2016)	Taiwan, China	Subtropical	12 - 24.1	-	0.00012 30	17.5 - 32.9	13.3	-	46.7
(Zheng et al., 2016)	Xi'an, China	Warm temperate - Monsoon	0.9 - 27.4	-	0.068 40	53.28	55.56	70.39	90.23
(Pedescoll et al., 2016, 2013)	Northwest of Spain	Mediterranean	10.5 - 20.5	7	0.0104 30 - 50	24.1 - 80	32.29	77.81	84.76
(Zhang et al., 2014)	Beijing, China	Warm temperate - Monsoon	-3.3 - 26.4	0.49 - 3.24	1 65 - 145	44.1	21.05	2.86	-
(Batson et al., 2012)	Columbus, Ohio	Humid continental	-5.6 - 29	-	- 0 - 60	-	-	-	-
(Díaz et al., 2012)	Central Valley, California	Mediterranean	3 - 34	0.9 - 20	4.5 - 173 50 - 125	22 - 98	-20 - 69	-	-20 - 60
(Gunes et al., 2012)	Garip Village, Turkey	Mediterranean	3 - 24.4	1.4	0.284 75	51.4	52.4	69.9	77.5
(Moreno-Mateos et al., 2010)	Monegros, NE Spain	Semi-desert	3.9 - 20.7	4 - 14	0.005 - 0.5 100	36 - 88	-	-	-
(Bastviken et al., 2009)	Plonninge, Sweden	cool-temperate	-12.2 - 14.4	1 - 3	0.0020 40	3 - 15	-	-	-
(Beutel et al., 2009)	Yakima River Basin, Washington	-	-	8	0.795 - 0.696 0.6	91 - 93	-	-	-
(Akratos and Tsihrintzis, 2007)	-	-	-	6 - 20	0.04 100	-0.2 - 79.1	28.2 - 88.6	84.9 - 89.5	84.6 - 89
(Li et al., 2008)	Wuli Lake, China	Subtropical monsoon	-	14	0.003 25 - 30	19.8	35.1	16.5	-
(Poe et al., 2003)	Eastern North Carolina	Humid subtropical	13.3 - 32.2	-	0.06 30	3.5 - 75	-	-	-
(Koskiaho et al., 2003)	Southern Finland	Humid continental mild summer	-9.8 - 16.5	0.25 - 1.6	0.48 - 0.6 0.9 - 2	0 - 34	-20 - 59	-	-
(Braskerud, 2002)	Central and Southern Norway	Marine And Northern European	-5 - 15	-	0.03 - 0.09 20-80	-10 - 32	-	-	-
(Kovacic et al., 2000)	Champaign County, Illinois	Humid continental	5.1 - 15.5	7	0.03 - 0.06 40 - 90	33 - 55	32 - 52	-	-

According to Table 1, chemical oxygen demand (COD) and biochemical oxygen demand (BOD) can also be removed by constructed wetlands. Studies have shown that the average removal efficiency of BOD was around 70% (Chyan et al., 2016; Wang et al., 2015; Zheng et al., 2016). The highest BOD removal rate of 90.23% was obtained by the constructed wetlands in Xi'an, China (Zheng et al., 2016). For COD, there was no clear correlation between the hydraulic residence time and the removal efficiency (Table 1). Generally, the removal performance of BOD was better than that of COD in most cases (Gunes et al., 2012; Pedescoll et al., 2016, 2013; Zheng et al., 2016). However, Díaz et al. (2012) found that BOD might increase because of different vegetation and microorganisms. The highest removal rate was 77.81%, while the hydraulic residence time and area were not the longest and the largest (Pedescoll et al., 2016, 2013). Some studies have shown that the larger the surface areas contributed to the higher COD removal rate (Pedescoll et al., 2016; Zheng et al., 2016). Nevertheless, other studies have reported that even though the surface area of constructed wetlands was large, COD removal was not efficient due to other influencing factors, like vegetation, temperature, or soil types (Zhang et al., 2014; Gunes et al., 2012). Thus, compared to the correlation between the area and the removal efficiency of N and P, the performance of constructed wetlands in removing COD and BOD still needs more research.

3. Mechanisms

Constructed wetlands are integrated systems involving substrates, native microbes, and plants (Liu et al., 2019). The removal of NPSP through the constructed wetlands includes physical, chemical, and biological processes (Bois et al., 2013; Budd et al., 2011; Liu et al., 2019; O'Geen et al., 2010; Wang et al., 2017). Physical processes mainly incorporate sedimentation, volatilization, adsorption, and others (Liu et al., 2019; O'Geen et al., 2010). Chemical methods include denitrification, reduction, oxidation, redox transformation, and others (Liu et al., 2019; O'Geen et al., 2010; Wang et al., 2017). Biological processes rely on the biotic uptake of nutrients, microbial activities, and others (Bois et al., 2013; Budd et al., 2011; Liu et al., 2019; O'Geen et al., 2010). Plant assimilation processes were not considered removal processes unless the plants were harvested, removed, or burned (Díaz et al., 2012; Diaz and Rosenberg, 2008; O'Geen et al., 2010). The discussion will mainly focus on the mechanisms for N and P removal.

3.1. Mechanisms for N Removal

Figure 1 explains the mechanism for N removal in the constructed wetlands. The primary N removal process in constructed wetlands is denitrification, transforming nitrate to N_2O and N_2 gases without oxygen (Díaz et al., 2012; O'Geen et al., 2010). The soils in constructed wetlands have a low redox potential, which largely benefits the denitrification process (Díaz et al., 2012; O'Geen et al., 2010). As shown in Figure 1, other methods for N removal through constructed wetlands include sedimentation, plant assimilation, ammonia volatilization, and particulate N burial (Díaz et al., 2012; O'Geen et al., 2010; Tanner et al., 2005). Several studies have found that the denitrification rate depended on the dissolved oxygen concentration, sediment organic matter concentration, nitrate levels, macrophyte cover, and temperature (Li et al., 2019; Liu et al., 2019; O'Geen et al., 2010; Poe et al., 2003).

Studies have also shown that the denitrification rate decreased as the temperature dropped, which resulted in less optimal removal performances, as shown in Table 1 (Li et al., 2019; Liu et al., 2019; O'Geen et al., 2010; Poe et al., 2003). It was found that the ideal temperature range for denitrification rate was 20°C - 25°C, and the rate dropped below 15° C due to the decrease of the diffusion rate and microbial activity (Beutel et al., 2009; Díaz et al., 2012; O'Geen et al., 2010). Researchers have found that the denitrification rate was largely dependent on the organic carbon available for microorganisms, and the surrounding vegetation primarily affected the amount of available organic carbon (Li et al., 2019; Liu et al., 2019; O'Geen et al., 2010; Poe et al., 2003). In constructed wetlands, a large input of organic carbon is the algae (Díaz et al., 2012; O'Geen et al., 2010).

However, some studies have shown an adverse effect of denitrification (Liu et al., 2008; Mitsch and Gosselink, 2000; O'Geen et al., 2010; Wang et al., 2015). The denitrification process in the constructed wetlands may release the greenhouse gas (N_2O) into the atmosphere (Liu et al., 2008; Mitsch and Gosselink, 2000; O'Geen et al., 2010; Wang et al., 2015). The surrounding vegetation near the wetlands might also release N_2O into the atmosphere (Bruhn et al., 2014; Lenhart et al., 2019; Ni et al., 2013). By releasing additional pollutants into the atmosphere, the performance of wetlands can be affected (Liu et al., 2008; O’Geen et al., 2010; Wang et al., 2015). The removal efficiency of N may be decreased due to the pollutants released (Liu et al., 2008; O’Geen et al., 2010; Wang et al., 2015). Thus, future studies should focus more on reducing greenhouse gases released from both the constructed wetlands and the surrounding plants.

In areas where the dominant forms in the input water are N or NH_4^+ rather than nitrate, mineralization and nitrification are more crucial than denitrification (O’Geen et al., 2010; Wang et al., 2015). Nitrification happens together with oxygen, and as shown in Figure 1, oxygen occurs in the aerobic soil zone and the water body (Diaz and Rosenberg, 2008; O’Geen et al., 2010). An essential mechanism maintaining the aerobic layer is the transport of oxygen to the root zone via the parenchyma of wetland plants (Díaz et al., 2012; Diaz and Rosenberg, 2008; Dowd et al., 2008; O’Geen et al., 2010). Plants with larger root biomass had a greater absorbing ability, and thus, more of the pollutants could be absorbed (Li et al., 2019; Wang et al., 2017; Xia et al., 2020; Zheng et al., 2016). Additionally, other variables affecting N conversions to NO_3^- include the need for chemical oxygen, the available carbon supply, pH, and temperature (Díaz et al., 2012; Diaz and Rosenberg, 2008; Dowd et al., 2008; O’Geen et al., 2010; Xia et al., 2020).

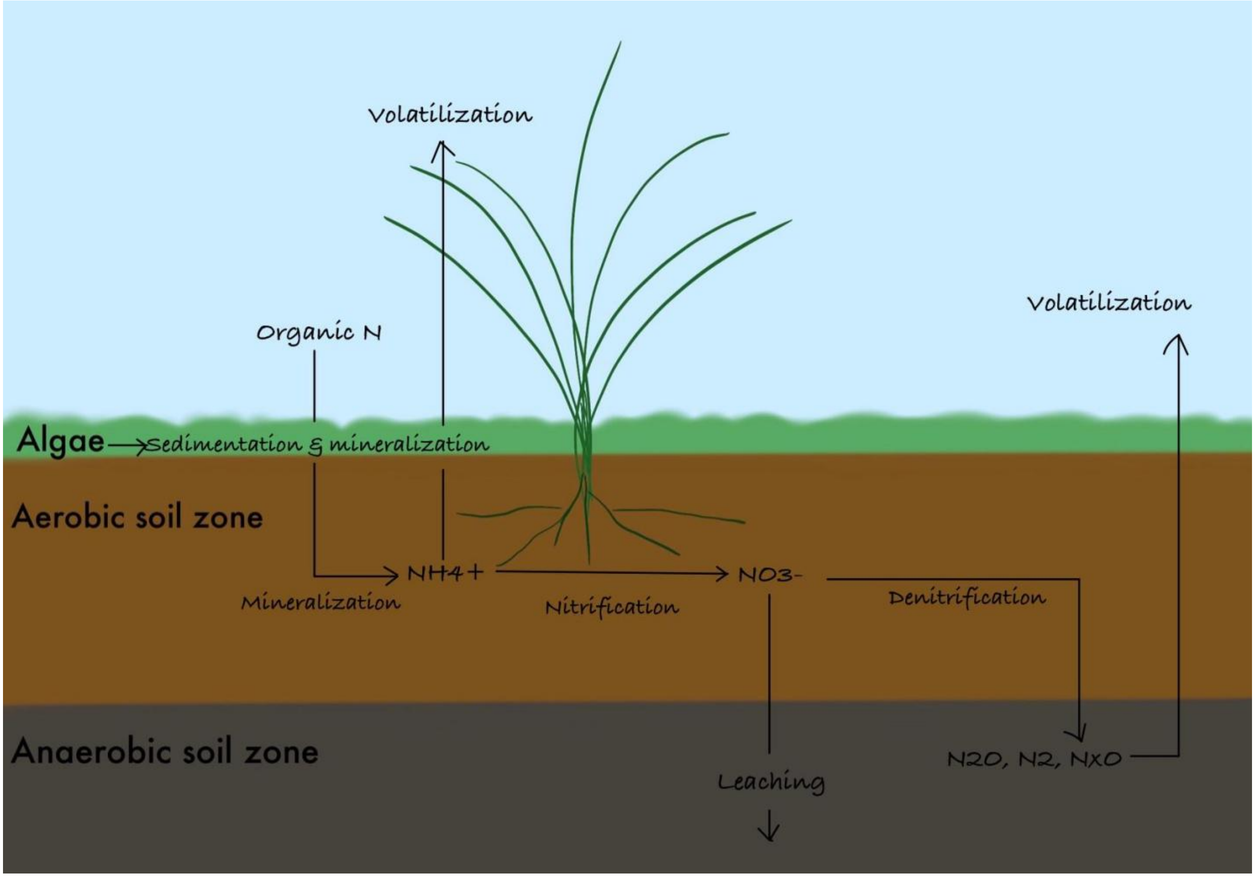

Figure.1. The possible mechanism for N removal in constructed wetlands (O’Geen et al., 2010)

3.2. Mechanisms for P removal

Figure 2 shows the mechanism for P removal in constructed wetlands. When wetland plants and microorganisms decompose, the majority of the P in cellular components is mineralized and made available for future cycling, while a lesser percentage is retained inside refractory organic compounds that contribute to soil accretion (Budd et al., 2011; Diaz and Rosenberg, 2008; O’Geen et al., 2010; Tao et al., 2020). As shown in Figure 2, the mechanisms of P removal also involve mineralization, sedimentation, and assimilation (Diaz and Rosenberg, 2008; O’Geen et al., 2010). In general, both the removal of N and P requires aerobic and anaerobic conditions to finish the processes in removing pollutants (Brauer et al., 2015; Budd et al., 2011; Diaz and Rosenberg, 2008; O’Geen et al., 2010).

Many studies have shown that one of the most crucial P sequestration mechanisms was the process of adsorption (Li et al., 2018; Liu et al., 2019; O’Geen et al., 2010). The most significant P adsorption capacity wetlands are generally alkaline mineral soils with high levels of Ca or neutral to acidic mineral soils with substantial amounts of Fe and Al oxides (Díaz et al., 2012; Litaor et al., 2003; Mitsch and Gosselink, 2000; O'Geen et al., 2010). Some other researchers have shown that the P sorption capacity of constructed wetlands was highly affected by redox processes (Diaz and Rosenberg, 2008; Li et al., 2018; O'Geen et al., 2010; Wang et al., 2017). Redox processes involve iron and the potential interaction with sulfur (Diaz and Rosenberg, 2008; Li et al., 2018; O'Geen et al., 2010; Wang et al., 2017). Lucassen et al. (2004) found that SO_4^{2-} leaching from fields had also been related to eutrophication in freshwater wetlands in many agricultural regions because of its influence on P mobility.

The removal of bioavailable P fractions via sorption processes is a critical mechanism for controlling surface water eutrophication (O'Geen et al., 2010). However, in systems with high sedimentation rates, the influx of fresh surface material containing new sorption sites may prevent P saturation in constructed wetland soils (Diaz and Rosenberg, 2008; O'Geen et al., 2010). Previous research has shown that in anaerobic conditions, many denitrifications phosphorus accumulating bacteria (DPAB) would absorb and store fatty acids in the form of PHA (Li and Huang, 2013; Liu et al., 2013; Sun et al., 2015). In the aerobic process, P in the constructed wetlands (PHA in cells) was decomposed and greatly absorbed by using NO_3^- or O_2 as electron acceptors (Sun et al., 2015; Wang et al., 2008). Thus, both the N and P concentrations were reduced (Sun et al., 2015; Wang et al., 2008).

Many studies have explained the mechanisms for removing N and P (Budd et al., 2011; Díaz et al., 2012; Diaz and Rosenberg, 2008; Litaor et al., 2003; Lucassen et al., 2004; O'Geen et al., 2010). However, few of these studies have measured the actual values of these processes and results in removing NPSP through constructed wetlands (Diaz and Rosenberg, 2008; O'Geen et al., 2010). Thus, more future work should focus on the actual measurement and comparisons of these critical processes. Future studies should also find out under what circumstances the assimilation of P and N will reach optimal conditions. Many other specific vegetation and microorganisms contributing to the processes should also be noticed.

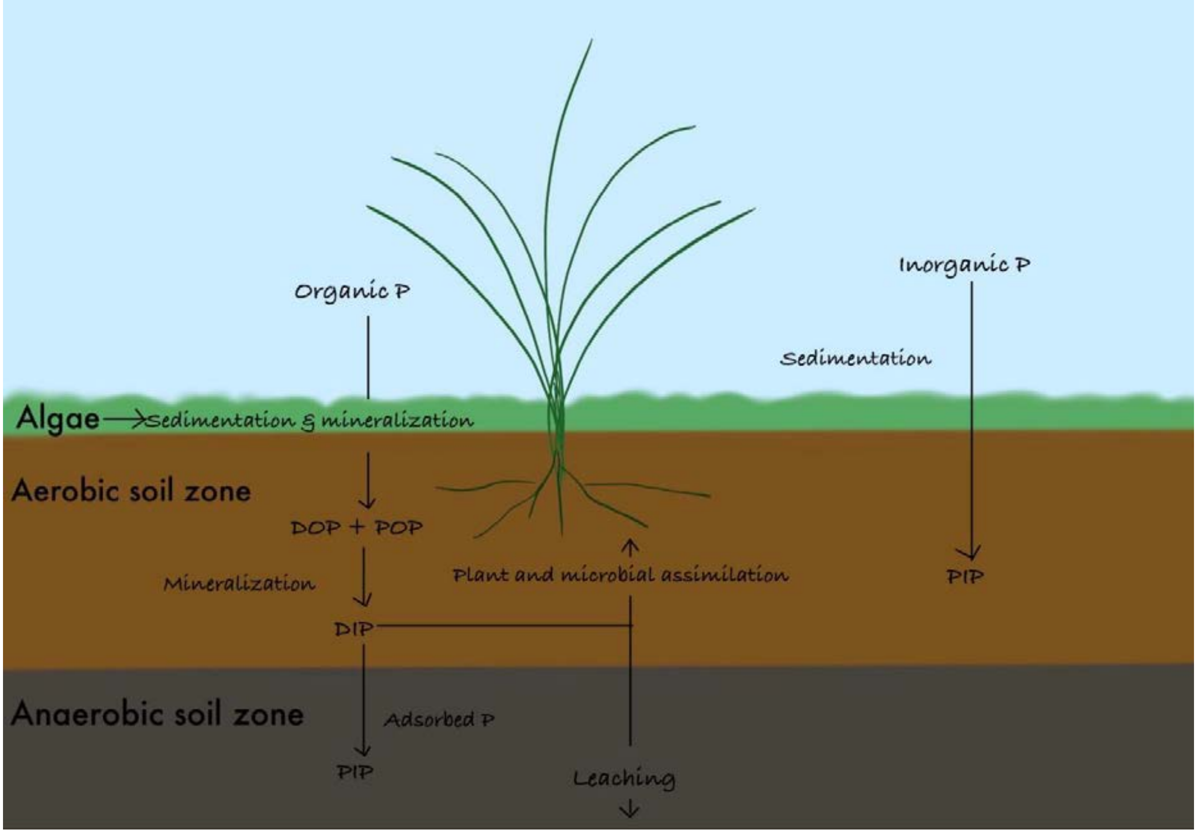

Figure.2. P transformation in constructed wetlands. DOP: dissolved organic P. POP: particulate organic P. DIP: dissolved inorganic P. PIP: particulate inorganic P (O'Geen et al., 2010)

4. Impact Factors

4.1. Temperature

Temperature controls the reaction rates in the constructed wetlands, which indirectly impact the removal efficiencies of the pollutants (Díaz et al., 2012; Diaz and Rosenberg, 2008; O'Geen et al., 2010; Yi et al., 2020). Warmer climate can accelerate the reaction speed, which increases the absorbing rate of N and P (Chyan et al., 2016; Liu et al., 2013; Xia et al., 2020; Yi et al., 2020). As shown in Table 1, better performances of N and P removal could be achieved in higher temperatures (Beutel et al., 2009; Díaz et al., 2012; Dotro et al., 2017; Li et al., 2019; Liu et al., 2013; Xia et al., 2020; Yi et al., 2020). The removal rate achieved the highest while the temperature was the highest. The removal rate of N was 98%, and that of P was 69%, which were performed under 34°C (Díaz et al., 2012). Higher temperatures can accelerate the absorbing processes needed to remove the pollutants, such as assimilation, denitrification, or nitrification (Díaz et al., 2012; Diaz and Rosenberg, 2008; O'Geen et al., 2010; Yi et al., 2020). Furthermore, since some microorganisms may not adapt to large temperature differences or colder conditions, wetlands in areas with smaller temperature differences or higher temperatures were more effective in removing N and P (Chyan et al., 2016; Wang et al., 2015; Zheng et al., 2016).

4.2. Hydraulic Residence Time

Hydraulic residence time refers to the contact time of pollutants with the components in constructed wetlands, including the plant root zone, substrate, and microorganisms (Liu et al., 2019; Stottmeister et al., 2003). Hydraulic residence time is mainly dependent on the wetlands area and depth (Díaz et al., 2012; Diaz and Rosenberg, 2008; O'Geen et al., 2010; Yi et al., 2020). Generally, wetlands with larger surface areas or deeper depths could have a longer hydraulic residence time (Xia et al., 2020; Yi et al., 2020; Cha et al., 2012; O'Geen et al., 2010; Diaz and Rosenberg, 2008; Boesch et al., 2001). Longer hydraulic residence time could allow the pollutants to fully react with the components in the constructed wetlands, increasing the removal efficiency (Xia et al., 2020; Yi et al., 2020; Diaz and Rosenberg, 2008; Boesch et al., 2001). From Table 1, more efficient removal rates could be achieved under a longer hydraulic residence time because the bacteria or enzymes would have a longer time to react and absorb the pollutants (Gunes et al., 2012; Koskiaho et al., 2003; Li et al., 2008; Zheng et al., 2016). However, Li et al. (2008) and Gunes et al. (2012) found an opposite trend that when hydraulic residence time increased from 1.4 days to 14 days, the removal rate of N decreased from 51.4% to 19.8%. Possible reasons for this would be the difference in vegetation and microbes, and the holding capacity of constructed wetlands might be reached (Li et al., 2008; Zheng et al., 2016).

4.3. Vegetation

In constructed wetlands, vegetation plays an essential role in the infiltration of pollutants like N and P (O'Geen et al., 2010). Plants with larger root biomass can indirectly increase the absorbing processes (Li et al., 2019, 2008; Xia et al., 2020). Studies have found that the stems and leaves of vegetation under the water can also prevent sediment resuspension and promote particles of pollutants settling (Díaz et al., 2012; Diaz and Rosenberg, 2008; O'Geen et al., 2010; Yi et al., 2020). Braskerud (2001) has found that vegetation in constructed wetlands also increased the surface area of the substrate, which provided more space for microorganisms to react with the pollutants. Surrounding plants also provide organic carbon to the microbes as the plants die, which promotes the denitrification process (Akratos and Tsihrintzis, 2007; Braskerud, 2001; Diaz and Rosenberg, 2008; O'Geen et al., 2010). Akratos and Tsihrintzis (2007) found that cattail seemed to be the most effective plant to absorb N and P because of its high stand and leaf mass.

4.4 Input Concentrations

Wetlands receiving irrigation runoff would have seasonal variability of input concentrations of pollutants in terms of the different cropping systems and growing seasons (O'Geen et al., 2010). In California Central Valley, the input concentrations of contaminants of the constructed wetlands were highly variable because of its unique cropping systems (Brauer et al., 2009; O’Geen et al., 2010). Studies have found that the removal efficiency of pollutants could be affected by the input concentrations (Brauer et al., 2009; Li et al., 2008; O’Geen et al., 2010). In general, a constructed wetland with a more constant input concentration of pollutants could be more effective in removing those contaminants (Brauer et al., 2009; Li et al., 2008; O’Geen et al., 2010). Brauer et al. (2009) has found that the input concentrations of contaminants were less variable in larger areas with constantly higher input loads. The concentration of pollutants would be more variable in smaller wetlands because of the timing of biochemical processes, cultivation, irrigation, and other factors (Brauer et al., 2009; Li et al., 2008; O’Geen et al., 2010). The higher the initial concentration would require a more extensive artificial wetland with a longer reacting time with microorganisms and vegetation (Diaz and Rosenberg, 2008; Dotro et al., 2017; Gunes et al., 2012; Yang, 2003).

5. Conclusions

The performance of constructed wetlands was comprehensively and systematically reviewed in this text. In this context, the treatment performance, the mechanisms, and the impact factors of constructed wetlands were discussed. The treatment efficiency in N and P removal ranged from 17.5% to 98% and from 13.3% to 69%, respectively. The performance of treatments can be effectively affected by several factors, including temperature, hydraulic residence time, vegetation, and input concentrations. The higher temperature and more negligible temperature difference would benefit the removing processes and the activities of the microorganisms. A longer hydraulic residence time would be preferred. The removal efficiency would be increased if the surrounding plants had larger root biomass. A more constant input concentration of contaminants could be more effective in removing the pollutants. The general mechanisms in removing N and P include denitrification, nitrification, plant assimilation, adsorption, and sorption processes. The denitrification rate increased as the temperature increased, improving the performance of constructed wetlands. Generally, both aerobic and anaerobic conditions were required in removing N and P.

Even though many studies focused on the performance of constructed wetlands in removing NPSP, the pathway to improve constructed wetlands still needs more research. Guaranteeing the efficiency of pollutant removal of wetlands in colder areas or areas with a significant temperature difference and determining the optimal conditions of N and P assimilation still requires more studies. Since the denitrification process would release greenhouse gases into the atmosphere, future studies should find a way to decrease pollutants from constructed wetlands and the surrounding vegetation. The actual measurement and comparisons of the critical removal processes should be the subject of additional future research, such as more specific beneficial plants and microorganisms.

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