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Articles

State of art: A current review of the mechanisms that make the artificial wetlands for the removal of nitrogen and phosphorus

Estado del arte: una revisión actual a los mecanismos que realizan los humedales artificiales para la remoción de nitrógeno y fósforo

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Abstract

Constructed wetlands for wastewater treatment are used as green technology, resulting from the need to replicate the ecological benefits of natural wetlands to treat various tributaries of wastewater. This work is a literature review of the different types of constructed wetlands and their treatment processes. Many studies have been conducted on constructed wetlands, but a synergy of this information remains to be done. However, although constructed wetlands are a common management practice for mitigating pollutants from agricultural and municipal runoff, many countries do not have comparative studies of the effectiveness of disposal, maintenance neither extensive research on alternative substrates nor preventive measures to avoid substrate clogging.

Keywords: Wastewater treatment, constructed wetlands, removal, nitrogen, phosphorus.

Resumen

El tratamiento de aguas residuales por medio de los humedales artificiales se utiliza como una tecnología verde que surge de la necesidad de replicar los beneficios ecosistémicos de los humedales naturales para tratar diversos afluentes de aguas residuales. Este trabajo presenta una revisión bibliográfica acerca de los diferentes tipos de humedales artificiales y sus procesos depurativos. Si bien existen muchos estudios sobre humedales artificiales, es necesario realizar una sinergia de dicha información. No obstante, aunque los humedales artificiales son una frecuente práctica de gestión para la mitigación de contaminantes provenientes de escorrentía agrícola y municipal, en muchos países faltan estudios comparativos sobre su eficiencia depurativa y el mantenimiento a los mismos, así como profundizar en la investigación de sustratos alternativos y detallar medidas preventivas para la evitar la colmatación del sustrato.

Palabras clave: tratamiento de aguas residuales, humedales construidos, remoción, nitrógeno, fósforo.

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Introduction

Today, there is a serious problem of pollution of natural watercourses and water bodies that receive domestic, industrial and agricultural effluents without treatment of any kind (Cloter, Mazari, & De Anda, 2006).

The problem is the declining water quality of lakes and reservoirs characterized by a high concentration of organic matter, suspended solids, dissolved solids, nutrients, toxic compounds and microorganisms posing a health risk. Discharges from agro-food industries and from rural, urban and tourist areas are characterized by high levels of organic inputs. Therefore, the reuse of this wastewater for agricultural irrigation entails collateral risks to public health, related to the concentration level of pollutants (Ramírez-Carrillo, Luna-Pabello, & Arredondo-Figueroa, 2009). This wastewater must be treated, but it is expensive, and the construction and implementation of the system can have a major environmental impact. In this sense, wastewater management in rural and urban areas is a challenge because of the lack of adequate infrastructure and economic capacity.

Wastewater treatment is essential and seeks to make the most of eco-technologies or appropriate technologies using or imitating nature, taking advantage of its components, such as biota and soils.

Constructed wetlands are systems specifically engineered for wastewater treatment, in which natural remediation processes and system efficiency are enhanced by optimizing the physical, chemical and biological processes occurring in natural wetland ecosystems (Vymazal & Brix, 1998). Nitrogen removal begins with the transformation of organic nitrogen (N_{Org}) to ammoniacal nitrogen ($N\text{-}NH_4^+$) via ammonification. $N\text{-}NH_4^+$ can be assimilated by plant roots or micro-organisms and volatize if the pH of the system is greater than 8 or oxidized to nitrate (NO_3^-) (nitrification) by the action of ammonia-oxidizing and nitrite-oxidizing bacteria. The last step is the reduction of NO_3^- to molecular nitrogen (N_2) under anoxic / anaerobic conditions (denitrification) (Torres-Bojorges, Zurita, & Tejeda, 2017).

In order to treat high organic loads, wetlands called HIGH-rate constructed WETlands (HIGHWET) are created, using plastic elements as a substrate, thereby obtaining high porosity for the treatment of wastewater. Plant diversity is an important factor in pollutant removal capacity in wetlands. Macrophytes rhizosphere stimulates the growth of microbial communities, thus, any modification concerning plant diversity and its habitat leads to changes in the microbial community, and thus affects the removal efficiency of pollutants (Corzo, Sanabria, & García, 2016).

The main purpose of this paper is to review and discuss the current status of constructed wetlands, different types of wetlands and, most importantly, technology to remove nitrogen and organic matter.

Materials and methods

A comprehensive literature search was conducted to collect studies providing more information on constructed wetlands. The following are the databases used to compile these data: Elsevier, Ebsco, Springer, Science Citation Index Expanded (SCIE) and Social Sciences Citation

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Index (SSCI) from Web of Science (WOS) and Scopus. The results of the online search include studies conducted up to August 1, 2018.

Natural and constructed wetlands

A wetland is defined as any saturated zone of fresh or saltwater, temporary or permanent, with typical vegetation suitable for saturated soils (Vymazal & Brix, 1998). Riparian ecosystems act as a nutrient sink for upland runoff. As a result, these wetlands are important buffer zones between farmland and watercourses. There are mitigation techniques commonly used in the field to prevent the introduction of pesticides into water bodies, such as hedgerows, vegetative barriers (dense vegetation strips, serving as a porous filtering barrier for runoff water) (Vymazal & Březinová, 2015), vegetated ditches and Constructed Wetlands (CW). Constructed wetlands provide a surface for the growth of the micro-organisms responsible for the filtration and absorption of pollutants and inhibit the growth of algae.

Constructed wetlands are classified as Free Water Surface (FWS) wetlands or Floating Aquatic Plant (FAP) systems and SubSurface Flow (SSF) wetlands or Rooted Emergent Plants systems, which are divided in turn into Vertical Flow systems (VSSF) and Horizontal Flow systems (HSSF).

Free Water Surface wetlands are ponds or canals with floating root plants in which the surface of the water is exposed to the atmosphere. On the other hand, SubSurface Flow wetlands are ponds with emergent plants and a porous substrate (sand, gravel or any type of coarse-textured soil). There are two types: Horizontal Flow and Vertical Flow wetlands, depending on how the effluent feeds the wetland. The feeding of the Vertical Flow wetlands is carried out at intervals of time, in order to allow percolation of the tributary into the substrate.

Although constructed wetlands are intended for various types of wastewater, they have been documented as natural methods of water treatment since 1912. The United States Environmental Protection

Agency (EPA, 1993), was the first to take samples from 1960 to 1970. World-wide projects from 1972 to 1983 have also been documented and studies on the removal of phosphorus and nitrogen (N and P) from constructed wetlands have been conducted since 1970. Constructed wetland-based studies to eliminate pesticides also began in the 1970s. And in the 1990s, studies were conducted on nutrient treatment in constructed wetlands on rivers (Vymazal & Březinová, 2015).

In 1967 a scale Free Water Surface system was developed. In Germany, in the 1970s Dr. Kichuth created a system called the "Root Zone Method", which consisted of a Horizontal Flow wetland in which he planted *Phragmites australis*, adding a combination of calcium and iron or aluminum to cause precipitation of phosphorus. In the United States, the study on wetlands is based on the results of European studies, particularly on natural wetlands. This green technology has also been studied by NASA, which has developed its own system called "Hybrid Treatment System" because it uses anaerobic microorganisms and emerging plants (*Phragmites communis*) (Rodríguez, 2003).

Advantages and disadvantages

Constructed wetlands have great technical, economic, social and aesthetic advantages over conventional wastewater treatment. In accordance with the regulations, quality treated water is obtained which is suitable for agricultural irrigation as it eliminates pathogenic micro-organisms. The costs of implementation, operation and maintenance compared to traditional wastewater treatment systems are lower because they have a useful life of 25 years and minimal energy requirements because gravity is used to bring water to the wetlands. The construction characteristics of wetlands make it difficult to develop imbalances due to changes in pollutant concentrations or oscillations in wetland tributaries (Miranda & Luna-Pabello, 2001). In addition, these systems, where the water flows under the surface of the support, do not favor the development of mosquitoes and unpleasant odors, and even offer a thermal protection to the system (plants, substrate and water), allowing the installation of wetlands in places with heavy frosts (Llagas, Wilmer, & Gómez, 2006).

Although having many advantages, this type of wastewater treatment system has the main disadvantage of requiring a lot of ground for its installation. Consideration should also be given to the disadvantages of SubSurface Flow wetlands, such as the cost of the media used, as well as its routing and installation (Rodríguez, 2003).

Types of constructed wetlands

The establishment of constructed wetlands is a sensitive issue because of the variability in wastewater composition that often changes treatment needs. Plant selection is an important issue in this type of design as it must survive the potential toxic effects of wastewater (Calheiros, Rangel, & Castro, 2007).

Free water surface (FWS)

Free Water Surface wetlands, perhaps the oldest, are used as secondary treatment for the purification of pesticides. They are designed for low surface loads, with depths ranging from 5 to 90 cm. However, they often have a depth of between 30 and 40 cm on trenches 3 m wide and 100 m long. The plant used is *Scirpus lacustris*. Removal effectiveness in Free Water Surface wetlands is 96% for TSS, 96% for BOD, 87% for COD (Chemical Oxygen Demand) and 30% for TP (Total Phosphorus) (Rodríguez, 2003).

Horizontal subsurface flow

HSSF systems emerged as an alternative to secondary treatments with saturated porous media, planted with emerging plants. They are used for industrial wastewater, especially for the treatment of wastewater from food processing (Vymazal, 2009).

HSSF have a high capacity for removal of organic matter, BOD_5 (Biochemical Oxygen Demand measured at 5 days), COD and Total Suspended Solids. However, eliminating fewer nutrients. Therefore, *T. latifolia* and *P. australis* are plant species that adapt better to tannery wastewaters in terms of survival and spread. HSSFs are a viable alternative to reduce the organic matter content of wastewater because they tolerate fluctuations or intermittent flow (Calheiros *et al.*, 2007). Likewise, they act as a protection against secondary salinization of the soil. The following are the plants used for the desalination of agricultural substrates: *Typha spp., Phragmites communis, Phragmites japonica, Medicago sativa Linn., Lemna minor L.* and *Potamogeton crispus. Typha spp., Phragmites communis* and *Potamogeton crispus*. The removal efficiencies of Ca^{2+}, Mg^{2+}, Na^{+} Cl^{-} and SO_4^{2-} can reach 80% with *Typha* spp. (Yang, Sheng, Zhang, Kang, & Liu, 2015).

Clay soils, through their ion exchange capacity, allow the temporary removal of nitrogen present in wastewater, depending on the time of stabilization of the system. In the case of HF constructed wetlands using soil, there is an additional potential for the removal of phosphorus and ammonium. While in VF systems, due to intermittent flow, aerobic conditions are restored, and ammonium adsorbed. When using gravel in wet areas, phosphorus removal capacity is limited.

The most used macrophytes for the treatment of wastewater in pond-type systems fall mainly into two classes: floating aquatic plants and submerged aquatic plants. Floating plants absorb carbon dioxide according to their oxygen requirements, while submerged plants are inhibited by turbidity (Yang *et al*., 2015).

Vertical subsurface flow

The application of water in Vertical SubSurface Flow constructed wetlands (VSSF) is carried out uniformly on the bed. They are commonly used as secondary systems in two steps: one with two vertical flow cells, and one with a horizontal flow cell. These steps are intended to depurate the effluents. The main advantage of this type of system lies in the restoration of aerobic conditions during dry periods (Rodríguez, 2003). The effectiveness of the treatment process depends to a large extent on the aeration of the substrate. In addition, this type of system may become clogged. Therefore, it is advisable to limit the organic load fed to 25 g of COD / m2 per day, and to rotate the system to oxygenate the bed to let it rest and dry (Ramírez-Carrillo *et al*., 2009).

Vertical SubSurface Flow with recirculation and intermittent operation, always operating under high loads, promote better mixing in the wetland bed, accelerating oxygen diffusion and increasing COD and NO3- removal, thus reducing the area used, which makes it favorable for mountainous wetlands where limited space is available (Foladori, Ruaben, & Ortigara, 2013).

Combined or hybrid wetlands systems

A common feature of HSSF is the preservation of anoxic conditions, thus creating conditions conducive to denitration. On the other hand, the VSSF maintains favorable aerobic conditions for nitrification, thus combining the two types of wetlands (built in series and thus constituting hybrid wetlands) that potentiate the total elimination of nitrogen (Ntotal), (Vymazal, 2014). These combined wetlands provide greater efficiency in wastewater treatment (Vymazal, 2009), at different stages of treatment (Torres-Bojorges *et al*., 2017).

There is another type of hybridization combining superficial and subsurface flow systems, depending on the pollutants to be treated, in order to obtain an optimally functioning system. Vymazal (2009) compiles information on the different combinations of hybrid systems, as well as on the different types of tributaries used for each system (table 1).

Table 1. Hybrid systems of constructed wetlands. Synopsis of wetland prototype and type of tributary (Vymazal, 2009).

<table>
<tr><th>Type of wetland</th><th>Country</th><th>Type of wastewater</th></tr>
<tr><td>VF-HF</td><td>United Kingdom, USA, Estonia, France, Ireland, Tunisia</td><td rowspan="8">Wastewater</td></tr>
<tr><td>HF-VF</td><td>Denmark, Poland, Mexico</td></tr>
<tr><td>FWS-HF</td><td>Greece</td></tr>
<tr><td>HF-FWS</td><td>Canada, Kenya</td></tr>
<tr><td>HF-VF-HF</td><td>Poland</td></tr>
<tr><td>VF-HF-FWS-P</td><td>Estonia</td></tr>
<tr><td>VF-HF-FWS-P</td><td>Thailand</td></tr>
<tr><td>HF-VF-HF-FWS</td><td>Italy</td></tr>
<tr><td>VF-HF</td><td>Slovenia</td><td rowspan="4">Leachate from landfills</td></tr>
<tr><td>HF-FWS</td><td>Norway, Canada</td></tr>
<tr><td>FL-HF</td><td>USA</td></tr>
<tr><td>VF-HF-P</td><td>Portugal</td></tr>
<tr><td>HF-VF</td><td>Nepal</td><td>Hospital</td></tr>
<tr><td rowspan="3">VF-HF</td><td>Japan</td><td>Dairy</td></tr>
<tr><td>France</td><td>Creamery</td></tr>
<tr><td>Thailand</td><td>Pig farm</td></tr>
<tr><td>HF-FWS</td><td>Italy</td><td rowspan="2">Winepress</td></tr>
<tr><td>VF-HF-FWS-P</td><td>Italy</td></tr>
<tr><td rowspan="2">FWS-HF</td><td>Taiwan</td><td>Aquaculture (fish)</td></tr>
<tr><td>Taiwan</td><td>Aquaculture (shrimp)</td></tr>
</table>

	Taiwan	Polluted river
	China	Industrial
	Uganda	Mining
VF-HF	France	Compost leachate
	Poland	Slaughterhouse

VF = Vertical Flow, HF = Horizontal Flow, FWS = Free Water Surface or P = Pond.

Treatment processes

The constructed wetlands are primarily used for the retention of nutrients and organic matter in domestic and municipal wastewater, rainwater and agricultural runoff. Fertilizers used for agriculture mainly contain phosphate, which seeps into groundwater from agricultural runoff (Zhang, Moon, Myneni, & Jaffé, 2017). Although P is important for ecosystems, large amounts can lead to eutrophication of water bodies, caused by excess nitrogen (N) and phosphorus (P), which causes algal growth and reduction of oxygen levels. Within constructed wetlands, physical, chemical and biological processes are carried out, removing pollutants from wastewater. These processes include sedimentation, adsorption on soil particles, plant uptake and microbial transformation (Rodríguez, 2003).

Selecting a suitable substrate is an important step in promoting biofilm development within the wetland (Wu, Kuschk, Brix, Vymazal, & Dong, 2014). The microflora that grows in a wetland is varied, including bacteria, protozoa and even small animals, with bacteria constituting the basic purifier group of wastewater treatment processes.

Water moves slowly through the wetland, due to the laminar flow of these systems and the resistance provided by the roots and vegetation, which serves as sediment traps, while constituting the main means of elimination of phosphorus (Pavlineri, Skoulikidis, & Tsihrintzis, 2017). Although wetlands are effective in purifying organic compounds and suspended solids to further eliminate nitrogen, it is essential to consider feeding, wetland type (Vymazal, 2018) and recirculation (Wu *et al*., 2014).

The biological processes of elimination are certainly the most important for the elimination of pollutants. These processes begin with the uptake of oxygen by the plant. Some of the pollutants are nutrients for plants, such as nitrate, ammonium and phosphate ions, which are absorbed by plants. The elimination of pollutants by plants can vary depending on the age of the plant. Bacteria and other soil micro-organisms also provide, capture and store short-term nutrients, as well as some other pollutants. Microorganisms in wetlands remove organic compounds. Treatment in this type of system is usually due to the presence of microbial populations adhering to the surface of the plants and the support. Microbial metabolism also produces the removal of inorganic nitrogen, namely nitrate and ammonium in wetlands. Nitrogen removal begins with the transformation of organic nitrogen (N_{Org}) to ammonia nitrogen ($N\text{-}NH_4^+$) by ammonification. The $N\text{-}NH_4^+$ can be assimilated by plant roots or microorganisms and volatilized if the pH of the system is greater than 9 or oxidized to nitrate ($NO3^-$) by the action of ammonium-oxidizing and nitrite-oxidizing bacteria (nitrification). The last step is the reduction of $NO3^-$ in molecular nitrogen (N2) under anoxic/anaerobic conditions (denitrification). Transformations suffered by nitrogen in wetlands vary according to whether their structure is horizontal or vertical (Torres-Bojorges *et al*., 2017).

The most important chemical removal process in soil is absorption, resulting in short-term retention and long-term immobilization of various types of pollutants. Another important process in wetlands is adsorption, which involves binding ions to soil particles by cation exchange on the surface of clay particles and soil organic matter.

It is from the joint action of removal and metabolic processes carried out in the wetland by the microflora, that the removal of Total Suspended Solids (TSS) and some of the biodegradable organic matter (BOD) occurs by sedimentation and filtration of water. While biodegradable organic matter (BOD) is purified through microbial degradation (aerobic, anaerobic, and facultative). To eliminate nitrogen, the mechanisms of removal are ammonification, followed by bacterial nitrification-denitrification, volatilization of ammonia, in addition to the consumption of the plant.

Phosphorus in turn exhibits adsorption-precipitation reactions with aluminum, iron, calcium and the minerals characteristic of clay, in addition to a portion consumed by the plant. The removal of heavy metals is achieved by sedimentation and adsorption on the surface of the plant and debris.

Constructed wetlands encourage the removal of pathogens, through sedimentation and filtration, ultraviolet radiation, excretion of antibiotics from plant roots and natural death (Rodríguez, 2003). Plants within the wetlands provide the necessary surface for microbial growth, allow filtration and adsorption of pollutants in wastewater, inhibit the growth of algae, and promote the circulation of oxygen, which plants capture through their stems and leaves to be used by the roots.

Similarly, in constructed wetlands, several aerobic and anaerobic biogeochemical processes govern the retention and removal of pollutants. Carbon and the efficiency of the removal of toxic organic compounds are obtained by measuring the oxygen in the soil or in the water of the effluent. Although the removal of nitrates can be verified by measuring dissolved organic carbon, phosphorus retention can also be verified by the availability of reactive iron and aluminum in acid soils or in alkaline soils for Ca and Mg (Reddy & D’Angelo, 1997).

Nitrogen removal in constructed wetlands includes processes such as NH_3 volatilization, nitrification, denitrification, N_2 fixation, plant and microbial uptake, mineralization, nitrate reduction to ammonium, anaerobic oxidation of ammonia, fragmentation, adsorption, desorption, landfilling, leaching, etc. (Gao, Zhang, Gao, Jia, & Yang, 2018).

Plants indirectly influence the removal of nitrogen by nitrification and denitrification. These processes affect oxygen concentration, particularly in the rhizosphere, and increase the supply of potentially denitrifying bacteria, by limiting organic carbon and nitrates.

The transport of oxygen to the rhizosphere through the plants promotes the oxygenation points adjacent to the root zone and triggers the nitrification process (Ye & Li, 2009).

The presence of plants in wetlands promotes the elimination of nutrients by decreasing flow velocity, increasing hydraulic loading, and reducing resuspension of sediments (Laterra, Booman, Picone, Videla, & Orúe, 2018). In the same way, intermittent aeration promotes nitrification and denitrification (Llyas & Masih, 2017).

The removal of phosphorus from wetlands begins with the process of adsorption, precipitation, plant uptake and peat accumulation, fragmentation, leaching, mineralization and sedimentation. However, the limited adsorption capacity of the substrate and the inhibitory effect of microbes and plants at low temperatures are serious obstacles preventing constructed wetlands from effectively removing nitrogen and phosphorus.

Phosphorus removal in constructed wetlands is carried out in a biological and physicochemical way. Although the plant-nutrient interaction of the wetland is important for streamlining the eutrophic water mass treatment process, nutrient uptake by plants and microbes in wetlands is a complex process that includes series of chemical and biological reactions (Zhao, Li, & Chen, 2018). Biological methods are given by phosphorus uptake in plant tissues and finalized by harvest, while in physico-chemical methods, where the precipitation and adsorption process is carried out, the oxidation-reduction potential and the support are the most important (Andrés, Araya, Vera, Pozo, & Vidal, 2018).

Currently, more attention is being paid to the elimination of pesticides. These products are removed in these systems by physical (sedimentation, flocculation, absorption, coprecipitation, precipitation), chemical (oxidation, reduction, cation exchange, hydrolysis, photolysis), biological (absorption and metabolism of the plant) or biochemical (microbial degradation) processes (Vymazal & Březinová, 2015). Constructed wetlands can be classified according to different criteria: hydrology (surface flow and subsurface flow), types of macrophytes (floating, emergent and submerged) and flow path (horizontal or vertical) (Vymazal, 2011). They can be successfully applied for the decentralized treatment of wastewater in sparsely populated areas (Machado, Beretta, Fragoso, & Duarte, 2017).

In the subsurface flow wetlands, the flow of water runs underground, allowing oxygenation of the system and the treatment of high loads of organic pollutants, while FWS and FIs (Floating Islands) are systems flooded with a water mirror exposed to the environment whose only form of oxygenation of the system is through the vegetation.

The depth of the IFs must allow the vegetation to settle in the bottom, which allows the accumulation of organic remains from plant, animal and human sources.

Although different types of constructed wetlands offer different advantages in terms of wastewater treatment, Table 2 compares the advantages and disadvantages, both operational and functional, of water purification efficiency for nitrogen (ammoniacal, nitrates, nitrites, organic) and phosphorus (phosphates, organic) between different constructed wetlands (Free Water Surface, Subsurface Flow and Floating Islands). In Horizontal Flow wetlands the decomposition of organic matter occurs through aerobic and anaerobic microbial processes, as well as sedimentation and filtration of particulate organic matter. Although the removal of nitrogen is by nitrification, anoxic and anaerobic conditions are suitable for denitrification. Although the removal of phosphorus is produced by adsorption and precipitation (Vymazal, 2014). In Vertical Flow wetlands, oxygen diffusion from the air contributes much more to the oxygenation of the filtration bed.

Table 2. Advantages and disadvantages of removal mechanisms in constructed wetlands (Pavlineri *et al*., 2017; Vymazal, 2014; Vymazal, 2005; Foladori *et al*., 2013; Cooper & Knight, 1996; Cooper, 1999).

Mechanisms for removal of pollutants in wetland systems					
Pollutant	**Advantages**		**Disadvantages**		**Type of wetland**
Nitrogen	Sedimentation by gravity, organic soluble by suspended bacteria, benthic and attached to plants	Water volatilization, microbial metabolism, sedimentation, adsorption	When nitrogen levels are less than 1.5%, organisms use that N in their biosynthesis and not the vegetation	Not 100% degradable	Superficial flow, subsuperficial flow and floating islands
Ammonia nitrogen	Less concentration in FSSCW	Water volatilization, nitrification	Less concentration in FWS and FI	Not 100% degradable	Removes up to 94% in VF, up to 30% in FWS and HF

Nitrates	Ammonification, nitrification, denitrification and adsorption	Decomposition and mineralization	The process depends on the oxygen concentration	Not 100% degradable	Removes up to 95% in FWS, up to 80% in combo VF + HF systems
Nitrites	Ammonification, nitrification, denitrification and adsorption	Decomposition and mineralization	The process depends on the oxygen concentration for removal	Not 100% degradable	
Organic nitrogen		Sedimentation, filtration, microbial metabolism, decomposition	The process depends on the oxygen concentration for removal	Not 100% degradable	
Phosphorus	Formation or coprecipitation with insoluble compounds	Precipitation, adsorption, sedimentation			Removes up to 96% in VF, up to 91% in combo VF + HF systems
Phosphates		Adsorption and precipitation	Slightly soluble in the substrate, must use reverse osmosis or activated carbon for removal		
Organic phosphorus	Adsorption on the surface of the substrate and the plant	Sedimentation, filtration, microbial metabolism, decomposition, adsorption		Not 100% degradable	

VF = Vertical Flow, HF = Horizontal Flow, FWS = Free Water Surface or P = Pond, IF = Floating Island.

Higher system oxygenation (> 1.50 mg OD L^{-1} for nitrification and < 0.50 mg OD L^{-1} for denitrification), produces increased biodegradation and efficiency for the removal of nitrogen and organic matter in the system.

Floating island plants have a good ability to absorb N and P. The following are the most important processes in aquatic models: nutrient uptake by emerging macrophytes, phytoplankton and submerged plants, zooplankton feeding, detritus, sediments, phosphorus and sediment mineralization, nutrient propagation, and diffusion of phosphorus and nitrogen (Pavlineri *et al*., 2017; Kedlec y Wallace, 2009; Vymazal, 2013; Vymazal, 2005; Foladori *et al*., 2013; Cooper & Knight, 1996).

In Vertical Flow wetlands, the diffusion of oxygen in the air contributes a lot to the oxygenation of the filtration bed. Hybrid wetlands stem from the need to increase the benefits of vertical and horizontal flow wetlands (Vymazal, 2014).

Low treatment efficiency, as well as clogging, are problems caused by conventional substrates, for which the research also focuses on the search for profitable and efficient substrates (oyster shells, pieces of tires, construction waste, expansive clay aggregates, etc.) to increase the purification capacity and to minimize clogging issues. Ideally, substrates have unique physicochemical properties for the efficient removal of pollutants (Gao *et al*., 2018).

The longer the retention time, the higher the pollutant removal percentage (Ramírez-Carrillo *et al*., 2009).

In order to remove high rates of organic matter, so-called HIGH-rate constructed WETlands (HIGHWET) are emerging as a new variant of wetlands. These systems use plastic as a support, which promotes biofilm formation and achieves a porosity of up to 94-96% (Corzo *et al*., 2016).

Gravel and volcanic slag are often used as substrates for the rehabilitation of polluted rivers. By using slag as a substrate, it is possible to further eliminate Total Phosphorus (TP) and to reduce the Chemical Oxygen Demand (COD). However, the adsorption of TP (Total Phosphorus) by slag quickly saturates during the follow-up period (Ge *et al*., 2015). P concentration is regulated in wetland sediments by adsorbing it and releasing it under certain physicochemical and biological conditions (Cui, Xiao Xie, & Zhang, 2018). To optimize P removal in wetlands, different materials have been used, allowing this process in the long run. The following are some of the media used in wetlands to improve the removal of P: zeolite, dolomite, gravel, sand, limestone and apatite, alunite, red mud, ash and slag (Gao *et al*., 2018).

Conclusions

Although many studies have been conducted on constructed wetlands, the search for information is subject to professional bias. A synergy of this information is therefore necessary.

Constructed wetlands are the best management practice for mitigating pollutants (pesticides, non-point sources, agricultural run-off and drainage) in many countries. However, comparative studies on the effectiveness of treatment of pollutants and constructed wetlands are still lacking. Additional knowledge about the advantages and disadvantages of alternative substrates and how to combine them (which are preventative measures to avoid clogging the substrate in the wetland) is also needed.

References

EPA, Agencia de Protección Ambiental de Estados Unidos. (1993). *Guía de diseño y construcción de un humedal construido con flujo superficial*. Región 6. Dallas, EUA: Agencia de Protección Ambiental de Estados Unidos.

Andrés, E., Araya, F., Vera, I., Pozo, G., & Vidal, G. (2018). Phosphate removal using zeolite in treatment wetlands under different oxidation-reduction potentials. *Ecological Engineering*, 117, 18-27.

Calheiros, C., Rangel, A., & Castro, P. (2007). Constructed wetland systems vegetated with different plants applied to the treatment of tannery wastewater. *Water Research*, 41(8), 1790–1798.

Cloter, A., Mazari, H., & De Anda, S. (2006). *Atlas de la cuenca Lerma Chapala construyendo una visión conjunta*. México, DF, México: Secretaría de Medio Ambiente y Recursos Naturales.

Cooper, C., & Knight, S. (1996). Insecticide and metal contamination of a mixed cover agricultural watershed. *Water Science and Technology*, 33(2), 227-234.

Cooper, P. (1999). A review of the design and performance of vertical-flow and hybrid reed bed treatment systems. *Water Science and Technology*, 40(3), 1-9.

Corzo, A., Sanabria, O., & García, M. (2016). Optimización hidráulica de humedales artificiales de alta tasa de rellenos con medios de soporte plástico. *Memorias de la III Conferencia Panamericana de Sistemas de Humedales para el Tratamiento y Mejoramiento de la calidad del Agua, 2016*, Universidad Nacional del Litoral, Facultad de Ingeniería Química. Recovered fromhttp://www.fiq.unl.edu.ar

Cui, Y., Xiao R., Xie, Y., & Zhang, M. (2018). Phosphorus fraction and phosphate sorption-release characteristics of the wetland sediments in the Yellow River Delta. *Physics and Chemistry of the Earth*, Parts A/B/C, 103, 19-27.

Foladori, P., Ruaben, J., & Ortigara, A. (2013). Recirculation or artificial aeration in vertical flow constructed wetlands: A comparative study for treating high load wastewater. *Bioresource Technology*, 49, 398-405.

Gao, Y., Zhang, W., Gao, B., Jia, W., & Yang, L. (2018). Highly efficient removal of nitrogen and phosphorus in an electrolysis-integrated horizontal subsurface-flow constructed wetland amended with biochar. *Water Research*, 139, 301-310.

Ge, Y., Wang, X., Zheng, Y., Dzakpasu, M., Zhao, Y., & Xiong, J. (2015). Functions of slags and gravels as substrates in large-scale demonstration constructed wetland systems for polluted river water treatment *Environmental Science and Pollution Research*. Articles not published yet, but available online. https://doi.org/10.1007/s11356-015-4573-9

Kadlec, R. H., & Wallace, S. (2009). *Treatment wetlands* (2nd ed.). Boca Raton, USA: CRC Press.

Laterra, P., Booman, G., Picone, L., Videla, C., & Orúe, M. (2018). Indicators of nutrient removal efficiency for riverine wetlands in agricultural landscapes of Argentine Pampas. *Journal of Environmental Management*, 222, 148-154.

Llagas, Ch., Wilmer A., & Gómez, A. (2006). Diseño de humedales artificiales para el tratamiento de aguas residuales en la UNMSM. *Revista del instituto de investigaciones FIGMMG*, 15(17), 85-96.

Llyas, H., & Masih, Ll. (2017). The performance of the intensified constructed wetlands for organic matter and nitrogen removal: A review. *Journal of Environmental Management*, 198(1), 372-383.

Machado, A., Beretta, M., Fragoso, R., & Duarte, E. (2017). Overview of the state of the art of constructed wetlands for decentralized wastewater management in Brazil. *Journal of Environmental Management*, 187, 560-570.

Miranda, M., & Luna-Pabello, V. (2001). *Estado del arte y perspectivas de aplicación de los humedales artificiales de flujo horizontal en México*. Serie Tratamiento Biológica de Aguas Residuales. México, DF, México: Facultad de Química, Universidad Nacional Autónoma de México.

Pavlineri, N., Skoulikidis, N., & Tsihrintzis, V. (2017). Constructed floating wetlands: A review of research, design, operation and management aspects, and data meta-analysis. *Chemical Engineering Journal*, 308, 1120-1132.

Ramírez-Carrillo, H., Luna-Pabello, V., & Arredondo-Figueroa, J. (2009). Evaluación de un humedal artificial de flujo vertical intermitente, para obtener agua de buena calidad para la agricultura. *Revista Mexicana de Ingeniería Química*, 8(1), 93-99.

Reddy, K., & D'Angelo, E. (1997). Biogeoquimical indicators to evaluate pollutant removal efficiency in constructed wetlands. *Ciencia y Tecnología del Agua*, 35(5), 1-10.

Rodríguez, C. (2003). Humedales construidos. Estado del arte (II). México. *Ingeniería hidráulica y ambiental*, 24(3), 42-48.

Torres-Bojorges, A., Zurita, F., & Tejeda, A. (2017). Carbamazepine removal in three pilot-scale hybrid wetlands planted with ornamental species. *Ecological Engineering*, 98, 410-417.

Vymazal, J., & Brix, H., (1998). *Constructed wetlands for waste treatment in Europe* (pp. 1-15). Leiden, Netherlands: Ed. Backhuys Publishers.

Vymazal, J. (2005). Horizontal sub-surface flow and hybrid constructed wetlands systems for wastewater treatment. *Ecological Engineering*, 25(5), 478-490.

Vymazal, J. (2009). The use constructed wetlands with horizontal sub-surface flow for various types of wastewater. *Ecological Engineering*, 35(1), 1-17.

Vymazal, J. (2009). The use constructed wetlands with horizontal sub-surface flow for various types of wastewater. *Ecological Engineering*, 35(1), 1–17, https://doi.org/10.1016/j.ecoleng.2008.08.016

Vymazal, J. (2011). Constructed wetlands for wastewater treatment: Five decades of experience. *Environmental Science & Technology*, 45, 61-69.

Vymazal, J. (2013). The use of hybrid constructed wetlands for wastewater treatment with special attention to nitrogen removal: A review of a recent development. *Water Research*, 14, 4795-4811.

Vymazal, J. (2014). Constructed wetlands for treatment of industrial wastewaters: A review. *Ecological Engineering*, 73, 724-751.

Vymazal, J., & Březinová, T. (2015). The use constructed wetlands with horizontal sub-surface flow for various types of wastewater. *Environment International*, 75(2), 11-20.

Vymazal, J. (2018). Constructed wetlands for wastewater treatment. Reference module in Earth Systems and environmental sciences. In: *Encyclopedia of Ecology* (pp. 765-776). Recovered fromhttps://books.google.com.mx/books?hl=es&lr=&id=x1h7DwAAQBAJ&oi=fnd&pg=PA14&dq=vymazal,+2018.+Constructed+wetlands+for+wastewater+treatment.+&ots=cq-7vKw3Ed&sig=bc1kisW6XNUD75x_4XZEC_rdO0M#v=onepage&q=vymazal%2C%202018.%20Constructed%20wetlands%20for%20wastewater%20treatment.&f=false

Wu, S., Kuschk, P., Brix, H., Vymazal, V., & Dong, R. (2014). Development of constructed wetlands in performance intensifications for wastewater treatment: A nitrogen and organic matter targeted review. *Water Research*, 57, 40-55.

Yang, Y., Sheng, Q., Zhang, L., Kang, H. Q., & Liu, Y. (2015). Desalination of saline farmland drainage water through wetland plants. *Agricultural Water Management*, 156(7), 19-29.

Ye, F., & Li, Y. (2009). Enhancement of nitrogen removal in towery hybrid constructed wetland to treat domestic wastewater for small rural communities. *Ecological Engineering*, 35, 1043-1050.

Zhang, Z., Moon, H., Myneni, S., & Jaffé, P. (2017). Phosphate enhanced abiotic and biotic arsenic mobilization in the wetland rhizosphere. Research article. *Chemosphere*, 187, 130-139.

Zhao, Z., Li, Q., & Chen, L. (2018). Effect of rhizosphere dispersal and impulsive input on the growth of wetland plant. *Mathematics and Computers in Simulation*, 152, 69-80.