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From natural habitats to successful application - Role of halophytes in the treatment of saline wastewater in constructed wetlands with a focus on Latin America

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ABSTRACT

In many parts of the world wastewater is not treated at all or only to a limited extend because there are no resources available to establish an efficient wastewater treatment plant and there are also insufficient resources for operation and maintenance costs. Constructed wetlands (CWs) are nature-based solutions to treat wastewater in a highly cost-efficient manner. They can be very efficient and effective when well designed and maintained. Latin America is rich in saline natural wetlands. These can be used as prototypes for CWs treating saline process or wastewater. Similar to natural saline wetlands CWs can deliver several ecosystem services. This review focuses on saline wetlands and will first present the protagonists, the salt-tolerant plant species belonging to the halophytes with respect to their physiological and biochemical functions in wetlands. In a second step, their remediating activities which are used in many ways by local people will be shown in an exemplary manner. A number of CWs established in different regions, including Latin America, will be introduced as case studies. Halophytes are already being used in a number of CWs as biofilter but their usage could be increased, for example to treat aquaculture effluents and the biomass has a high potential for valuable compounds (i.e. metabolites) or for bioenergy production. Lastly, aspects of sustainability and ecosystem services of saline natural and constructed wetlands are shown with an emphasis on charting a way forward for the future holistic implementation of saline systems in Latin America.

1. Introduction

Globally, population growth and economic expansion are putting increasing pressure on freshwater resources, with the global rate of groundwater withdrawals rising steadily by 1% per year since the 1980s, and these pressures now being increasingly exacerbated by climate change (FAO, 2017). The increase in demand for water resources also leads to an increase in wastewater. However, the treatment of wastewater is often complicated and expensive, and it is more common to discharge it with little to no treatment in many countries. The untreated wastewater often contains chemicals, microbes and pathogens, antibiotic residues, and other threats to human health, thus posing severe environmental concerns. Untreated wastewater can also cause contamination of drinking water sources, soil pollution for agricultural purposes, visual contamination as well as generation of bad odors. These problems can be aggravated when domestic wastewater is combined with wastewater from factories, which contains toxic substances. However, organic matter from households may be necessary as an energy source for microorganisms for the degradation of toxic substances. Here, comprehensive and specialized wastewater treatment methods

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should be implemented depending on the substances.

In Europe, 71 % of the municipal and industrial wastewater generated undergoes treatment, while only 20 % is treated in the Latin American countries. Since 1990, water pollution has been increasing in most rivers in Africa, Asia and Latin America, due to the increasing amounts of wastewater as a result of population growth, increased economic activity and expanding agriculture, as well as the release of sewage with no treatment. Agriculture is the largest user of water, accounting for over 70 % of withdrawals, while domestic supplies and industry represent 17 % and 13 %, respectively (AQUASTAT, 2016). The pollution load and type of pollutants vary between countries, sub-regions as well as between different sectors, such as industry, mining and agriculture. For example, agricultural effluents contain nutrients, salts, organic matter and pesticides, while industrial discharges contain heavy metals, chemicals, organic matter and salts. Domestic effluents contain detergents, grease, dissolved solids and microorganisms. The negative effects of agriculture on water quality are mainly due to chemical pollution of pesticides and fertilizers, and the reuse of wastewater effluents for irrigation without adequate treatment. Significant water pollution due to irrigation has been reported in Mexico, Nicaragua, Barbados, Panama, Peru, Dominican Republic and Venezuela (Campuzano et al., 2014). Arsenic and fluoride affect groundwater quality in several parts in Latin America and the Caribbean (LAC). Arsenic content in groundwater can be attributed to economic activities such as gold or lead mining or industrial effluents. High arsenic concentrations are known to be a problem in parts of Mexico, Argentina and the Andes region. High fluoride concentrations are often associated with sodium-bicarbonate waters found in weathered alkaline and metamorphic rocks. Thus, high fluoride concentrations have been observed in parts of Brazil and the Andes (Campuzano et al., 2014).

Severe organic pollution already affects around one seventh of all river stretches in Africa, Asia and Latin America, and has been steadily increasing for years. In addition, early findings from the global water quality monitoring program show that high pathogen contamination affects around one third of all river stretches in Africa, Asia and Latin America, putting the health of millions of people at risk. As a result of the high pollution of rivers, most of the largest lakes in Latin America have seen increasing anthropogenic loads of phosphorus, which can accelerate eutrophication processes (WWAP (United Nations World Water Assessment Programme), 2017).

LAC countries would need to invest more than US$33 billion to increase the coverage of wastewater treatment to 64 % by 2030 (Mejía et al., 2012). In addition, approximately US$34 billion is required for the expansion of storm water drainage systems (Mejía et al., 2012), which would reduce pollution resulting from uncontrolled urban runoff. This is an important aspect of urban wastewater management that also has significant social and economic implications: since much of the region lies in tropical and subtropical zones characterized by heavy rainfall, and most cities lack adequate storm water drainage infrastructure, urban flooding is a common and costly phenomenon which affects a large part of the population (WWAP (United Nations World Water Assessment Programme), 2017). In many developing countries, also in some LAC countries, most wastewater treatment systems have proven to be unsustainable as they are economically, technically, socially and/or environmentally unviable, either in their construction, operation or maintenance. It is therefore necessary to develop appropriate technologies that are economical, efficient, and reliable. In some countries in the North of Africa, where water supplies are limited and wastewater tends to be highly contaminated, constructed wetlands (CWs) are proving to be a promising, economically viable approach for water treatment. In Egypt and also in Tunisia wastewater is being widely used in agroforestry projects, supporting both wood production as well as anti-desertification efforts, while in Mexico, municipal wastewater has long been used to irrigate crops (FAO, 2017). Therefore, one nature-based solution (NBS) for wastewater treatment with high efficiency and with relatively low construction and maintenance costs are wetlands (Almuktar et al., 2018; Omotade et al., 2019; Rahi et al., 2020; Turcios and Papenbrock, 2014), thereby preventing environmental pollution and solving the problem of water scarcity in some regions. Wetlands are constructed at shallow depths and are planted with aquatic species that purify water through biological processes. In addition, wetlands are an alternative where conventional treatment systems are difficult to construct, operate or maintain adequately.

However, there is currently little knowledge about the contribution of CWs to the global amount of treated wastewater. Because of this there are currently some initiatives like the project Constructed Wetlands Knowledge Platform (https://cwetlandsdata.com/) to take CWs to the next level, to develop one-stop solutions for CW-related data and mechanisms to support research, policy development and funding, and to empower civil society organizations and practitioners to implement NBS for sustainable development.

In addition to the role of microorganisms, the plant species play an important part in natural or CWs since they are highly efficient in the uptake and degradation of organic and inorganic contaminants (phytoremediation). Phytoremediation offers an innovative, environmentally friendly and cost-effective option to treat contaminated areas. The use of plants to restore or stabilize contaminated places takes advantage of the natural abilities of plants to take up, accumulate, store, or degrade organic and inorganic substances.

Salinity due to irrigation has also been a serious problem in countries such as Mexico, Argentina, Cuba and Peru, to a lesser extent in the arid regions of northeastern Brazil, north and central Chile and some small areas of Central America (Campuzano et al., 2014). Salt, according to the assessment from the United Nations University (Smith, 2014), is degrading 20 % of the world's irrigated land and causing around US $27.3 billion per year in economic losses. Halophytes, naturally salt-tolerant plants, have attracted the attention of the scientific community. Several studies have been conducted using different aquatic plants including halophytes confirming that these plants are able to uptake and degrade several pollutants, including xenobiotics and other organic compounds (Barac et al., 2004; Meagher, 2000; Turcios et al., 2016; Turcios and Papenbrock, 2019a). Halophytes thus have a clear potential to treat contaminated substrate or wastewater. The aim of this manuscript is to review the applications of halophytes for wastewater treatment using nature-based solutions with emphasis in LAC countries, as well as their potential for other applications.

2. Potential use of constructed wetlands for wastewater treatment

Constructed wetlands are examples of NBS being used worldwide to treat and manage several types of process and wastewater (Dotro et al., 2017; Vymazal, 2011). They are particularly suited for stormwater retention and treatment (Duclos et al., 2013), especially for run-off from all kinds of urban sealed surfaces (Bergier et al., 2014), including roads, parking lots or even fuel distribution facilities, which may cause strong contamination with petroleum compounds and saltwater (Bergier and Wlodyka-Bergier, 2016a). Constructed wetlands are also widely used for the effective treatment of municipal wastewater, especially in the case of scattered buildings and in places remote from urban centers (Oakley et al., 2010), without access to municipal grids, i.e. a sewage collection system or even an electric power network. There are also several CWs, especially in Scandinavia, whose main purpose is to treat and retain municipal wastewater treated in conventional mechanical-biological treatment plants (Leto et al., 2013), even for urban agglomerations with a significant number of equivalent inhabitants. Constructed wetlands are also used as a component of complex and advanced systems, employed for treatment of difficult-to-treat wastewater, e.g. due to high concentrations of pollutants or their strong variability (qualitative and/or quantitative). In this respect, CWs are particularly used for the treatment or pre-treatment of landfill leachate (Bakhshoodeh et al., 2020), highly saline mine water (Pat-Espadas et al., 2018), wastewater from metallurgic industry (Maine et al., 2006) and tanneries (Calheiros et al., 2014).

Constructed wetlands are ecological engineering solutions, based on the ability of natural wetland systems to treat water and wastewater, creating semi-natural solutions (Langergraber et al., 2019), replacing or complementing conventional utilities (so-called grey infrastructure). They allow efficient in-situ treatment of water and wastewater, eliminating the need of their transport to a central facility, thereby minimizing costs and negative environmental impacts (Langergraber et al., 2020). Therefore, there is no need to apply chemical agents and a reduction of electricity consumption for aeration and/or pumping additionally minimizes environmental and financial costs. There are many more factors resulting in the popularity of CWs. The most important are the high physiological flexibility of macrophytes to changing conditions, among them flow rate and water quantity, and even high concentrations of pollutants, high activity and diversity of microorganisms of the wetland microcosm, relatively simple and inexpensive maintenance and additional ecosystem services, e.g. increase in biodiversity and aesthetic aspect. Also, the hydrological aspect of the functioning CWs should not be neglected. Treated water is retained locally in the catchment, improving local retention and microclimate, and evapotranspiration by wetland plants increases the amount of water circulating in a small cycle (Bergier et al., 2014).

Constructed wetlands are usually characterized both by a relatively simple design and by their enormous scalability and flexibility. These characteristics allow to create a variety of configurations, combining the plots in a serial, parallel or mixed way (Brown et al., 2000). Thus, the practical designs and constructions of CWs are very individual and unique, depending on the designer's preferences and imagination and the given parameters, such as the quality and type of treated medium, and the local topographical and spatial conditions. Despite their individual construction diversity, it is worthwhile to identify and discuss the basic construction types. They differ significantly in their characteristics and parameters, and thus in their applicability to different kinds of wastewater or water. The basic way to create a topological division of CWs is the sewage flow. Generally, one can distinguish two main categories of CWs in this regard: 1) subsurface flow (SSF) and 2) free water surface (FWS) (Fig. 1).

Constructed wetlands with FWS are usually constructed in a form of ponds or reservoirs planted with vegetation. The flow takes place above the surface of the ground, i.e. the bottom of the CW, and water or wastewater forms a free surface. The forms of vegetation can be different (Fig. 1), e.g. bottom-rooted emerged or submerged vegetation or floating vegetation. The forms and dimensions of FWS systems can vary greatly, thus their depth in practice can range from a dozen (or even a few) centimeters to several meters. In facilities of this type, anaerobic conditions prevail (Vymazal, 2007). Therefore, the processes of biological removal of pollutants, especially nutrients, have limited effectiveness. However, mechanical wastewater treatment, especially removal of suspended solids by sedimentation, can be very effective. A combination of zones with different flow rates is often used to enhance the sedimentation and removal of suspended solids. Due to their good volume-space ratio, these facilities are ideal for wastewater retention, temporary retention and quality equalization. Hence, they are often used as an initial, pre-treatment facility for wastewater prior to proper treatment at SSF CWs. They can also be used as the final stage, after wastewater treatment in CWs or conventional facilities, as a buffer and retention pond, before discharge to a receiver, usually a river.

In the case of SSF CWs, wastewater flows through the porous filling of the bed, under its surface, not being present at the surface, thus avoiding many nuisances (no odor, no visibility, and no possibility of direct contact with sewage). It is a significant importance and makes it easier to integrate CWs into the landscape, especially urbanized, so they can function relatively close to residential areas, a key feature in the case of domestic sewage treatment plants. Of course, SSF CWs require filling, which creates proper conditions for plants and microorganisms to live (Fu et al., 2020), and to provide adequate hydraulic conditions for efficient wastewater flow (Manios et al., 2003). In practice, mineral fillings with high porosity (usually gravel or sand) are often used, although inert waste materials (e.g. cullet), expanded clay and other materials with similar properties can be used. The substrate filling the bed has many important functions and is crucial to the proper operation of SSF CWs, improving the efficiency of both dissolved and suspended solids removal (Kataki et al., 2021). On the other hand, by using some volume of a CW facility, it lowers its retention capacity. Thus, SSF CWs have higher space requirements in comparison with FWS CWs to keep a necessary retention time and loading rate.

Often SSF CWs are divided into horizontal (HSF) and vertical flow (VSF) facilities (Kataki et al., 2021; Vymazal, 2011). The first ones (HSF – Fig. 1a) are usually not very deep (30–50 cm), which results from the actual range of plant roots. Wastewater moves horizontally with laminar flow. The water level in the CW bed is constant, fresh wastewater "pushes" and replaces treated wastewater. Anaerobic conditions prevail in HSF, however, due to the ability of macrophytes to transport oxygen to their root zone, a resospheric effect occurs (Stottmeister et al., 2003). Thus, the micro-zones are created in the bed with varying levels of oxygenation, allowing a variety of microorganisms to develop. They uptake nutrients and thereby effectively treat the wastewater. This is

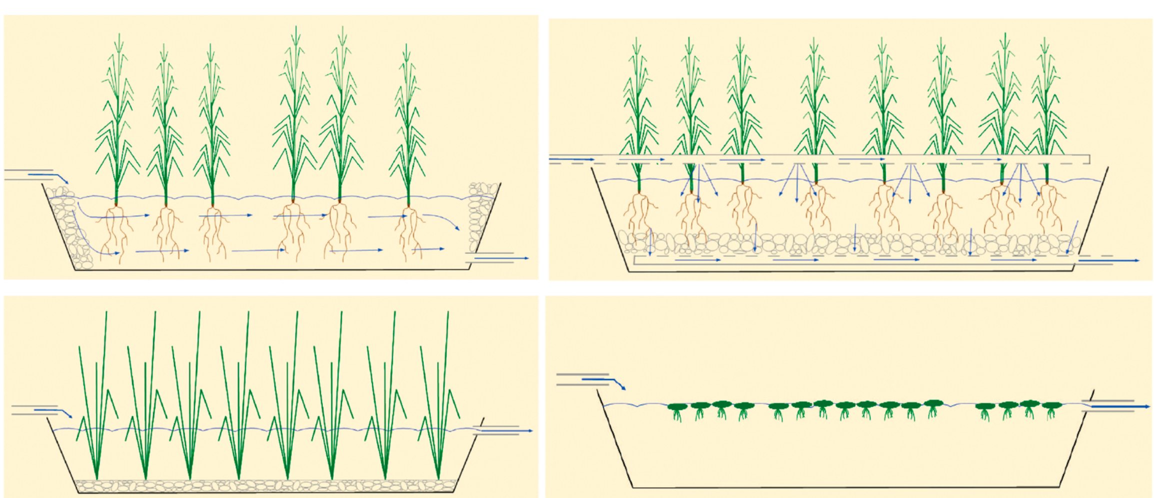

Fig. 1. Types of constructed wetlands: (a) horizontal subsurface flow; (b) vertical subsurface flow; (c) surface flow with emergent vegetation; (d) surface flow with floating vegetation. Source: Magdalena Szymura and Tomasz Szymura.

especially important for the efficient removal of various forms of nitrogen, including its nitrification and denitrification (Tang et al., 2020), and ultimately the conversion to gaseous nitrogen, which is harmless to the environment (Włodyka-Bergier et al., 2010). VSF CWs (Fig. 1b) are characterized by a greater depth (up to 2 m) and the changing level of wastewater. Depending on the inflow rate, it periodically rises and runs lower, which results in more intensive wastewater aeration, thus more efficient treatment in comparison to HSF CWs (Vymazal, 2007).

Sophisticated and complex configurations of CW systems are used to improve the efficiency of wastewater treatment to enable the removal of difficult-to-degrade compounds, including salts (Calheiros et al., 2014), primarily by combining plots of different designs (described above), but also by using multiple recirculation (Calheiros et al., 2014; Langergraber et al., 2020). This technique further increases the resistance of CWs to high variability of effluent quantity (and quality). The use of recirculation is an effective way to improve hydraulic conditions and to control and maintain a stable wastewater flow through the bed (Langergraber et al., 2019). Moreover, recirculation is strongly recommended when wastewater inflow is intermittent, for example during long dry periods causing no water or wastewater inflow (Brown et al., 2000). The most common methods of wastewater distribution in CWs are presented in Fig. 2.

While the design and construction of CWs are relatively simple, the contamination removal processes occurring in CW beds are comprehensive and diverse (Kataki et al., 2021). Initially, pollutants are retained in the bed due to mechanical processes (i.e. filtration, sedimentation), as well as adsorption on the bed filling and biosorption on plants and microorganisms (Tang et al., 2020). These processes are well known and described, and also relatively simple. However, the actual pollutants removal by the CW bed, or rather by the microcosm developed in it, results from much more complex, interlinked processes, taking place due to a kind of interdependence between higher plants and microorganisms living on their roots and the substrate filling CWs bed (Kataki et al., 2021). The key is the resospheric effect described above, which allows the existence of bacteria and other microorganisms with different environmental requirements, most important the oxygen conditions, which are responsible for phytoremediation of water and wastewater, i.e. the effective removal of various pollutants. The process of significant importance is the uptake of biogenic pollutants by bacteria and other microorganisms, and their biological decomposition (Vymazal, 2011, 2007). Pollutants are also taken up and immobilized by macrophytes and other plants, inhabiting CWs bed (Shelef et al., 2013). Indirectly, the resospheric effect causes the CW bed to be a kind of chemical reactor, in which processes important for pollutants' removal occur, such as ion exchange, pH neutralization, etc. Exposing CWs to sunlight, especially UV, allows photolysis and advanced oxidation processes to occur, as well as disinfection that inactivates pathogenic bacteria and viruses, which is especially important for domestic sewage treatment (Bergier and Wlodyka-Bergier, 2013). Evapotranspiration of water or wastewater plays an important role in water budget of CWs, however for the pollutant removal the volatilization is a process of great importance (Bergier and Wlodyka-Bergier, 2016a). In the case of lighter fractions of hydrocarbons and other oil-derivatives it is the main path of their removal by CWs (Bergier and Włodyka-Bergier, 2016b). The contribution and importance of the above-described mechanisms differs depending on the type and form of pollution, but the correct operation of CWs strongly depends on the synergistic interaction of higher plants, microorganisms, and the substrate.

While treating saline water, analogous processes take place (Liang et al., 2017), but the key factor is the physiological tolerance of higher plants to salt (Wang et al., 2019, 2021). For the treatment of saline water salt-tolerant plant species, halophytes, are used in CWs. Halophytes are plant species that can grow and complete their life cycle in a salt concentration of at least 200 mM NaCl (Flowers and Colmer, 2008). These are, for example, plant species from the Chenopodiaceae family, such as *Salicornia europaea*, *Salsola crassa* and *Bienertia cycloptera* (Farzi et al., 2017), and many more described in this review. Water salinity can also influence the microorganism population, inhibiting some species of bacteria (Gao et al., 2021), however, their role is usually taken by other groups (Fu et al., 2019), playing similar functions, thus the CW microcosm seems to be much more resilient in this regard than higher plants.

3. Description of examples of constructed wetlands in Latin America and Europe (case studies)

3.1. The case study of Werk Tanne, Germany

The Werk Tanne is considered the largest CW in Europe for explosive-type compounds, with the aim of degrading pollutants with the power of nature. The site Werk Tanne, is a former explosives factory where explosives (mainly TNT) were produced during the Second World War. Large parts of the site are extensively contaminated with explosive-type compounds. Due to their diffuse distribution in the soil, large-scale decontamination is not possible, so that photolysis as well as phytoremediation is now being carried out by means of collection and treatment of contaminated leachate (as main contamination source), using a CW system (Fig. 3).

The CW is a foil-sealed basin of 3630 m^2, filled with an 80 cm thick gravel bed and planted with 28,000 rhizomes of common reed (*Phragmites australis*), which is also considered a salt-tolerant plant (Link for more information: https://cwetlandsdata.com/casestudies).

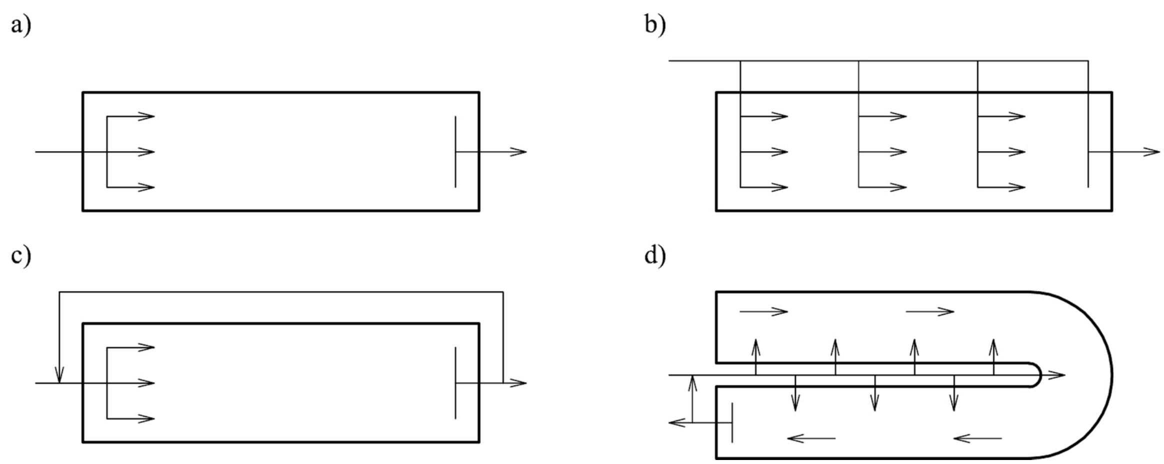

Fig. 2. Types of wastewater distribution in hydrophytic systems: a) uniform piston flow with single-stage feed, b) uniform flow with multi-stage feed, c) uniform piston flow with single-stage feed and recirculation, d) circular flow with multi-stage feed and recirculation. Source: modified from Brown et al. (2000).

Fig. 3. Retention basin (left figure, at the bottom,), Constructed Wetland (left figure, center); Constructed wetland planted with Common reed (*Phragmites australis*) (right figure). Photo: Halali Verwaltungs GmbH, Landkreis Goslar.

3.2. The case study of Vattenparken Korsängen, Sweden

Vattenparken (Water Park in Swedish) is a complex free-water system of CWs (Fig. 4), which was designed and constructed to receive, store and treat stormwater, from the urban and residential areas of Enköping (WRS, 2020). In winter, the system is additionally supplied with snow removed from the city. The main reason for construction of the Vattenparken (in 2001) was to protect the nearby Lake Mälaren, receiving nutrients and other pollutants from urban stormwater from Enköping.

Despite the fact that the described system is a fully artificial CW, its shape, appearance and many features perfectly mimic those of natural wetland habitat (Fig. 5). This was achieved by the careful and advanced design of the CW system, especially the semi-natural shaping of the banks and bottom of the reservoirs. As it can be seen in Fig. 5, these reservoirs are shaped into serially connected canals that make up a 9-hectare system of free-water CWs. They have various shapes, and the depths of their bottoms vary from 20 cm, through 70 cm, up to 1.5 m, changing repeatedly along the entire length of the canal (Fig. 5). As a result, zones with different stormwater flow rates are created, which allow effective removal of pollutants in suspended form by sedimentation. Hence, the diverse wetland ecosystem effectively removes dissolved compounds, in particular nitrogen and phosphorus, as well as heavy metals and other pollutants.

The average nutrient removal efficiency of Vattenparken is 55 % for total phosphorus, 70 % for ammonia and 40 % for total nitrogen. Heavy metals are also removed relatively efficiently by the CWs at Enköping, thus cadmium is removed with an average efficiency of 51 %, zinc 56 %, chromium 53 % and lead as high as 83 % (Enköping, 2019). Most importantly, the system effectively protects the ecosystem of Lake Malaren against the eutrophication and the toxic effects of heavy metals washed off roads and other urban paved surfaces of the city of Enköping. The scale of the positive impact of these CWs on nature is evidenced by the fact that annually circa 3–5 tons of nitrogen and nearly 1 ton of phosphorus are removed from stormwater, which otherwise would go directly to Lake Malaren, and subsequently to the Baltic Sea.

3.3. The case study of UNACEM cement company, Lima, Perú

Since 2005, UNACEM began pilot tests to implement a Wastewater Treatment Plant (WWTP) using CWs with a project size of 25,000 m^2, consisting of a HSSF CW with 6 cells of 30m $\times$ 30m each and a depth of 0.6 m. The objective of the project is to collect and treat 100 % of the company's domestic and industrial effluents, and reach a quality for reuse in irrigation, achieving the discharge in the sewer network. Two plant species were selected: Achira (*Canna indica*) and Paragüitas (*Cyperus alternifolius*) (Fig. 6), both fitting to the landscape and local environment and having a fast growth and moderate development.

Currently, the effluent is used to irrigate parks and gardens and provide water for the hydrant system. Treatment efficiency is greater than 95 %, reaching an average BOD below 10 mg/l (Link for more information: https://cwetlandsdata.com/casestudies).

3.4. The case study of the Atitlán Lake, Guatemala

Close to the the Atitlán Lake in Guatemala there is a horizontal subsurface flow CW which provides a reliable solution for wastewater treatment. The system can be swiftly installed, in a matter of days and can be constructed anywhere in the basin. The high flexibility of the system is an important parameter due to the rough topography of the basin. However, the system has not been tested yet. High population growth and an augmented tourist industry in the Atitlán basin have led to increases in the amount of wastewater discharged into the lake. The polluted wastewater has a negative effect on the ecosystem in the basin. Drinking water that is taken from the lake or the streams is highly polluted as a result of the wastewater mismanagement. There are seven centralized treatment plants in different communities in the basin, but they function poorly or are completely out of function due to lack of

Fig. 4. Overview of Vattenparken – FWS CWs treating stromwater from Enköping (a view prior planting with macrophytes) (left), and current CW which mimics a natural habitat, providing a wide range of ecosystem services (right). Photo: Pereric Öberg (left); Tomasz Bergier (right).

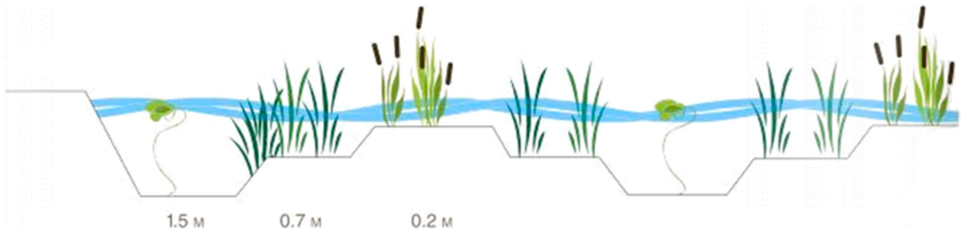

Fig. 5. Cross-section showing different depth zones of Vattenparken CWs, providing diverse conditions contributing to effectively remove pollutants (mechanically and microbiologically).

Fig. 6. Wetland cells cultivated with Achira (*Canna edulis*) (left), and Paragüitas (*Cyperus alternifolius*) (right). Photo: Rosa Miglio.

economic resources, skill and competence, political problems, and natural catastrophes. In order to improve the wastewater management in the basin, an inexpensive system with swift installation is proposed and designed for small communities. The system includes a septic tank followed by a constructed horizontal subsurface flow wetland. The design of the system considers the topography, climate, economic limitations, land limitation due to agriculture, and culture within the basin. Two Guatemalan villages near the turquoise lagoons of Sepalau in Chisec, Alta Verapaz, made these lagoons the communal washing place for more than 200 families. As a result, the lagoons became contaminated with detergents and other chemicals. Community members, with the help of a Guatemalan sustainable development organization (Fundación Solar), the US Peace Corps and Sandia National Laboratories, designed a submersible electric water pump system that is used to fill the communal washing tanks located in the jungle surrounding the lagoons. The project was prepared and submitted with a detailed budget to the United States Agency for International Development (USAID) Mission in Guatemala in 2004. As part of the project, "Artificial Wetlands" were built in a series of three drainage ponds connected to the washing station by tubing, designed to treat the soap and bleach contaminated wastewater with native plants before it flowed back into the lagoons. These plants were very effective in removing chemicals associated with soaps. The project's implementation successfully improved the environmentally destructive washing practices and has raised the health and economic status of community members. To ensure project sustainability, payment and washing schedules were established in a 2-month training course for the community members after construction. Currently, the community uses funds from a small washing fee that is collected to repair the pump and maintain the site (Smith and Ley, 2009).

As can be seen from the case studies above, constructed wetlands are feasible to integrate into the water treatment process. It should be noted that their efficiency will depend on many factors, including type of CW, plant species to be used, environmental factors, hydraulic performance which in turn is affected by the loading of such facilities with wastewater, among others described below. The costs of construction, operation and maintenance also depend on the degree of technology used and project size, although there is the advantage of being able to build wetlands at low cost using local materials. In larger scale projects the costs may increase, although compared to other types of technologies used in wastewater treatment plants they can be relatively low. In the case of Korsängen Water Park people and institutions, who are responsible for the designing, constructing and maintaining, emphasize that it was a very good decision to create it. The cost-benefit analysis carried out by the municipality has shown the positive balance of this investment, which is fully consistent with numerous literature reports on financial benefits of constructed wetlands and generally of NBS, applied in water and wastewater management (DiMuro et al., 2014; Gachango et al., 2015).

4. Saline wetlands in Latin America

Saline wetlands can be salt-tolerant marshes, mangroves, or wetlands in the tidal zone of estuaries. Latin America has a long coastal zone towards the Atlantic as well as the Pacific Ocean spanning a multitude of climatic zones. Prominent examples of saline wetlands include for instance the mangrove forests of the Pacific Ocean coast of Central American countries (from Mexico to Columbia) that provide a multitude of ecosystem services. This includes the spawning ground for fish, shrimp, and other food stuff as well as protection against sea level rise providing basic income to local population. Coastal lagoons are prominent on the Atlantic Ocean coast of the Southern part of Brazil and of Uruguay. Here, freshwater lagoons are mostly cut off from the ocean; however, during storm events or induced by human activity the thin sand dune that separate the lagoon from the ocean breaks causing an influx of salt water into the coastal lagoon. A series of transformations occur that result in spawning of other fish species and short-term adaptation of plant species to increased salt concentrations (Rodríguez-Gallego et al., 2015). Another famous example of saline wetlands are the estuaries of the large river basins of the South American rivers be it the Amazon, the Orinoco, or the Rio de la Plata. Here in the tidal zones the amount of salinity changes with the ocean tides and waves as well as with the freshwater amounts from the upstream parts of the river resulting in constantly changing levels of water and salinity. Some of these estuaries form enormous areas of floodplains covered with salt tolerant grasses. These habitats serve as flood risk control measures, recharge aquifers and are biodiversity hotspots.

The Ramsar Convention (https://www.ramsar.org/) covers protected wetlands all over the world and follows the mission of “the conservation and wise use of all wetlands through local and national actions and international cooperation, as a contribution towards achieving sustainable development throughout the world”. In the LAC region, a total of 61,599,173.01 ha are protected in 208 protected wetlands (Ramsar Sites Information Service, 2014), and many of them are saline wetlands. Argentina has the largest number of protected wetlands. There are 23 in total, scattered over a total of 5,714,016 ha (Ramsar Sites Information Service, 2014). One example is the wetland "Humedales de Península Valdés". It is located in the Chubut region along the Patagonian coast. Here, for example, there are halophytes of the genera *Spartina*, *Sarcocornia* and *Distichlis*, which play an essential role, together with phytoplankton, in the survival of the endangered bird *Calidris canutus* (Musmeci et al., 2012).Another example of wetlands in Argentina is Laguna Blanca in the Patagonian region of Neuquén. The vegetation consists of many plants with deep roots, such as the halophyte *Potamogeton pectinatus* and *Myriophyllum alatinoides*. This wetland is very important for the endemic frog *Atelognathus patagonicus* (Fawcett, 1994). Another example is Bahía de Samborombón. This is a bay on the coast of Mar del Plata in the province of Buenos Aires. The salt prairie consists of salt-tolerant plants of the family Poaceae, Amaranthaceae and Brassicaceae.

Chile also has many protected wetlands, 14 in total, one example of which is the Sanctuary Carlos Anwandter. It is a riparian zone with marshes, large meadows and islands along the Valdivia River (Ramsar Sites Information Service, 2014). It is habitat for plants that tolerate brackish water, such as Totora (*Schoenoplectus californicus*), which is used for boat building. Some wetlands are also found in Peru. On the Pacific coast, for example, there is the Paracas protected area, which covers 335,000 ha, with the presence of the halophytes *Distichlis spicata* and *Sesuvium portulacastrum* (Fawcett, 1995). *Sesuvium portulacastrum* plays an important role, it colonizes the sand and serves as a ground cover to limit the erosion of the dunes (“Useful Tropical Plants,” 2019). The Santuario Nacional lagunas de Mejía with a total of 690.6 ha is also located on the Pacific coast.

In Panama, protected wetlands are located on both the Pacific and Atlantic sides of the country. On the Pacific side, for example, there is Punta Patiño with a total of 13,805 ha (Ramsar Sites Information Service, 2014), with different mangrove species like *Avicennia germinans*, *Laguncularia racemosa*, *Rhizophora mangle* and *Pelliciera rhizophorae*. Guatemala, like Panama, also has some protected wetlands along both coasts. One wetland of 132,900 ha on the Atlantic Caribbean coast is Punta de Manabique (Ramsar Sites Information Service, 2014). Here, for example, the halophyte *Montrichardia arborescens* serves as a refuge for many bird species, reptiles and fish, and its seeds are also important for the diet of many species. Another wetland with 13,500 ha in Guatemala is Manchón-Guamuchal on the Pacific coast, with several halophyte species (Fig. 7).

The LAC region is located in a tropical and subtropical area, and therefore the variety of wetland plants that can be used is wider than in temperate zones; the plants are not affected by cold winters, they do not have dormant periods and can grow throughout the year, thus actively participating in the treatment process in the CW throughout the year (Rodriguez-Dominguez et al., 2020).

The large number of plant species reported in Latin America is a precedent for future studies, where plants could take on other roles in wetlands, in addition to the effects on treatment performance. In the study by Rodriguez-Dominguez et al. (2020), they found 112 different species of plants used in various conditions; the most common plants were *Typha domingensis,* reported in 54 experiences, but also other species such as *Eichhornia crassipes* (40 experiences), *Typha latifolia* (36), *Cyperus papyrus* (34), *Phragmites australis* (33), *Heliconia psittacorm* (30) and *Pistia stratiotes* (27). On the other hand, some species were reported in only one case, i.e., *Cocos nucifera* (coconut), *Carica papaya* (papaya) and *Aloe vera*.

Several studies of vascular flora of natural wetlands in Argentina, Chile, Colombia, and Peru were also reviewed, obtaining a list of hydrohalophyte herbaceous species, plants that can grow in aquatic environments or in humid conditions, having great potential to be used in CWs. Particularly noteworthy in Peru is the Cyperaceae family, being the most representative species Schoenoplectus americanus (syn. Scirpus americanus) (American bulrush or “*junco”*). Also, among the most characteristic species that surround the waterbodies are *Salicornia fruticosa* and *Typha angustifolia* (cattail or “*totora”*), while the most abundant submerged plant is *Ruppia marítima* (Fundación Peruana para la Conservación de la Naturaleza, 2010).

This is evidenced by the studies of vascular flora conducted by Bopp and Peláez (2019) in four coastal wetlands in the department of La Libertad in Peru, in which Cyperaceae reported eight species followed by Poaceae. The salinity characteristics in these wetlands suggest electrical conductivity in ranges from 0.22 to 1.07 mS/cm. While Monzón and Peláez (2015) identified that Schoenoplectus americanus occupied all habitats except water bodies and shrub areas in the Tres Palos wetlands in La Libertad. Whereas Argentina by its geographical conditions has greater diversity of halophyte flora, particularly the wetlands of the Salt River basin in the Chaco region that has halo-hydromorphic flooded grasslands. In the Puna region, the high Andean wetlands present ponds

Fig. 7. Mangrove forest of the Pacific Ocean coast of Nicaragua (left) and Juncales (*Schoenoplectus* spp.) of the Río de la Plata/Río Santa Lucía Basin in Uruguay (right). Photo: Tamara Avellán.

with diverse degree of salinity. In Colombia, wetlands with saline environments are scarce, being the Flora and Fauna Sanctuary of the Ciénaga Grande de Santa Marta, the main ecosystem that presents coastal lagoons and estuaries with mangrove forests (PQRS, 2013). As described above, the Latin American region has many saline wetlands and a wide diversity of halophyte species (Table 1).

5. Ecosystem services of saline wetlands

The ecosystem services approach is a tool for the sustainable management of natural resources. Considering the conceptual evolution and the diversity of classifications, there is not one that can be used globally, but all can be applied in the management of natural resources in order to maintain the health of ecosystems and guarantee the provision of their services. The main objective is to emphasize the dependence of society on natural ecosystems, in addition to promoting public interest in the conservation of biodiversity.

Daily (1997) considered the ecosystem services as the conditions and processes through which natural ecosystems, and their constituent species, sustain and satisfy human life. The author separates services into goods, mainly food, which are physical, tangible objects and intangible services or processes that influence the human being positively Millennium Ecosystem Assessment (2005). The benefits that the population obtains from ecosystems are defined in different ways by different authors. As those ecological functions or processes that directly or indirectly contribute to human well-being or have a potential to do so in the future. This includes potential services, not contemplated by other definitions. Boyd and Banzhaf (2007) emphasize that the consumption or enjoyment of services must be direct, which according to Freeman (2010) would be advantageous to avoid duplication in the estimation of the value of services by considering only the final phase of the processes so that the population can benefit directly. Fisher et al. (2009) consider the aspects of ecosystems used actively or passively to produce human well-being. In contrast, they emphasize that services are strictly ecological phenomena (structure, processes or functions), whose passive or active use can be direct or indirect and they become services if humans benefit from them, so without these beneficiaries, there are no services. Classification systems are driven by the purpose of the research and by how ecosystem services are defined. The main unifying characteristic is the relationship between ecosystem services and human well-being. According to Daily (1997) the following ecosystem Services can be listed: food, supporting different artisanal and sport fisheries, damping of extreme events, detoxification and decomposition of waste, water treatment, generation and renovation of soils and their fertility, pollination of crops and natural vegetation, control of the vast majority of potential agricultural pests, seed dispersal and nutrient translocation; maintenance of biodiversity and maintenance of habitats where different communities (plants and animals) develop from which human beings obtain key elements for agriculture, medicine, and industrial enterprises; protection from ultraviolet rays; moderation of extreme temperatures and the force of wind and waves; support of diverse cultures; recreation; provision of scenic beauty and intellectual stimulation for the elevation of the human spirit. According to the Millennium Ecosystem Assessment (2005) they can classify on supply services, regulatory services, cultural services and base services (Table 2).

Otherwise, Fisher and Turner (2009) consider abiotic inputs, intermediate services, final services and profits (Table 3).

Some goods and services including sediment capture, nutrient uptake and processing, primary production, and provision of food and habitat for animals, are essential to preserve ecosystem integrity and regional biodiversity. Others do not occur without considerable human intervention, such as biomass harvesting. Mangroves, for example, provide a wide range of goods and services including nutrient recycling, carbon sequestration, aesthetically pleasing environment, primary productivity as well as shorelines protection (Ewel et al., 1998). Primary production forms the basis of the food chain for all higher consumers, both herbivores and carnivores. The production of atmospheric oxygen through photosynthesis is often classified as a support service, as oxygen is the basis of all animal life on Earth. The magnitude and quality of each of these goods and services is likely to vary between the different zones. Wetlands provide many valuable ecosystem services, including carbon sequestration. Wetlands therefore play a key role in climate regulation. Their ability to sequester carbon is therefore being taken into account in national greenhouse gas emission assessments and private initiatives as a potential source of revenue to manage carbon-balanced landscapes and pay for ecosystem services (Villa and Bernal, 2018). Carbon sequestration should therefore be considered in project design and policy implementation, to enhance existing climate mitigation schemes and payment for ecosystem services, and to encourage the implementation worldwide of wetland creation, restoration, and conservation projects for sustainable development and climate change mitigation and adaptation. In addition, saline wetlands are a natural habitat for many species, improving local biodiversity and the attractiveness of the local areas. It can also be a popular destiny among inhabitants and tourists, as an ideal place for walks, bicycle trips, sports activities, family picnics and a good opportunity to relax in nature. The wealth of species of birds and other representatives of fauna and flora causes that numerous educational activities for children and adolescents can be carried out.

Wetlands containing various plant species including halophytes offer transitional zones between water and land, with better microclimatic conditions, providing a suitable habitat for a wide range of organisms including microorganisms and larger invertebrates. Bird populations are often very diverse in wetlands, as many bird species use the marsh habitat for at least part of their life cycle. Several bird species are found in the saline wetlands of the Netherlands (De Lange et al., 2013). To optimize a CW to support wildlife, the wetland must be of sufficient size and structural diversity (Worrall et al., 1997). One of the main ecological benefits of CWs with halophytes is to compensate for the loss of saltmarsh and mangrove habitats worldwide. This is critical as the restoration and protection of wetlands and in particular mangroves is a global target of the Sustainable Development Goals (UNWATER, 2008). The aesthetic value of CWs can be enhanced if it is well integrated into the surrounding landscape. This can be as simple as camouflaging an essentially artificial landscape feature (De Lange et al., 2013).

6. Physiological, and biochemical functions of halophytes in wetlands

Halophytes, as described above, are salt tolerant plants which survive to reproduce in environments where the salt concentration is around 200 mM NaCl or more (Flowers and Colmer, 2008). Halophytes comprise an important group of plant species in saline ecosystems and also for different applications due to their special physiological characteristics, and biochemical composition. Plants have several mechanisms to cope with salt stress including the restriction of Na^+ uptake and exclusion, cellular compartmentalization of Na^+ in the vacuole, compatible solutes (osmolytes), antioxidant regulation, morphological adaptations (e.g. salt bladders). The mechanism used depends on the group of plants, glycophytes or halophytes, and on each species (Turcios et al., 2021a, 2021b). Halophytes, are of particular importance as they can remove excess of salt from the soil and water and at the same time food products can be obtained. Their great potential for nutrient uptake and remediation in natural and CWs has been investigated with promising results. However, the choice of plant species is of key importance in maximizing the removal efficiencies of CWs. Nevertheless, knowledge is still limited on which morphological, physiological, and biochemical characteristics of plants determine their efficiency (Brisson and Chazarenc, 2009; Manousaki and Kalogerakis, 2011).

As in constructed freshwater wetlands, pollutants present in saline water are removed or reduced by different physical, chemical and biological processes. The most active reaction zone in wetlands is the rhizosphere, where biological and physicochemical processes are

Table 1
Examples of some salt-tolerant plant species reported in natural saline wetlands in the Latin America and the Caribbean (LAC) region.

Plant species	Family	Distribution	Reported salt tolerance to NaCl (mM)	References
Acrostichum aureum	Polypodiaceae	Pantropical, occurring along the coasts of Asia, America and Africa.	170	Gautier et al., 2001; Kapler, 2019; Sun et al., 1999
Avicennia germinans	Acanthaceae	Along coasts of tropical America and coasts of western Africa.	>500	Gautier et al., 2001; Madrid et al., 2014
Baccharis salicifolia	Asteraceae	United States and northern Mexico, as well as parts of South America	~150	Vandersande et al., 2001
Canavalia maritima	Fabaceae	Pantropical	150	Kekere, 2014
Carex spp.	Cyperaceae	Across most of the world		Grieve et al., 2011
Chenopodium ambrosioides	Amaranthaceae	Wide distribution around the world	400	Limaverde et al., 2017
Chenopodium quinoa	Amaranthaceae	Originated from the Andean highlands and distributed worldwide	400	Adolf et al., 2013
Cocos nucifera	Arecaceae	Island and coastal ecosystems around the world, occurring in more than 80 countries across Asia, Africa, America and Oceania	~110	CABI, 2021; Rodriguez-Dominguez et al., 2020
Conocarpus erectus	Combretaceae	Throughout the world	400	Naseer et al., 2017
Cynodon dactylon	Poaceae	Worldwide in both tropical and subtropical regions including Asia, North, Central and South America, the Caribbean, and islands in the Pacific Ocean	200	Hameed and Ashraf, 2008; PQRS, 2013
Cyperus spp.	Cyperaceae	Distributed throughout all continents in both tropical and temperate regions		PQRS, 2013
Deschampsia ssp.	Poaceae	Widespread including the eastern and western coasts of North America, parts of South America, Eurasia and Australia.		Walsh, 1995
Deyeuxia ssp.	Poaceae	Temperate regions		Benzaquen et al., 2017
Digitaria canescens	Poaceae	Distributed throughout the tropics and sub-tropics	200	PQRS, 2013
Distichlis humilis	Poaceae	America	~250	Benzaquen et al., 2017
Distichlis spicata	Poaceae	America	280	eHALOPH; Fawcett, 1995;
Echinochloa crus-pavonis	Poaceae	Americas, Africa, Asia, Oceania and Europe.		Bopp and Peláez, 2019; CABI, 2021
Echinodorus longipetalus	Alismataceae	Western hemisphere, from northern United States of America to Argentina		Pansarin, 2008
Eichhornia crassipes	Pontederiaceae	Originated from South America, but is now naturalized in Africa, Australia, India and many other countries.	<130	CABI, 2021; Maine et al., 2006
Eleocharis geniculata	Cyperaceae	America, Asia, Africa, Australia, Madagascar, and some Pacific Islands		Bopp and Peláez, 2019
Eleocharis mutata	Cyperaceae	America, Africa		PQRS, 2013
Gunnera tinctoria	Gunneraceae	Europe, North and South America, Oceania		CABI, 2021
Ipomoea pes-caprae	Convolvulaceae	Pantropical	300	Devall, 1992; Kapler, 2019; Zhang et al., 2018
Laguncularia racemosa	Combretaceae	Central America	360	eHALOPH; Gautier et al., 2001
Malvella leprosa	Malvaceae	Australia, western United States, Mexico, Argentina, and Chile		eHALOPH
Muhlenbergia peruviana	Poaceae	South of the Flora region, extending from the southwestern United States through Mexico to Ecuador, Peru, Bolivia, and Argentina		Benzaquen et al., 2017
Myriophyllum quitense	Haloragaceae	Americas	~240	Benzaquen et al., 2017; McAlpine et al., 2007
Oxychloe andina	Juncaceae	South America		Benzaquen et al., 2017
Paspalum repens	Poaceae	Native to South America, Central America, and North America		PQRS, 2013
Paspalum vaginatum	Poaceae	Coastal salt marshes of the tropics and sub-tropics	250–540	eHALOPH;Lin et al., 2002a, 2002b
Pelliciera rhizophorae	Tetrameristaceae	Tropical America	~60	eHALOPH
Phragmites australis	Poaceae	Cosmopolitan	250–740	CABI, 2021; eHALOPH; Schierano et al., 2018
Pontederia cordata	Pontederiaceae	Mainly in north America and south America		Benzaquen et al., 2017; CABI, 2021
Portulaca oleracea	Portulacaceae	Temperate and subtropical regions, although it extends into the tropics and higher latitudes	140–200	CABI, 2021; eHALOPH; Hasanuzzaman et al., 2014; Kapler, 2019; Simopoulos, 2004; Yazici et al., 2007
Potamogeton pectinatus	Potamogetonaceae	An almost cosmopolitan plant, found in most areas of the world including Britain.	>230	eHALOPH
Puccinellia glaucescens	Poaceae	South America		eHALOPH
Rhizophora mangle	Rhizophoraceae	Tropical and subtropical American species	>500	CABI, 2021; eHALOPH; Gautier et al., 2001
Salicornia fruticosa	Amaranthaceae	Africa, Europe	500–1030	eHALOPH; Figueroa et al., 2009
Salicornia virginica	Amaranthaceae	North and central America	500	eHALOPH
Schoenoplectus americanus	Cyperaceae	Mainly in north America	~200	eHALOPH; Monzón and Peláez, 2015
Schoenoplectus californicus	Cyperaceae	North America and south America	~300	Benzaquen et al., 2017; eHALOPH
Schoenoplectus pungens	Cyperaceae	North and South America, Europe, New Zealand and Australia	~200	Benzaquen et al., 2017; CABI, 2021; eHALOPH
Sesuvium portulacastrum	Aizoaceae	Pantropical	400	Fawcett, 1995 Kapler, 2019; Messeddi et al., 2001; Turcios and Papenbrock, 2019a
Spartina argentinae	Poaceae	Southern south America (invasive in other parts of world)		Benzaquen et al., 2017
Spartina densiflora	Poaceae	North America, south America, Morocco and Spain	510	CABI, 2021; Figueroa et al., 2009; Mateos-Naranjo and Redondo-Gómez, 2016

(*continued on next page*)

Table 1 (*continued*)

Plant species	Family	Distribution	Reported salt tolerance to NaCl (mM)	References
Pennisetum clandestinum (syn. *Sporobolus virginicus)*	Poaceae	Pantropical	>200	Kapler, 2019; Muscolo et al., 2013; PQRS, 2013
Sporobolus indicus	Poaceae	Widespread in almost every tropical and warm-temperate region in Europe, America and Asia		CABI, 2021
Typha angustifolia	Typhaceae	Throughout the temperate northern hemisphere	260	CABI, 2021; eHALOPH; Figueroa et al., 2009
Typha latifolia	Typhaceae	Cosmopolitan	175	Benzaquen et al., 2017; CABI, 2021; eHALOPH

Table 2
Classification of ecosystem services.

Supply services	Regulatory services	Cultural services
Products obtained from ecosystems: • Food • Freshwater • Firewood • Fibers • Biochemicals • Genetic resources	Benefits obtained from process regulation: • Climate regulation • Disease regulation • Water regulation and sanitation • Pollination	Non-material benefits obtained from ecosystems: • Spiritual and religious • Recreational and tourist • Aesthetic • Inspirational • Educational • Site identity • Cultural heritage
Basic services Services necessary for providing other ecosystem services: Soil formation, nutrient recycling, primary production		

Based on Millennium Ecosystem Assessment (2005).

Table 3
General ecosystem services.

Abiotic inputs	Intermediate services	Final services	Profits
Sunlight, rain, nutrients, etc.	Soil formation, primary productivity, nutrient cycling, photosynthesis, pollination, pest regulation	Water regulation. Primary productivity	Primary productivity. Water for irrigation, drinking water, electricity from hydroelectric plants. Food, wood, non-wood products

Based on Fisher and Turner (2009).

enhanced by the interaction of microorganisms, soil, pollutants, and plants (Stottmeister et al., 2003). Plant growth transports oxygen from the air into the rhizosphere, creating small spaces of oxygenated substrate and oxygen leakage where aerobic and anaerobic processes occur intermittently. This leads to an increase in the reduction of pollutants including nitrification and denitrification processes as well as precipitation of heavy metals. Plant roots favor also a number of physical effects such as filtering, increased rate of sedimentation, velocity reduction, improved hydraulic conductivity and reduced risk of resuspension (Shelef et al., 2013; Vymazal, 2011). Plants increase the contact time between wastewater and the different substrates, thus increasing the treatment efficiency. Many studies show that the aboveground and belowground parts of plants provide large surface areas for the development of biofilm, which is responsible for most of the microbial processes occurring in the wetlands (Leto et al., 2013). Degradation of several pollutants may occur in the rhizosphere as a result of the presence of microorganisms or root exudates (Lin et al., 2010). Halophytes are also able to uptake and degrade emerging pollutants like antibiotics (Turcios et al., 2016; Turcios and Papenbrock, 2019a). The degradation of organic pollutants in the plant tissues also depends on the plant species. For example, Turcios and Papenbrock (2019b) conducted an experiment using different enzyme extracts from different halophytes including *Chenopodium quinoa, Sesuvium portulacastrum*, and *Tripolium pannonicum*, where *Tripolium pannonicum* showed the highest potential to biodegrade sulfamethazine with a degradation up to 85.4 %. The halophyte species *Tripolium pannonicum* has also shown the ability to degrade other xenobiotics commonly found in estuaries (Turcios et al., 2021a, 2021b). According to Mathews and Reinhold (2013), there are three phases of plant metabolism of organic contaminants: Phase I, transformation of organic contaminants; Phase II, conjugation of parent contaminants and Phase I metabolites; and Phase III, sequestration or compartmentalization of Phase II metabolites. Burken (2004) also reported that hydroxylation is the most prevalent metabolic process for organic compounds in plants.

7. Examples of wetland plants used for various applications

Although the contribution of wetlands to the economy has been largely ignored, many rural populations depend on them for various activities and it is the only means through which they manage to fulfill their basic subsistence needs; at the same time, they increase the beauty of the landscape and present a high level of biological diversity (Table 4). However, Ciria et al. (2005) indicated that plants should be harvested for the most efficient removal of pollutants. This leads to a large amount of biomass being available for different uses such as composting, biogas production through the anaerobic digestion process or animal feed, while the potential of biomass for fuel production has not been given the necessary importance. Avellán and Gremillion (2019) showed that depending on the plant species used in the system up to 55 % of energy needs of a 200 people town in Sub-Saharan Africa can be furnished through the biomass of a CW thus potentially saving up to 12 ha of forests that would otherwise be used for cooking fuel. Another characteristic of the plants identified in wetlands is their high fiber content. Macía (2006) carried out a study on the use of fiber plants in Ecuador, Peru, and Bolivia, and found applications in basketry, cordage, house roofing and broom manufacturing. The products elaborated with *Agave Americana*, *Arundo donax*, *Aulonemia queko*, *Furcraea andina, Heteropsis ecuadorensis*, *Juncus arcticus* and *Schoenoplectus californicus* are commercialized in the local or national markets and its exploitation represents a good source of economic income for the families that work intensively with the plants. The use of biomass produced in CWs in handicrafts has also been observed in the Pontes dos Leites wastewater treatment plant, located in the state of Rio de Janeiro, Brazil, using species such as *Salvina auriculata* and *Pistia stratiostes* in surface flow wetlands and *Cyperus fifanteus, Cyperus comosus* and *Cyperus alternifolius* in horizontal subsurface flow wetlands. This WWTP generates 45 tons of waste per month, a part of which is destined to the ECOFIBRAS project where handicrafts are produced and later commercialized in the region, while the other part is sent to a composting plant to produce quality fertilizer (Altafin, 2020). In the same way, *Cyperus papyrus* has the potential to generate energy as mentioned by Jones et al. (2018) as long as it is done in a sustainable manner because the wetlands provide ecosystem services that could be affected if there is not adequate regulation, while for Díaz-Espinoza et al. (2012), it is characterized by its ornamental use in gardens.

Schoenoplectus (*Scirpus*) *californicus* is traditionally used as a raw material in the manufacturing of mats. For this purpose, the stems are harvested in early summer and dried in large areas in the open air and in

Table 4
Summary of the use of the different plant species found in Latin America and the Caribbean.

Family	Species	Use	Reference
Amaranthaceae	*Chenopodium quinoa*	Food	Adolf et al., 2013
	Teloxys (Dysphania) ambrosioides	Medicinal and culinary	Cáceres, 2015
Cucurbitaceae	*Momordica charantia*	Medicine	Cáceres, 2015
Cyperaceae	*Cyperus papyrus*	Energy production, ornamental use	Díaz Espinosa et al., 2012; Jones et al., 2018
	Schoenoplectus (Scirpus) californicus	Construction materials Elaboration of handicrafts, mats, and chair seats; also, in traditional medicine for lung diseases and against cramps	Lot et al., 2015; Macía and Balslev, 2000
Moringaceae	*Moringa oleifera*	Food and medicine	Cáceres, 2015
Poaceae	*Arundo donax*	The dried stems are woven into mats, ornamental use in botanical gardens and green areas	Lot et al., 2015; Macía, 2006
	Phragmites australis	Construction material, crafts, cattle fodder	Gerritsen et al., 2009
	Cymbopogon citratus	Fragrance and flavoring agent and in folk medicine	Gartenjournal, 2020
Rutaceae	*Ruta chalepensis*	Medicine	Cáceres, 2015
Typhaceae	*Typha angustifolia*	Food source for aquatic mammals	Vidal and Hormazabal, 2016
	Typha domingensis	Craft (basketry), food (rhizome), in construction of small huts and ornamental uses (inflorescences)	Lot et al., 2015; Vidal and Hormazabal, 2016
	Typha latifolia	Food source for aquatic mammals	Vidal and Hormazabal, 2016
Verbenaceae	*Aloysia triphylla*	Medicine	Cáceres, 2015

full sunshine. The woven stems are used in Bolivia to make floors and also mats of different sizes, for roofing homes and making crafts that are sold in cities. Its high nutritional value as a fodder plant is remarkable and it is an excellent resource for livestock during periods of drought (Macía and Balslev, 2000). The only species used to build boats is cattail or totora (*Schoenoplectus californicus*), which is used as a means of transportation in coastal and Andean cities in Peru. In addition, it has an ancestral use in the construction of the Uros Islands in Lake Titicaca, which are floating surfaces formed by layers of woven cattail mats. The stems are used to weave mats that are sold in local markets and are also used as walls, ceilings and to divide up rooms in houses; products are woven for sale as handicrafts (Lot et al., 2015; Macía, 2006). The *Typhaceae* family, mainly *Typha angustifolia* and *Typha domingensis* have been used as a food source by aquatic mammals and have a higher tolerance to salinity than *Typha latifolia* (Vidal and Hormazabal, 2016).

Regarding the use of *Phragmites australis*, Troya et al. (2009) recommend extracting the plants periodically and evaluating their use as a construction material. Gerritsen et al. (2009) mention that in the municipalities of El Grullo and El Limón, in Mexico, the main use of reed is to manufacture rings for wreaths, crosses, *chiquihuites* (small reed baskets), baskets and frames for fireworks castles, and they also take advantage of the tender sprouts as fodder for livestock through direct grazing.

Momordica charantia is a salt-tolerant plant that has many medicinal properties. It is an originally African plant but dispersed in the Americas (Cáceres, 2015). Its salt tolerance has been experimentally demonstrated as well as the effects of jasmonic acid under high salt stress. Jasmonic acid has a positive effect on the plant when it suffers from abiotic stress and protects it from oxidative stress. The seedling of *Momordica charantia* tolerates up to 300 mM salt. There are many uses for *Momordica charantia* including the treatment of numerous diseases such as anorexia, bronchitis, diabetes mellitus, dysmenorrhoea and rheumatism and to treat digestive problems, fever and parasites. The leaves are also used to treat parasites and digestive problems, and other diseases such as anaemia, hypertension, malaria, and rheumatism and also for respiratory problems, treating wounds, stimulating blood flow and stimulating lactation. It is also used in the form of compresses or ointments for the treatment of aphtae and mucosal diseases (Cáceres, 2015).

Teloxys ambrosioides is also a halophyte (Dagar et al., 2019) and native to the American tropics (Cáceres, 2015). It spreads in coastal zones. *Teloxys ambrosioides* has many medicinal properties. It is used to treat inflammation and wound healing, acts as an antiseptic, antifungal, anthelmintic. It also acts against parasites and against asthma and helps digestion. In addition, the leaves are used as a ripening agent for food. The oil of the plant acts as a spasmolytic, a muscle relaxant, stimulates respiration but also gastric motility and reduces heart rate.

The species *Aloysia triphylla*, native to South America (Cáceres, 2015), forms a symbiosis with endophyte bacteria (*Sphingomonas paucimobilis*) and endophyte fungi (*Aspergillus* spp.). These endophytes help plants during stress conditions, but they also improve plant growth (Golparyan et al., 2018). *Aloysia triphylla* offers many medicinal healing properties and is also used in the cosmetics and food industries. Generally, the plant serves as a spasmolytic, emmenagogue, expectorant, antipyretic, sedative and digestive aid.

The leaf infusions are used to treat many gastrointestinal complaints such as nausea, parasites, indigestion, flatulence and intestinal catarrh. And the ethanol extract is effective against *Escherichia coli*, *Mycobacterium tuberculosis* and *Staphylococcus aureus*. The leaf infusions are also used to treat respiratory and nervous complaints such as anxiety disorders, hysteria, insomnia, and inner restlessness. The crushed leaves are used as cataplasm for the treatment of toothache. In addition, the essences of the leaves are used in cosmetics to make perfumes, but also in the patisserie and liqueur industry as an aromatization and flavoring agent (Cáceres, 2015).

Moringa oleifera is also a salt-tolerant plant originating in the Himalayas (Cáceres, 2015), but has been dispersed in Latin America for nutritional, medicinal and forage purposes (Nouman et al., 2012). *Moringa oleifera* has shown positive correlation between salinity and growth parameters and antioxidant activities. It is also interesting to note the increase in root length of *Moringa oleifera* at higher salinities. This phenomenon suggests that its roots prove a tendency to grow, increase branching, expand, and elongate under saline conditions (Nouman et al., 2012), which could have a positive effect through its use in saline wetlands. *Moringa oleifera* has many uses, including medicine and in the energy industry, but it is also used for the purification process as filtration. The boiled roots are used to treat smallpox, fever, epilepsy, stomach aches and rheumatism. The root juice is used against asthma and lumbago, the capsule fruits for liver diseases and as an aphrodisiac. The tea infusions with the capsule seed serve as a laxative and are antipyretic but also serve in the treatment of ascites, catarrh, cholera, dysentery, epilepsy, inflammations, neuralgia, rheumatism, spasms, toothache, tumors and ulcers. The flowers, leaves and roots have general cholagogue, cleansing, diuretic, stimulant, bactericidal properties and oestrogenic effects and are used in worming. The seed oil is used dropwise as a healing agent for burns and indurations of the skin (Cáceres, 2015). Another very interesting property of the plant is its ability to purify water. Its seed powder serves as a natural coagulant, antimicrobial agent and heavy metal remover from aqueous systems (Abiyu et al., 2018). Moreover, the properties of the seed powder can replace the chemical coagulants (flocculants), especially in countries where it is hardly possible to use the chemical purification process due to the high cost (Abiyu et al., 2018).

Ruta chalepensis is also widespread throughout Latin America and is a salt-tolerant plant with many medicinal and pharmacological properties (Cáceres, 2015). Under salt stress, *Ruta chalepensis* produces more secondary metabolites such as polyphenol flavonoids, thus, the increase in salt concentration is coupled with the increase in secondary metabolites and phytochemicals within the plant (Amdouni et al., 2016). The pharmacological properties of *Ruta chalepensis* also have to do with the salt content of the plant. This is because salt stress increases the antibacterial property activity of the plant leaf oil against bacteria *Listeria 477*, *Escherichia coli* and *Pseudomonas aeruginosa* (Amdouni et al., 2016). The medicinal properties of *Ruta chalepensis* are immense: the boiled leaves are used to treat digestive and respiratory disorders, nervous disorders, amenorrhoea, headaches, cycle pains, uterine bleeding, rheumatism, heart, and circulatory problems. The decoction of the plant is used to treat insect bites, skin diseases, rashes, and nosebleeds. The vapors of the decoction are used to treat nasal congestion, conjunctivitis, and cough. The pulp from crushed fresh leaves is used as an ointment for abscess treatment (Cáceres, 2015).

Cymbopogon citratus is also distributed throughout Latin America and originates from India and South Asia. Guatemala is currently the main exporter of *Cymbopogon citratus* in the world, with trade volume sales of about 250,000 kg annually (Ullah et al., 2020). *Cymbopogon citratus* produces the highest biomass yield at salt concentration of 4 dS/m and can tolerate 10 dS/m but with reduced biomass yield (Ullah et al., 2020). For this reason, the cultivation of *Cymbopogon citratus* in saline environments is nowadays intensively researched. *Cymbopogon citratus* is an aromatic plant and is used in cosmetics for the production of perfumes. In addition, *Cymbopogon citratus* is also used in culinary applications because of its aroma. Its aromatic substances also act as a natural repellent against insects (Gartenjournal, 2020). However, *Cymbopogon citratus* is also a medicinal plant. It is used as an antiseptic, antipyretic, carminative, sedative and to inhibit inflammation. It also acts as a medicinal plant for its antibacterial, antifungal, antiprotozoal, anticarcinogenic, anti-inflammatory and antioxidant effects. It is also used to treat diabetes, malaria, influenza, pneumonia and for inhibiting platelet aggregation. Tea infusion is used as a digestive, antispasmodic, anti-allergic and against colds (Ullah et al., 2020).

Chenopodium quinoa is a native Latin American halophyte. It originates from the Andean highlands from Bolivia to Chile (Franke et al., 2012). It is cultivated in salt-affected areas, as it tolerates very high salt concentrations. The protein concentration of its seeds is also not affected by irrigation with saline water. The salt resistance value of the plant without affecting the seed quality reaches about 20 dS/m (200 mM NaCl) (Eisa et al., 2017). Quinoa seeds are prepared as food and have important nutritional properties. Traditionally, quinoa seeds are prepared as rice, or as an ingredient for soups or even as popcorn (Lack and Fuentes, 2013). Nowadays, quinoa is also known for its flour, for pasta making and as an ingredient in salads and vegetarian hamburgers. The protein content of quinoa seeds is very high and the amino acid composition is better than cereals. Seeds also have a higher content of vitamin E and of many minerals such as Ca, Mg, Fe, Cu and Zn, which are important for human metabolism. For example, the value of calcium content is sufficient for bone and teeth development in infancy. Quinoa seeds are also used in the pharmaceutical industry. Furthermore, quinoa seeds reveal a higher zinc content, which has antiviral, antibacterial, antifungal and anticarcinogenic properties (Vega-Gálvez et al., 2010).

8. Halophytes being used in constructed wetlands in Latin America

A survey on common emergent macrophytes used in FWS wetland by Vymazal (2013) showed that *Phragmites australis* is the most popular plant in Europe and Asia, *Typha latifolia* was recorded as the most used species in North America, while *Phragmites australis* and *Typha domingensis* are the most popular plants in Central and South America. An overview study of macrophytes used in CW systems in the LAC countries showed a clear preference for *Typha* spp. (Rodriguez-Dominguez et al., 2020). However, there are also other species capable of adapting to saline conditions, which dominate the vegetation in natural saline wetlands, such as inland and coastal marshes and coastal marginal forests, which have been found in many coastal areas in Latin America.

Although in the case of saline CWs the function of plants and microorganisms can be inhibited by salts, an acceptable treatment efficiency is still achieved by using halophytes and optimizing the structure and operating parameters of the wetland (Liang et al., 2017). The behavior of halophytes planted in CWs has been evaluated in several studies conducted in Latin America. For example, Castillo-Castañeda and Agudelo-Valencia (2020), analyzed the efficiency of a pilot horizontal subsurface flow CW planted with *Limonium perezzi,* in the removal of salinity and organic load from leather soaking wastewater (Electrical conductivity 60.3 mS/cm, chlorides 44,414.8 mg/L, total organic carbon 755.9 mg/L). Chloride removal efficiency was 49.2 % and total organic carbon was 86.2 %. The plant showed high tolerance to high concentrations of dissolved salt in the water for most of the time, presenting transpiration of sodium chloride crystals through the leaves and stem. Towards the end of the 32 days of operation the plant died, a fact that according to the authors of the study could have been avoided by increasing the population density of the plants to better distribute the salt load. This study was developed in the facilities of the Universidad Libre de Colombia, Bogotá, at an altitude of 2630 m above sea level and average temperature of 14.55 °C.

Fia et al. (2017) evaluated the influence of *Typha latifolia* and *Cynodon* spp. on the removal of wastewater pollutants from swine rearing (Electrical conductivity, 4.3 $\pm$ 0.41 mS/cm, COD, 2492 $\pm$ 1705 mg/L, BOD 777 $\pm$ 519 mg/L, TSS 953 $\pm$ 803 mg/L). They worked with pilot horizontal subsurface flow wetlands installed at the Federal University of Vicosa - Vicosa (Minas Gerais), Brazil. The efficiencies of COD, BOD and TSS removal for wetlands planted with *Typha latifolia* and *Cynodon* spp. were 79 $\pm$ 14 and 80 $\pm$ 13 mg/L, 83 $\pm$ 20 and 86 $\pm$ 15, 84 $\pm$ 19 and 86 $\pm$ 14, respectively, with significant differences observed only between COD removal values.

Schierano et al. (2018) operated horizontal subsurface flow wetlands at microcosm level, planted with *Typha domingensis* and *Phragmites australis,* in order to analyze their efficiency in the final treatment of wastewater from the dairy industry (TSS 159 mg/L, COD 157 mg/L, ammonia nitrogen 17.3 mg N/L, total phosphorus 14.3 mg/L). The values of pH and electrical conductivity at the entrance and exit of the wetlands did not show significant differences, varying in the first case from 7.95 to 8.30 and in the second case from 4.82 to 5.07 mS/cm. The ammonium removal percentages in the planted wetlands with both species was higher than 96 %, the COD decreased around 75 %, while the removal of suspended solids was between 78.4 and 81.1 %. In contrast, in total phosphorus removal, wetlands planted with *Typha domingensis* were significantly more efficient (88.5 %) than those planted with *Phragmites australis* (71.6 %). Although both plants developed very well, the authors explain these latter results based on the higher aerial biomass presented by *Typha domingensis*, which could contribute with a greater accumulation of phosphorus in the tissues. The study was developed by a research group from the Universidad Nacional del Litoral, Santa Fe, Argentina.

Maine et al. (2006) evaluated the metal and nutrient removal efficiency of free-flowing wetlands for the treatment of wastewater from a metallurgical industry (conductivity 2.9 mS/cm, range 0.4–8.5 mS/cm; Cr 22 μg/L, range 3.3−150 μg/L; Ni 17 μg/L, range 6.1−60 μg/L, N-NO_3^- 16 mg/L, range 1.6−68 mg/L, N-NO_2^- 0.79 mg/L, range 0.021–3.4). The removal percentages obtained for nitrite and nitrate were 70 % and 60 %, 86 % for chromium and 67 % for nickel. As for the species used, *Eichhornia crassipes* (water hyacinth) presented a rapid growth, becoming the dominant species. *Typha domingensis* and *Panicum elephantipes* were developed as companion species. The metal content increased significantly in the tissue of *Eichhornia crassipes* and *Typha* *domingensis*, after one year of operation, indicating that the removal mechanism was based on absorption by macrophytes.

In addition, in Latin America, applications of halophytes in wetlands have been found for the treatment of leachate from landfills. Leachates typically contain relatively high concentrations of organic matter and ammonium nitrogen, and in some cases may also contain significant levels of salts, metals and xenobiotic organic compounds (Langengraber et al., 2020). For installation in wetlands that treat leachate, locally adapted native plants must be selected that can develop under the hydrological conditions of the type of wetland used, and that can tolerate the specific characteristics of the water, as some leachate contains considerable concentrations of salts, boron and other potentially toxic substances that can compromise the health and vigor of the wetland vegetation.

Jiménez Cerón et al. (2018) conducted a pilot study using horizontal flow CWs as a tertiary treatment of treated leachate in an anaerobic stabilization pond. The species used were *Heliconia psittacorum* and *Cyperus haspan*, the conductivity at the entrance of the unit was 14.82 mS/cm, and a decrease was registered at the exit of the wetlands with values of 5.38 mS/cm for *Heliconia psittacorun* and 4.48 mS/cm for *Cyperus haspan*. The systems proved to be a feasible alternative in the secondary treatment of mature landfill leachate for the removal of COD, N-NO_3^-, P-PO_4^{3-} and Pb^{2+}, with a hydraulic retention time of 4 days. *Cyperus haspan* was the species that adapted more easily to the conditions of the systems evaluated, possibly because of its characteristics as an invasive species and its capacity to develop in flooded environments, while *Heliconia psittacorum* presented symptoms of possible damage to its physiology. The study was developed in the "El Ojito" landfill, in the municipality of Popayán-Cauca, Colombia.

Madera (2016) developed a pilot-scale research in the sanitary landfill of Presidente, municipality of San Pedro, Valle del Cauca, Colombia in 2015; its aim was to evaluate the use of the coupling eco-technology BLAAT® (High Rate Anaerobic Pond Bioreactor) + CW planted with polyculture of the tropical species *Colocasia esculenta*, *Heliconia psittacorum* and *Gynerium sagittatum*. Four wetland cells were installed, three cells were divided into three sections and in each section (5.98 m^2) 36 seedlings of one species were planted. The other unit was planted at random. The electrical conductivity of the units was on average 4.8 mS/cm and was reduced to 3.7, 3.8, 3.7, and 3.4 mS/cm in each cell. respectively, without showing significant statistical differences between units. The evaluated vegetable species maintained a good growth and physiological response with good chlorophyll-a content and good photosynthetic rate throughout the study.

Another interesting application is the use of mangrove wetlands as a biofilter to treat effluents from a shrimp pond. Agrosoledad, a 286 ha shrimp farm located on the Caribbean coast of Colombia, was built behind a 1 km wide mangrove. The experience reported by Gautier et al. (2001) indicates that the effluents were partially recirculated through a 120 ha mangrove wetland used as a biofilter. The shrimp farm pumps 345,600 m^3 of water per day, to exchange about 8 cm of water/day in each pond; the biofilter is characterized by surface flow and emergent vegetation composed of *Rhizophora mangle* (46 %), *Laguncularia racemosa* (11 %), *Avicennia germinans* (1%) and *Cotenenocarpus erectus* (1%) trees and the fern *Acrostichum aureum* (41 %). Water quality was monitored for 3 months in the dry season and it was found that salinity increased steadily from 10 g/l to 23 g/l during the experiment. Suspended solids present in the shrimp pond effluent were drastically reduced in the biofilter, but dissolved inorganic nitrogen and phosphorus were not. In another 5-year study using mangroves as a biofilter in an intensive shrimp farm on the coast of Yucatan, Mexico, the mangrove biofilter had the capacity to retain 44 % of $NO_2^- + NO_3^-$, 55 % of NH_4^+ and 80 % of PO_4^{3-} (Zaldívar-Jiménez et al., 2012). These studies, including others where mangroves were also used (Tilley et al., 2002), demonstrate the efficiency of mangroves to uptake nutrients, so they could be considered as an alternative for the treatment of saline effluents, and simultaneously can give protection against natural disasters (Turcios and Papenbrock, 2014).

9. Potential use of wetlands to treat water from aquaculture systems

Agriculture and livestock activities have intensified in recent years. Changes in these systems have generated undeniable socio-economic achievements but have created major environmental problems. Aquaculture production has also intensified in recent years. Global fish production is estimated to have reached about 179 million tons in 2018. Of the overall total, 156 million tons were used for human consumption, equivalent to an estimated annual supply of 20.5 kg per capita. Aquaculture accounted for 46 percent of the total production and 52 percent of fish for human consumption (FAO, 2018). Aquaculture production in the LAC region in 1997 was 2.1 percent of the volume of world aquaculture output. It was 4 percent of the total fisheries production in the region. Real annual growth of production in the South American subregion was about 20 percent. In 2017 the aquaculture production in the LAC region increased to 2.96 million tons (2.64 percent of world total) (FAO, 2018) and is expected to continue growing. Due to the social and economic situation in Latin America, aquaculture production tends to place priority on the generation of foreign exchange (Hernández-Rodríguez et al., 2001).

Aquaculture causes problems in freshwater environments, estuaries, and coasts, mainly by eutrophication of oceans, lakes and rivers. Eutrophication occurs when water quality deteriorates due to nutrient overload, mainly nitrates and phosphates. Growth of aquatic weeds, algae and cyanobacteria increases massively, resulting in oxygen depletion. Therefore, it has caused the depletion for other aquatic life in the ecosystem.

In addition, toxins produced by cyanobacteria are powerful natural poisons which can kill many forms of life and may be a serious health hazard to humans (Carpenter et al., 1998). About 70,000 known and emerging chemicals have been identified that might be present in various water resources, including for drinking water production (Korostynska et al., 2013). Among them are organic compounds, which include phthalates, bisphenols, alkyl phenols, alkyl phenol ethoxylates, polyethoxylates, pesticides, human hormones and pharmaceuticals (Fawell and Nieuwenhuijsen, 2003). Also, in aquaculture systems a number of chemicals are applied, such as antibiotics.

Therefore, wastewater treatment using well-established and cost-effective method is of great importance. Biofiltration in CWs is also used in aquaculture as a way to minimize water replacement while increasing water quality (Buhmann and Papenbrock, 2013; Turcios and Papenbrock, 2014). It contributes to the improvement of the surrounding microclimate, providing a suitable habitat for other organisms (DWA, 2014). Constructed wetlands technology is also becoming more and more important in recirculating aquaculture system (RAS). Since the introduction of RAS in the late 1980′s its production increased significantly in volume and species diversity (Martins et al., 2010). RAS are systems in which water is recycled by running it through filters to remove food and fish waste and then recirculating it back into the tanks. This saves water and the waste gathered can be used in compost or, in some cases, could even be treated and used on land.

In conventional aquaculture, excretions from the animals being raised can accumulate in the water and increase toxicity. In an aquaponics system, water from an aquaculture system is fed to a hydroponic system where the by-products are broken down by bacteria into nitrate and ammonium which are utilized by the plants as nutrients. Most CWs used in aquaculture are soil based horizontal SFS and FWS systems (Lin et al., 2002a, 2002b; Martins et al., 2010), although in recent years, to improve TAN and NO_3 removal efficiency, VHF-CWs with partial recirculation have been installed.

Several studies (Lin et al., 2002a, 2002b; Lin et al., 2005; Schwartz and Boyd, 1994) have demonstrated that CWs using different plant species can efficiently remove the major pollutants from catfish, shrimp and milkfish pond effluents, including organic matter, SS, N, P, and phytoplankton under a low hydraulic loading rate (HLR) and long hydraulic retention time (HRT) ranging between 0.018–0.135 m day^{-1} and 1–12.8 days, respectively. Lin et al. (2003) used SF and FWS CWs planted with *Phragmites australis* arranged in series and integrated into a RAS for culturing Pacific white shrimp (*Litopenaeus vannamei*). They demonstrated a decrease of BOD_5 (24 %), SS (71 %), TAN (57 %), NO_2-N (90 %) and NO_3-N (68 %) using mean hydraulic loading rate of 0.3 m/day, the reduction of phosphate (PO_4-P) was the least efficient (5.4 %). Nevertheless, in other study (Lin et al., 2002a, 2002b), phosphate removal of 32%–71% was reported, with the efficiencies being inversely related to hydraulic loading, and a removal of 82 %–99 % for NO_3–N, and 95 %–98 % for total inorganic nitrogen (TIN), but they used three different plant species: The FWS wetland was planted with water spinach (*Ipomoea aquatica*) in the front half and with a native weed (*Paspalum vaginatum*) in the second half and in the SSF wetland was planted with *Phragmites australis*. Therefore, different factors affect the treatment efficiency of wetlands including nutrient concentration, plant species, root system, wetland type, construction materials, environmental factors, hydraulic parameters, and other technical applications.

In recent years, aquaculture in marine waters has also increased (FAO, 2018). Because there is an increasing demand for seafood with a simultaneous decrease of natural stocks and eligible coastal areas, inland marine aquaculture and therefore the treatment of generated saline effluents becomes more important. A possibility to meet this trend is the development of applicable CWs planted with halophytic macrophytes (Buhmann and Papenbrock, 2013). Removal of 62 % of total N and 76.5 % of total phosphate (Lymbery et al., 2006) and 99 % of total N and total P (Brown et al., 2000) were reached at salinities of 411 mM NaCl and 599 mM NaCl, respectively (Buhmann and Papenbrock, 2013). Webb et al. (2012) also demonstrated the effectiveness of wastewater treatment from land-based intensive marine aquaculture farms by CWs planted with *Salicornia* spp. However, halophytes show different sensitivity toward salinity depending on the plant species, therefore their performance can be affected by high salinities even for halophytes being tolerant to seawater salinity. These NBS have great potential, especially in developing countries, but there is still a lot of research and dissemination to be done in different regions, including research with native species.

10. Facts on the efficiency of wetlands in wastewater treatment

The treatment efficiency of CWs is relatively high, however, the importance of their implementation in LAC countries is unfortunately still limited. The efficiency of CWs can be evaluated in different ways, for example with respect to the efficiency of the removal of nutrients, organic compounds, trace metals, microorganisms and other parameters. The efficiency depends on many factors. The type of CW has a major influence on vegetation and the exposure of the plants to the sunlight. For example, planted emergent vegetation assists in removing pathogens, but even more other pollutants, such as nutrients. Thus, the importance of sunlight exposure is minimized in a free water surface flow wetland (Maiga et al., 2019). Tanaka et al. (2011) provide a systematic analysis of the design features of CWs and their management in terms of location, physical maintenance, and operation. The selection of plant species, managing their growth and harvesting cycles have an impact on the removal of organic and inorganic pollutants, nutrients, and pathogens. However, reliable studies on this aspect are rare for the tropics and subtropics.

According to Rodriguez-Dominguez et al. (2020), horizontal subsurface flow wetlands are the most reported CW in the LAC countries (62 %) (from 520 cases in 20 countries), the second most common CW technology in the region is free water surface CW (17 %), then vertical flow systems (9%), followed by intensified CWs (8%), and finally French systems (4%). The performance for nutrient removal was also analyzed, finding that the mean of COD, TN, TP removal efficiencies varied from 65 % to 83 %, 55%–72%, and 30%–84%, respectively. The results suggest a generally good performance for COD and TN removal, but a low performance for TP removal.

In the pilot treatment plant at the University of San Carlos of Guatemala, Blandón and Carrera (2017) showed the removal levels of nitrites, nitrates, phosphate, and ammonium that can be achieved by means of the use of microalgae (*Chlorella* spp., *Closteriopsis* spp., *Microsystis* spp., and *Sphaerocystis* spp.). Ammonium removal was 25.55 % (from 17.50 mg/l to 13.03 mg/l). Phosphate decreased from 19 mg/l to 8.5 mg/l (55.1 %) at low concentrations while at high concentrations it decreased from 204 mg/l to 155.9 mg/l (23.6 %). Nitrate was reduced from 116 mg/l to 53.6 mg/l (53.8 %) at high concentrations while at low concentrations it decreased up to 76.0 %. Nitrites were decreased 56.8 % (1.55 mg/l to 0.67 mg/l) when present at high concentration. Caselles Osorio (2007) investigated the treatment efficiency of horizontal SSF CWs. After 8 months of operation, the COD removal results indicated that the SSF CWs were not sensitive to the type of organic matter. Average COD removal rates for glucose ranged from 76 to 94 %, while values for starch were 70–94%. Furthermore, COD removals for both forms of organic matter were not affected by hydraulic retention time or sulfate concentrations. The removal of ammonium-N was low for both forms of organic matter but was slightly greater in the wetland fed with glucose (29–57%) as compared to starch (20–53%). In Brazil, Fia et al. (2014) studied the agronomic performance and capacity of nutrient removal by bermudagrass (*Cynodon* spp.) and cattail (*Typha* spp.) when grown in CWs of vertical and horizontal flow, respectively. The average yield of dry matter (DM) of bermudagrass in sections of 60-day interval ranged from 14 to 43 t ha^{-1}, while the cultivated cattail produced in a single cut after 200 days of cultivation between 45 and 67 t ha^{-1} of DM.

11. Sustainability aspects of constructed wetlands

Bui (2018) found that CW publications document mostly systems found in the Global North and studies about pilot or mesoscale systems. In contrast, systems in the Global South as well as long term studies of operational treatment systems are often lacking (Tischbein et al., 2021). However, in particular countries with tropical or sub-tropical climate could heavily benefit from the co-benefits of CWs of continued biomass production as a means of supplementing energy demands. However, to ensure sustainability, a system also needs to comply with criteria in environmental, economic, and social (as well as more recently institutional) dimensions (Toumi et al., 2017; Waas et al., 2011; WCSD, 1987). It should do so without hampering the well-being of future generations. Currently natural wetland systems are threatened by a variety of degradations, such as increased pollution loads – liquid and solid – into surface water bodies (just think of the plastic problem around you) or overfishing and overuse of the wetland system in general. The floodplains of the Río Uruguay/Río Paraná are extensively used for cattle grazing. A common practice in the late winter months (July and August) is the widespread burning of the wetland vegetation (pampa grass, juncus, etc.) to foster new re-growth that is more palatable to the cattle. This causes high air pollution loads over vast areas and rapid releases of greenhouse gases that would otherwise be bound to the vegetation. On the other hand, the seeds of a number of native species require fire events. Prevention of fire events could have negative effects on biodiversity. To implement a concept of balance is therefore crucial. Another common phenomenon along the South American coast lines is the transformation of natural seaside vegetation (be it mangroves or dunes) into prime real estate. This causes severe damage to the natural environment resulting, amongst others, in loss of beaches due to disturbed dune migrations or further inland damage form tides due to the lack of protective mangrove forests.

Using CWs can, to certain degree, offset some of the damage caused by the loss of wetlands, however maintaining pristine environments is always to be preferred over substitution projects – manmade systems elsewhere cannot not provide the same ecosystem services as virgin, natural environments. The co-benefits that nature-based solutions offer such as enhanced biodiversity or the possibility for circular use of resources over grey infrastructure are the leading reason for their preferential construction. However, enhanced circularity does not equate in improved sustainability (Kravchenko et al., 2019). All infrastructure intervention needs to be fit-for-purpose and be adapted to local circumstances. Even if CWs are relatively easy in their operation and maintenance requirements in comparison to other wastewater treatment systems, they still require personnel dedicated to this task with a level of capacity to carry this out. If the locality is not willing or capable to provide the necessary capacity development for this task, the system will be doomed to fail sooner or later, thus severely hampering the sustainability of the system. Other aspects that can affect the sustainability is the level of knowledge of the local population about the systems and their functioning. A lack of knowledge about the need and about how the system will address those needs can lead to a rejection of the treatment system by the population. This can strongly influence the willingness to pay for service or worse to the sabotaging of it through willful destruction. A paradigm shift needs to happen, in particular in development aid, away from one-way information and awareness raising campaigns towards sincere two-way communications that result in a co-decision process where true ownership lays with the local community rather than the (foreign) construction/engineering company (Avellán et al., 2021).

12. Conclusions

Constructed wetlands are nature-based solutions which have a good potential to be implemented worldwide, especially in developing countries mainly due to their relatively low operating and maintenance costs, with relatively high efficiency for wastewater treatment. Latin America is a region rich in natural wetlands with several salt tolerant plants. These plants have a great potential to be used in the phytoremediation process for the treatment of saline wastewater (e.g. saline aquaculture effluents). Regarding the current situation of constructed wetlands with halophytes for the treatment of saline water, although they already exist in Latin America, there are few reported cases. With the increase of salinity in water resources and soil worldwide, as well as the expansion of saline aquaculture, the use of this technology for the treatment of saline effluent is becoming more necessary. However, in order to optimize the system adapted to local conditions taking into account technical, economic, social, environmental and legal aspects more research and dissemination is needed in this field.

Author statement

All persons designated as authors have participated sufficiently in the work to take public responsibility for appropriate parts of the content.

All authors have made substantial contributions to all three of sections (1),(2) and (3) below:

1. The conception and design of the study, or acquisition of data, or analysis and interpretation of data
2. Drafting the article or revising it critically for important intellectual content
3. Final approval of the version to be submitted

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Declaration of Competing Interest

The authors declare no conflict of interest.

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