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Halophytes as vertical-flow constructed wetland vegetation for domestic wastewater treatment

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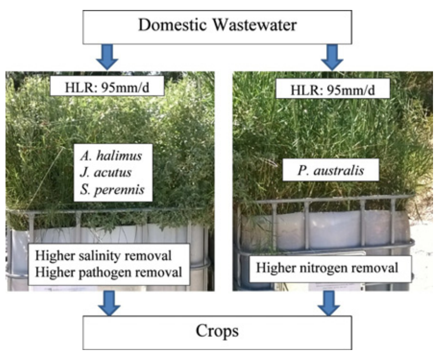
HIGHLIGHTS

- *Atriplex halimus* showed great potential to accumulate salts in its tissues.
- *Atriplex halimus* was the halophyte species with the highest biomass production.
- Enhanced pathogen removal efficiency was recorded in CW planted with halophytes.
- Enhanced nitrogen removal efficiency was recorded in CW planted with reeds.
- *J. acutus* and *S. perennis* are not recommended for salt phytoremediation.

GRAPHICAL ABSTRACT



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ABSTRACT

Recent findings show that halophytes have the ability to accumulate salts in their tissues, making them a very interesting group of plants for domestic wastewater treatment in constructed wetlands (CWs). In that case, it might be possible to reduce the salinity of the final effluent, which is a crucial parameter for wastewater reuse in agriculture. During this study three halophytes, *Atriplex halimus*, *Juncus acutus* and *Sarcocornia perennis*, were tested for phyto-desalination of domestic wastewater in a vertical flow constructed wetland (VFCW) and compared with common reeds (*Phragmites australis*). In addition, the effect of this alternative vegetation on the overall performance of the system regarding organic matter, nutrients, boron and pathogen removal was monitored. The organic loading rate (OLR) was about 21 gCOD/m^2/d and the hydraulic loading rate (HLR) was 95 mm/d in both cases. Promising results were obtained for *A. halimus*, which shows high biomass productivity and significant capability to accumulate salts, mainly Na, in its tissues. A positive effect on pathogen removal efficiency was also recorded. However, nitrogen concentration in the effluent of the VFCW planted with halophytes was found to be higher than in the effluent of the VFCW planted with reeds. Finally, no significant effect on organic matter and phosphorus removal efficiency was observed from the use of halophytes in place of reeds.

1. Introduction

CWs are a very appropriate technology for the treatment of domestic wastewater in small communities (Molinos-Senante et al., 2015). Their simplicity and low cost of operation and maintenance have resulted in

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increasing popularity in the Mediterranean basin in the last two decades (Ghrabi et al., 2011). These systems use the natural functions of wetland vegetation, granular media and their microbial populations to treat contaminants in wastewater (Vymazal, 2011a). Removal mechanisms include sedimentation, filtration, biodegradation, adsorption, plant uptake, precipitation, photodegradation and volatilization (Kadlec and Wallace, 2009). From all of these, it is recognized that most of the contaminant removal is mediated by microbial processes (Faulwetter et al., 2009).

There is a considerable amount of research related to the role of plants in CWs (Brix, 1997; Carballeira et al., 2016; Shelef et al., 2013; Vymazal, 2011b). Their effects on removal mechanisms include: a) increased filtration and sedimentation due to physical effect of root structure on hydraulics of CWs (Vymazal, 2011b); b) increased microbial activity (aerobic degradation, nitrification, denitrification) by providing structural support for microbial community attachment to root systems and oxygen transfer from aerial tissues into the rhizosphere (Button et al., 2015); c) increased plant uptake by utilizing nitrogen, phosphorus and heavy metals (Vymazal, 2011b; Weis and Weis, 2004); and d) increased water loss through transpiration of plants (Headley et al., 2012). In addition, plants can improve microclimatic conditions, control odor nuisances, enhance aesthetic appearance and increase wildlife diversity of systems (Shelef et al., 2013). Furthermore, when plants decompose during senescence period they may severely affect treatment performance, and harvesting is recommended (Ge et al., 2016; Li et al., 2008). In any case, plant species, growth condition, tolerance and adaptation to wastewater seem to play an important role in the overall effect of plants on CWs performance.

Plant uptake found in some cases to be an important removal mechanism for several contaminants such as nitrogen, phosphorus and heavy metals. Specifically, plant nutrient uptake in CWs found to contribute from 3% to 47% of nitrogen removal and 3% to 60% of phosphorus removal (Gottschall et al., 2007). In addition, the role of plant uptake for heavy metals removal was variable with values as high as 71% for cadmium, 55% for chromium and 49% for zinc (Vymazal and Brezinova, 2016). Finally, the presence of plants in CWs can have a minor positive effect on improving the quality of the wastewater due to direct uptake of B in tissues (Türker et al., 2016).

Plants commonly used in CWs are helophytic species such as common reed (*Phragmites australis*), giant reed (*Arundo donax*) and cattail (*Typha latifolia*). These plants adapted well to the CWs environment and the systems usually achieved satisfactory removal efficiencies for organic matter, nutrient and pathogens (Carballeira et al., 2016; Vymazal, 2013; Wu et al., 2016). Recently, the use of halophytes (salt-tolerant plants) for salt-phytoremediation in CWs has been proposed (Shelef et al., 2013; Shelef et al., 2012) as a novel strategy for managing salinity, which causes soil degradation and has adverse effects on crops (Muyen et al., 2011). It is known that many halophytic plants have the ability to accumulate salts and heavy metals in their tissues (Manousaki and Kalogerakis, 2011). The criteria for the selection of best-suited halophytic plant for CW vegetation are: a) ability to grow in a CW environment, b) ability to accumulate enough ions within its tissues to significantly reduce wastewater salinity, c) low transpiration in order to mitigate the evapotranspiration of the CW, and d) having at least the same positive contribution to CWs as the established halophytes regarding organic matter, nutrient and pathogen removal. To date, the halophyte species examined in CWs are very limited. Shelef et al. (2012) examined the use of *Bassia indica* for salt phytoremediation in VFCWs. They reported that *B. indica* developed successfully in these systems, achieving a reduced effluent salinity by 20–60% in comparison with unplanted systems. The capacity of the same species to accumulate salts is reaffirmed by another study (Freedman et al., 2014) using horizontal subsurface flow CW (HSSF CW). However, the value of electrical conductivity in the effluent was no lower than in the influent due to high evapotranspiration. Guesdon et al. (2016) evaluated the potential of two salt tolerant plants (*Typha angustifolia* and *Eleocharis palustris*) and one halophyte (*Juncus maritimus*) to remove de-icing salts from runoff water in lab-scale HSSF CW. A reduction of 20–40% was observed for Na and Cl in the effluent compared to the influent. Jesus et al. (2017) reported that *Spartina maritima*, *Juncus maritimus* and *Arundo donax* have limited salt removal capacity in lab-scale CWs. There are also some other works regarding the use of halophytes in CWs for the treatment of saline wastewater from aquaculture (Buhmann and Papenbrock, 2013; Shpigel et al., 2013; Webb et al., 2013; Webb et al., 2012). In these cases, the halophytes were used due to their ability to grow in the high salinity environment of aquaculture, focusing mainly on nutrient removal rather than salt removal. Results show the effectiveness of N and P removal from the aquaculture wastewater.

All these studies published in the last five years indicate the growing interest in the use of halophytes in CWs. However, there are still many questions to answer regarding the successful application of halophytes for salt phytoremediation in CWs, such as the best-suited halophytic species, the type of CW, the operational characteristics and the effect on the removal of other pollutants such as organic matter, nutrients, heavy metals and pathogens. The aim of this work was to evaluate the ability of three halophytic plants, *Atriplex halimus*, *Sarcocornia perennis* and *Juncus acutus*, to accumulate salts in their tissues when planted in a pilot scale vertical flow CW treating domestic wastewater, and to determine the effect on the efficiency of the system in removing salts, organic matter, nutrients, pathogenic bacteria and boron in comparison with reeds (*Phragmites australis*). *A. halimus* is a xero-halophytic shrub native to arid and semi-arid regions around the Mediterranean basin. It has already been tested for remediation of heavy metals and salts from contaminated and saline soils with very promising results (Manousaki and Kalogerakis, 2011; Suaire et al., 2016) but to the best of our knowledge has never been tested in CWs. *S. perennis* is a common halophyte in salt-marshes in Europe, Africa and America. Previous works have found that it can accumulate heavy metals and nitrogen in its tissues (Caçador et al., 2009; Duarte et al., 2010; Gonzalez-Alcaraz et al., 2013; Reboreda et al., 2008; Sousa et al., 2010). There are no studies on the use of this species in CWs. However, another species of genus *Sarcocornia*, *S. fruticosa*, has been tested in CWs for polishing high salinity tannery wastewater (Calheiros et al., 2012). *J. acutus* is a common halophytic plant in Mediterranean ecosystems and is known for its ability to accumulate heavy metals in its tissues (Christofilopoulos et al., 2016; Mateos-Naranjo et al., 2014; Santos et al., 2014). Additionally, some species of genus *Juncus* have been used in CWs treating several types of wastewater (Ladislas et al., 2013; Menon and Holland, 2013; Rahman et al., 2014; Wiessner et al., 2007).

2. Materials & methods

2.1. Design and operation of VF-CWs

The experiment was carried out at the outdoor research facility of the Technological Educational Institute of Crete in South Greece. Two identical VF-CWs were constructed using modified pallet tanks (length: 1.20 m, width: 0.90, height: 0.95 m). The beds were filled with three successive layers of materials: a drainage layer (15 cm) filled with gravel with a diameter of 20 mm to 40 mm, a transition layer (10 cm) filled with gravel with a diameter of 8 mm to 20 mm, and a main layer (55 cm) filled with well-washed coarse sand (1–3 mm). The wastewater was distributed evenly over the surface of the beds by a network of plastic pipes (Ø 20 mm). Small orifices (8 mm) were drilled in these pipes. The treated wastewater was collected in a network of drainpipes (Ø 32 mm) at the bottom of the beds. The drainage system was passively aerated by vertical pipes extending 30 cm over the filter bed surface.

Different vegetation was used in the two VF-CWs: one was planted with three species of halophyte: *A. halimus* (3 plants), *J. acutus* (3 plants) and *S. perennis* (3 plants), and the other with reeds: *P. australis* (9 plants). Planting density used in this study (9 plants/m^2) was in accordance (5–12 plants/m^2) with previous works (Nivala et al., 2013;