Macrophytes in Constructed wetlands

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The vegetation in constructed wetlands (CWs) plays an important role in wastewater treatment. Popularly, the common emergent plants in CWs have been vegetation of natural wetlands. However, there are ornamental flowering plants that have some physiological characteristics similar to the plants of natural wetlands that can stimulate the removal of pollutants in wastewater treatments.

Keywords: ornamental flowering plants ; constructed wetlands ; wastewater ; pollutants

1. Introduction

Nowadays, the use of constructed wetlands (CWs) for wastewater treatment is an option widely recognized. This sustainable ecotechnology is based on natural wetland processes for the removal of contaminants, including physical, chemical and biological routes, but in a more controlled environment compared with natural ecosystems [1][2][3]. These ecologically engineered systems involve three important components: porous-filter media, microorganism and vegetation [2]. The mechanisms for the transformation of nutrient and organic matter compounds are conducted by biofilms of microorganisms formed in the porous media and the rhizosphere zone [4][5]. The media materials (soil, sand, rocks, and gravel) provide a huge surface area for microorganisms to attach, contributing to macrophyte growth, and also act as filtration and/or adsorption medium for contaminants present in the water [6]. Regarding the vegetation, one of the most conspicuous features of wetlands is the role that plants play in the production of root and rhizomes in order to provide substrates for attached bacteria and oxygenation of areas adjacent to the root, and absorb pollutants from water. Nitrogen (N), Phosphorus (P) and other nutrients are mainly taken up by wetland plants through the epidermis and vascular bundles of the roots, and are further transported upward to the stem and leaves [7]. This provides carbon for denitrification during biomass decomposition and prevents pollutants from being released from sediments [8][9][10]. The use of the CW technology began in Europe during the 1960s [1], and has been replicated on other continents. The type of vegetation used are plants from natural wetlands, including *Cyperus papyrus*, *Phragmites australis*, *Typha* and *Scirpus* spp., which have been evaluated for their positive effects on treatment efficiency for nutrient and organic compounds around the globe [8][9][11]. In Americas, such species are typical in CWs, and are found mainly in the United States, where the technology has been used extensively and is implemented in different rural and urban zones [12][13][14][15][16]. In recent studies (15 years ago), the goal of CW studies involved an investigation into the use of herbaceous perennial ornamental plants in CWs, including the use of species with different colored flowers to make the systems more esthetic, and therefore making it more probable for adoption and replication.

2. Role of Macrophytes in CWs

The plants that grow in constructed wetlands have several properties related to the water treatment process that make them an essential component of the design. Macrophytes are the main source of oxygen in CWs through a process that occurs in the root zone, called radial oxygen loss (ROL) [17]. The ROL contributes to the removal of pollutants because it favors an aerobic micro-environment, and waste removal is therefore accelerated, whereas, in anaerobic conditions (the main environment in CWs), there is less pollutant removal. In a recent study [18] comparing the use of plants in high density (32 plants m^{-2}) and low density (16 plants m^{-2}) CWs, the removal of nitrogen compounds in high density CWs was twice that of CWs using a low density of plants, which is strong evidence of the importance of plants in such systems. The removal rate of total nitrogen (TN) and total phosphorous (TP) were also positively correlated with the ROL of wetland plants, according to a study involving 35 different species [19].

The roots of plants are the site of many microorganisms because they provide a source of microbial attachment [8] and release exudates, an excretion of carbon that contributes to the denitrification process, which increases the removal of pollutants in anoxic conditions [20][21]. Other physical effects in plant tissue in water include: reduction in the velocity of water flow, promotion of sedimentation, decreased resuspension, and uptake of nutrients. However, for roots and rhizomes in the sediment, the physical effects include: stabilizing the sediment surface, less erosion, nutrient absorption, prevention of medium clogging (in subsurface conditions) and improved hydraulic conductivity. Aerial plant tissue favors in the light attenuation (reduced growth of photosynthesis), reduced wind velocity, storage of nutrients and aesthetic pleasing appearance of the system [2][5]. A 5-year study evaluated the influence of vegetation on sedimentation and resuspension of soil particles in small CWs [22]. The author showed that macrophytes stimulated sediment retention by mitigating the resuspension of the CW sediment (14 to 121 kg m^{-2}). Macrophytes increased the hydraulic efficiency by reducing short-circuit or preferential flow. Plant presence led to decreasing saturated hydraulic conductivity in horizontal subsurface flow. This study was relevant, since monitoring macrophytes is essential for understanding and controlling clogging in subsurface CWs [22].

The removal of organic and inorganic pollutants in CWs is not only the role of microorganisms. This function is also exerted by plants that are able to tolerate high concentrations of nutrients and heavy metals, and, in some cases, plants are able to accumulate them in their tissues [23]. It has been estimated that between 15 and 32 mg g^{-1} of TN and 2–6 mg g^{-1} (dry mass) of TP are removed by CW plants, which was measured in the aboveground biomass [24][25].

Other uptakes of xenobiotic compounds (organic pollutants) are also the result of the presence of plants, involving processes such as transformation, conjugation and compartmentation [23].

3. Survey Results of the Use of Ornamental Flowering Plants in CWs

Many CWs around the world used OFP for the removal of various types of wastewater (Table 1). For example, in China, the most popular plants used is *Canna* sp., while in Mexico the ornamental plant used is more diverse, including plants with flowers of different colors, shapes and aromatic characteristics (*Canna*, *Heliconia*, *Zantedeschia*, *Strelitzia* spp).

Table 1. Ornamental flowering plants and removal of wastewater pollutants in CWs (constructed wetlands) around the globe.

Country	Type of Wastewater	Vegetation	Removal Efficiency of Pollutants (%)	Reference
Brazil	Domestic	*Heliconia psittacorum*	TSS: 88, COD: 95, BOD: 95	Paulo et al. [26]
	Domestic	*Alpinia purpurataArundina bambusifoliaCanna* spp. *Heliconia psittacorum* L.F.	COD: 48-90, PO_4-P: 20, TKN: 31 and TSS: 34.	Paulo et al. [27]
	Swine	*Hedychium coronarium* *Heliconia rostrata*	COD: 59, TP: 44, TKN: 34 and NHx 35 COD: 57, TP: 38, TKN: 34 and NHx: 37	Sarmento et al. [28]
		Hemerocallis flava	COD: 72, BOD: 90, TN: 52, TP: 41 and SST: 72.	Prata et al. [29]
		Heliconia psittacorum L.F.		Teodoro et al. [30]
China	Municipal	*Canna indica*	COD: 77, BOD: 86, TP: >82, TN: >45	Shi et al. [31]

Country	Type of Wastewater	Vegetation	Removal Efficiency of Pollutants (%)	Reference
	Aquaculture ponds	*Canna indica* mixed with other species	BOD: 71, TSS: 82, chlorophyll-a: 91.9, NH_4-N: 62, NO_3-N: 68 and TP: 20.	Li et al. [32]
	Domestic	*Canna indica* Linn	COD: 82.31, BOD: 88.6, TP: >80, TN: >85	Yang et al. [33]
	Municipal	*Canna indica*	NH_4-N: 99, PO_4-P: 87	Zhang et al. [34]
	Drain of some factories	*R. carnea*, *I. pseudacorus*, *L. salicaria*	COD: 58-92, BOD: 60-90 TN: 60-92, TP: 50-97,	Zhang et al. [35]
	River	*Canna* sp	COD: 95, N-NH_4: 100, N-NO_3: 76, TN: 72	Sun et al. [36]
	Domestic	*Canna indica*	TP: 60, NH_4-N: 30-70, TN: ~25	Cui et al. [37]
	Aquaculture ponds	*Canna indica* mixed with other natural wetland plants	BOD: 56, COD: 26, TSS: 58, TP: 17, TN: 48 and NH_4-N: 34.	Zhang et al. [38]
	Wastewater from a student dormitory (University)	*Canna indica* mixed with other natural wetland plants	COD: 50–70, BOD: 60–80, N-NO_3: 65–75, TP: 50–80	Qiu et al. [39]
	Domestic	*Canna indica* and *Hedychium coronarium*	TP: 40–70	Wen et al. [40]
	Polluted river	*Iris pseudacorus* mixed with other natural wetland plants	TN: 68, NH_4-N: 93, TP: 67	Wu et al. [41]
	Sewage	*Iris pseudacorus,* mixed with other plants of natural wetlands	TN: 20 and TP: 44	Xie et al. [42]
	Municipal	*Canna indica*	COD: 60, NO_3-N: 80, TN: 15, TP: 52	Chang et al. [43]
	Simulated polluted river water	*Iris sibirica*	COD: 22, TN: 46, NH_4-N: 62, TP: 58	Gao et al. [44]
	Synthetic	*Canna sp*	Fluoride: 51, Arsenic: 95	Li et al. [45]

Country	Type of Wastewater	Vegetation	Removal Efficiency of Pollutants (%)	Reference
	Simulated polluted river water	*Iris sibirica*	Cd: 92	Gao et al. [46]
	Synthetic	*Canna indica* L.	N: 56–60	Hu et al. [47]
	Synthetic (hydrophonic sol.)	*Canna indica L.*	TN: 40–60, N-NO_3: 20–95, NH_4-N: 20–55	Wang et al. [48]
Chile	Sewage	*Zantedeschia aethiopica, Canna* spp. and *Iris* spp	BOD: 82, TN: 53, TP: 60.	Morales et al. [49]
	Sewage	*Tulbaghia violácea, and Iris pseudacorus.*	BOD: 57–88, COD: 45–72, TSS: 70–93, PO_4-P: 6–20.	Burgos et al. [50]
	Ww rural community	*Zantedeschia aethiopica*	Organic matter: 60%, TSS: 90%	Leyva et al. [51]
Colombia	Domestic	*Heliconia psíttacorum*	NH_3: 57 COD: 70	Gutiérrez-Mosquera and Peña-Varón [52]
	Synthetic landfill leachate	*Heliconia psittacorum*	COD, TKN and NH_4 (all: 65–75)	Madera-Parra et al. [53]
	Cattle bath	*Alpinia purpurata*	SST: 58, TP: 85, COD: 63	Marrugo-Negrete et al. [54]
	Municipal	*Heliconia psitacorum*	Bisphenol A: 73, Nonylphenols: 63	Toro-Vélez et al. [55]
Costa Rica	Dairy raw manure	*Ludwigia inucta, Zantedechia aetiopica, Hedychium coronarium* and *Canna generalis*	BOD: 62, NO_3-N: 93, PO_4-P: 91, TSS: 84	León and Cháves [56]
Egypt	Municipal	*Canna* sp	TSS: 92, COD: 88, BOD: 90	Abou-Elela and Hellal [57]
	Municipal	*Canna* sp	TSS: 92, COD: 92, BOD: 92	Abou-Elela et al. [58]
India	Paper mill effluent	*Canna indica*	9,10,12,13-tetrachlor-ostearic acid: 92 and 9,10-dichlorostearic acid: 96	Choudhary et al. [59]

Country	Type of Wastewater	Vegetation	Removal Efficiency of Pollutants (%)	Reference
	Synthetic	*Canna indica*	Dye: 70–90 COD: 75	Yadav et al. [60]
	Synthetic greywater	*Heliconia angusta*	COD:40, BOD: 70, TSS: 62, TDS: 19	Saumya et al. [61]
	Domestic	*Canna generalis*	TN: 52, T-PO3: 9	Ojoawo et al. [62]
	Collection pond	*Canna Lily*	BOD: 70–96, COD: 64–99	Haritash et al. [63]
	Hostel greywater	*Canna indica*	COD, TKN and Pathogen all up 70	Patil and Munavalli, [64]
	Domestic	*Polianthus tuberosa* L.	Heavy metals (Pb and Fe: 73–87), (Cu and Zn: 31–34) and Ni and Al: 20–26	Singh and Srivastava [65]
Ireland	Domestic	*Iris pseudacorus*	TN: 30, TP:28	Gill and O'Luanaigh [66]
Italy	Synthetic	*Zantedeschia aethiopica, Canna indica*	N: 65–67, P: 63–74, Zn and Cu: 98–99, Carbamazepine: 25–51, LAS: 60–72	Macci et al. [67]
Kenya	Flower farm	*Canna* spp.	BOD: 87, COD: 67, TSS: 90, TN: 61	Kimani et al. [68]
Mexico	Municipal	*Zantedeschia aethiopoca*	COD: 35, TN: 45.6	Belmont and Metcalfe [69]
	Domestic	*ZantedeschiaAethiopica* and *Canna flaccid*	SST: 85.9, COD: 85.8, NO_3-N: 81.7, NH_4-N: 65.5, NT: 72.6	Belmont et al. [70]
	Coffee processing	*Heliconia psittacorum*	COD: 91, Coliformes: 93	Orozco et al. [71]
	Domestic	*Strelitzia reginae, Zantedeschia esthiopica, Canna hybrids, Anthurium andreanum, Hemerocallis Dumortieri*	COD: >75, P: 66, Coliforms: 99	Zurita et al. [72]
	Domestic	*Zantedeschia aethiopica*	BOD: 79, TN: 55, PT: 50	Zurita et al. [73]

Country	Type of Wastewater	Vegetation	Removal Efficiency of Pollutants (%)	Reference
	Wastewater form canals	*Zantedeschia aethiopica*	COD: 92, $N\text{-}NH_4$: 85, $P\text{-}PO_4$: 80	Ramírez-Carrillo et al. [74]
	Municipal	*Strelitzia reginae*, *Anthurium, andreanum.*	TSS: 62, COD: 80, BOD: 82, TP: >50, TN: >49	Zurita et al. [75]
	Groundwater	*Zantedeschia aethiopica and Anemopsis californica*	As: 75–78	Zurita et al. [76]
	Domestic	*Gladiolus* spp	BOD: 33, TN: 53, TP: 75	Castañeda and Flores [77]
	Mixture of greywater (from a cafeteria and research laboratories)	*Zantedeschia aethiopica* and *Canna indica*	COD: 65, NT: 22.4, PT: 5.	Zurita and White [78]
	Domestic	*Zantedeschia aethiopica*	BOD: 70	Hallack et al. [79]
	Domestic	*Heliconia stricta, Heliconia psittacorum* and *Alpinia purpurata*	BOD: 48, COD: 64, TP: 39, TN: 39	Méndez-Mendoza et al. [80]
	Municipal	*Canna hybrids* and *Strelitzia reginae*	DQO: 86, NT: 30–33, PT: 24–44	Merino-Solís et al. [81]
	Municipal	*Zantedeschia aethiopica* and *Strelitzia reginae*	COD: 75, TN: 18, TP: 2, TSS: 88.	Zurita and Carreón-Álvarez [82]
	Domiciliar	*Spathiphyllum wallisii*, *Zantedechia aethiopica*, *Iris japonica, Hedychium coronarium, Alocasia* sp, *Heliconia* sp. and *Strelitzia reginae*.	$N\text{-}NH_4$: 64-93 BOD: 22–96 COD: 25–64	Garzón et al. [83]
	Community	*Zantedeschia aethiopica, Lilium* sp, *Anturium* spp and *Hedychium coronarium*	NT: 47, PT: 33, COD: 67	Hernández [84]
	Stillage Treatment	*Canna indica*	BOD: 87, COD: 70	López-Rivera et al. [85]
	Artificial	*Iris sibirica* and *Zantedeschia aethiopica*	Carbamazepine: 50–65	Tejeda et al. [86]

Country	Type of Wastewater	Vegetation	Removal Efficiency of Pollutants (%)	Reference
	Community	*Alpinia purpurata* and *Zantedeschia aethiopica*		Marín-Muñiz et al. [87]
	Polluted river	*Zantedeschia aethiopica*	NO_3-N: 45, NH_4-N: 70, PO_4-P: 30	Hernández et al. [18]
	Municipal	*Spathiphyllum wallisii*, and *Zantedeschia aethiopica*		Sandoval-Herazo et al. [88]
	University	*Strelitzia reginae*		Martínez et al. [21]
Nepal	Municipal	*Canna latifolia*	TSS: 97, COD: 97, BOD: 89, TP: >30	Sigh et al. [89]
Portugal	Tannery	*Canna indica mixed with other plants*	COD: 41–73, BOD: 41–58	Calheiros et al. [90]
	Community	*Canna flaccida, Zantedeschia aethiopica, Canna indica, Agapanthus africanus* and *Watsonia borbonica*	BOD, COD, P-PO_4, NH_4 and total coliform bacteria (all up to 84)	Calheiros et al. [91]
Spain	Domestic	*Iris* spp	Bacteria: 37	García et al. [92]
	Municipal	*Iris pseudacorus*	Bacteria: 43	Ansola et al. [93]
Sri Lanka	Municipal	*Canna iridiflora*	BOD: 66, TP: 89, NH_4-N: 82, N-NO_3: 50	Weragoda et al. [94]
Taiwan	Domestic	*Canna indica*	N-NH_4: 73, BOD: 11	Chyan et al. [95]
		Canna indica	N-NH_4: 57, N-NO_3: 57	Chyan et al. [96]
Thailand	Domestic	*Canna* spp	COD: 92, BOD: 93, TSS: 84, NH_4-N: 88, TP: 90	Sirianuntapiboon and Jitvimolnimit [97]
	Seafood	*Canna siamensis, Heliconia* spp and *Hymenocallis littoralis*	BOD: 91–99, SS: 52–90, TN: 72–92 and TP: 72–77	Sohsalam et al. [98]
	Domestic	*Heliconia psittacorum* L.f. and *Canna generalis* L. Bailey	TSS: Both > 88, COD: 42-83	Konnerup et al. [99]
	Fermented fish production	*Canna hybrid*	BOD, COD, TKN: ~ 97	Kantawanichkul et al. [100]

Country	Type of Wastewater	Vegetation	Removal Efficiency of Pollutants (%)	Reference
	Collection system for business and hotel	*Cannae lilies, Heliconia*	BOD: 92, TSS: 90, NO_3-N: 50, TP: 46	Brix et al. [101]
	Domestic	*Crinum asiaticum, Spathiphyllum clevelandii* Schott	PO_4-P: ~20	Torit et al. [102]
Turkey	Municipal	*Iris australis*	NH_4-N: 91, NO_3-N: 89, TN: 91	Tunçsiper [103]
USA	Domestic	*Canna flaccida*, *Gladiolus* sp., *Iris* sp.	Baceria: ~50	Neralla et al. [104]
	Nursery	*Canna· generalis, Eleocharis dulcis, Iris Peltandravirginica.*	N: ~50, P: ~60	Palomsky et al. [105]
	Domestic	*Iris pseudacorus* L., *Canna x. generalis* L.H. Bail., *Hemerocallis fulva* L. and *Hibiscus moscheutos*L.	BOD > 75, TSS > 88, Fecal baceteria > 93	Karathanasis et al. [14]
	Tilapia production	*Canna* sp.	TSS: 90, NO_2-N: 91, NO_3-N: 76, COD: 12.5 and NH_3-N: 7.5	Zachritz et al. [106]
	Stormwater runoff	*Canna x generalis* Bailey, *Iris pseudacorus* L., *Zantedeschia aethiopica* (L.)	N and P *Canna* (>90), *Iris* (>30) *Zantedeschia* (>90)	Chen et al. [107]
	Residential	*Aeonium purpureum and Crassula ovate, Equisetum hyemale, Nasturtium, Narcissus impatiens,* and *Anigozanthos*	TSS: 95 BOD: 97	Yu et al. [16]
Vietnam	Fishpond	*Canna generalis*	BOD: 50, COD: 25–55	Konnerup et al. [108]
United Kingdom	Herbicide polluted water	*Iris pseudacorus*	Atrazine: 90–100	McKinlay and Kasperek. [109]

A review of the available literature showed that ornamental plants are used to remove pollutants from domestic, municipal, aquaculture ponds, industrial or farm wastewater. The removal efficiency of ornamental plants was also evaluated for the following parameters: biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), total nitrogen (TN), total phosphorous (TP), ammonium (NH_4-N), nitrates (NO_3-N), coliforms and some metals (Cu, Zn, Ni and Al). There is no clear pattern in the use of certain species of ornamental plants for certain types of wastewater. However, it is important to keep in mind that CWs using ornamental plants are usually utilized as secondary or tertiary treatments, due to the reported toxic effects that high organic/inorganic loading has on plants in systems that use them for primary treatment (in the absence of other complementary treatment options) [110][111]. The use of OFP in CWs generates an esthetic appearance in the systems. In CWs with high plant production, OFP harvesting can be an economic entity for CW operators, providing social and economic benefits, such as the improvement of system landscapes and a better habitat quality. Some authors have reported that polyculture systems enhanced the CW resistance to environmental stress and disease [14][112].

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