WASTEWATER TREATMENT BY CONSTRUCTED WETLANDS WITH *THALIA GENICULATA* AND *PASPALUM PANICULATUM* IN A TROPICAL SYSTEM OF MEXICO

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ABSTRACT
Constructed wetlands (CWs) have increasingly been developed worldwide for stormwater and wastewater treatment. In this context, CWs have been seen as an economically attractive, energy-efficient way of providing high standards of wastewater treatment. In the present study, a CWS has specifically been designed and operated for domestic wastewater treatment. The removal efficiency of basic pollutants was evaluated in the CWs under free water surface (FWS) and horizontal subsurface flow conditions, employing two native species: *Paspalum paniculatum* and *Thalia geniculata*. The experimental results showed that the retention time throughout the treatments varied from 6.5 to 7.5 days; while temperatures of approximately 26°C were observed to reduce the load of pollutants. The experimental tests were highly effective for the wastewater treatment since the removal efficiencies of biological oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids, total nitrogen, and total phosphorus were found to be in the range of 79%–94%. The experimental data were statistically analyzed by the ANOVA approach and Tukey´s test. The treatments showed highly significant statistical differences ($P<0.05$). From the operating cost standpoint, the current native vegetation was proven to be satisfactory for wastewater treatment in tropical regions of Mexico.
Keywords: constructed wetlands, removal efficiency, wastewater treatment.

1 INTRODUCTION

In the mid-1950s, views on wastewater treatment were limited to physical, chemical, and biological methods. The controlled use of macrophytes for water purification was not taken into consideration. Furthermore, it was believed that most macrophytes cannot grow well in polluted water and the ability of macrophytes to eliminate toxic substances in water was not recognized well [1]. In the past three decades of the twentieth century, constructed wetlands (CWs) became a viable technology for various types of wastewater treatment around the world. In this context, CWs are primarily used to treat domestic and municipal wastewaters but their use for other types of wastewater such as agricultural and industrial wastewaters, various runoff waters and landfill leachate have become more frequent [2, 3]. From the total wastewater generated in Mexico (210 m^3/s), only 46.5% receives appropriate treatment [4].

Wetlands are known to offer a suitable combination of physical, chemical and biological factors for the removal of pathogenic organisms. Physical factors include mechanical filtration, exposure to ultraviolet radiation, and sedimentation. Chemical factors include oxidation, exposure to biocides excreted by some wetland plants, and absorption by organic matter.

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Table 1: Types of CWs for wastewater treatment.

	Constructed Wetlands						
Water Level	Free water surface				Subsurface		
Plants	Free-floating	Floating-leaved	Submerged	Emergent	Emergent		
Flow Direction	Horizontal				Horizontal	Vertical	
						Downflow	Upflow

Biological removal mechanisms include antibiosis, predation by nematodes and protists, attack by lytic bacteria and viruses, and natural die-off [5].

From the engineering standpoint, there are several types of CWs that could be distinguished according to several criteria such as the presence/absence of free water surface (FWS), macrophytes used or direction of flow (Table 1). At present, there are thousands of FWS-CWs with emergent vegetation treating municipal and industrial wastewaters, agricultural runoff, mine drainage waters, and stormwaters around the world [6].

In Europe, the most commonly used species for FWS-CWs are: *Phragmites australis* (Common reed), *Scirpus (Schoenoplectus) lacustris*; North America: *Typha* spp. (Cattail), *Scirpus* spp. (Bulrush), *Sagittaria latifolia* (Arrowhead); Australia and New Zealand: *Phragmites australis*, *Typha* spp. *Bolboschoenus* (*Scirpus*) *fluviatilis* (Marsh clubrush), *Eleocharis sphacelata* (Tall spikerush), *Scirpus tubernaemontani* (=*Scirpus validus*, Soft-stem bulrush). In the United States and New Zealand, *Phragmites australis* is considered as an invasive, non-native species, and its use is either restricted or prohibited. In Tabasco-Mexico, more than 300 native species exist to be potentially studied as wetlands, among them being: *Phragmites australis*, *Thalia geniculata*, *Paspalum paniculatum* and *Typha domingensis*.

Free-floating macrophytes are highly diverse in form and habit, ranging from large plants with rosettes of aerial and/or floating leaves and well-developed submerged roots (e.g. *Eichhornia crassipes* - water hyacinth or *Pistia stratiotes* - water lettuce) to minute surface-floating plants with few or no roots (Lemnaceae-duckweed; e.g. *Lemna* spp., *Spirodela polyrhiza*, *Wolffia* spp.). Submerged vegetation has also been found to be developed in FWS-CWs if the growth conditions are suitable [7, 8].

At present, horizontal flow systems (HFS) probably represent the most commonly used type of CWs all over the world. Vertical flow systems (VFS) have also been proved to be effective for the removal of organics, suspended solids, and ammonia; however, VFS require more maintenance and operation efforts because of the use of pumps, timers, and other electrical and mechanical devices. Likewise, various types of CWs may be combined in order to achieve higher removal efficiency. Such combinations of CWs are known as *hybrid systems*, which comprise most frequently VFS and HFS arranged in a staged manner [9, 10].

The objective of the present investigation was to evaluate the removal efficiency of basic contaminants in CWs under FWS and horizontal subsurface flow conditions, employing two native species: *Paspalum paniculatum* and *Thalia geniculata*. The CWs were specifically designed and operated to treat domestic wastewater at pilot scale.

2 MATERIALS AND METHODS

2.1 Location of the pilot-scale CWs

The field work was performed at the Academic Division of Biological Sciences (DACBiol) - Universidad Juárez Autónoma de Tabasco (UJAT) located in Villahermosa-Tabasco, Mexico (N 17º 59' 26" and 17º 59' 17"; W 92° 58' 16" and 92º 58' 37"). The application of the Mexican environmental legislation [6] is compulsory at the DACBiol-UJAT since it must comply with specific regulations for its handling, disposal, and wastewater discharge. The pilot-scale CWs were installed and operated since 2013. The implementation was made in order to solve the problem of continuous pollution in superficial water receptors, water underground, and aquatic flora and fauna.

2.2 Experimental set-up

The hydraulic installation consisted of two wastewater tank receptors of 200 L capacity each and four CWs cells: two free water horizontal flow (FW-HF) and two subsurface horizontal flow (SS-HF). The CWs were made up of carbon steel with dimensions of 2.5 × 1.2 × 1.0 m (length-width-depth). The FW-HF and SS-HF systems were provided with native vegetation: *Thalia geniculata* and *Paspalum paniculatum*.

The units were connected in series with hydraulic polyvinyl chloride pipes of 0.0254 m diameter. A control valve was installed for two main purposes: 1) to feed the CWs with the wastewater, and 2) to take samples during the tests. The wastewater samples were collected and analyzed at various times. The results were then used to evaluate the removal efficiency for each FW-HF and SS-HF systems (Fig. 1).

For the FW-HF system, average sand particles (dp) of 1.5 mm diameter were employed as support media and having a static bed height (Hs) of 0.5 m [11]. The vegetation was rooted on the surface with height variations between 0.5 and 1 m. For the SS-HF systems, the bed material was made up of sand (Hs = 0.1 m) and river gravel (Hs = 0.4 m, dp = 19 mm). The vegetation was then fixed in the gravel with the stem having 0.1 m height and the root planted 0.05 m underneath the surface of the support material.

2.3 Wastewater composition analysis

The physicochemical characterization of the wastewater was undertaken following the analytical procedures established in the Mexican environmental legislation [12]. During the

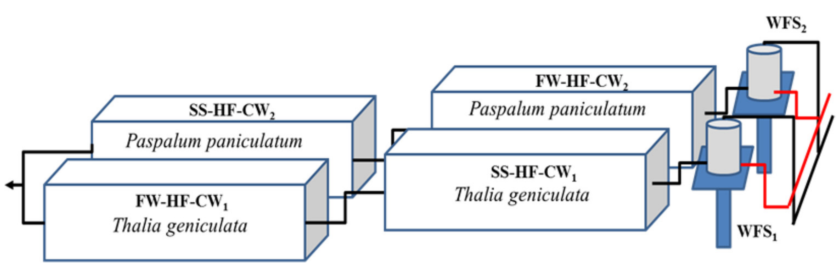

Figure 1: Schematic of the CWs cells (CW_1 and CW_2).

Table 2: Control parameters evaluated during the 1st and 2nd stage, for the corresponding method of analysis.

Stage of stabilization		Stage of operation	
Parameter	Normativity	Parameter	Normativity
Temperature	NMX-AA-007-SCFI-2000	TSS	NMX-AA-034-SCFI-2001
Turbidity	NMX-AA-038-SCFI-2001	BOD	NMX-AA-028-SCFI-2001
EC	NMX-AA-093-SCFI-2000	COD	NMX-AA-030-SCFI-2001
pH	NMX-AA-008-SCFI-2000	Total N	NMX-AA-026-SCFI-2001
		Total P	NMX-AA-029-SCFI-2001

monitoring, the influent and effluent were sampled daily to evaluate the efficiency of the treatment system. The samples were analyzed immediately, following the methods and the calibration guidelines suggested by Hach Company [13]. The effluent quality was assessed based on the official permissible levels for different components in wastewater, in order to establish whether treated wastewater from the CWs can be used for irrigation purposes without causing harm to crops and soils.

2.4 Performance of the CWs system

The CWs system comprised two stages: a) stage of stabilization, and b) stage of continuous operation. In the first stage, the temperature, turbidity, electric conductivity (EC), and pH were measured for a period of three months. In the second stage, the control parameters of the evaluated process were biological oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), total phosphorous (total P) and total nitrogen (total N). During the monitoring, all the parameters were analyzed according to the environmental normativity (Table 2). The pilot-scale CWs system was operated at room temperature.

The CWs performance was evaluated based on the differences in influent and effluent concentrations, where control parameter was turbidity for the numerical calculation. The removal efficiency was then calculated using the following formula:

$$\eta = [(C_1 - C_2) / C_1] \times 100$$

Where η represents the percent removal efficiency, C_1 the wastewater influent concentration and C_2 the wastewater effluent concentration.

The hydraulic retention time was also calculated to estimate the degradation time of the organic matter. Such a parameter was calculated from the following equation [11]:

$$\tau = - \ln (C_n / C_o) / K_o$$

Where τ = retention time for BOD removal, C_n = BOD influent concentration of the reactor "n" (mg/L), C_o = influent concentration, K_o = degradation constant. The experimental data was statistically analyzed by 2 × 2 factorial design, an ANOVA approach and Tukey's test by applying the SAS computational package version 9.4.

3 RESULTS AND DISCUSSION

The wastewater flowrate of the pilot-scale CWs was initially recorded for three months at the DACBiol-UJAT. Such wastewater flowrates were found to be Q_{min} = 345 L/day (minimum flowrate), Q_{mid} = 400 L/day (middle flowrate) and Q_{max} = 450 L/day (maximum flowrate). It is worth mentioning that the CWs system did not have a regular operating timetable since its operation varies because of the user's availability. The start-up of the pilot-scale CWs was usually initiated between 8:00 and 9:00 hours, while the shutdown occurred between 16:00 and 18:00 hours (Fig. 2). After analyzing the wastewater flowrate, two stages were established: 1) stabilization stage and 2) operation stage.

3.1 Stage 1: Stabilization

At this stage, the parameters pH, temperature, EC and turbidity were evaluated in the CWs system (Table 3).

Regarding the turbidity, the treatments showed highly significant statistical differences ($P < 0.05$). The average wastewater inlet concentration was recorded to be 33.89 TNU. The highest removal efficiencies were found to be 79.59% and 53.53% for the FW-HF-CW1 and SS-HF-CW2, respectively; while the lowest removal efficiency (38.74%) was measured for the SS-HF-CW1 (Table 3).

Although the experimental pH values showed significant statistical differences within a neutral range (7.4–7.6), higher values were recorded (7.88) at the wastewater intake. This

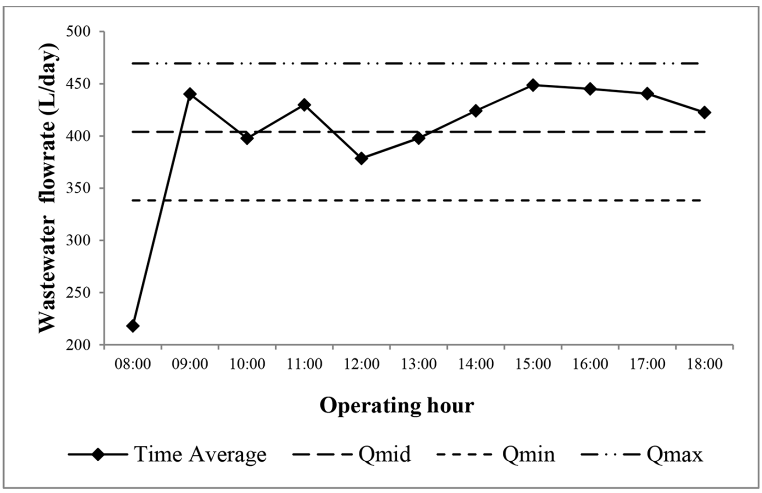

Figure 2: Influent flowrate of the CWs system.

Table 3: Experimental values observed during the stabilization stage.

Cell	pH	Temperature (°C)	EC (dS/m)	Turbidity (TNU)	η (%)
SS-HF-CW1	7.60 ± 0.16	25.84 ± 1.59	2.95 ± 0.62	20.76 ± 10.90	38.74
FW-HF-CW1	7.41 ± 0.14	25.75 ± 1.44	2.65 ± 0.33	4.24 ± 2.43	79.59
FW-HF-CW2	7.61 ± 0.17	25.96 ± 1.49	2.85 ± 0.45	16.43 ± 11.84	51.54
SS-HF-CW2	7.50 ± 0.12	25.61 ± 1.37	2.60 ± 0.37	7.63 ± 5.51	53.53
C_1	7.88 ± 0.26	27.04 ± 1.71	3.10 ± 0.70	33.89 ± 12.29	------

pH difference of 0.3–0.5 may be explained by the substrate and biofilm formed within the CWs [14].

The EC oscillated between 2.6 and 3.0 dS/m and no significant statistical difference was found during the tests. From the Mexican normativity standpoint, these values are acceptable for agricultural irrigation since the salinity concentration is lower than the maximum permissible limits. The temperature did not present a significant variation' in fact, this variable was constant around 25°C–26°C.

3.2 Stage 2: Operation

Once the CWs system was stabilized, the experimental trials were set up at this operation stage. The treatments showed highly significant statistical differences (P< 0.05). For all variables, the cell FW-HF-CW2 (93.96%) presented the highest removal efficiencies, while the SS-HF-CW2 showed negative values throughout the tests (Table 4). An excess amount of vegetation released from the FW-HF-CW2 led to a rapid decomposition of the macrophytes as well as the transport of contaminants from the previous cell.

The type of flow caused the TSS concentration to diminish since the solids removal is a physical settling and a filtration process, generally independent of the microbial activity [15]. Another study was comparable to the current results when removal efficiencies were obtained up to 94% by using *Thalia geniculata* in a CW with a subsuperficial flow [16].

The rapid decrease in total nitrogen indicated the degradation of organic nitrogen by an ammonia process [17]. The results obtained in the SS-HF-CW2 were comparable to those removal efficiencies (73.68%) reported in a CW with a free-water flow and employing *Thalia geniculata* as native vegetation [16].

Regarding the total phosphorous, high removal efficiencies were found in this investigation because of its degradation by microbial activity and type of vegetation in the short term, but becoming a more important substrate in the long-term. Similar results were reported previously [14] with efficiencies up to 86% when using fine gravel as support material and *Phragmites australis* in a CWs under subsuperficial flow conditions.

Concerning the COD concentration, the organic degradation was due to physical processes, mainly sedimentation and filtration. In the case of BOD, the most important removal

Table 4: Experimental values measured during the operation stage.

Cell (η)	TSS (mg/l)	Total N (mg/l)	Total P (mg/l)	COD (mg/l)	BOD (mg/l)
SS-HF-CW1	48.51 ± 12.84	11.76 ± 3.11	2.09 ± 0.57	55.31 ± 14.66	138.24 ± 36.59
η_1	85.33	85.34	85.28	85.06	85.33
FW-HF-CW1	9.74 ± 4.26	2.37 ± 1.02	0.43 ± 0.20	11.09 ± 4.87	27.76 ± 12.16
η_2	79.91	79.83	79.47	79.95	79.91
FW-HF-CW2	19.97 ± 2.13	4.84 ± 0.52	0.86 ± 0.08	22.77 ± 2.43	56.93 ± 6.05
η_3	93.96	93.96	93.95	93.97	93.95
SS-HF-CW2	28.79 ± 16.23	6.99 ± 3.93	1.24 ± 0.69	32.81 ± 18.49	82.06 ± 46.20
η_4	–44.13	–44.24	–44.92	–44.10	–44.14
C_1	330.69 ± 51.39	80.21 ± 12.46	14.17 ± 2.18	376.97 ± 58.59	942.44 ± 46.44

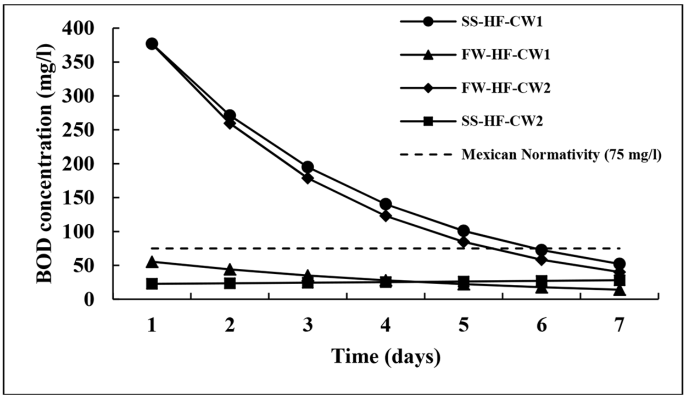

Figure 3: Degradation of organic matter (BOD) as a function of the type of flow (FW-HF and SS-HF) and vegetation (CW_1 = *Thalia geniculata* and CW_2 = *Paspalum paniculatum*) for wastewater treatment.

mechanism was an aerobic-anaerobic degradation caused by bacteria adhered to the root and rhizomes of the plants. Other research works support the previous statements [18, 19]. They reported removal efficiencies in the range of 80%–90% based on CWs with free water vertical flows using *Typha latypholia* and *Phragmites australis*.

From the experimental BOD results, the current CWs system performance was studied in order to estimate the degradation rate of organic matter and the required time to treat a specific volume of wastewater, namely hydraulic retention time (τ). The cells SS-HF-CW1 and FW-HF-CW2 presented a minimum τ = 5.5 days. However, the CWs wastewater discharge complied with the Mexican normativity when $\tau \geq 6$ days (Fig. 3). In general, a τ = 8 days has been reported to be sufficient to remove organic matter for temperatures above 15°C [14].

A number of investigations regarding the wastewater treatment by CWs systems appear in the literature; however, CWs using *Thalia geniculata* has not been cited frequently, while *Paspalum paniculatum* has not been reported as a native species. Finally, the most important effects of emergent macrophytes on CWs wastewater treatment can be described as physical on the plants tissue, adherence or filtration of microorganisms, and the absorption of plants for the elimination of nutrients.

4 CONCLUSIONS

The proposed pilot-scale CWs system with *Thalia geniculata* and *Paspalum paniculatum* has been demonstrated to be a viable wastewater treatment technology in the tropical regions of Mexico. For the CWs performance, the cell FW-HF-CW2 presented the highest average removal efficiency with 93.95%, followed by SS-HF-CW1 with 85.26% and FW-HF-CW1 with 79.81%. The treatments showed highly significant statistical differences ($P < 0.05$). However, the cell SS-HF-CW2 produced negative values because of an excess amount of vegetation released from the FW-HF-CW2.

In compliance with the Mexican environmental legislation, the outcome concentrations were found to be lower than the maximum permissible limits, allowing their use for agricultural irrigation and water discharge. From the experimental BOD results, the cells SS-HF-CW1 and FW-HF-CW2 complied with the Mexican normativity when the hydraulic retention time (τ) attained 6 days.

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