

DOMESTIC WASTEWATER TREATMENT VIA CONSTRUCTED WETLANDS WITH *Gymnocoronis sessilis* IN STABILIZATION

Tratamiento de aguas residuales domésticas mediante humedales artificiales con
Gymnocoronis sessilis durante la fase de estabilización

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Key words: subsurface flow, color, turbidity, chemical oxygen demand (COD).

ABSTRACT

The use of constructed wetlands (CWs) has gained relevance due to their high efficiency in wastewater treatment, low operational costs, and minimal maintenance, which facilitates compliance with Mexican regulations. However, the effectiveness of CWs depends on the adaptability of plant species to different climatic conditions and wetland configurations. This study evaluated the performance of *Gymnocoronis sessilis* S.F. Blake after six months of establishment in free-flow constructed wetlands (FFCW) and subsurface-flow constructed wetlands (SFCW). Twelve CW units ($2.5 \times 1.2 \times 1.0$ m; water depth 0.5 m) were operated with a flow rate of 200 L/day, using hydraulic retention times (HRTs) of 4.5 days for SFCW and 7.5 days for FFCW. Treatments consisted of three FFCW with plants (FFCW-GYM), three FFCW without plants (FFCW-W), three SFCW with plants (SFCW-GYM), and three SFCW without plants (SFCW-W). Removal efficiencies of color, turbidity, and chemical oxygen demand (COD) from domestic wastewater were determined. SFCW achieved the highest removal rates, with color removals of 63.5% (SFCW-W) and 63.2% (SFCW-GYM); turbidity removals of 61.5% (SFCW-W) and 66.2% (SFCW-GYM); and COD removals of 81.3% (SFCW-W) and 87.5% (SFCW-GYM). In contrast, FFCW exhibited negative color and turbidity removals and lower COD performance (45.5% in FFCW-W and 74.7% in FFCW-GYM). These findings indicate that *G. sessilis* enhances pollutant removal in SFCW, supporting its potential use as a suitable species for CW applications in Tabasco, Mexico.

Palabras clave: flujo subsuperficial, color, turbiedad, demanda química de oxígeno (DQO).

RESUMEN

El uso de humedales artificiales (HA) se ha incrementado debido a su alta eficiencia en la depuración de aguas residuales, bajos costos operativos y reducido mantenimiento,

lo que facilita el cumplimiento de las normas mexicanas. No obstante, la eficacia de los HA depende de la adaptación de las especies vegetales utilizadas a las condiciones climáticas y al tipo de flujo del sistema. En este estudio se evaluó el desempeño de *Gymnocoronis sessilis* S.F. Blake en humedales de flujo libre (HAFL) y subsuperficial (HAFS). Se implementaron 12 reactores ($2.5\text{ m} \times 1.2\text{ m} \times 1\text{ m}$; tirante 0.5 m) operando con 200 L/día, con tiempos de retención hidráulica de 4.5 días para HAFS y 7.5 días para HAFL. Los tratamientos incluyeron tres HAFL con especie (HAFL-GYM), tres HAFL sin especie (HAFL-T), tres HAFS con especie (HAFS-GYM) y tres HAFS sin especie (HAFS-T). Durante seis meses se evaluó la remoción de color, turbiedad y demanda química de oxígeno (DQO) en aguas residuales domésticas. Los HAFS mostraron los mejores resultados, con remociones de color de 63.5 % (HAFS-T) y 63.2 % (HAFS-GYM), y de turbiedad de 61.5 % (HAFS-T) y 66.2 % (HAFS-GYM). Para DQO, HAFS-T y HAFS-GYM alcanzaron 81.3 y 87.5 %, respectivamente. En contraste, los HAFL registraron remociones negativas de color y turbiedad y menores porcentajes de DQO (45.5 % en HAFL-T y 74.7 % en HAFL-GYM). Los resultados indican que *G. sessilis* es más eficiente en humedales de flujo subsuperficial, lo que la convierte en una alternativa viable para sistemas de tratamiento en Tabasco, México.

INTRODUCTION

Population growth, technological development, and the large-scale use of water resources have intensified pressure on global freshwater supplies, leading to water stress that disrupts biogeochemical cycles and compromises the ecosystem services they provide (Castillo-Castillo et al. 2017, Gran-Castro 2020, Díaz et al. 2021). These changes directly impact water availability and quality, threatening both human consumption needs and the integrity of aquatic ecosystems.

Wastewater generated from domestic activities such as cleaning, personal hygiene, and food preparation contains physical, chemical, and biological characteristics that make it unsuitable for human consumption (Osorio-Rivera et al. 2021). In addition, wastewater from agricultural activities introduces elevated concentrations of nutrients, such as nitrogen and phosphorus, which accelerate eutrophication processes in receiving water bodies (Deng et al. 2024). Each year, millions of cubic meters of untreated effluents are discharged into rivers, lakes, and aquifers, severely affecting their quality and functionality (López-Ramírez et al. 2021).

Globally, many countries lack the economic resources or technical capacity to treat wastewater efficiently (Vargas et al. 2020), which exacerbates public health and environmental issues (Castillo-Sánchez and Chimbo-Solórzano 2021), highlighting the urgent need for alternative treatment technologies that are affordable, sustainable, and adapted to local conditions (Arias-Guido et al. 2021).

In Mexico, by the end of 2023, there were 2928 wastewater treatment plants in operation, of which

100 were located in the state of Tabasco. However, the total treated flow in Mexico decreased compared to 2022 due to the decommissioning of 139 plants that collectively processed 2920.3 L/s, primarily due to poor maintenance (CONAGUA 2023). This underscores the importance of developing low-cost, resilient solutions with minimal technical requirements for operation and maintenance.

Constructed wetlands (CWs) represent a promising alternative for wastewater treatment due to their capacity to remove multiple contaminants, adaptability to diverse conditions, and potential to enhance the aesthetics of surrounding landscapes (Nava-Rojas et al. 2023). CWs can be implemented in several configurations, including free-water surface flow (FWS), horizontal subsurface flow (HSSF), and vertical subsurface flow (VSSF), and can be planted with selected macrophyte species tailored to specific removal goals (Arivoli and Mohanraj 2013, Saeed et al. 2014, Mustapha et al. 2018). FWS systems generally consist of shallow basins with floating or emergent vegetation and water exposed to the atmosphere, whereas HSSF systems employ a porous substrate through which water flows, serving as both a filtration medium and plant support (Arteaga-Cortez et al. 2019).

Recent literature highlights that CWs are particularly viable in rural and peri-urban communities with limited sanitation infrastructure, in small public facilities (schools, community centers), and in residential developments requiring decentralized solutions. In these contexts, HSSF systems are often preferred due to their greater control of odors and algal proliferation, while FWS systems are employed

when landscape integration and tertiary polishing are desired. CWs represent an excellent alternative in areas where access to conventional treatment plants is limited, contributing significantly to the protection of water bodies (Pérez et al. 2022). Moreover, they constitute a nature-based solution essential for improving water quality, removing pollutants, and building more resilient and sustainable cities (Nava-Rojas et al. 2023, González et al. 2024).

Macrophytes used in CWs typically display varying degrees of tolerance to unstable hydraulic flows, pH fluctuations, and changes in organic load (González-Díaz et al. 2022). When all these characteristics are present, CWs can achieve highly efficient pollutant removal. However, in tropical climates, the performance of these systems is not fully understood, as temperature variations can significantly affect the biological processes responsible for contaminant degradation (Mora-Orozco et al. 2020, Alufasi et al. 2024).

In Mexico, 234 wastewater treatment plants currently incorporate CW systems, 18 of which are located in Tabasco (CONAGUA 2023). Despite this, only 36% of the country's wastewater receives adequate treatment (Arciniega-Galaviz et al., 2024). Furthermore, although the majority of the population has access to water, only 14% have the means to treat it at the household level, according to the World Health Organization (OMS 2023).

The feasibility of CWs depends on design and construction conditions, such as selecting a configuration aligned with removal objectives, ensuring adequate hydraulic sizing, choosing substrates with controlled granulometry, applying pretreatment to protect the bed, and using native macrophytes adapted to tropical climates.

In regions such as Tabasco, subsurface systems are recommended due to their thermal stability, complemented by maintenance protocols such as plant harvesting and solids control (Arteaga-Cortez et al. 2019, Verduzco-Garibay et al. 2022). These considerations reinforce the relevance of evaluating local species such as *Gymnocoronis sessilis* in constructed wetlands, as they reduce acquisition and transport costs and favor ecological adaptation.

Most CW projects are implemented with plant species that have been extensively studied and are even recommended by institutions such as the National Water Commission (CONAGUA) and the United States Environmental Protection Agency (USEPA). In contrast, the present study focuses on *G. sessilis* S.F. Blake, a species with limited technical documentation. The first record of this macrophyte

in Mexico was reported by Blake (1923), who noted that J.N. Rovirosa had observed it in 1889 in the state of Tabasco and described it for the United States National Herbarium. According to CONABIO (2016), it is a native freshwater species distributed across Campeche, Chiapas, Nayarit, Tabasco, Tamaulipas, and Veracruz. CONABIO (2010) reported that *G. sessilis* does not tolerate abrupt environmental changes, a trait that could limit its use in CWs. However, during this research, the species was observed and collected from a stream polluted with domestic wastewater, where it formed a dense, well-established patch, providing a strong rationale for evaluating its potential in constructed wetland systems for wastewater treatment.

MATERIALS AND METHODS

General information

This study was conducted at the CW experimental plant of the Water Technology Laboratory in the Academic Division of Biological Sciences at Universidad Juárez Autónoma de Tabasco. The facility comprises experimental CW units measuring 2.5 m in length $\times$ 1.2 m in width $\times$ 1.0 m in height, with an operating water depth of 0.5 m, as designed by López et al. (2014).

It should be noted that this study is an experimental evaluation conducted under controlled conditions, aimed at analyzing the adaptation and performance of *G. sessilis* in constructed wetlands, as a basis for its future application in community or municipal treatment plants.

Plant collection and preparation

For this experiment, six SFCWs and six FFCWs were set up using young specimens of *G. sessilis* collected from the regulating basin near the wastewater treatment plant in Macultepec, Centro, Tabasco (coordinates: 18.1480123, -92.855817).

The domestic wastewater used in the trials was pumped from the sump into a sewage storage tank (ST), where the influent was concentrated and homogenized. From this tank, the water was then distributed to the experimental CW units in a regulated manner. It is important to note that the ST does not correspond to a septic tank, but rather to a control and homogenization unit designed to stabilize influent conditions prior to treatment.

Young specimens were collected in the early morning to minimize thermal stress associated with the region's characteristic high temperatures. Special

attention was given to selecting plants of comparable size, and sampling was conducted throughout the regulating basin to ensure a representative and homogeneous collection. Immediately after harvesting, the specimens were placed in containers filled with fresh water and transported to the experimental site. There, they were carefully cleaned and re-selected, with damaged individuals discarded and senescent or damaged leaves and roots removed.

Planting procedure

Each CW unit was planted with 25 *G. sessilis* specimens. In the SFCW, 3/4 in river gravel was used as the support matrix. Excavations of approximately 10 cm were made in the gravel, where the young specimens were placed to ensure root anchorage and stability during the adaptation phase. In the FFCW, the plants were uniformly distributed across the water surface, simulating the species' natural distribution in its habitat (Fig. 1).

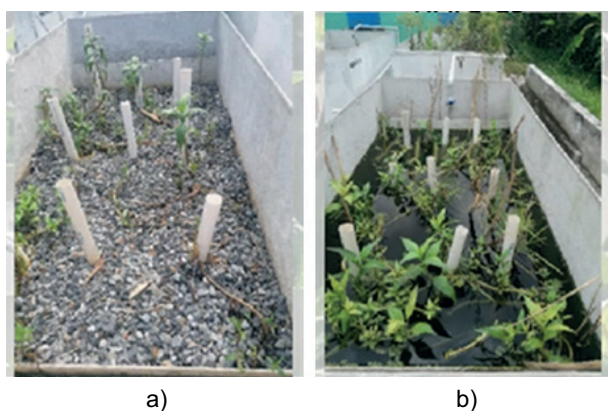


Fig. 1. Initial planting of *Gymnocoronis sessilis* in constructed wetlands with 25 specimens each. (a) Subsurface-flow wetland, (b) free-flow wetland.

Operational conditions

These systems treated the domestic wastewater generated by the Academic Division of Biological Sciences' daily activities. The initial characteristics of the wastewater were obtained from the ST, where the influent was concentrated and homogenized. They were operated with a flow rate of 200 L/day, using hydraulic retention times (HRT) of 4.5 days for subsurface-flow wetlands (SFCW) and 7.5 days for free-flow wetlands (FFCW). However, before reaching the operational stage at 200 L/day of domestic wastewater, an approximately 1-month adaptation phase was implemented. During this stage, the systems were fed with 200 L/day of diluted waste-

water, starting with potable water and gradually increasing the wastewater fraction until typical influent conditions were achieved. This procedure facilitated plant acclimatization and system stabilization prior to full operation.

Monitoring and analytical methods

The plant species underwent an overall stabilization period of six months. The first month was an adaptation stage during which no parameter measurements were taken, as the purpose was solely to acclimatize the plants to wastewater conditions. Over the following five months, the plants grew under these conditions until full stabilization was achieved.

The data reported here were obtained once the species had stabilized, defined as full plant development and surface coverage of the CW units. Wastewater monitoring was carried out using standard methods SM 9040 B (APHA 2017a), SM 2550 (APHA 2017b), APHA 2120 (APHA 2017c), and USEPA 410.4 (USEPA 1993) to assess pH, temperature, apparent color, turbidity, and COD, respectively. Removal efficiency (η) for each treatment was calculated using equation 1 (García-Ocaña et al. 2019):

$$\eta = \left(\frac{C_e - C_s}{C_e} \right) 100 \quad (1)$$

where η is the removal in percentage, C_e is the average concentration of wastewater inlet and C_s is the average concentration of treated wastewater outlet.

Experimental design

A randomized one-factor, two-level experimental design was used: vegetation vs. no vegetation. The dependent variables were pH, temperature, apparent color, turbidity, and COD of the influent and effluent wastewater. The experimental treatments were:

- ST: sewage storage tank/control tank.
- FFCW-GYM: free-flow CW with *G. sessilis*
- FFCW-W: Free-flow CW without vegetation (control).
- SFCW-GYM: subsurface-flow CW with *G. sessilis*.
- SFCW-W: subsurface-flow CW without vegetation (control).
- The layout of the CW units is illustrated in **figure 2**.

Statistical analysis

Statistical analysis was performed using Statgraphics Centurion v. 18.0. For non-parametric data, Kruskal-Wallis analysis of variance and Mann-Whitney U median test were used. For parametric

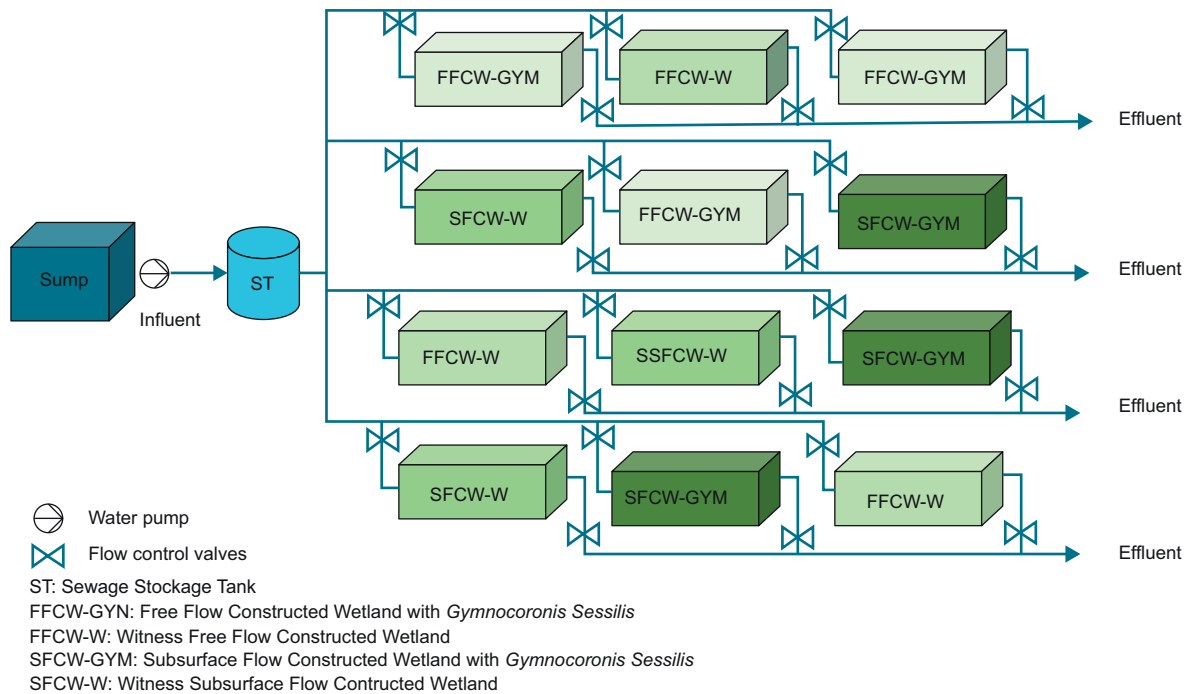


Fig. 2. Statistical design and layout of constructed wetlands.

data, Fisher's least significant difference (LSD) test and multiple range comparisons were applied. The significance level was set at $\alpha = 0.05$. Parametric data are presented as mean $\pm$ standard deviation, while non-parametric data are reported as median $\pm$ interquartile range (IQR).

RESULTS AND DISCUSSION

Summary of results and regulatory compliance

The following subsections detail the behavior of each parameter, while **table I** summarizes compliance

with Mexican regulations. The results indicate that SFCWs were the most efficient during the stabilization phase of *G. sessilis*, with SFCW-GYM showing the lowest values for most parameters. However, this system did not meet the maximum permissible limits (MPL) for color, although it did comply with standards for pH, temperature, turbidity, and COD, according to Mexican regulation NOM-001-SEMARNAT-2021 (SEMARNAT 2021), as shown in **table I**. In contrast, the performance of FFCW systems reflects the species' behavior, as *G. sessilis* failed to stabilize in this wetland type. As a result, vegetation coverage was limited at the time of monitoring.

TABLE I. MEDIAN ($\bar{X}$) $\pm$ INTERQUARTILE RANGE (IQR) VALUES AND ENVIRONMENTAL COMPLIANCE OF CONSTRUCTED WETLANDS SYSTEMS.

Parameter	ST		FFCW-W		FFCW-GYM		SFCW-W		SFCW-GYM		MPL
	$\bar{X}$	$\pm$ IQR	$\bar{X}$	$\pm$ IQR	$\bar{X}$	$\pm$ IQR	$\bar{X}$	$\pm$ IQR	$\bar{X}$	$\pm$ IQR	
pH	8.7	2.6	7.9	0.9	8.2	0.4	7.9	0.0	8.0	0.2	6-9
Temperature ($^{\circ}\text{C}$)	25.4	1.1	25.3	1.3	24.3	1.4	24.3	1.2	25.2	1.5	35
Color (CU)	372.5	116.5	1064.0	169.5	353.5	130.5	136.0	66.0	137.0	41.0	15
Turbidity (NTU)	6.5	2.3	8.9	3.2	3.7	0.8	2.5	0.6	2.2	0.7	5
COD (mg/L)	206.5	0.0	112.5	46.5	52.3	17.1	38.6	25.9	25.8	266.0	150

ST: sewage storage tank (control tank); FFCW-GYM: free-flow constructed wetland with *Gymnocoronis sessilis*; FFCW-W: free-flow constructed wetland without vegetation (control); SFCW-GYM: subsurface-flow constructed wetland with *G. sessilis*; SFCW-W: Subsurface-flow constructed Wetland without vegetation (control); CU: color units; NTU: nephelometric turbidity units; COD: chemical oxygen demand.

This finding confirms that *G. sessilis* is better adapted to SFCW, as organic load removal efficiencies are higher when vegetation grows properly; the greater the vegetative growth, the higher the pollutant removal efficiency (González-Díaz et al. 2022). These observations challenge the statement made by CONABIO (2010), as in the present study *G. sessilis* survived a drastic habitat transition from an open-water environment (stream) where roots develop freely to a confined-root environment within the wetland substrate, under significantly higher organic-load conditions.

pH behavior

The pH of the wastewater in the sewage storage tank was 8.74 ± 0.27 . The Kruskal-Wallis test for median comparison showed statistically significant differences ($p < 0.05$) among treatments, with 95% confidence (Fig. 3). The lowest median pH values were observed in SFCW-W (7.94 ± 0.09) and FFCW-W (7.9 ± 0.9), while the highest were recorded in FFCW-GYM (8.27 ± 0.4) and SFCW-GYM (8.0 ± 0.29). This decrease in pH is favorable for wetland function and aquatic life, as pH spikes can add toxicity to constructed wetlands and impair their purification processes, according to Mexican Standard NMX-AA-008-SCFI-2016 (SECOFI 2016).

These results provide robust evidence of the intrinsic buffering capacity of fully operational constructed wetlands, which effectively modulate

pH fluctuations by driving slightly alkaline waters toward neutral conditions. Notably, this capability is not restricted to alkaline systems. Sánchez-Araujo et al. (2021) demonstrated comparable buffering performance in acidic environments, employing CWs vegetated with *Phragmites australis* (reeds) and *Nasturtium officinale* (watercress). In their study, slightly acidic influents ($\text{pH} = 6.74$) were adjusted to near-neutral pH values of 7.36 in reed-based CWs and 7.29 in watercress-based CWs. Consistent with these findings, Arévalo-Aranda et al. (2023) reported that a batch-type anaerobic CW planted with *P. australis* effectively neutralized acid mine drainage, elevating pH from 3.2 to 7.4 within 48 h. Such performance underscores the potential of vegetated anaerobic CWs as efficient passive treatment systems for pH stabilization under diverse water quality conditions.

Temperature behavior

The temperature of the wastewater in the control tank was 25.41 ± 1.1 °C. Fisher's test for comparing means indicated no differences among the treatments at the 95% confidence level (Fig. 4). This suggests good temperature control in the CW, which is essential to avoid disturbances that could affect the nitrogen cycles in particular (Mora-Orozco et al. 2020) and affect microbial activity as well as absorption and purification processes (Martínez-Delgadillo et al. 2005).

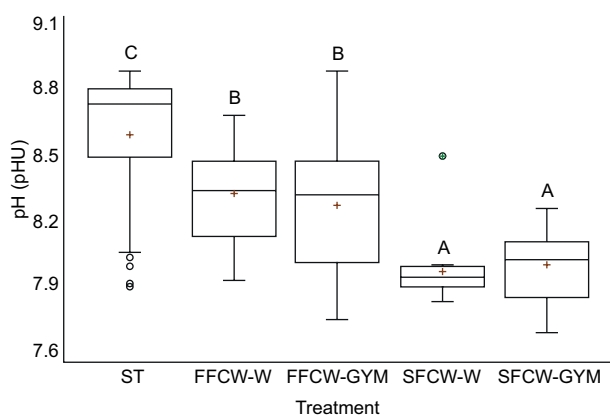


Fig. 3. Median values $\pm$ interquartile range for pH. Different letters indicate differences ($p < 0.05$) at the 95% confidence level ($n = 72$). (ST: sewage storage tank [control tank]; FFCW-GYM: free-flow constructed wetland with *Gymnocoronis sessilis*; FFCW-W: free-flow constructed wetland without vegetation [control]; SFCW-GYM: subsurface-flow constructed wetland with *G. sessilis*; SFCW-W: subsurface-flow constructed wetland without vegetation [control]).

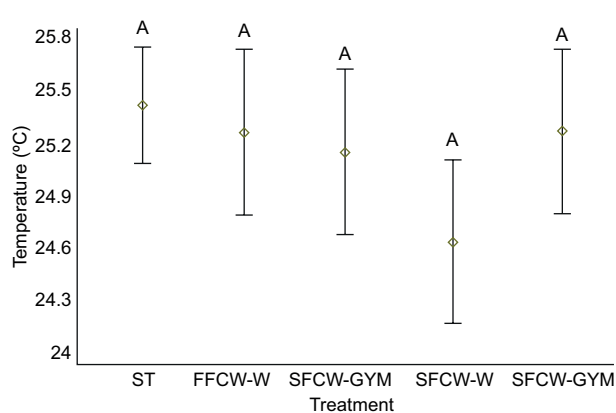


Fig. 4. Mean values $\pm$ standard deviation for temperature. Different letters indicate differences ($p < 0.05$) at the 95% confidence level ($n = 72$). (ST: sewage storage tank [control tank]; FFCW-GYM: free-flow constructed wetland with *Gymnocoronis sessilis*; FFCW-W: free-flow constructed wetland without vegetation [control]; SFCW-GYM: subsurface-flow constructed wetland with *G. sessilis*; SFCW-W: subsurface-flow constructed wetland without vegetation [control]).

Color behavior

The watercolor in the control tank was 372.5 ± 116.5 color units (CU). The Kruskal-Wallis test for contrasting medians indicated highly significant differences between treatments ($p < 0.05$) with a 95% confidence level (**Fig. 5**). The lowest median color value was found in the SSFCW-W with 136 ± 66 CU, followed by the SSFCW-GYM with 137 ± 41 CU, and the highest value was found in the FFCW-W with 1064 ± 66 CU, followed by the FFCW-GYM with 353.5 ± 130.5 CU. In this case, a marked increase in color is observed in the FFCW-W due to the formation of microalgae and duckweed that grow naturally in it. Since the control treatments were not inert, there was natural proliferation of environmental species.

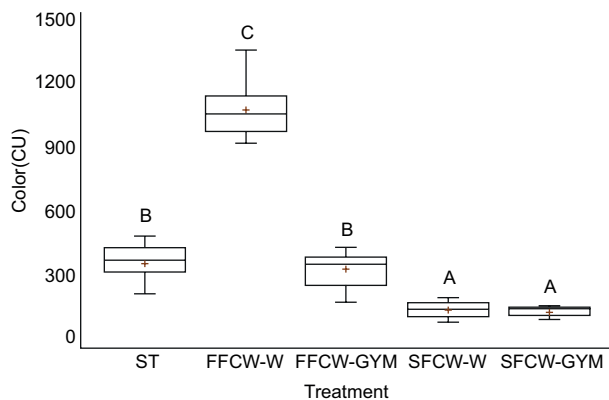


Fig. 5. Median of apparent color values $\pm$ interquartile range for each treatment. Different letters indicate differences ($p < 0.05$) at the 95% confidence level ($n = 72$). (ST: sewage storage tank [control tank]; FFCW-GYM: free-flow constructed wetland with *Gymnocoronis sessilis*; FFCW-W: free-flow constructed wetland without vegetation [control]; SFCW-GYM: subsurface-flow constructed wetland with *G. sessilis*; SFCW-W: subsurface-flow constructed wetland without vegetation [control]; CU: color units).

Turbidity behavior

The turbidity of the wastewater in the control tank was 6.5 ± 2.3 nephelometric turbidity units (NTU). The Kruskal-Wallis test for median comparison showed highly significant differences ($p < 0.05$) among treatments, with 95% confidence (**Fig. 6**). The lowest median turbidity values were observed in SFCW-GYM (2.2 ± 0.7 NTU) and SFCW-W (2.55 ± 0.06 NTU). The highest values were found in FFCW-GYM (3.75 ± 0.8 NTU) and FFCW-W (8.95 ± 3.2 NTU). This parameter shows a pattern like that of apparent color, most likely also influenced by the growth of plant species and microalgae within the systems.

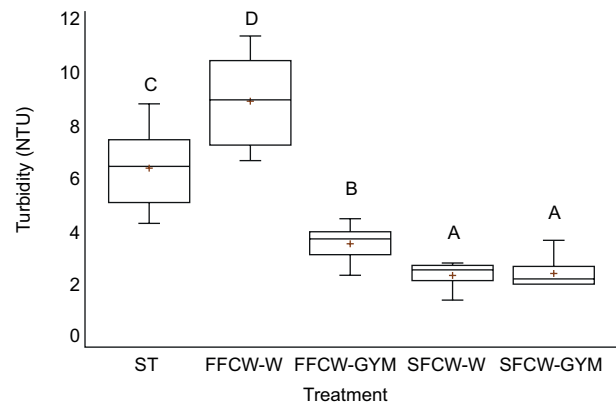


Fig. 6. Median turbidity values $\pm$ interquartile range for each treatment. Different letters indicate differences ($p < 0.05$) at the 95% confidence level ($n = 72$). (ST: sewage storage tank [control tank]; FFCW-GYM: free-flow constructed wetland with *Gymnocoronis sessilis*; FFCW-W: free-flow constructed wetland without vegetation [control]; SFCW-GYM: subsurface-flow constructed wetland with *G. sessilis*; SFCW-W: subsurface-flow constructed wetland without vegetation [control]; NTU: nephelometric turbidity units).

COD behavior

The chemical oxygen demand (COD) of the wastewater in the control tank was 206 ± 0.01 mg/L. The Kruskal-Wallis test for median comparison revealed statistically significant differences ($p < 0.05$) between the FFCW-W treatment and the other evaluated treatments, with 95% confidence (**Fig. 7**). The lowest median COD value was observed in

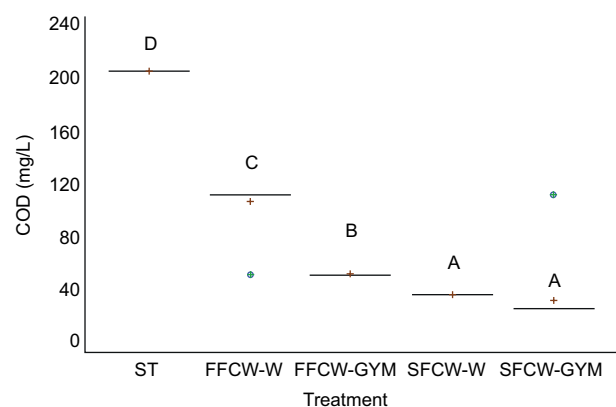


Fig. 7. Median values $\pm$ interquartile range of chemical oxygen demand (COD). Different letters indicate differences ($p < 0.05$) at the 95% confidence level ($n = 72$). (ST: sewage storage tank [control tank]; FFCW-GYM: free-flow constructed wetland with *Gymnocoronis sessilis*; FFCW-W: free-flow constructed wetland without vegetation [control]; SFCW-GYM: subsurface-flow constructed wetland with *G. sessilis*; SFCW-W: subsurface-flow constructed wetland without vegetation [control]).

SFCW-GYM (25.0 ± 0.0 mg/L), followed by SFCW-W (37.25 ± 0.0 mg/L). The highest values were recorded in FFCW-W (112.5 ± 0.0 mg/L) and FFCW-GYM (52.25 ± 0.0 mg/L).

Removal efficiencies

Table II presents the average removal efficiencies (%) of the CWs during the stabilization stage of *G. sessilis*. The highest efficiencies were observed in the SFCW systems, with SFCW-GYM being the most effective across all parameters. In contrast, FFCW-W showed the lowest performance, even exhibiting negative removal efficiencies. This indicates that the system accumulated contaminants during treatment, likely due to the proliferation of microalgae on the water surface. FFCW-GYM also exhibited low removal efficiency, primarily because *G. sessilis* did not stabilize adequately in this type of wetland, resulting in poor vegetation coverage.

The negative efficiencies observed in free-flow wetlands are attributed to malfunction phenomena such as hydraulic short-circuiting, plant collapse, and algal proliferation, which lead to the accumulation and release of organic matter, as previously reported in similar systems (Arteaga-Cortez et al. 2019, Sánchez-Araujo et al. 2021). Moreover, the proper functioning of a constructed wetland depends on several factors, including microbial activity, interactions among system components, and the plant species employed, as different species may exhibit varying removal efficiencies (Nava-Rojas et al. 2023). As previously noted, in the FFCW, some of these elements were lacking, which explains the limitations observed in their performance.

During the stabilization phase, *G. sessilis* exhibited contrasting behavior depending on the wetland configuration. In free-flow wetlands, the plants

collapsed into the water column, promoting the decomposition of plant material, the appearance of algae, and, consequently, the release of previously absorbed organic matter (no stabilization was achieved). This outcome was consistent with the negative values observed for color and turbidity removal. In contrast, in subsurface-flow wetlands, the species achieved healthy stabilization and complete surface coverage, supporting the higher efficiencies reported for COD, color, and turbidity. These differences are clearly illustrated in **figure 8**, which shows the final condition of both wetland types.

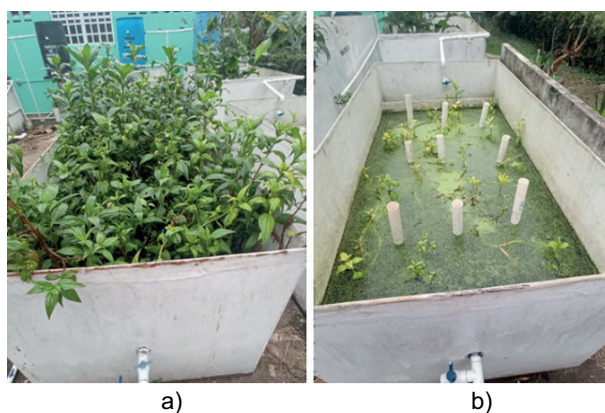


Fig. 8. Final condition of *Gymnocoronis sessilis* in constructed wetlands. (a) Subsurface-flow wetland, (b) free-flow wetland.

The pH and temperature parameters exhibited low variability, indicating adequate regulatory capacity within the constructed wetland and enabling synergistic functioning among all system components. Extremely low temperatures can inhibit

TABLE II. AVERAGE REMOVAL EFFICIENCY (%) OF BASIC CONTAMINANTS IN CONSTRUCTED WETLANDS SYSTEMS.

Parameter	FFCW-W	FFCW-GYM	SFCW-W	SFCW-GYM
pH	9.6	6.2	9.6	8.5
Temperature	0.4	4.3	4.3	0.8
Color	-185.6	5.1	63.5	63.2
Turbidity	-36.9	43.1	61.5	66.2
COD	45.5	74.7	81.3	87.5

Note: All removal efficiencies are expressed as percentages (%).

FFCW-GYM: free-flow constructed wetland with *Gymnocoronis sessilis*; FFCW-W: free-flow constructed wetland without vegetation (control); SFCW-GYM: subsurface-flow constructed wetland with *G. sessilis*; SFCW-W: subsurface-flow constructed wetland without vegetation (control).

oxygen transfer and microbial activity (Hua et al. 2017), while temperatures exceeding 50 °C can halt critical processes such as aerobic digestion and bacterial nitrification (Sánchez-Araujo et al. 2021). The optimal pH range for the proliferation of both macrophytes and associated microbial communities lies between 6.5 and 8.5. Outside this range, alkaline conditions promote ammonium formation, whereas acidic conditions favor the release of metal ions, both of which can significantly reduce the operational lifespan of the wetland (Olivo-Gutiérrez et al. 2018).

Regarding COD removal, *G. sessilis* in horizontal subsurface flow systems demonstrated performance exceeding that reported by Castillo-Sánchez and Chimbo-Solórzano (2021), who achieved 66.74% removal using vermifilters in rural domestic wastewater. The results are comparable to those obtained by Alufasi et al. (2024) with vertical flow CWs planted with *Typha latifolia* (82.87% removal) and higher than those reported by Marín-Muñiz et al. (2024) in ornamental plants cultivated in vertical subsurface CWs (64-77% removal). However, COD removal with *G. sessilis* in SFCW was slightly below the efficiencies reported for *Sagittaria latifolia* (96%) and *S. lancifolia* (93%) in free-flow CWs (Estrada-Pérez et al. 2025).

It should be noted that the hydraulic retention time (4.5 days in SFCW and 7.5 days in FFCW) and the support medium (3/4 in river gravel) were kept constant across treatments, ensuring comparable hydraulic permeability. The selected gravel size ensured adequate hydraulic permeability and minimized clogging, as reported in similar studies (Hua et al. 2017, García-Ocaña et al. 2019). Therefore, the differences observed in COD removal are attributed to the presence of *G. sessilis* and the wetland configuration rather than substrate or hydraulic variability.

CONCLUSION

This study demonstrated that subsurface-flow constructed wetlands (SFCWs) with *Gymnocoronis sessilis* achieved higher removal efficiencies for COD, color, and turbidity than free-flow systems (FFCWs), which exhibited negative efficiencies due to malfunctions. These findings highlight the importance of appropriate plant species selection and hydraulic design to ensure system stability and performance. Temperature was maintained as an operational control parameter to confirm system stability during the stabilization stage.

The work provides experimental evidence of the potential of *G. sessilis* in wastewater treatment wetlands, emphasizing the relevance of plant-micro-organism interactions and hydraulic conditions. Although the results focused on the stabilization stage, future research could explore the kinetic dynamics of the processes and evaluate alternative plant species to further optimize efficiency and broaden the applicability of constructed wetlands in diverse contexts.

The high COD removal achieved with *G. sessilis* in SFCW highlights its potential for future studies focusing on nutrient assimilation (nitrogen and phosphorus), heavy metal uptake, and removal of emerging contaminants.

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