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Full-scale ornamental constructed wetlands for caffeine removal from rural wastewater and coffee-processing effluents

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Abstract: The coffee agroindustry is one of the main economic activities in rural communities of developing countries. However, its processing generates wastewater with high organic loads and emerging contaminants such as caffeine. In the absence of proper sanitation infrastructure, these discharges are often combined with municipal wastewater, increasing the risk of water pollution and threatening both environmental and community health. In this context, sustainable and low cost treatment alternatives are requerid to mitigate these impacts, particularly in rural settings. This study evaluated the performance of a full-scale hybrid system consisting of a settler tank followed by constructed wetland cells (SF-CW and SSF-CW) planted with ornamental species (*Eichhornia crassipes, Alocasia odora, Hedychium coronarium, Heliconia psittacorum* and *Zantedeschia aethiopica*). Monitoring was carried out from February to July 2024, including caffeine analysis by UV-Vis spectrophotometry during both the coffee harvesting and processing season and periods when only rural domestic wastewater was treated. The system achieved an average caffeine removal efficiency of over 99% during the coffee processing season. The ornamental plants adapted well to the operational conditions, showing high resilience and stable growth, as well as potential ornamental and commercial value. This work provides full-scale operational evidence of the potential of ornamental constructed wetlands as a practical and replicable solution for treating rural wastewater mixed with coffee-processing effluents, while simultaneously delivering environmental protection, social benefits, and local economic opportunities for rural communities.

Keywords: caffeine, coffee processing, rural economy, sustainable treatments, constructed wetlands

Introduction

Rural communities rely heavily on local agro-industries, which serve not only as sources of employment and income but also as essential pillars of their cultural and social identity. These activities also have the potential to invigorate rural economies, create meaningful job opportunities, and help curb migration to urban areas (Mazloum Yar, 2024).

Among these agro-industries, coffee cultivation and processing stand out for their economic and social relevance across many tropical countries in Latin America, Asia, and Africa, while also contributing to biodiversity conservation and sustainable development (Utrilla-Catalan *et al*., 2022). In Latin America, coffee production, harvesting, processing, and retail activities contribute between 0.3% and 3.7% of national gross domestic product. In Mexico, as of 2017, 48% of all coffee producers were classified as smallholders. Nearly half of the country's coffee production takes place on small plots (Harvey *et al*., 2021), and globally, farmers with less than 5 ha supply about 60% of the world's coffee market (Siles *et al*., 2022).

This agricultural activity, while sustaining thousands of families, requires intensive water use and produces large volumes of wastewater with high organic loads, which are often discharged without adequate treatment (Alemayehu *et al*., 2020; Campos *et al*., 2021). In rural communities, this wastewater commonly mixes with municipal effluents, increasing the complexity of its management and heightening the risk of pollution in nearby rivers, streams, and soils (Dadi *et al*., 2018). Coffee-processing wastewater (CPWW) may contain high concentrations of organic matter, nutrients, and elevated acidity (Amare *et al*., 2023). Previous research has largely focused on conventional water quality parameters (BOD, COD, TDS, pH, TN, among others), often neglecting emerging contaminants present in coffee-processing wastewater, such as caffeine.

Caffeine is an alkaloid widely consumed and valued for its stimulating effects on humans. It is present in a broad range of everyday foods and products, including coffee, tea, chocolate, soft drinks, energy beverages, and pharmaceutical formulations (Quadra *et al*., 2020). Daily caffeine intake per person is estimated to range from 400 to 800 mg (Ebrahimzadeh *et al*., 2021).

The presence of caffeine in water bodies is directly associated with human-derived pollution and is considered an emerging risk in aquatic systems. Studies have shown that caffeine can alter the physiology of aquatic organisms and affect the reproduction and growth of fish and plants, owing to its ability to easily cross biological membranes and accumulate within cells and tissues (de Cravalho *et al*., 2024). Evidence also shows that, in several vertebrates, caffeine can inhibit phosphodiesterases, modulate adenosine receptors, and induce oxidative stress mechanisms that help explain its effects on aquatic species (Rodrigues *et al*., 2025). Furthermore, caffeine can persist in aquatic environments for periods ranging fromseveral months to multiple years, and it shows high stability under various environmental conditions, including changes in salinity, temperature, and light (Rodrigues *et al*., 2025).

Caffeine has been detected in municipal and rural wastewater at concentrations ranging from 22.29 to 64 µg/L (de Oliveira *et al*., 2019; Vymazal *et al*., 2017), while values between 13.6 and 388 mg/L have been reported in wastewater from coffee processing (Figueroa Campos *et al*., 2020). These differences demonstrate the wide range of caffeine concentrations that can occur in wastewater, reflecting both the diversity of consumption patterns and the types of activities carried out within communities. Moreover, caffeine has been identified as a persistent compound in the environment, further increasing its environmental relevance (Korekar *et al*., 2020). This variability represents a significant environmental challenge, particularly in rural settings where the lack of adequate sanitation infrastructure allows these compounds to reach surface and groundwater bodies directly.

The inadequate management of these combined discharges compromises not only environmental health but also the well-being of rural communities that depend on water for drinking, irrigation, and productive activities (Liang & Yue, 2021). Consequently, there is a pressing need to implement sustainable, accessible, and low-cost alternatives that align with the real conditions of these localities while generating sufficient scientific evidence to allow their replication in areas with similar characteristics.

One promising solution is the use of constructed wetlands systems that mimic the functioning of natural wetlands through the interaction of plants, microorganisms, and substrates (Mihret *et al*., 2024). Their treatment efficiency relies on a combination of physical, chemical, and biological processes that act synergistically (Brix, 2020). Among the key physicochemical mechanisms are contaminant adsorption onto substrates and organic matter, as well as the filtration and sedimentation of suspended particles (Vispo *et al*., 2023). Biologically, plants play a central role by absorbing and accumulating contaminants in their tissues, releasing oxygen into the rhizosphere, and stimulating the microbial activity associated with their root systems, thereby enhancing both aerobic and anaerobic biodegradation processes (Sandoval *et al*., 2019). These removal mechanisms can eliminate emerging organic contaminants such as caffeine (Ilyas & van Hullebusch, 2019).

Constructed wetlands provide multiple benefits: they diversify rural economies by incorporating commercially valuable ornamental plants, enhance the visual quality of community spaces, promote biodiversity, and foster social engagement in water management and stewardship (Monzón-Reyes *et al*., 2025; Zitácuaro-Contreras *et al*., 2021). However, most studies to date have been conducted at the laboratory scale, and only a small proportion involve full-scale systems (C. Chen *et al*., 2022; Nocetti *et al*., 2024; Sandoval Herazo *et al*., 2023). This limitation hinders the broader implementation of real-scale wetland technologies implemented under actual operating conditions.

In this context, the objective of this study is to evaluate caffeine removal from rural and coffee-processing wastewater using full-scale ornamental constructed wetlands, highlighting their role as an innovative and sustainable strategy to address both environmental and social challenges faced by rural communities.

Materials and Methods

Study site

This study was conducted in the rural community of Salvador Díaz Mirón, located in the municipality of Misantla, Veracruz, Mexico, located at coordinates 19°47'20" N and 96°52'20" W (Figure 1). Data were collected from February to July 2024. Due to its mountainous location at 917 m above sea level. Community is primarily dedicated to agricultural activities such as coffee cultivation and livestock production (Rodríguez-Macedo *et al*., 2014). The climate is classified as temperate tropical, semi-warm, and humid, with an average annual temperature of 20.1 °C and annual precipitation of 1,900 mm (INEGI, 2024).

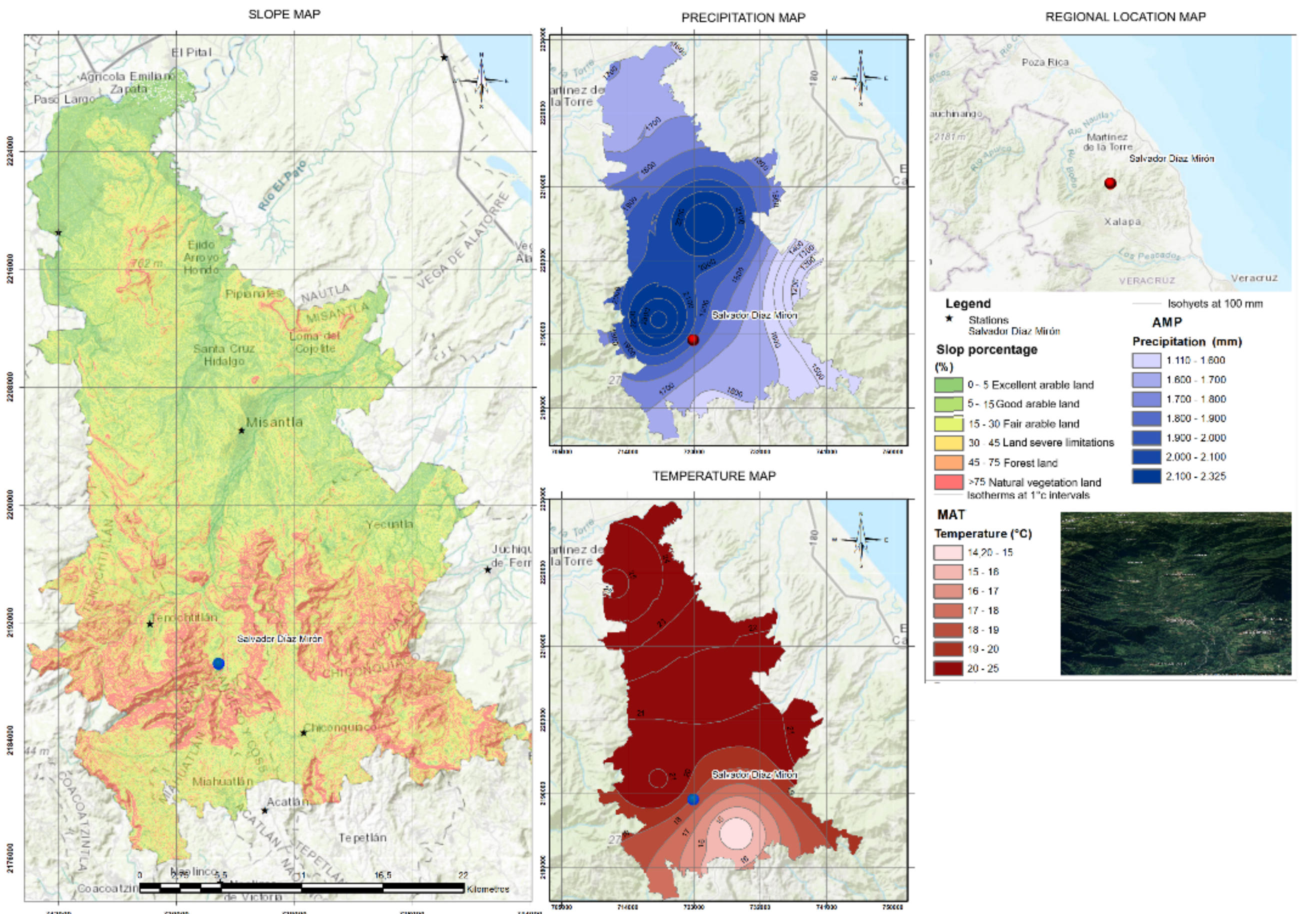

Figure 1. Location map of Salvador Díaz Mirón, Misantla, Veracruz, México

Experimental desing

The full-scale treatment system was constructed in 2022 with funding from the "Proyectos para el Fomento Ambiental 2022" program issued by the Secretaría de Medio Ambiente del Estado (SEDEMA). The system consists of a sedimentation tank followed by a hybrid constructed wetland: one free-surface flow cell (SF-CW) and three subsurface flow cells (SSF-CWs), as shown in Figure 2. The cells were filled with red volcanic gravel with a particle size of 3–5 cm, with coarser material placed at the bottom to reduce clogging risk. The system operated continuously with a hydraulic retention time (HRT) of 4 days. Ornamental plants were arranged in monoculture and polyculture, including the following species: *Eichhornia crassipes* (SSF-CW), *Alocasia odora* + *Hedychium coronarium* (SSF-CW), *Heliconia psittacorum* (SSF-CW), and *Zantedeschia aethiopica* (SSF-CW). Plants in the SSF-CW cells were planted at a density of 4 units/m² (Calheiros *et al*., 2015), except for *Eichhornia crassipes*, which was established at a density of 40 units/m². Six sampling points were selected within the system (Figure 2), in addition to the direct discharge from coffee-processing activities.

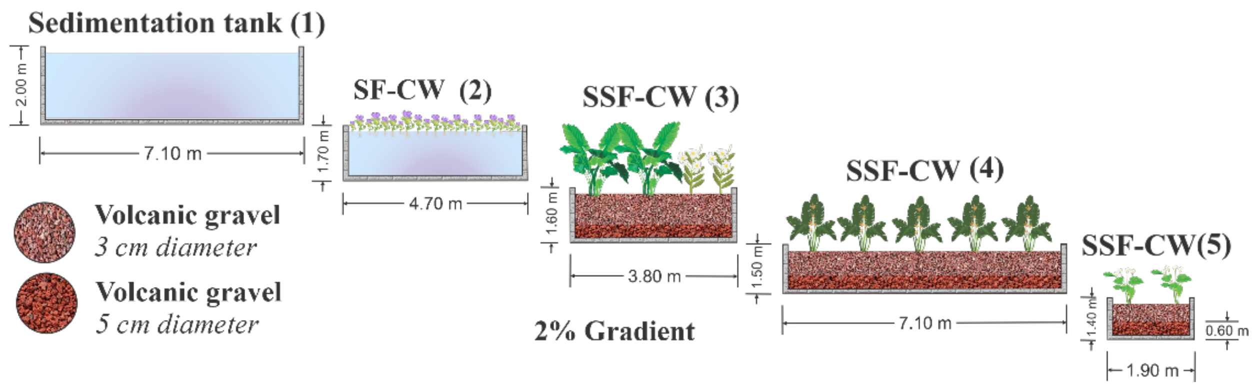

Figure 2. Layout of the constructed wetland cells (Monzón-Reyes *et al.*, 2026)

Data collection and analysis

Caffeine was analyzed monthly during the coffee-processing season (February–April 2024), as well as during the three subsequent months (May–July 2024). Samples were collected every 15 days,at three different times of the day. Caffeine quantification was performed using UV–Vis spectrophotometry with a Genesys 10S Vis instrument, previously calibrated with the C0750 caffeine standard (Sigma-Aldrich). The methodology adopted was taken from García Martínez *et al*. (2018).

Removal efficiency was determined using the equation 1 (M. Sandoval-Herazo *et al*., 2021):

$$Removal\ efficiency = \frac{Ci - Ce}{Ci} \times 100 \quad \textbf{(1)}$$

where Ci represents the influent contaminant concentration (mg/L) and Ce corresponds to the effluent concentration (mg/L).

Data normality was examined using the Kolmogorov–Smirnov test, with a significance threshold of $\alpha = 0.05$. As the data did not meet normality assumptions, a non-parametric Kruskal-Wallis test was applied, and multiple comparisons among groups were conducted using Dunn's post-hoc procedure. All statistical analyses were performed in Minitab® v.16 (Minitab Inc., State College, Pennsylvania). This analytical approach is similar to that described by Vera-Puerto *et al*. (2021).

To assess the growth of the plant species implemented in the system, their height was measured using a measuring tape.

Results and Discussion

Caffeine removal

The characterization of the community's wastewater, including caffeine concentrations at the washing point, at the point without CPWW influence, and at the system inlet, is presented in Table 1.

Table 1. Caffeine concentrations at different sampling points during and outside the coffee-processing season

Sampling point	Harvest season (mg/L)	Outside harvest season (mg/L)
Washing point CPWW	335.03 ± 45.30	NR*
Point without CPWW discharge	0.08 ± 0.03	0.15 ± 0.08
Influent	38.85 ± 10.40	0.84 ± 0.57

* NR= No reported

Figure 3 shows the point where the coffee-processing wastewater mixes with the community's municipal wastewater.

Figure 3. Discharge of community's municipal wastewater and coffee-processing wastewater

Caffeine concentrations found in this study were markedly higher than those typically observed in municipal wastewater. Li *et al*. (2013), Vymazal *et al*. (2017), and Herrera-Melián *et al*. (2023) documented values of 0.057 mg/L, 0.083 mg/L, and 0.124 mg/L, respectively. The elevated levels reported here are attributed to the combined discharge of municipal effluents with CPWW, where caffeine concentrations during the fermentation stage can reach up to 388.6 ± 85.9 mg/L (Figueroa Campos *et al*., 2020). On average, the system achieved removal efficiencies above 99%, aligning with findings reported by de Oliveira *et al*. (2019) and Teoh *et al*. (2022) for tropical environments, as well as with full-scale observations reported by Chen *et al*. (2016) for rural wastewater treatment.

Caffeine reduction in constructed wetlands is commonly associated with photodegradation and aerobic biodegradation, both facilitated by oxygen availability and atmospheric exposure (M. Sánchez *et al*., 2022; Vymazal *et al*., 2017). Nonetheless, Chen *et al*. (2016) noted that anaerobic biodegradation may also play an important role.This pathway may contribute significantly in the present system, as illustrated in Figure 4, where the highest removal contributions were observed in zones characterized by low oxygen availability: sedimentation tank and the SSF-CW cells.

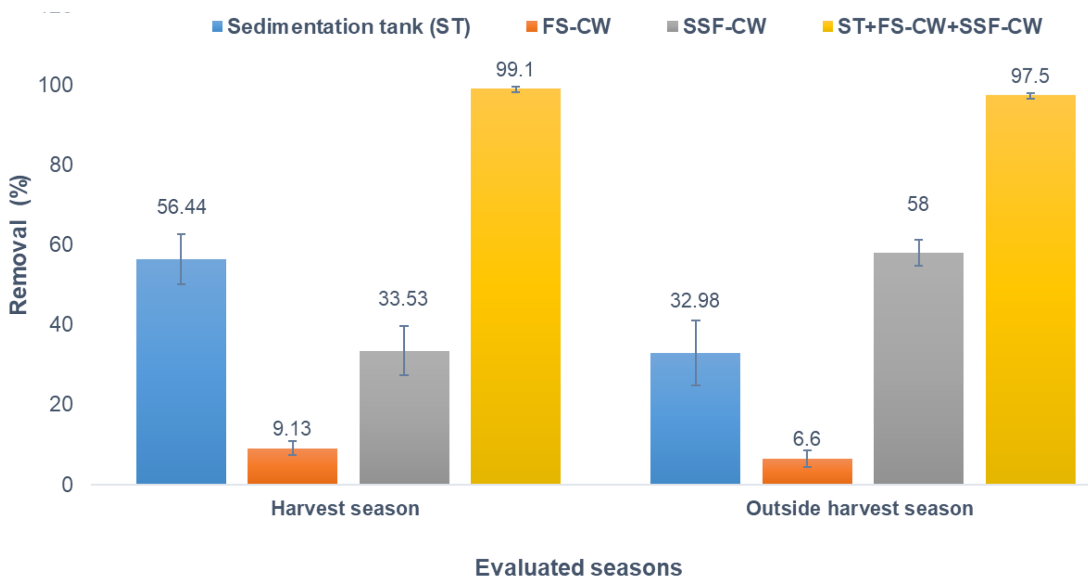

Figure 4. Caffeine removal efficiencies of the wetland system

Vegetation has additionally been identified as a significant contributor to caffeine attenuation (Ilyas and van Hullebusch, 2020; Zhang *et al*., 2013). This effect appears more pronounced in cells that host a larger number and greater diversity of plant species under both monoculture and mixed-species configurations.

Removal performance across the integrated wetland system (Figure 4) revealed that the SSF-CW contributed 33.53% and 58% of the total removal during the two evaluated periods. However, maximum removal were observed when the treatment system was evaluated as an integrated treatment train. No significant seasonal differences were detected across treatment stages ($p > 0.05$), suggesting that the proposed configuration is capable of buffering the seasonal rise in caffeine concentrations during the harvest period. This indicates that the combined operation of the SF-CW and SSF-CW represents an effective treatment strategy.

Plant growth and adaptation

Figure 5 illustrates plant height throughout the monitoring period, with measurements taken every two and three months. In the case of *Eichhornia crassipes*, which is not included in the graph, the population increased from 120 to 920 individuals within a 15 m² area, reaching its peak flowering in July. In this system, *Heliconia psittacorum* and *Hedychium coronarium* exhibited flowering levels that exceeded those reported in previous studies (Carrera-Alvarado *et al*., 2023), demonstrating strong performance under real operating conditions. However, no significant differences were detected for *Zantedeschia aethiopica* by the end of the study ($p > 0.05$). This limited response may be associated with the high temperatures recorded at the site, which ranged from 28 to 35 °C, given that this species reaches optimal growth between 15 and 28 °C (Casierra *et al*., 2012).

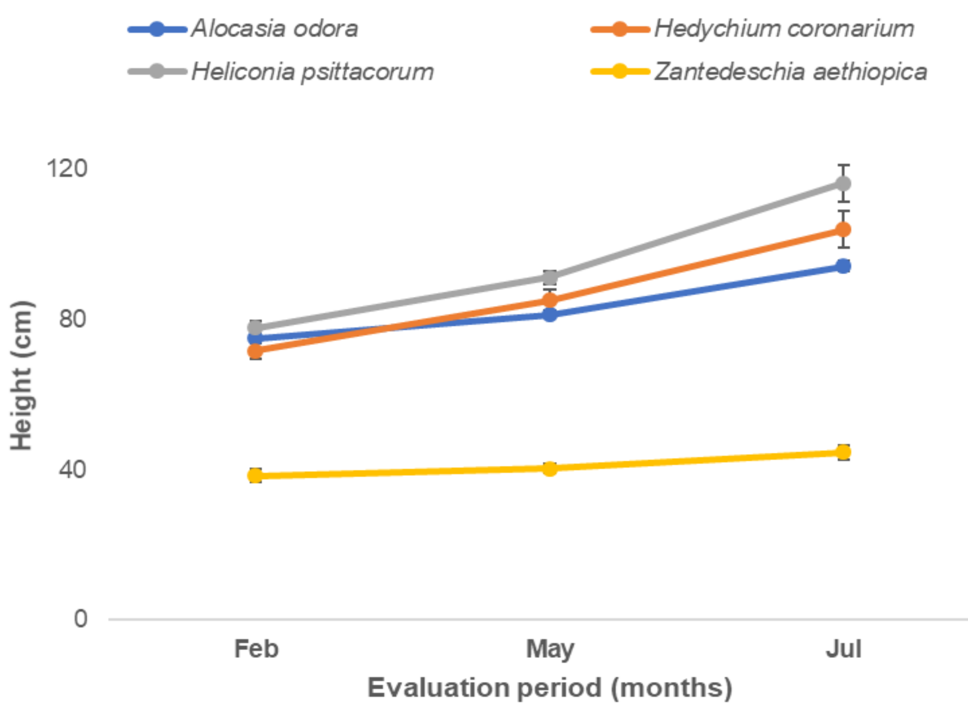

Figure 5. Growth of the evaluated species during the study period

Overall, the plant species exhibited healthy development despite the elevated caffeine concentrations present in the system (Figure 6). *Heliconia psittacorum* and *Hedychium coronarium* are highly resilient to toxic conditions and are recognized for their effectiveness in removing pharmaceutical compounds, including caffeine (Arredondo *et al*., 2022). This resilience not only supports the continuity of treatment processes but also helps maintain the ornamental quality of the plants, which sustained vigorous growth, flowering, and visually attractive foliage.

Their tolerance to elevated contaminant concentrations, combined with sustained ornamental quality, suppor their suitability for use in constructd wetlands in tropical regions. In addition to contributing to contaminant removal, they help preserve the visual appeal of the system, which enhances social acceptance, and they also provide meaningful commercial value through the sale of flowers and foliage. Their incorporation therefore serves environmental, social, and economic functions.

Figure 6. Vegetative development of the evaluated species in the hybrid wetland system

Perspectives and future challenges

This study provides valuable evidence on the effectiveness of full-scale constructed wetlands in removing caffeine from rural wastewater, where effluents from coffee processing are mixed with municipal discharges. However, several limitations should be acknowledged. The results are based on a single coffee harvest and processing season, highlighting the need for longer-term monitoring to assess system performance over time. Additional research is also required to better understand caffeine accumulation in plant biomass, sludge, and the filter media, as well as to identify potential intermediate metabolites formed during degradation processes.

Future work should aim to validate these results in rural communities with varying climatic, topographic, and sociocultural conditions to strengthen model reproducibility and regional applicability. Long-term assessments are likewise recommended to capture seasonal dynamics, regeneration cycles of ornamental species, and a comprehensive evaluation of the ultimate fate of caffeine within the system.

Conclusions

The ornamental constructed wetlands achieved average caffeine removal efficiencies exceeding 99% when treating rural wastewater mixed with coffee-processing discharges, demonstrating their effectiveness as a treatment option under real operating conditions. Furthermore, ornamental species such as *Heliconia psittacorum* and *Hedychium coronarium* showed good adaptation to the system conditions, maintaining their ornamental quality and suggesting potential added value through their commercial use. This multifunctionality supports the role of ornamental constructed wetlands as an integrated solution with environmental and socio-economic benefits for rural communities.

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Author contributions: B.L.M-R: Writing, analysis and interpretation of data; M.C.L-M: Analysis and interpretation of data; I.V-P: Design, Conceptualization and editing; L.C.S-H: Editing, supervision, funding acquisition and provide materials.

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