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Vertical flow wetlands as the core for the sustainable treatment of coffee wastewater in small communities in Colombia: preliminary results

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ABSTRACT

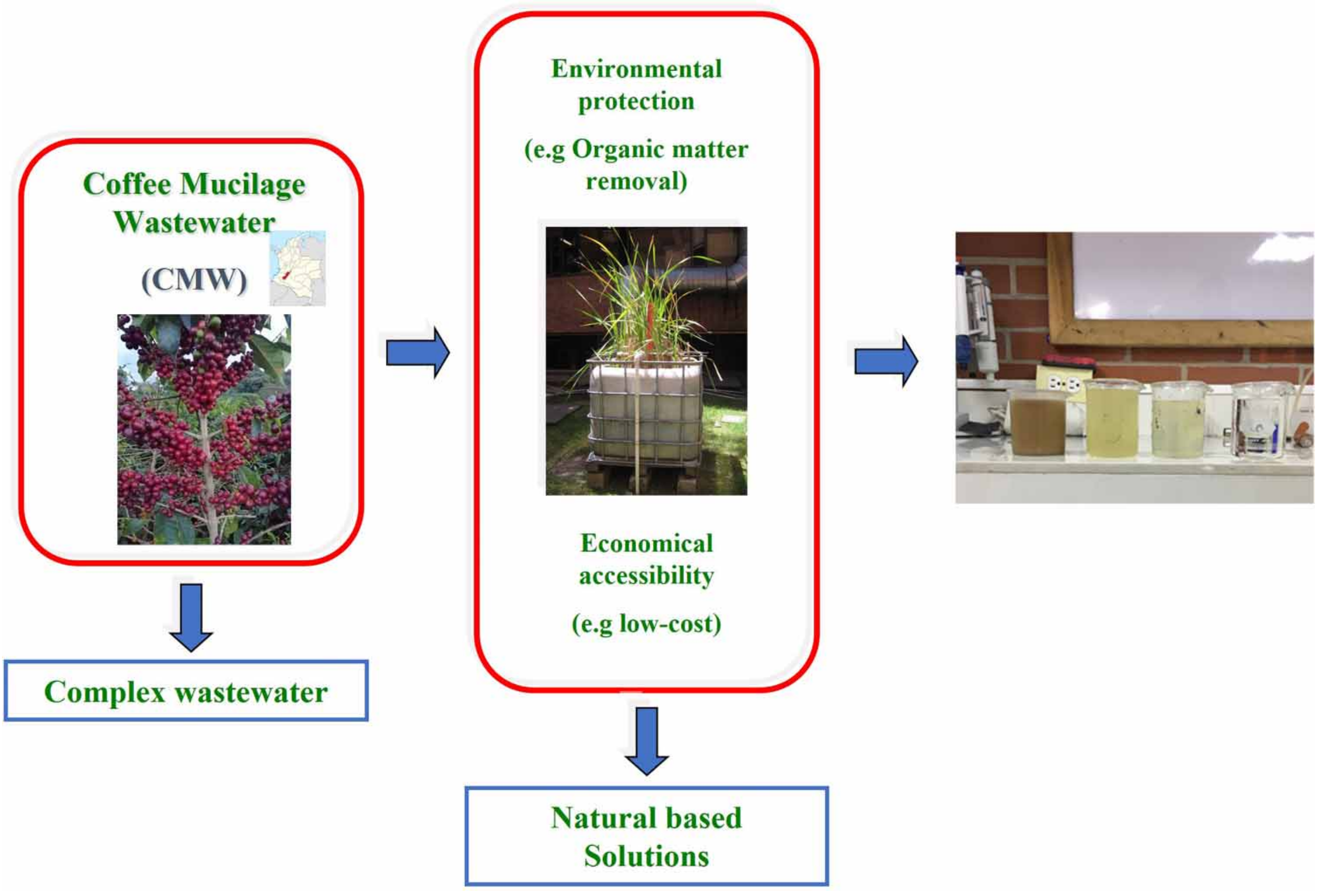
Coffee is one of the most important agricultural products in Colombia. To date, small-scale Colombian coffee growers have developed this activity with a simple infrastructure and random use of water that generates harmful by-products to the water resource mainly in the stage of separation of the mucilage. The coffee mucilage wastewater (CMW) is composed of high organic loads and its impact on water sources is due to its high load of nutrients such as nitrogen (N), phosphorus (P), and chemical oxygen demand (COD) values of over 25,000 mg/L. However, there is no consensus on what treatment can be used, especially whether it is accessible to coffee producers. Thus , the aim of this study consisted of assessing the performance of the combination of a carbon filter (CF) as pretreatment and vertical flow wetland (VFW) as a Natural-based Solution (NbS). The results show a reduction of more than 85% of COD, 96% of total solids, and UV254 close to 94%. It was remarkable that both treatments are appropriate for waters with a high concentration of solids. Finally, it can be concluded that CF + VFW is a feasible technology to treat the coffee wastewater from small communities of coffee producers.

Key words: activated carbon, coffee mucilage wastewater, lignocellulosic residues, Nature-based Solutions

HIGHLIGHTS

- It is feasible to treat waters from the peeled cherry coffee process through NbSs as the vertical flow wetlands.
- The proposed CF + VFW system is appropriate for dispersed rural communities in Colombia.
- UV_{254} can be a complementary measure to evaluate performance in complex waters such as CMW.
- This work contributes to improving the coffee production chain because the impact on the receiving sources of small producers decreases.

GRAPHICAL ABSTRACT



INTRODUCTION

Colombia is the third-largest producer of coffee worldwide and the largest producer of soft coffee in the world. Coffee production in 2022 was 11.1 million bags of 60 kg (Cafeteros 2023). To date, in Colombia, there are 540,000 producers of coffee and nearly 100% are small-scale coffee growers, that is, cultivation areas up to 5 Ha. Huila is the main department in coffee production, in this region, the cultivation is mainly done by communities located in rural areas. Approximately 83,000 families are cultivating 144.895 Ha. This type of coffee is known as high-altitude coffee since the crops are located above 1,600 msnm. In this Colombian department, 74% of its rural population is dedicated to this economic activity.

The coffee cherries are made up of several parts, the outer skin is called the exocarp that surrounds the mesocarp. Another component of the cherry is the mucilage and parchment that are found under the pulp, which in turn, is wrapped by a membrane known as the silver skin. The coffee process begins when the mature bean is harvested (Federación Nacional de Cafeteros de Colombia (FNCC), Cenicafé *et al.* 2019). Once harvested, coffee beans can be processed in two ways, either dry or wet process. The dry process occurs when the product is washed and immediately dried. In the wet process, the cherries are peeled and/or pulped using water. The processes produce several residues including bark, pulp, and coffee parchment.

According to Cafeteros (2023), the stages in the processing of coffee are the reception of the cherries, extraction of the pulp, either manually or mechanically, fermentation, washing, drying, and finally the handling of the by-products. Regarding liquid waste, the greatest contribution occurs in the washing stage, in which the fermented mucilage is washed with water and its residue is known as coffee mucilage wastewater (CMW).

Campos *et al.* (2021) mentioned that the wastewater (CMW) generated in the demucilator, has chemical oxygen demand (COD) concentrations ranging between 18.600 and 29.500 mg/L, BOD_5 of 10.500 and 14.340 mg/L, total nitrogen (TN) ca.

168 mg/L, total phosphorus (TP) of ~23 mg/L, potassium of 157 mg/L, sodium of 46 mg/L, and total solids in the range of 14.000–18.500 mg/L. The direct discharge of this wastewater without prior treatment to any receiving source has great potential of deteriorating the quality of the water. Also, since Colombia is one of the largest coffee producers in the world, the discharge of untreated water in rivers and streams is common, affecting water quality, and the environment and limiting the further use of the waters. This practice is not only limited to coffee growers but is a general trend for small-scale growers (República 2023).

Campos *et al.* (2021) and Presta-Novello *et al.* (2023) indicate that the discharge is toxic to the aquatic ecosystem, generating bad odors, poor aesthetic appearance, and growth of microorganisms that endanger health. In this sense, it is essential not only to treat CMW before discharge to accomplish the regulations but also to recover the nutrients that remain in the treated water in the crops. Among nature-based solutions (NbSs) for water treatment, wetlands are recognized not only for their tolerance to high organic loads and robustness but also for their versatility to be combined with other processes, either pre- or post-treatment (Vymazal 2018).

In Colombia, the use of wetlands as a core of a sustainable water treatment system in rural coffee communities promotes not only environmental benefits but also economic, social, and cultural added values. Likewise, this type of NbS promotes the active participation of the rural population because the community can participate in the planning, construction, operation, and maintenance of the system, which makes the solution to the management of the WW during the harvest stable and sustainable over time (Presta-Novello *et al.* 2023).

According to Alemayehu *et al.* (2020), the main treatments used for wastewater generated from coffee processes might include, advanced oxidation processes, physicochemical processes such as coagulation–flocculation, anaerobic digestion, and wetlands. However, they mention that the most common practice in coffee-producing countries is direct discharge of the process waters on the soil as fertigation, to take advantage of the considerable concentration of nutrients and is technologically easy to apply. However, it is important to mention that in Colombia, 2021 Resolution 699 (Ministerio de Ambiente y Desarrollo Sostenible 2021) limits the discharge and infiltration of treated and untreated wastewater into the soil.

The coffee production belongs to a small family farm, a typical Colombian 'Finca Cafetera', located at Los Arrayanes' in El Pital (Huila-Colombia). Hence, this study presents the preliminary results of the performance of a system that combines a carbon filter (CF) as a pretreatment followed by a vertical flow wetland (VFW) treating the CMW. The combination of these two technologies with the adsorption process with the activated carbon preceding the natural treatment allows the application of the concept of circular economy in the treatment of wastewater to reclaim and reuse the treated water safely which will provide ecosystem services. These treatment trains will surely be a viable option for one of the most important industries of Colombia, the coffee industry, and to be used by similar 'Fincas Cafeteras', where according to the National Coffee Federation more than 55,000 are found around the country.

MATERIALS AND METHODS

Coffee mucilage wastewater

The wastewater was obtained from the demucilator during the coffee harvest at 'Finca Los Arrayanes' (Huila-Colombia – 1,600 msnm) between the months of April and May 2019. The site follows the wet way traditional process to benefit the coffee. From the harvest, 500 bags of 60 kg of Arabica-type coffee are produced each year. It is important to mention that for each bag, 150 L of wastewater are generated, resulting in ca. 1,250 L/day of CMW during the harvest months. The wastewater was characterized by grab samples every 2 weeks for pH, total suspended solids (TSS), turbidity, COD, TN, TP, and organic constituents as UV_{254} absorbance according to APHA (2012).

Experimental setup for the CF + VFW

The CF + VFW system operated continuously for 62 days (the harvest period). The CF was designed with the same dimensions as the wetland, but in this case, it was filled with two layers of carbon, 40 cm of activated carbon and 60 cm of natural carbon. The influent water was fed to the CF by a centrifugal pump model JET Barner that distributed the water homogeneously on the surface of the CF. The system operated unsaturated, and water was collected at the bottom of the filter and evacuated by a manifold that conducted the water to a tank to pump it to the VFW. On the surface of the CF, geotextile was installed to retain the residues of the mucilage. The VFW was constructed in a plastic container of ca. 200 L. The depth of the sand as the support medium was 1.0 m ($d_{10} = 0.25$ mm, $d_{60} = 1$–4 mm – UC = 2.75). The bottom of the VFW was filled with a layer of 0.2 m of medium-sized gravel (ϕ 8–16 mm) engulfing the drainage system (PVC Ø 75 mm), as suggested by Brix &

Arias (2005). The distribution manifold was placed on the surface built from Ø 50 mm with orifices every 20 cm to guarantee homogeneous distribution of the water. The coffee wastewater (CW) was planted with *Phragmites australis* at a density of four plants/m^2. The hydraulic load of 2 cm/day and eight pulses/day resulted in a flow rate of 56 L/day. Then, the CMW was fed by a peristaltic pump model Masterflex to the VFW. Figure 1 shows a schematic of the combined CF + VFW system. The initial pH values were not adjusted during the experiment.

Data analysis

The results were analyzed based on the removal efficiency using descriptive statistics in the ORIGIN PRO 8.5 software.

RESULTS

Characteristics of the CMW effluent

Table 1 shows the mean values of the CMW of 'Finca los Arrayanes' and the Colombian Regulations for discharge in receiving sources, Resolution 631/2015- Minambiente (2015) and infiltration in the soil, Resolution 699/2021, Minambiente (2021).

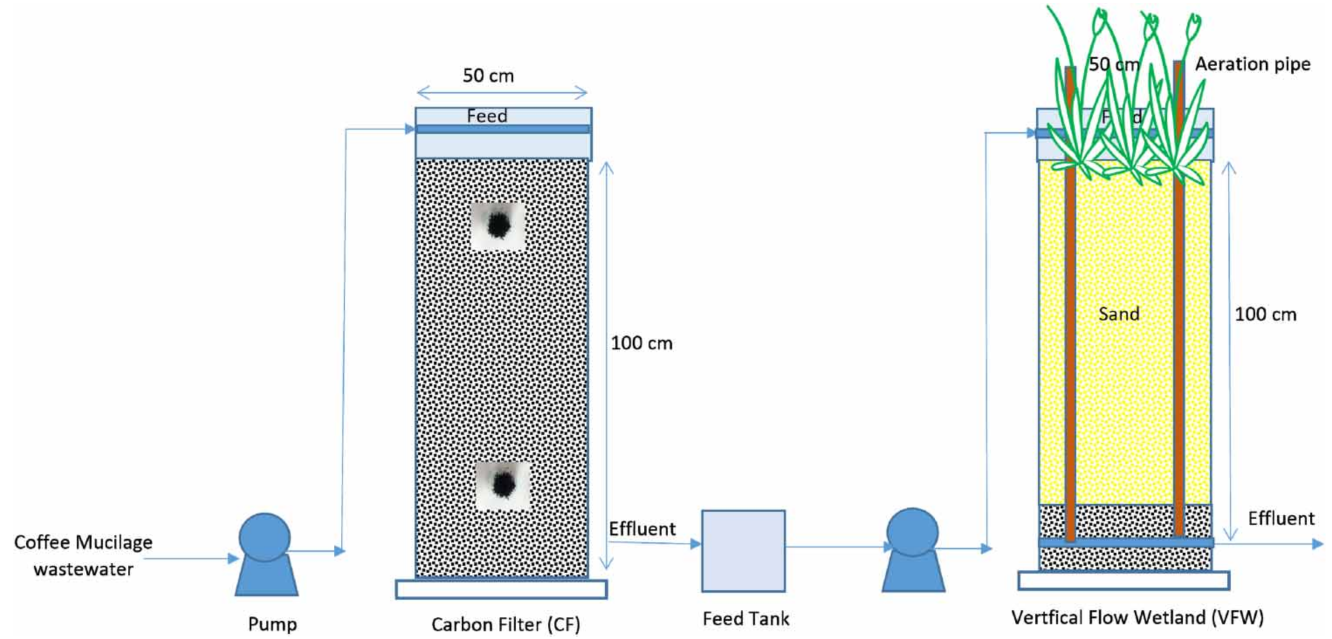


Figure 1 | Setup of the CF + VFW system.

Table 1 | Characteristics of raw CMW – Finca Los Arrayanes (Huila – Colombia) and values of Colombian discharge demands

Parameters	Raw CMW[a]	R0631/2015 (Colombian standard) – traditional coffee process	R699/2021 (Colombian standard) – infiltration rate soil (16–27 mm/h)	R699/2021 (Colombian standard) – infiltration rate soil (28–52 mm/h)	R699/2021 (Colombian standard) – infiltration rate soil (>53 mm/h)
pH	3.6 ± 0.20^b	5.0–9.0	6.5–8.5	6.5–8.5	6.5–8.5
Turbidity (NTU)	2,945	Analysis and report	–	–	–
UV_{254} (cm^{-1}) (DF: 1:20)	1.07 ± 0.4^a	Analysis and report	–	–	–
TSS (mg/L)	$11,455 \pm 1,178^a$	400	100	70	50
COD (mg/L)	$27,356 \pm 3,786^a$	650	200	200	200
TP (mg/L)	843 ± 370^a	Analysis and report	5.0	5.0	2.0
TN (mg/L)	202 ± 175^a	Analysis and report	30	20	20

[a]Mean ± S.D. (standard deviation).
[b]Geometric mean, $n = 4$.

The results show that the water is acidic mainly because of the fermentation of the coffee cherry with a high concentration of organic matter, solids, and nutrients. Moreover, the water quality parameters show that it does not meet any of the Colombian standards demand; neither the discharge standards for surface receiving sources nor the infiltration into the soil. As mentioned before, a common practice in Colombia is free discharge of the waters or the infiltration in the soil with wastewater to take advantage of the nutrients in their crops, since coffee plantations are commonly associated with food crops as an extra economic source.

The values found in Table 1 are much higher than other studies that were found in the literature by Said *et al.* (2020), Presta-Novello *et al.* (2023), and Rossmann *et al.* (2013). It can be said that this difference may be because of the individual practices, equipment used, agro toxics, and fertilizers used by the owners of the farm. This justifies even further the need to treat these effluents before being discharged to receiving sources or infiltrated into the soil.

Global performance of the CF + VFW system

The initial pH was not adjusted during the study to avoid the addition of chemicals to the process. The results show that the initial pH was close to 3.4 and the combination of the systems stabilizes it close to 6.6. It is important to highlight that during the 60 days of continuous operation, the combined system was effective in removing TSS regardless of the high concentration of solids being discharged. Figure 2 shows the visual difference of color, the removal efficiency individually as well as combined between untreated and treated.

Table 2 shows the final values of the treated CMW. The pH and TSS parameters are met for discharges into receiving sources. In regard to the infiltration of treated waters into the soil, the water quality of the effluent of the experiment still does not meet the quality required by the national authorities. One of the objectives of the Colombian national government when emanating the new discharge regulation was to reduce pollution of surface water as well as for ground water while taking into consideration the economic as well as the technical capacity of the small-scale coffee producers, as it is indicated in 'Analysis and report'.

Figure 3 shows the removal efficiency in the different stages of the system. Regarding the organic matter, even though a considerable removal of COD was obtained, with mean values of 3,415 mg/L, the effluent still does not comply with the Colombian Standard Minambiente (2015). Therefore, it is necessary to continue the treatment in a second phase with another wetland system. Said *et al.* (2020) studied the performance of a two-phase wetland system (vertical and floating) treating wastewater from a coffee industry. They used *Phragmites karka* and *Eichornia crassipes* and in both cases found removals greater than 95% of COD with initial values of 13,000 mg/L.

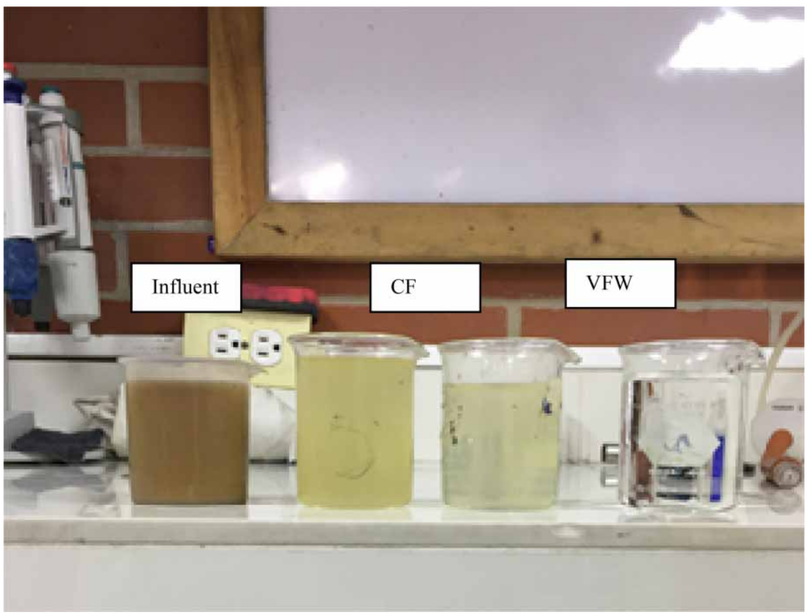


Figure 2 | Coffee mucilage wastewater (CMW) before and after the applied treatment.

Table 2 | Final-treated CMW from Finca los Arrayanes (Huila-Colombia**)**

Parameters	CMW treated	R0631/2015 (Colombian standard) – traditional coffee process	R699/2021 (Colombian standard) – infiltration rate soil(16–27 mm/h)	R699/2021 (Colombian standard) – infiltration rate soil (28–52 mm/h)	R699/2021 (Colombian standard) – infiltration rate soil (>53 mm/h)
pH	6.57	5.0–9.0	6.5–8.5	6.5–8.5	6.5–8.5
Turbidity (NTU)	68	Analysis and report	–	–	–
UV_{254} (cm^{-1}) (DF: 1:20)	0.94	Analysis and report	–	–	–
TSS (mg/L)	251	400	100	70	50
COD (mg/L)	3,415	650	200	200	200
TP (mg/L)	35	Analysis and report	5.0	5.0	2.0
TN (mg/L)	11	Analysis and report	30	20	20

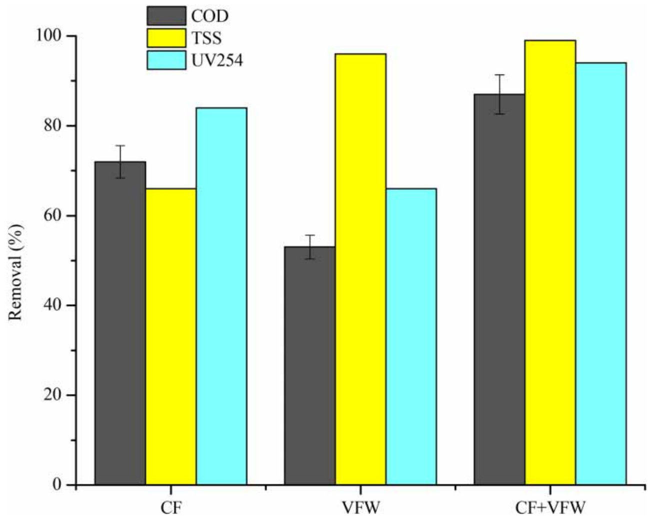


Figure 3 | Removal efficiency during the different stages of the treatment of the CF + VFW system.

In the CF, the adsorption of organic particles was favored when the water enters this stage; however there is no removal of organic matter in the VFW. Similarly, Rossmann *et al.* (2013) studied the performance of four horizontal subsurface flow constructed wetlands (CWs) treating aerated and non-aerated CW) They observed that although aeration did not contribute to COD removal, it does improve the biodegradability of the CW, and this contributes to improving the organic matter removal efficiency of the CW. It is important to mention that the applied organic load in this study was 1,531 gCOD/d ± 41, and for TP and TN was 47 gPT/d ± 41 and 12 gTN/d ± 9, respectively.

Regarding the aromaticity of organic carbon measured as UV_{254}, the values show a high concentration of aromatic organics, which are probably the result of the agrotoxics applied to the crop, in this case, glyphosate. It is worth mentioning that authors such as Çeçen (1999), Vaillant *et al.* (2002), and Coque *et al.* (2002) recommend measurements of absorbance at different wavelengths as complementary measures to global ones (i.e. COD, BOD), not only to evaluate the efficiency in treatments but also to identify groups of aromatic-type compounds. Chaparro *et al.* (2010) and Chaparro & Pires (2015) evaluated the removal of lignin in wastewater from the pulp and paper industry by anaerobic digestion followed by advanced oxidation processes such as O_3/UV. These authors measured the absorbance in the wavelength at 280 nm. The results showed that for this type of lignocellulosic wastewater, conventional measures such as COD and total organic carbon (TOC) do not show appropriate information to make decisions. Instead, the value of the absorbance at wavelengths such as those evaluated by these authors allowed us to see that the application of process O_3/UV, although it reduces organic matter, increases the toxicity of this type of industrial effluent.

The removal of UV_{254} was 94% (Figure 3), with final values in the range of 0.94 cm^{-1}. These results can be related to the color, whose origin in this type of water is also organic, derived from the lignin and cellulose of the plant and coffee cherry. No similar studies were found where the value of UV_{254} is used in this type of wastewater to evaluate the performance. This represents an opportunity because it is a test that does not generate more toxic or more polluting waste than the same water that is being measured. In that case, residues such as CMW must combine both conventional measures of water quality and those based on absorbance in the UV-VIS spectrum.

CONCLUSIONS

The combination of combined CF (activated and natural) and VFW system (CF + VFW) resulted in a good alternative to treat the CMW produced by the conventional process from rural coffee producers in Colombia. The removal efficiency of aromatic compounds, as well as organic matter, was close to 90% during the time of harvest. However, it is necessary to continue with the treatment of the VFW effluent because the regulations have not yet been achieved. Besides, this study shows the the advantages of a rural coffee producer family by using wetlands as NbSs for the treatment of CW. Both the low initial investment and the environmental co-benefits can give added value to the traditional coffee production chain, the basis of the economy family. Finally, it should be mentioned that more feedback is needed to assess the feasibility of this treatment configuration over the long term, but the initial results are promising.

Although the system was able to remove considerable concentrations of organic matter and nutrients, the effluent in our case did not meet the discharge standards demanded by the government. Taking into consideration that the farm evaluated is similar to several thousands of farms in the country, the discharge of untreated and treated waters of the environment is a serious issue that should be tackled by the authorities. The authorities should also provide technical and economic support to the small-scale coffee producers.

ACKNOWLEDGEMENTS

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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