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Aged Refuse Recycling to Treat Wastewater from Coffee Processing

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Abstract: Over the last two decades, the use of bioreactors filled with aged refuse extracted from closed areas of landfills has proven to be a viable alternative for the treatment of different types of wastewater. This study presents the results obtained during the evaluation of aged refuse used as filling material for a downflow bioreactor during the removal of the organic load present in wastewater generated in the wet processing of coffee. The tests were carried out over a period of 120 days, with 15 days to start up and stabilize the bioreactor and 105 days to perform treatability tests. The aged refuse, once extracted, was dried and sifted to a particle size of less than 50 mm. The bioreactor used had a cylindrical geometry (Ø = 0.20 m, and h = 3.40 m), and it was fed with hydraulic loads of 50, 100, and 150 L m^{-3} d^{-1}. The analysis of the data obtained shows that the system studied achieves the removal of 98.3% of the initial organic load when fed with 150 L m^{-3} d^{-1}. This showcases recycling aged refuse as a technically viable alternative to treat the wastewater generated during coffee processing. Also, the evaluated system has the advantage of needing a short period of time to achieve its stabilization, which turns out to be of great value, especially in its possible use in the treatment of residual water generated in the harvest of agricultural products where the period of harvest is very short.

Keywords: bioreactor filled with aged refuse; municipal solid waste; landfills; organic load removal; wastewater from coffee processing

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1. Introduction

According to the International Coffee Association, over the last 10 years, the total production generated among exporting countries has been 9,338,700 tons of coffee per year on average [1], which causes the harvest of said grain to be considered one of the primary activities of the greatest economic importance worldwide [2]. However, collaterally to the economic benefit generated by this activity, environmental damage is also generated, which is difficult to deal with considering the pollution of bodies of water as one of the main types of pollution, where large volumes of wastewater generated during the harvest period are dumped. Although alternatives have been sought to reduce water consumption in the activities involved in coffee processing, nowadays, it is estimated that up to 20 m^3 of water may be required for each ton of coffee obtained [3–6].

The pollution problem caused by the wastewater discharge generated during coffee processing is aggravated due to the complexity of the pollutants present in it [7–9]. Therefore, a large number of research groups around the world have focused their attention on the study of several wastewater treatment systems applied to the effluents generated in coffee farms. Biological [2,10], chemical [11], and electrochemical systems have been studied [9,12,13], including photocatalytic systems [6]. All of them have shown various advantages but also some drawbacks in their practical application.

Biological systems, although friendly to the environment and normally easy to implement, require long periods of time to stabilize [2], which is of great inconvenience given that the coffee harvest lasts only 4 months on average, which is to say, the systems only manage to stabilize when the harvest is already ending. On the other hand, more robust and fast-response systems, such as advanced oxidation processes, have also been used in treatability tests for this type of effluent [14,15]. However, the implementation of these systems requires numerous reagents and supplies that could hinder their application in coffee farms for both economic and technical reasons. In addition to all the previous information, coffee farms are typically located on land with steep slopes and difficult access. As a result, these areas usually lack municipal sewer systems that would allow the transport of wastewater to a municipal treatment plant. Nowadays, the above-mentioned problem has caused contamination in water generated by coffee processing activities, which continues to be an issue that has not yet been resolved.

An alternative to bioremediation in liquid media, which has started to be explored in the last two decades, is the use of the so-called aged refuse, another name for municipal solid waste (MSW) that has been confined in landfills for periods greater than 8 or 10 years and where during the said time, it has developed a broad consortium of microorganisms capable of degrading the large spectrum of polluting molecules and all matter susceptible to being degraded present in the MSW. Since 2002, when Zhao et al. published the first evidence of the benefits that recycling aged refuse offers for the treatment of wastewater [16], a large number of articles have been published describing the results obtained in the treatability tests of wastewater with different origins and physicochemical characteristics, such as effluents from the food industry [17], landfill [18–20], and the pharmaceutical industry [21,22], among others.

Treatability systems supported by the use of aged refuse have proven to be economical, robust, and efficient in treating different types of pollutants, as well as being easy to implement, with short hydraulic retention and stabilization times [20,22,23]. In [21], the efficiency of aged refuse to remove 20 antibiotics present in a wastewater sample was evaluated. The aged refuse in these tests demonstrated both its ability to remove, on average, 76.75% of the molecules studied and its stability under shock loads. On the other hand, in 2019, Najera-Aguilar et al. [18] reported the results obtained from leachate treatability tests, observing high values of Chemical Oxygen Demand (COD) removal and other physicochemical parameters. In these tests, the system proved to be stable from the first week of operation. Aged refuse has also been evaluated in the treatment of wastewater from different types of industries. Nájera-Aguilar et al. [24] recently monitored the organic load removal profile, measured as COD, from the wastewater generated in the production area of a sugar mill using an aged refuse-filled bioreactor (ARFB), where removal of 98.8% of the initial COD was achieved using a hydraulic load (HL) of 100 L m^{-3} d^{-1}. In light of the information provided, in this study, the results obtained from the treatability tests of the wastewater generated in the wet processing of coffee using a bioreactor filled with aged refuse are presented for the first time.

2. Results and Discussion

2.1. Wastewater Samples Characterization

The physicochemical characterization of the wastewater from the wet coffee mill (WWWCM), as well as that of the municipal wastewater (MWW) used in the initial stabilization stage of the bioreactor, are shown in Table 1.

The values of the different parameters shown in Table 1 for the MWW are typical characteristics for a medium load in this type of water [25] without reaching the high organic load values that can also occur [26]. This water was used during the first 15 days of feeding to promote the stabilization of the ARFB. On the other hand, for the studied water, that is, the WWWCM, the results display its acidic nature with a pH of 5.1, which is a value that is within the expected range if one considers that, in general, the effluents from wet coffee pulping processes lead to acidic conditions, with effluents that can be toxic to ecosystems when discharged [27].

Table 1. Physicochemical characteristics of wastewater fed to the bioreactor. MWW: Municipal wastewater; WWWCM: wastewater from the wet coffee mill.

Parameter	MWW	WWWCM
Chemical Oxygen Demand (mg L^{-1})	695 ± 79	6251.5 ± 1089
Biochemical Oxygen Demand (mg L^{-1})	254 ± 45	3937.4 ± 584
pH	6.7 ± 0.2	5.1 ± 0.6
Total Suspended Solids (mg L^{-1})	228 ± 36	576.2 ± 63
Color (Pt-Co Units)	192 ± 18	2925 ± 413

Regarding the organic load, it presents high values for color (2925 Pt-Co), COD (6252 mg L^{-1}), and BOD (3937 mg L^{-1}), similar to those reported in other studies [28,29]. With these concentrations, the WWWCM far exceeds the Official Mexican Environmental Regulations in its COD and TSS parameters, which makes it necessary to treat this wastewater before discharge. It is a highly biodegradable effluent (BI = 0.62) with most of its contaminants in the dissolved form.

2.2. Aged Refuse Characterization

The aged refuse used as packing for the bioreactor was dried at room temperature for 2 weeks. During this time, the larger materials were removed. The composition analysis of the aged refuse was performed both when the material was fresh as well as when it was dry. The composition of these materials is presented in Table 2. In the said table, it can be observed that the predominant materials are the fine ones with values at around 60%. The quantification of these fine materials is of the utmost importance because it defines the amount of aged refuse that will be useful as packing material in the studied system. These values are similar to those reported by Bautista-Ramírez et al. [30].

Table 2. Characterization of the aged refuse used to fill the bioreactor.

Aged Refuse	(%) Composition of Aged Refuse				
	Rigid Plastics	Nylon	Others	Fine Material	Total
WB	12.1	12.8	13.5	61.6	100
DB	11.4	10.8	18.1	59.7	100

WB: wet basis; DB: dry basis.

2.3. Bioreactor Start-Up and Conditioning

The start-up was achieved over a short period of only 15 days, which can be attributed to the variety and large number of microbiological consortiums present in the aged refuse, which promotes a rapid transformation and consumption of the organic matter present in the wastewater [16]. During this stage of the research, the bioreactor was fed with municipal wastewater, whose physicochemical characteristics are presented in Table 1. The feeding was carried out following the procedure described in the treatability tests. Figure 1 shows the COD behavior profile of both the bioreactor influent (695 mg L^{-1}) and effluent observed during the conditioning process. In Figure 1, it can also be seen that during the first 6 days of feeding, the COD of the effluent presented higher values than those of the influent; this behavior can be attributed to the washing process of the fine particles of the bioreactor filling material. That is to say, during the short period mentioned, the water sample fed to the bioreactor dragged the susceptible matter, so the apparent residual COD at the said time could be the result of the COD fed with the wastewater sample plus the COD present in the drawn matter minus the COD removed by the microbiological activity of the bioreactors; this behavior is similar to that described by [16]. In the following

9 days, it was observed that the COD of the effluent presented lower values than those of the influent, and of those 9 days, the last 7 showed a practically constant COD value (86.46 ± 19.15 mg L^{-1}). This last behavior allowed us to reason that the bioreactor was ready to start the treatability tests. As can be seen, this system presents short conditioning times compared to those reported in conventional biological processes [2], which allows the aged refuse to be seen as an important biological option for the treatment of wastewater generated for short periods of time, as is the case with the coffee harvest.

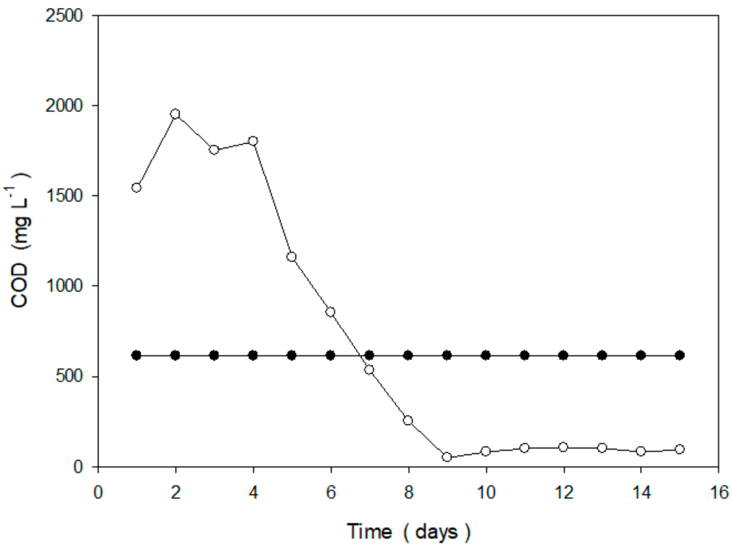

Figure 1. The behavior profile of the COD of the influent (•) and effluent (○) of the bioreactor over the start-up and conditioning periods. During this period, the bioreactor was fed with municipal wastewater with an HL of 50 L m^{-3} d^{-1}.

2.4. Effect of the Type of Wastewater Fed to the Bioreactor

After the 15-day period for bioreactor stabilization, the treatability tests began. On day 16, the bioreactor was fed with the wastewater obtained from the wet processing of coffee. Prior to feeding, in order to avoid blockages and the consequent "short circuits" within the bioreactor, the sample was sifted using a mesh with a pore size of 0.2 cm. As seen in Table 1, the physicochemical characteristics of the water fed to the bioreactor varied drastically from day 15 to day 16. The organic load fed to the bioreactor on day 16, measured as COD, increased approximately tenfold in relation to the organic load fed on day 15; this change manifested as a slight disturbance (elevation) in the behavior profile of the COD of the effluent (Figure 2). Nonetheless, the bioreactor was able to restore its stability in just three days of operation; that is, on day 18, the COD value in the effluent was already similar to the values detected in the last days of the bioreactor stabilization period. The set of COD values obtained in the bioreactor effluent during the stabilization period and through the evaluation of the first organic load were analyzed by means of a one-factor ANOVA. This variance analysis allowed us to establish that there was no significant difference between the two data sets (α = 0.05, F = 1.888, p = 0.177). This behavior could result in the great advantage of the evaluated system over conventional biological systems, given that the latter normally requires long start-up and stabilization periods [30,31], which is valuable time for crops such as coffee, where the harvest lasts only 3 or 4 months each year. In addition, the capacity that the studied system demonstrated to quickly adapt to the change from a type of municipal wastewater to water with the particularities of the wastewater generated in the wet processing of coffee allowed us to consider that this type of system could operate all year round on a coffee farm, treating the wastewater generated by the community that lives permanently on the farm for 8 to 9 months and, once the coffee harvest starts, the system could start treating the wastewater generated in the wet processing of coffee, and present high COD removal efficiencies after only three days of starting the change in wastewater type fed to the bioreactor. On the other hand, as a system that does not require any type of inputs, materials, and equipment that are difficult to acquire or qualified personnel for its operation, bioreactors filled with aged refuse have great advantages over physicochemical processes such as advanced oxidation processes [9] to treat wastewater with the characteristics of the effluent generated in the wet process of coffee.

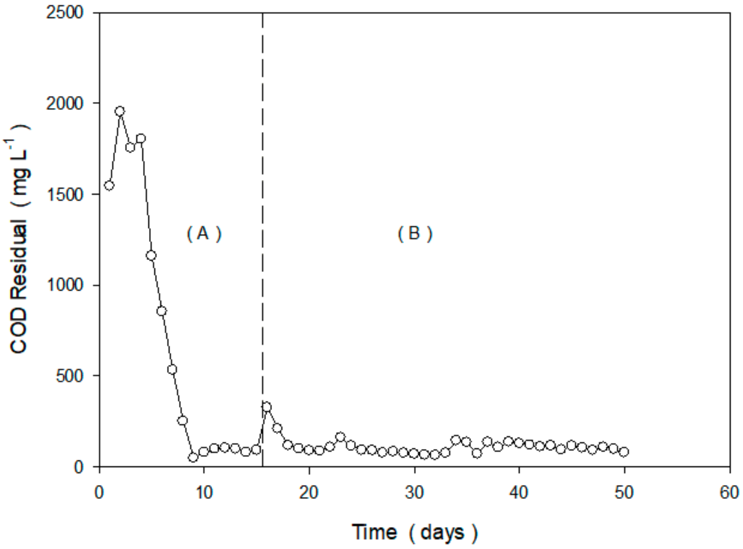

Figure 2. The behavior profile of the COD of the bioreactor effluent. (**A**) Start-up and conditioning periods with a municipal wastewater-fed bioreactor; (**B**) the first HL evaluated with feeding wastewater from the wet process of coffee. Both data sets were obtained by feeding an HL of 50 L m^{-3} d^{-1}.

2.5. *Effect of Hydraulic Load Fed*

Given the short time coffee bean harvesting and processing lasts, this article exhibits the results obtained with only three different HLs (50, 100, and 150 L m^{-3} d^{-1}), with each one fed to the bioreactor for a period of 35 days. It is important to point out that the hydraulic loads evaluated, although slightly smaller than the highest hydraulic load (200 L m^{-3} d^{-1}) assessed by [24], are higher than those reported by [30], whose maximum hydraulic load was 41 L m^{-3} d^{-1}. The COD behavior profile, both in the influent and the effluent of the bioreactor during the entire test period, is presented in Figure 3. As shown in the same figure, despite the great variability observed in the COD values of the influent, which were higher than 10% of the average COD (6251.5 ± 796.6 mg L^{-1}), for the behavior profile of the COD of the effluent, there were no significant changes ($\alpha = 0.05$, F = 1.080, $p = 0.343$) throughout the evaluation of the three mentioned HLs, presenting a value of 104.93 ± 30.05 mg L^{-1}. The above-mentioned findings make it possible to demonstrate the capacity of the studied system to mitigate the large differences in the organic load that may occur during its operation. On the other hand, although the quality of the effluent remains without significant variations despite the increase in HL, it is evident that the total amount of organic matter that is finally removed from the wastewater and, consequently, no longer reaches the receiving body of water, increases as the supplied HL rises. This direct relationship is clearly demonstrated by the positive slope of both Line 1 and Line 2, presented in Figure 4. However, the decrease in the slope of Line 2 in relation to the slope of Line 1 allows us to reason that the maximum HL that the system can support is not far from the 150 L m^{-3} d^{-1} proposed as the maximum HL to be evaluated. Table 3 shows the characteristics of the effluent from the bioreactor operated with 150 L m^{-3} d^{-1}; under these operating conditions, the removal efficiency of the organic load, measured as COD, was 98.3%. This efficiency is similar to that reported by [5], where they used an expanded granular sludge bed bioreactor to achieve removals of up to 98% of the initial COD over periods of up to 9 days. By contrast, [9] found that the operating conditions of a coupled system between anodic oxidation and hydrogen peroxide can achieve the removal of total organic carbon by up to 84% in just 240 min. In light of this information, it can be seen that the operating conditions of the evaluated system offer the advantage of a high percentage of organic load removal in not-so-aggressive conditions that are normally necessary in anodic oxidation, alongside shorter treatment times than those observed in conventional biological processes.

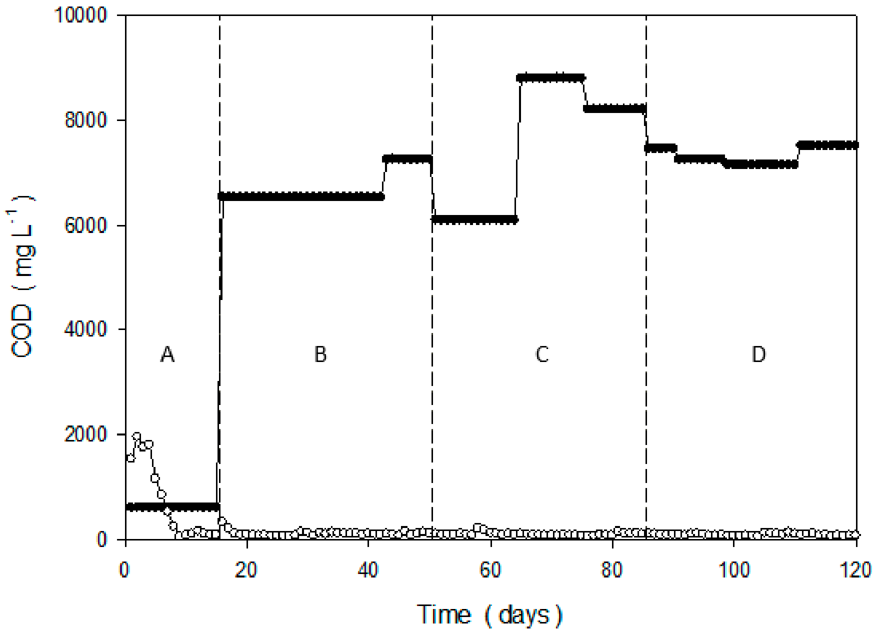

Figure 3. The COD behavior profile in the influent (•) and the effluent (○) of the bioreactor. (**A**) The bioreactor start-up and conditioning periods using an HL of 50 L m^{-3} d^{-1}. (**B–D**) Periods of 35 days feeding the reactor with wastewater generated in the wet processing of coffee with an HL of 50, 100, and 150 L m^{-3} d^{-1}, respectively.

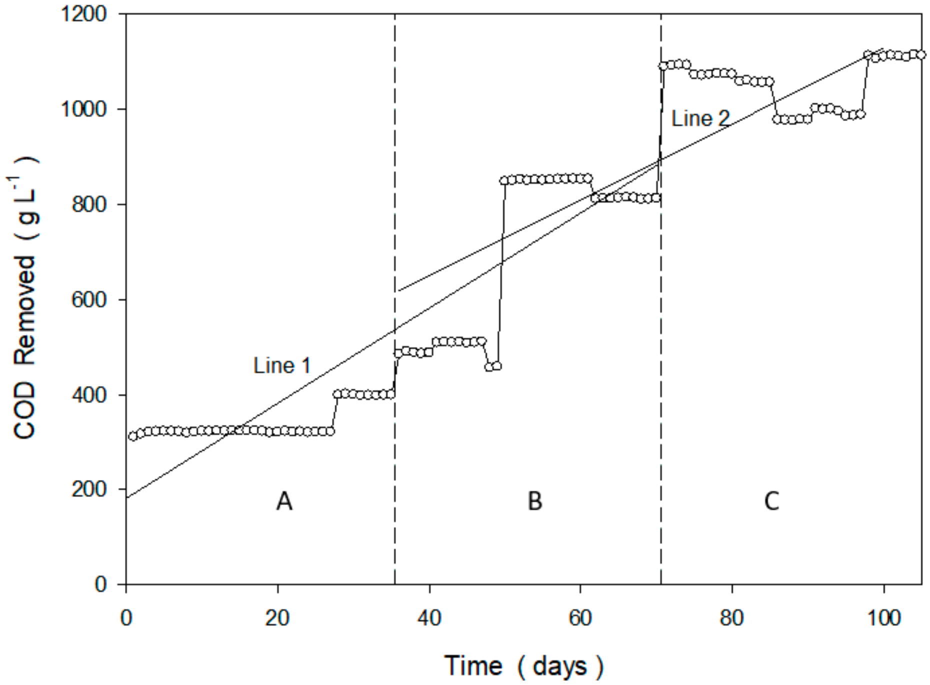

Figure 4. Total COD removal in treatability tests with (**A**) 50 L m^{-3} d^{-1}, (**B**) 100 L m^{-3} d^{-1}, and (**C**) 150 L m^{-3} d^{-1}.

Table 3. Physicochemical characteristics of the effluent and removal from the bioreactor operated with 150 L m^{-3} d^{-1} and its comparison with discharge regulations.

Parameter	% Removal	Effluent Quality	Mexican Regulations	World Bank Guidelines	World Health Organization
pH	-	6.1 ± 0.35	6–9	6–9	6.5–8.5
Chemical Oxygen Demand (mg L^{-1})	98.3	106.2 ± 8.3	150	250	300
Biochemical Oxygen Demand (mg L^{-1})	98.1	75.9 ± 5.9	-	50	100
Total Suspended Solids (mg L^{-1})	91.1	51.5 ± 4.8	60	50	125

2.6. Physicochemical Quality of Final Effluent

Parameters such as COD and TSS are regulated by Mexican legislation and are related to the organic load of water. The concentrations recorded in the effluent for these and other parameters are shown in Table 3, and they are compared with Mexican regulations [32] as well as the regulations issued by the World Bank Guideline [33] and the World Health Organization [34]. The results show an effluent that is below the maximum permissible limits established in the Official Mexican Environmental Regulations in relation to the organic load and also in international regulations, except for the BOD value (75.9 mg L^{-1}), which is slightly above the value contemplated by the World Bank Guideline (50 mg L^{-1}). Thus, the results of this study show the ARFB system as an efficient alternative (98% in COD and BOD) and technically viable, which can also be adapted to short coffee harvesting periods. The rapid transformation and consumption of the organic matter present in the wastewater can be attributed to the variety and large number of microbiological consortiums present in the aged refuse, and considering that the ARFB system operates under semi-aerobic conditions, its treatment mechanism can be related to the heterogeneous groups of bacteria that coexist and carry out both oxidation and reduction [16]. The variety of bacteria in ARFB systems is also reflected in other processes that may occur, such as nitrification, denitrification, and even phosphate reduction [18].

3. Materials and Methods

3.1. Chemical Substances

All chemicals used in the performance of the analytical determinations were purchased from J.T. Baker in analytical reagent grade. All solutions were prepared using distilled and deionized water.

3.2. Aged Refuse Extraction and Bioreactor Construction

The aged refuse used in the treatability tests was obtained from the closed area of the landfill in the municipality of Tuxtla Gutiérrez (16°39′0.819″ N, 93°12′0.85″ W), a city located in southeastern Mexico (Figure 5a). This material was extracted from an average depth of 2 m, dried in the shade (Figure 6), sifted, and selected according to its particle size (≤50 mm), and later it was used as the filling in a polyvinyl chloride (PVC) bioreactor with cylindrical geometry (h = 3.40 m, Ø = 0.20 m), where the treatability tests were carried out. This bioreactor was divided into three sections. The first section of 0.3 m was filled with gravel of approximately 2.54 cm particle size, the central section, 3.0 m high, was filled with aged refuse, and finally, the third section of 0.10 m was kept as a free border to avoid spillage during the bioreactor feeding (Figure 7). The bioreactor was installed and operated outdoors in the city of Tapachula (14°54′0″ N, 92°6′0″ W), which, like Tuxtla Gutierrez, is located in southeastern Mexico (Figure 5c).

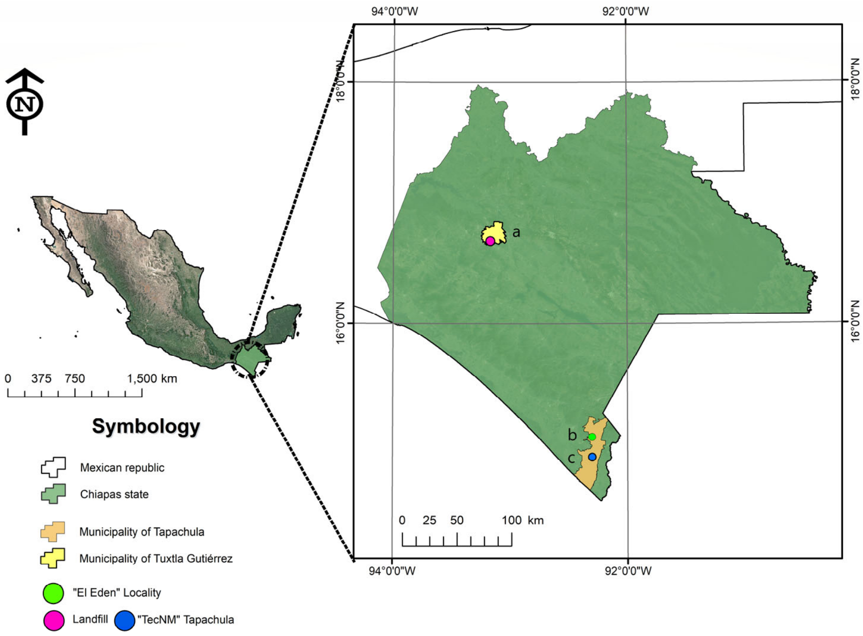

Figure 5. Location of (**a**) the sanitary landfill from which the aged refuse was extracted; (**b**) the coffee farm from which the wastewater sample to be treated was taken; and (**c**) the site where the ARFB was located.

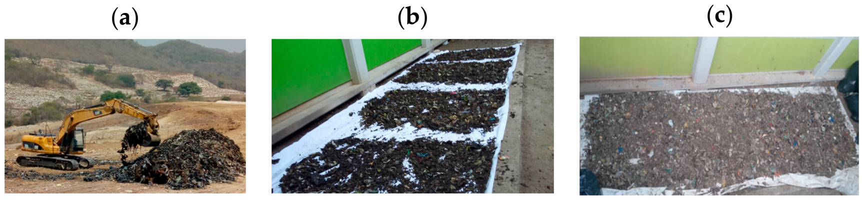

Figure 6. (**a**) Excavation of aged refuse; (**b**) the shade drying of the material; and (**c**) preparation of dried aged refuse for the bioreactor filled.

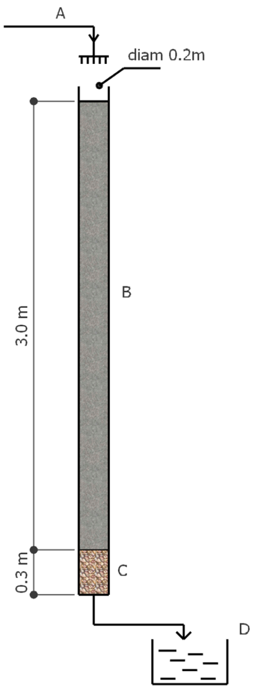

Figure 7. Aged refuse-filled bioreactor (ARFB) to treat wastewater from coffee processing. A, Influent; B, aged refuse (Ø $\leq$ 0.05 m); C, support material (crushed gravel, Ø $\approx$ 0.025 m); and D, effluent tank.

3.3. Wastewater Sampling and Characterization

The wastewater sample to be treated was collected from the effluent of the wet processing of a coffee farm located in the Soconusco geographical region (Figure 5b) and preserved at a temperature of 4 °C until later use. The sample was characterized by the following parameters: COD, Biochemical Oxygen Demand (BOD), Total Suspended Solids (TSSs), pH, and color (Table 1). All analyses were carried out following the methodology described in the Standardized Methods [35].

3.4. Start-Up, Treatability Tests Design and Experimental Data Analysis

Before starting the treatability tests, it was necessary to condition the bioreactor, which meant observing the behavior profile of the COD in the effluent, with values showing little variation between readings. During this process, feeding was carried out using an HL of 50 L m^{-3} d^{-1}. The treatability tests were performed by feeding the wastewater sample to the bioreactor with 3 HL (50, 100, and 150 L m^{-3} d^{-1}), and each of these was fed for a period of 35 days. To avoid both the flooding and spillage of the bioreactor, the volume corresponding to each HL was fed to the bioreactor at three specific times (07:00, 12:00, and 17:00 h), and at each time, the corresponding volume was poured over a 20 min period to avoid both the spillage of the sample through the free border and to avoid flooding the internal part of the bioreactor. On the other hand, in previous studies where ARFB systems were fed with wastewater with a slightly acidic pH (5.51–5.91), it was established that these systems perform better when the feed wastewater is adjusted to a near-neutral pH [24,36]. For this reason, before feeding the bioreactor, the pH of the sample was adjusted to a value between 6.5 and 7 using a NaOH solution at a 1.0 M concentration. During the entire test period, the operating efficiency of the bioreactor was monitored by quantifying the COD removal percentage (Equation (1)). The data obtained were analyzed by a one-way analysis of variance; a significance level of $\alpha = 0.05$ was used.

$$\%\ \text{COD Removal} = [(\text{COD}_i - \text{COD}_e)/\text{COD}_i] \times 100 \quad (1)$$

COD_i: Chemical Oxygen Demand in the bioreactor influent.
COD_e: Chemical Oxygen Demand in the bioreactor effluent.

4. Conclusions

The results obtained show aged refuse recycling as a promising and technically viable alternative for its implementation in the treatment of wastewater generated in the processing of crops with short harvest periods and located in sites of difficult access where there is no public sewer system to transport wastewater to a conventional wastewater treatment plant, such as coffee plantations. Additionally, it is possible to conclude that the following:

1. The aged refused filled bioreactor was able to stabilize in just nine days, which is a short period of time compared to that which conventional biological systems require.
2. The system studied was able to quickly and efficiently mitigate the change in the concentration and composition of the wastewater that was fed between the start-up and stabilization stages and that of the water fed during the treatability tests. This shows the evaluated system as a viable alternative to treat the wastewater of coffee farms throughout the year, purifying the domestic wastewater generated by the people who inhabit the farm throughout the year for eight to nine months and treating the wastewater generated during the processing of the coffee bean for three to four months.
3. It can be seen that the efficiency of the system studied did not decrease despite the surge in the supplied HL, which suggests that the system has the capacity to support an HL greater than 150 L m^{-3} d^{-1}. However, it is possible that the value of the maximum HL that could be supplied, without this having a negative effect on the efficiency of COD removal, is not far from 150 L m^{-3} d^{-1}.

4. As far as our research goes, this is the first document to report on the application of the ARFB system in the treatment of wastewater generated in coffee processing. The results obtained allow us to ask different questions, such as the following, among others: What is the maximum hydraulic load that the studied system can support without a significant decrease in COD removal efficiency? How will the ARFB behave in the presence of agrochemicals used during the activities of coffee production? Is there any variation in the composition of the microbiological consortium with respect to the treatment time?

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Conflicts of Interest: The authors declare no conflicts of interest.

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