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Removing Organic Matter and Nutrients from Swine Wastewater after Anaerobic–Aerobic Treatment

Rubén Alfonso Saucedo Terán [1,*,†], Celia de la Mora Orozco [2], Irma Julieta González Acuña [3], Sergio Gómez Rosales [4], Gerardo Domínguez Araujo [2] and Héctor Osbaldo Rubio Arias [5]

1 Sitio Experimental La Campana-INIFAP, Aldama, Chihuahua 32910, Mexico
2 Campo Experimental Central Altos de Jalisco-INIFAP, Tepatitlán de Morelos, Jalisco 47600, Mexico; delamora.celia@inifap.gob.mx (C.d.l.M.O.); dominguez.gerardo@inifap.gob.mx (G.D.A.)
3 Campo Experimental Santiago Ixcuintla-INIFAP, Santiago Ixcuintla, Nayarit 63300, Mexico; gonzalez.irmajulieta@inifap.gob.mx
4 CENID Fisiología-INIFAP, Ajuchitlán, Querétaro 76280, Mexico; gomez.sergio@inifap.gob.mx
5 Facultad de Zootecnia y Ecología-Universidad Autónoma de Chihuahua, Chihuahua 31031, Mexico; rubioa1105@hotmail.com
* Correspondence: rasteran@yahoo.com.mx; Tel.: +52-614-184-8582
† Retired, Former Researcher.

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Abstract: Anaerobic digesters generate effluent containing about 3000 mg L^{-1} of organic matter in terms of chemical oxygen demand (COD). This effluent must be treated before being reused or discharged into the environment. The objective of this study was to evaluate the efficiency of a trickling filter packed with red volcanic rock for the treatment of anaerobic digester effluent with COD concentrations of around 3000 mg L^{-1}. The trickling filter consisted of an aluminum cylinder, 2 mm thick, 3 m high, and 1 m in diameter. To evaluate the efficiency of the treatment system, there were three experimental runs, each lasting 20 days (d). The predictor variable was the initial COD concentration, which ranged from 2002 to 3074 mg L^{-1}. The hydraulic retention time was 9 h. The influent flow was 2.2 L min^{-1}, which amounts to a hydraulic load of 4033 m^3 m^{-2} day^{-1} and an organic load of 0.006342 to 0.009738 kg m^{-3} day^{-1} of COD. Independent of the initial concentration, COD removal efficiency was very high, varying from 90 to 96%. Final effluents met all the maximum permissible limits to be used as irrigation water, as well as for its release into natural or artificial water reservoirs, stored for agricultural crop irrigation.

Keywords: trickling filter; anaerobic digester; swine wastewater; organic matter; COD

1. Introduction

Pig farming represents the third most important livestock activity in Mexico. According to official statistics, the national inventory of pigs is estimated at more than 15.2 million heads, ranking as the third most important livestock animal in Mexico. Pig farming is concentrated in central and northern Mexico, mainly in the states of Jalisco and Sonora, which accounts for almost 49% of total production [1,2]. In these regions, pig-farming stands out not only because of its economic importance, but also its significant impact on the environment owing to the large volumes of solid and liquid wastes generated, altering the physical, chemical, and microbiological composition of soils and water bodies. In the case of liquid waste, a medium-sized farm generates between 30 and 35 m^{-3} day^{-1} of sewage, which contains high concentrations of solids, organic matter, nitrogen, and phosphorous, among other contaminants. Even with technologically advanced farms, which account for 56.9% of the total, treatment of wastes is a low priority. The vast majority of waste matter is discharged into the environment without any treatment and, evidently, without complying with official requirements.

The few pig producers that treat animal wastewater use anaerobic digesters. Nationally, there are 479 digesters registered in the states of Coahuila, Chihuahua Guanajuato, Durango, Guanajuato, Jalisco, Michoacan, Nuevo Leon, Puebla, Queretaro, Sonora, Veracruz, and Yucatan. Of these, only 82% are in operation and most of these are characterized by problems like oversizing, failures in the agitation systems and burners, irregular maintenance, and lack of knowledge of the operating systems among farmers [3]. Under normal operating conditions, anaerobic systems generate effluents containing organic matter of about 3000 mg L^{-1} in terms of chemical oxygen demand (COD), which is equivalent to five times the organic matter content of domestic wastewater, highlighting the level of contamination. Therefore, the effluent of anaerobic digesters must be treated before being reused or discharged into the environment. In this sense, aerobic systems present an important alternative, because they require short hydraulic retention times and do not generate bad odors, which is of particular importance because the majority of pig farms in Mexico are located in suburban areas.

Among the aerobic systems, trickling filters stand out. This is a widely-used technology for the treatment of industrial wastewater, which was recently adapted for the treatment of bio-waste. In the treatment of household wastewater, efficiencies of above 90% in the reduction of organic matter are reported, generating effluents with maximum COD concentrations of 30 mg L^{-1}, which complies with the quality standards for wastewater disposal. It is also reported that trickling filters can reduce dissolved organic nitrogen by up to 72%, resulting in effluents with less than 1.8 mg L^{-1} of biodegradable dissolved nitrogen [4]. In the case of a dairy processing plant, an efficiency rate of 96% in COD removal was obtained, with a hydraulic retention time of 7 h and an organic matter concentration in the influent of about 1700 mg L^{-1} COD [5]. In the same study, an efficiency of over 70% was reported in the removal of total nitrogen. Dairy wastewater has been successfully treated with organic loads up to 2700 mg L^{-1} COD and hydraulic retention times of 5 to 7 h. The main factors that limit the ability of trickling filter denitrification are excessive organic loads and the emergence of large populations of aquatic snails [6]. The key factors in the functioning of trickling filters are the hydraulic retention time, the concentration and type of organic matter in the influent, and the porosity and size of the particles that constitute the support material in which the degrading microorganisms of organic matter contaminants develop [7,8].

There is little information about trickling filters for treating wastewater from pig farms. In a work similar to ours, Szogi et al. [9] obtained a 54% reduction in the COD content in an anaerobic lagoon in which the initial concentration was 869 mg L^{-1}. Morton and Auvermann [10] also assessed the treatment of effluent from a lagoon storing wastewater from a pig farm, and reported very low removal efficiencies, including in some cases an increase in concentrations of COD, NH_3-N, and NO_3-N. Garzon-Zuñiga et al. [11] assessed the performance of a trickling filter with initial COD concentrations of 8668 to 19,320 mg L^{-1}, which were reduced to 1200 to 2400 mg L^{-1} after 100 days of operation. These authors indicate that the aeration rate is an important factor in the efficiency of COD removal of trickling filters packed with organic matter. Duda and Alves de Oliveira [12] obtained COD removal efficiencies of up to 96% using a treatment series system composed of a UASB reactor, an anaerobic filter, and a trickling filter. In addition to the efficiency of the trickling filters, a theme that has been amply studied is the search for the best support materials. In addition to PVC, other materials have been assessed such as gravel [9], plastic Bioballs™ (Meyer Aquascapes, Inc., Harrison, OH, USA), recycled soda six-pack rings [10], peat [11], bamboo rings [12], rubber, polystyrene, stone [13], sponge [14], and cotton sticks [15].

In general terms, the main advantages of trickling filters are the simplicity of operation, low environmental impact, low energy requirements for operation, and a very favorable cost–benefit ratio [16,17]. However, the effectiveness of trickling filters on the treatment of anaerobic digester effluents from pig farms is unknown. Similarly, we found no information on the use of volcanic rock as a substitute for PVC particles (Engineering360, Tulsa, OK, USA), which is the traditional support material used in trickling filters. The aim of this study was to evaluate the efficiency of a trickling filter packed with red volcanic rock for the treatment of effluents with COD concentrations of about

3000 mg L^{-1} from anaerobic digesters installed on pig farms. Volcanic rock is characterized by high degrees of porosity and absorption, it is widely available and inexpensive. These characteristics result in volcanic rock having great potential for use in trickling filters. Potential users of the information reported are pig producers, professional service providers of technical assistance, and government agencies related to this subsector of production.

2. Materials and Methods

This study was carried out on the Santa Maria pig farm, located at km 24 of San Miguel El Alto—Atotonilco highway, in the municipality of Arandas, Jalisco. The pigs are produced for slaughter and the farm has an inventory of 12,000 pigs. The anaerobic digester has a capacity of 9518 m^3 and generates approximately 2000 m^3 of bio-gas per day. The effluent of the anaerobic digester is sent to an artificial lagoon where it is stored and used as pasture irrigation water. The wastewater stored in the lagoon was the influent in this study (Figure 1).

Since the effluent from the anaerobic digester had a COD concentration of approximately 7160 mg L^{-1}, the lagoon water was diluted with well water to obtain the desired maximum COD concentration of 3000 mg L^{-1}, which is the average concentration of effluents from anaerobic digesters operating under normal conditions. The wastewater from the lagoon was pumped into a 10,000-liter tank with a submersible pump. The tank was equipped with a mechanical stirrer that was activated in accordance with the on–off cycles of the pump, which in turn were regulated with a float. The water tank was placed on the edge of the lagoon, 4 m above the trickling filter to ensure that residual diluted water flowed by gravity from the water tank to the trickling filter. The flow was controlled by a rotameter with a ball valve and an operating range from 0 to 7.5 liters per minute (L min^{-1}).

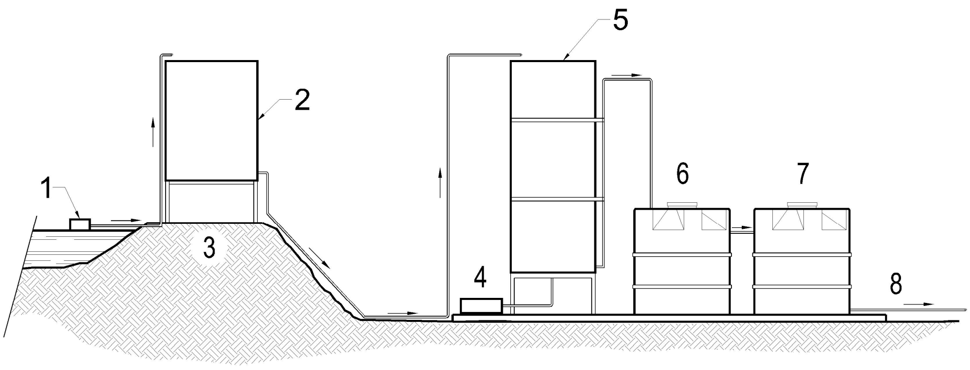

Figure 1. Schematic representation of the wastewater treatment system. (1) Pump; (2) Dilution tank; (3) Lagoon board; (4) Compressor; (5) Trickling filter; (6) Pre-clarifier; (7) Clarifier; (8) Final effluent.

The trickling filter consisted of an aluminum cylinder, 2 mm thick, 3 m high, and 1 m in diameter, with a cylindrical aluminum lid on top held up by four metal supports on the inner side of the trickling filter. The lid, which was placed at a height of 20 cm below the upper edge of the cylinder, functioned as a radial distribution system of the influent. For this purpose, the lid had multiple radial perforations, 1 cm in diameter each. The exterior edge of the lid was coated with a rubber gasket that prevented the flow through the inner wall of the cylinder. The wastewater was directed to the top part of the trickling filter and poured into the center of the lid. The trickling filter was filled with spherically-shaped red volcanic rock approximately 2–4 cm in diameter, which served as support material to the bacteria that degraded the organic matter in the wastewater under treatment (Table 1). The working group did not assess the physical characteristics of the red volcanic rock. However, there are several reports in this regard. Rodriguez Diaz et al. [18] reported that the volcanic rock from the site from which the rock used in this investigation was obtained has a total porosity of 55.5% and an aeration porosity of 40.7%. Total porosity reported in other studies range from 67 to 74.7%, with aeration porosity levels of 39.2 to 44.4%, and a real density of 2.45 g cm^{-3} [19,20]. The packing depth was 2.80 m. The average temperature of the influent was 20.84 °C and the pH level was in the range 7.72 to 8.53, with an average of 8.17. A radial aeration system was installed at the bottom of the trickling filter and connected to a compressor. Air was injected through a 1-npt spigot nozzle at a flow rate of 10 L min^{-1}. The dissolved oxygen (DO) content in the influent was in the range of 0.1 to 0.4 mg L^{-1}, with an average of 0.17 mg L^{-1}.Two 5000-liter water tanks were installed to separate the outgoing solids, each with a sedimentation system in series consisting of a pre-clarifier and clarifier. Both the pre-clarifier and clarifier had a purging and sewage collection system controlled by a ball valve. The sewage was purged weekly, collecting the sediments at a rate of 20 liters per day (L day^{-1}) from each sedimentation tank.

Table 1. General operating conditions.

Support Material	Red Volcanic Rock
Packing depth (m)	2.8
Inflow (L min^{-1})	2.2
Hydraulic retention time (h)	9
Hydraulic load (m^{-3} m^{-2} day^{-1})	4033
Air flow rate (L min^{-1})	10
Influent temperature (°C)	20.84 ± 2.07 (Mean ± standard deviation)
Influent COD concentration (mg L^{-1})	2002–3074
Organic load (kg m^{-3} day^{-1} of COD)	0.006342–0.009738
Influent total N concentration (mg L^{-1})	138.75–151.33
Influent NH_3-N concentration (mg L^{-1})	65.70–71.22
Influent total P concentration (mg L^{-1})	65.00–78.0
Influent EC concentration (mS cm^{-1})	1.24–1.75
Influent pH (dimensionless)	7.72–8.53
Influent DO concentration (mg L^{-1})	0.1–0.4

To evaluate the efficiency of the treatment system, an experiment was run for 60 days. A 20-d experimental adaptation was carried out previously, in which the trickling filter was inoculated with activated sludge from a suspended growth process wastewater treatment plant. The predictor variable was the COD concentration in the influent, which ranged from 2002 to 3074 mg L^{-1}. The hydraulic retention time for all experimental runs was 9 h. The influent flow was at 2.2 L min^{-1}, which resulted in a hydraulic load of 4033 m^{-3} m^{-2} day^{-1} and an organic load of 0.006342 to 0.009738 kg m^{-3} day^{-1} of COD, representing concentrations of 2002 and 3074 mg L^{-1}, respectively. The 12 samples of influent and effluent collected during the experimental run were analyzed measuring the following variables: COD, total nitrogen, total ammonia nitrogen, total phosphorus, electrical conductivity, and dissolved oxygen. COD was quantified by an oxidation potassium dichromate technique, using a digester and a colorimeter Hach, model 800. Total nitrogen was analyzed by the persulfate digestion method. To determine the concentration of ammonia nitrogen, a salicylate method was applied. Total phosphorous was determined using a molybdovanadate method with acid persulfate digestion. Electrical conductivity was measured with a MW 801 Milwaukee sensor. Dissolved oxygen was determined in the field, using a potentiometer JPB, model 607A. The paired difference test was applied to compare the means of influents and effluents, using a significance level of 0.01 ($\alpha = 0.01$).

3. Results

There were significant differences between the means of influents and effluents for COD and the other parameters ($p < 0.01$). Table 2 shows the results of COD removal from the trickling filter. As can be seen, the COD concentration in the influent ranged from 2002 to 3074 mg L^{-1}. Independent of the initial concentration, the removal efficiency was very high, varying from 90 to more than 96%, with an average of 93%. The average COD in the effluent was 172 mg L^{-1}, which is considered an acceptable quality level for wastewater used for the irrigation of pastures and for its disposal in water bodies. In this context, the legal standard indicates that the organic matter content, expressed in terms of biochemical oxygen demand (BOD_5), should not exceed the maximum allowed limit of 200 mg L^{-1}, applicable to wastewater released into rivers whose water is used for agricultural irrigation [21]. There is no maximum permissible limit for COD in Mexico. However, given that BOD_5 is equivalent to 1.6 times the organic matter content expressed by COD [22], the organic matter concentration of the effluent complied with the Mexican standards. International standards are stricter than those in Mexico. For example, the maximum permissible limit for using wastewater in agriculture is 60 mg L^{-1} in France and 100 mg L^{-1} in Italy [23]. Likewise, the COD levels obtained in this research were above the standard for wastewater reuse in the Middle East, with 100 mg L^{-1} in Jordan and Kuwait, and 150 mg L^{-1} in Oman [24].

Table 2. Efficiency of a trickling filter in removing COD from the effluent of an anaerobic digester.

Date	COD in the Influent (mg L^{-1})	COD in the Effluent (mg L^{-1})	Removal Efficiency (%)
2 June 2014	2100	198	90.6
7 June 2014	2002	200	90.0
12 June 2014	2678	183	93.2
17 June 2014	2560	163	93.6
22 June 2014	2484	165	93.4
27 June 2014	2522	140	94.4
2 July 2014	2410	140	94.2
7 July 2014	2216	162	92.7
12 July 2014	3054	117	96.2
17 July 2014	3006	196	93.5
22 July 2014	3010	201	93.3
27 July 2014	3074	203	93.4
Means	2593 ^{a}	172 ^{b}	93

Notes: ^{a,b}: different letters indicate significant differences ($p < 0.01$) between influent and effluent means.

Table 3 shows the results for total nitrogen removal. The average nitrogen concentration was 145 mg L^{-1} in the influent and 75 mg L^{-1} in the effluent, so the average removal rate was 48%. The final concentration of nitrogen exceeded the maximum permissible limit (60 mg L^{-1}) for release into rivers [21]. Thus, using this water for irrigation helps to reduce the nitrogen concentration before the water reaches rivers and natural or artificial water reservoirs. With additional treatment, the effluent from the system could meet more stringent standards for the water to be used for washing pens on farms.

Table 3. Efficiency of a trickling filter in removing total nitrogen from an anaerobic digester effluent.

Date	Total-N in the Influent (mg L^{-1})	Total-N in the Effluent (mg L^{-1})	Removal Efficiency (%)
2 June 2014	145.22	78.00	46.3
7 June 2014	142.01	79.00	44.4
12 June 2014	138.75	69.00	50.3
17 June 2014	140.22	65.00	53.6
22 June 2014	151.33	88.00	41.8
27 June 2014	149.20	76.50	48.7
2 July 2014	147.10	82.30	44.1
7 July 2014	145.30	81.78	43.7
12 July 2014	146.77	68.02	53.7
17 July 2014	142.12	65.12	54.2
22 July 2014	142.20	71.02	50.1
27 July 2014	151.10	81.22	46.2
Means	145 ^{a}	75 ^{b}	48

Notes: ^{a,b}: different letters indicate significant differences ($p < 0.01$) between influent and effluent means.

Table 4 shows the results for ammonia nitrogen removal. The concentration of ammonia nitrogen in the influent ranged between 66 and 71 mg L^{-1}. After treatment in the trickling filter, the concentration of ammonia nitrogen decreased by almost 99%, leaving an average residual concentration of 2.4 mg L^{-1}, which was low enough to even meet drinking water standards.

Table 4. Efficiency of a trickling filter in removing ammonia nitrogen from an anaerobic digester effluent.

Date	NH_3-N in the Influent (mg L^{-1})	NH_3-N in the Effluent (mg L^{-1})	Removal Efficiency (%)
2 June 2014	66.32	4.50	93.2
7 June 2014	65.70	2.00	97.0
12 June 2014	72.80	5.10	93.0
17 June 2014	70.12	1.30	98.1
22 June 2014	71.00	4.00	94.4
27 June 2014	68.75	3.50	94.9
2 July 2014	69.00	1.25	98.2
7 July 2014	71.22	1.00	98.6
12 July 2014	68.50	2.30	96.6
17 July 2014	71.00	2.20	96.9
22 July 2014	69.25	1.00	98.6
27 July 2014	70.00	0.98	98.6
Means.	69 ^{a}	2.4 ^{b}	98

Notes: ^{a,b}: different letters indicate significant differences ($p < 0.01$) between influent and effluent means.

Table 5 shows the results of the removal of total phosphorous. As can be seen, the efficiency of phosphorous removal was between 43 and 68%, starting from around 70 mg L^{-1} and resulting in an average of 29 mg L^{-1} in the effluent. This concentration was below the 30 mg L^{-1} maximum limit for releasing wastewater into rivers and water reservoirs to be used in agricultural irrigation [21]. However, because the concentration of phosphorous in the effluent varied (29 $\pm$ 5.6), batch-testing for phosphorous is needed to avoid non-compliance with regulations. Electrical conductivity decreased through the treatment by approximately 35%, going from an initial concentration of 1.57 to a final concentration of 1.02 mS cm^{-1} (Figure 2). Although there are no regulatory limits for this variable, it is an indicator of dissolved salt content in water. According to the final concentration of electrical conductivity, the treated water should be moderately restricted for agricultural irrigation, depending on the tolerance of the specific crop.

Table 5. Efficiency of a trickling filter in removing total phosphorous from an anaerobic digester effluent.

Date	Total-P in the Influent (mg L^{-1})	Total-P in the Effluent (mg L^{-1})	Removal Efficiency (%)
2 June 2014	69.57	34.28	50.7
7 June 2014	69.53	39.13	43.7
12 June 2014	78.00	38.45	50.7
17 June 2014	67.90	26.90	60.4
22 June 2014	70.22	25.50	63.7
27 June 2014	68.90	29.50	57.2
2 July 2014	66.50	28.20	57.6
7 July 2014	65.00	21.00	67.7
12 July 2014	70.22	23.40	66.7
17 July 2014	69.45	28.90	58.4
22 July 2014	70.31	31.60	55.1
27 July 2014	71.70	26.50	63.0
Means	70 ^{a}	29 ^{b}	58

Notes: ^{a,b}: different letters indicate significant differences ($p < 0.01$) between influent and effluent means.

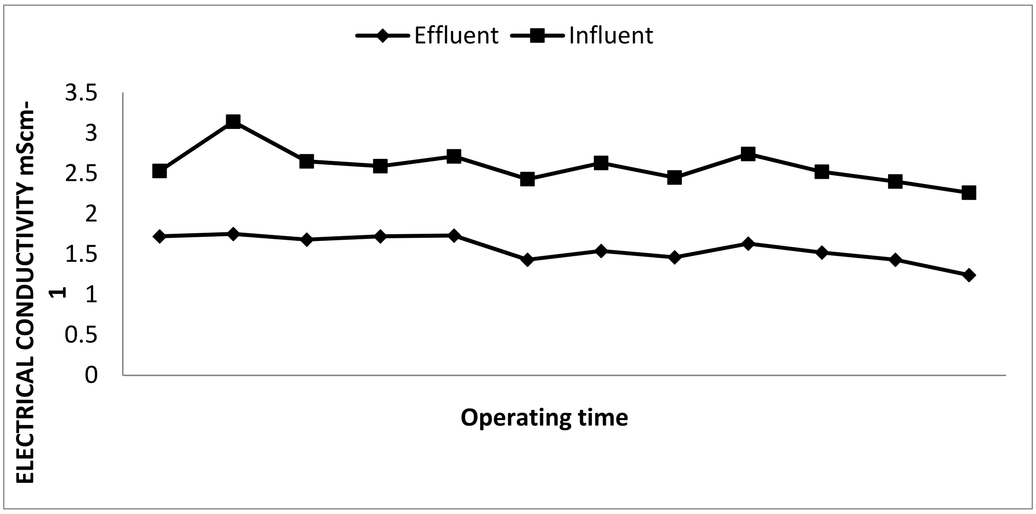

Figure 2. Efficiency of a trickling filter in removing electrical conductivity from an anaerobic digester effluent.

Figure 3 shows the changes in the dissolved oxygen concentration, which increased from 0.2 mg L^{-1} to an average of 3.1 mg L^{-1}. This variable is an indicator of water quality for the wellbeing of different aquatic organisms. Concentrations below 3 mg L^{-1} reduce the chances of survival of biotic communities and represent an imminent threat to the conservation of biodiversity in aquatic ecosystems [25]. Dissolved oxygen is also important for the efficient operation of the trickling filter, in which the bacteria aerobically degrades the organic matter in the wastewater under treatment [8]. The lower limit for the development of aerobic biofilms is around 0.57 mg L^{-1}, so that the oxygen concentration obtained in this study guarantees the adequate functioning of the treatment system.

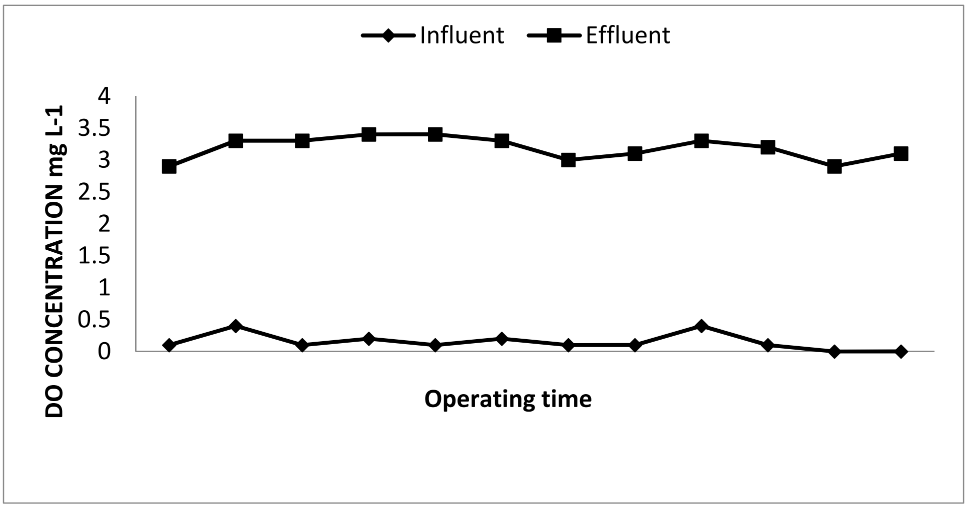

Figure 3. Efficiency of a trickling filter in increasing dissolved oxygen in wastewater from an anaerobic effluent.

4. Discussion

The efficiency of COD removal in this study was 90 to 96%, which exceeds the levels obtained in other studies. Reyes-Lara and Reyes-Mazzoco [26] evaluated a trickling filter with organic feed concentrations from 2114.8 to 3814.4 mg L^{-1} COD and reported removal rates of 54 to 66%. Braulio-Villalobos et al. [27] obtained a 72% organic matter removal rate from an influent with 300 mg L^{-1} COD. Gilbert et al. [28] also evaluated a trickling filter for treating wastewater from pig farms and observed a higher level of efficiency than that obtained in the present study, reducing COD content from 15,300 mg L^{-1} in the influent to 330 mg L^{-1} in the effluent. However, their trickling filter operated with a hydraulic load of 0.017 m^3 m^{-2} day^{-1}, which was much lower than the 4033 m^3 m^{-2} day^{-1} in our study. Similarly, Buelna et al. [29] obtained efficiencies in the removal of organic matter of up to 95% in a trickling filter designed for the treatment of 12 m^3 day^{-1} of pig wastewater with 10,000 to 20,000 mg L^{-1} BOD_5. According to the volume of the filter and the influent flow, the retention time was much longer in that study than in ours. Beyenal and Lewandowski [30] stated that the capacity of trickling filters to remove organic matter depends on the diffusion in the biofilm, which is directly proportional to the organic load, if there is no another limiting factor, such as oxygen availability. In this respect, Reyes-Lara and Reyes-Mazzoco [26] found that with low organic matter concentrations, similar to the levels evaluated in our study, the substrate may be the limiting reactant and not the available oxygen. The porosity of materials like red volcanic rock provides a larger surface area for adhesion of biofilms than commonly used particles [31]. This allows for the majority of particles to be coated with the biofilm in a maximum of three weeks, which results in a stable operational state within this period [32]. This was evident in our work in which, from the first day of operation, COD was reduced by 90.6%, going from an initial concentration of 2100 to a final concentration of 198 mg L^{-1}. According to Metcalf and Eddy [22], a steady operating state in trickling filters is usually reached in about four weeks of continuous operation, although other authors have observed that the steady state for COD removal can occur anywhere from three days to seven weeks [33,34]. Naz et al. evaluated different media in a trickling filter, and observed that the highest COD removal efficiency was obtained by stone (93.4%), outperforming plastic (89.4%), polystyrene (86.3%), and rubber (81.9%) [13].

It is difficult to compare our results to those of other studies in terms of nitrogen removal efficiency because of the differences in operating conditions. Gilbert et al. [28] obtained a removal efficiency of 75% for total nitrogen when treating pig wastewater with concentrations of 3200 mg L^{-1}, but with a very low hydraulic load. This study involved lower retention times and a lower nitrogen load (0.067 kg m^{-2} day^{-1}) than those of our study (0.559 kg m^{-2} day^{-1}). Buelna et al. [29] obtained a nitrogen removal rate of 26% in the treatment of swine wastewater, with a total nitrogen load of 2300 mg L^{-1}, and a very low hydraulic load (0.017 m^{-3} m^{-2} day^{-1}). Garzon Zuñiga et al. [11] reported an efficiency of 50% in the removal of total nitrogen content in swine wastewater with 2080 mg L^{-1} of nitrogen and a very low hydraulic load (0.5 m^{-3} m^{-2} day^{-1}). The main factors that limit the capacity of trickling filters for denitrification are excessive organic loads and the development of high populations of aquatic snails [6]. The efficiency of ammonia nitrogen removal in our study was very high (98%) but its concentration in the influent was very low (69 mg L^{-1}), which is equivalent to a mass load of 0.278 kg m^{-3} day^{-1}. Sabbah et al. [35] obtained similar results to those of the present study, reducing the content of ammonia nitrogen by up to 95%, from an initial concentration of 77.9 mg L^{-1}, under a much lower hydraulic load (0.093 m^{-3} m^{-2} day^{-1}). Hort et al. [36] were able to reduce ammonia nitrogen content by 94%, with a mass load of NH_4 of 0.0604 kg m^{-3} day^{-1}. Ying-Xu et al. [37] found a removal efficiency of 95–99% of ammonia nitrogen, with a very high concentration of ammonia in the influent (110 mg m^{-3}), but with a load rate similar to that in this research (0.243 kg m^{-3} day^{-1}).

We found few studies on the performance of trickling filters with respect to the removal of total phosphorus and the changes in electrical conductivity and dissolved oxygen. Buelna et al. [29] reported an efficiency of phosphorus removal of 71% from an influent with a concentration of 180 mg L^{-1} and a very low hydraulic load (0.017 m^{-3} m^{-2} day^{-1}). Garzon-Zùñiga et al. [11] evaluated various aeration rates, and observed effluents with dissolved oxygen contents from 7 to 8.5 mg L^{-1}, from an influent with 0.05 mg L^{-1}. No reports were found regarding changes of electrical conductivity in treated swine wastewater with trickling filters. Katukiza et al. [38] attributed the removal of dissolved nitrogen and phosphorous mainly to precipitation. In addition, adsorption and ionic exchange have been found to contribute to the removal of phosphates from wastewater [39]. However, the removal of dissolved nitrogen and phosphorus by adsorption is limited when the pH of the influent is above 7 [40].

In the present study, the pH of the influent ranged from 7.72 to 8.53. In addition, particulate nitrogen can be removed by straining during the trickling filter operation [38]. The physical and chemical adsorption of NH_4 in organic matter, and hence, its microbial assimilation, could be responsible for the removal of significant amounts of N from wastewater [40]. However, this could be supported by significant levels of nitrifying and denitrifying activity. Interestingly, Patel et al. [31] observed nitrifiers and denitrifiers in both anoxic and aerobic biofilms, which suggests a highly complex structure of multispecies biofilm. Although the existence of denitrifiers in the aerobic layer can be attributed to limited oxygen diffusion in the biofilm, the emergence of nitrifying bacteria in the anoxic bed was surprising. To make the results more complex, higher levels of phosphorus assimilating bacteria have been reported in the anoxic than in the aerobic biofilm [31]. Since there have been few studies on nitrogen and phosphorus removal mechanisms in volcanic rock biofilms, it is difficult to identify the factors that determined the high removal efficiency obtained in the present research. It was probably a combination of factors like precipitation, adsorption, straining, microbial denitrifying, and denitrifying transformation of nitrogen.

5. Conclusions

The trickling filter packed with red volcanic rock proved to be highly efficient in treating anaerobic digester effluent with COD concentrations of around 3000 mg L^{-1}. Final effluents met all the specifications in terms of maximum permissible limits for their use as irrigation water, as well as for their release into rivers and natural or artificial reservoirs that store water for agricultural crop irrigation. A nine-hour hydraulic retention time was used in the present research. It is highly recommended to evaluate shorter retention times in future studies.

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Author Contributions: R.A.S.T. conceived and designed the study, performed sample collection, conducted field analysis, and drafted the manuscript. C.d.l.M.O. and I.J.G.A. carried out the physical-chemical analysis of all samples and helped in the data´s interpretation. S.G.R. and G.D.A. interpreted the statistical analysis and participated in drafted the manuscript. H.O.R.A. suggested and performed the statistical analysis and helped in the interpretation of the levels of all parameters.

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