Vol. 20, No. 3(2021) IA2472
Revista Mexicana de Ingeniería Química
Ingeniería Ambiental

Comparison of two leachate treatment systems by use of bioreactors packed with stabilized material of different age

Comparación de dos sistemas de tratamiento de lixiviados, empleando biorreactores empacados con material estabilizado de diferente edad

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Received: May 14, 2021; Accepted: September 29, 2021

Abstract

Leachates that are generated in the sanitary landfills constitute a contamination problem for which a treatment is necessary. A viable alternative is an application of bioreactors packed with stabilized materials. In the present work, materials with two different ages were tested, which came from different closed sites. The stabilized materials (SM) were physically characterized with parameters such as humidity, volatile solids, pH, electrical conductivity and density. The bioreactor system was operated for a period of 30 weeks in two stages, by use of a complete 2^2 factorial design. In stage I, the study factors were the hydraulic head (25 and 40 L/m^{3}d) and the age of the SM (7 and 11 years), whereas in stage II the factors evaluated were age of the SM and type of feeding (continuous and semi-continuous). The highest average efficiency in pollutant removal was 79% for COD and 81% for BOD_5 and Color, which corresponded to a combination of factors, namely young and stabilized materials, continuous feeding and a hydraulic load of 25 L/m^{3}d. The final effluent had average values of 905 mg/L, 130 mg/L, 2388 Pt-Co and 0.09, for COD, BOD_5, Color and BI, respectively, for which a final purification stage was still required.

Keywords: Stabilized Material-Young, Stabilized Material-Old, Landfill, Mature Leachate, Hydraulic Load.

Resumen

Los lixiviados generados en los rellenos sanitarios constituyen un problema de contaminación, por lo que es necesario darles un tratamiento. Una alternativa es el empleo de biorreactores empacados con materiales estabilizados (SM). En el presente trabajo, se probaron dos diferentes edades de materiales estabilizados, provenientes de diferentes sitios clausurados. Los materiales estabilizados fueron caracterizados físicamente con parámetros como humedad, sólidos volátiles, pH, conductividad eléctrica y densidad. El sistema de biorreactores fue operado durante un periodo de 30 semanas en dos etapas, mediante un diseño factorial completo 2^2. Para la etapa I, los factores de estudio fueron la carga hidráulica (25 y 40 L/m^{3}d) y edad de los SM (7 y 11 años), y en la etapa II los factores evaluados fueron edad de los SM y tipo de alimentación (continuo y semicontinuo). La mayor eficiencia promedio en remoción de contaminantes fue de 79% en DQO y 81% en DBO5 y Color, correspondiendo a la combinación de factores: material estabilizado joven, alimentación continua y carga hidráulica de 25 L/m^{3}d. El efluente final tuvo valores promedio de 905 mg/L, 130 mg/L, 2388 Pt-Co y 0.09, en DQO, DBO5, color y BI, respectivamente, requiriendo de una etapa final de depuración.

Palabras clave: Material Estabilizado-Joven, Material Estabilizado-Viejo, Relleno Sanitario, Lixiviados Maduros, Carga Hidráulica.

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https://doi.org/10.24275/rmiq/IA2472
ISSN:1665-2738, *issn-e*: 2395-8472

1 Introduction

Municipal solid waste production has increased in recent years due to greater urbanization and progress in quality of life. The most common methods for the final disposal or treatment of these wastes are landfills, incineration, and composting. The sanitary landfill is widely used in developing countries, due to its treatment capacity, adaptability and cost of operation (He *et al*., 2017; Li *et al*., 2009; Zhang *et al*., 2018). A sanitary landfill involves engineering methods for waste disposal to control environmental impacts (Aranda-de la Teja *et al*. 2020). In Mexico, the final disposal of solid waste is distributed as follows: 87% is in open dumps and only 13% in sanitary landfills (Saldaña and Nájera, 2019; SEMARNAT, 2019), although the latter form of disposal still has a great potential in the country (Aldana-Espitia *et al*., 2017).

In the operation of the final disposal sites (FDS), liquids known as leachates are generated as a product of the decomposition of organic matter and the filtration of rain through the waste, among other processes (Chen *et al*., 2020; Li *et al*., 2009). Leachates are a heterogeneous mixture of high-resistance organic and inorganic pollutants that include humic acids, xenobiotic organic compounds, ammonia nitrogen, heavy metals, and other inorganic salts (Chen *et al*., 2019). Therefore, these liquids represent a potential risk of contamination if they are not managed properly. The preferred method for treating leachates depends on their composition and properties such as biodegradability. In the case of leachates, this property is defined by the biodegradability index (BI), which is derived from the BOD_5/COD ratio (Bautista-Ramírez *et al*., 2018). In general, when the BI values are greater than 0.3, the leachate is classified as young or biodegradable, and when the BI is minor than 0.3, the leachate is not biodegradable and is known as mature or old. Young leachates with a high BI are effectively treated with biological methods (Renou *et al*., 2008), as these processes can remove most of the organic pollutants and nitrogenous pollutants, thus achieving a high level of leachate decontamination (Chen *et al*., 2020). Zhao *et al*., (2002), developed a new biological treatment method using a biofilter that uses aged solid waste as a substrate. Aged waste can be defined as the waste of various materials that have been deposited in the FDS, which after eight years of being buried contains organic matter present that is considered mineralized (He *et al*., 2017; Li *et al*., 2017). In the present study, aged waste is called Stabilized Material (SM).

SM has a high cation exchange capacity (0.07 mol/g of dry litter), high porosity (37.25%) and an abundant microbial community (1.40×10^6 CFU/g), which is resistant to many extreme environmental conditions and can effectively degrade organic pollutants in the leachate (Chen *et al*., 2020; Feng *et al*., 2019), as they are a medium of adsorption and exchange that facilitates the elimination of pollutants and favors the life of microorganisms (Li *et al*., 2017). Recent studies with this technology have shown its good performance in the treatment of leachates, where high efficiencies in the elimination of COD, BOD_5 and total nitrogen were found, in ranges of 75-85, 86-95 and 49-97%, respectively (Erabee and Ethaib, 2018; Nájera-Aguilar *et al*., 2019; Xie *et al*., 2012). The use of SM as packaging for bioreactors for treating leachates has been reported mainly with waste extracted from landfills (Li *et al*., 2010; He *et al*., 2017; Xie *et al*., 2012; Bautista-Ramírez *et al*., 2018). However, there is no knowledge related to SM from open dumps. Therefore, this study focused on investigating the SM potential of a sanitary landfill with an estimated 11 years of age for the removal of contaminants from mature leachates with a biodegradability index (BI) of 0.1. For comparison purposes, SM extracted from an open dump of approximately 7 years of age was used in a parallel study.

2 Materials and methods

2.1 Leachate characterization

The influent used in this study was collected from an evaporation lagoon in the current sanitary landfill of Tuxtla Gutiérrez, Chiapas, Mexico. The influent was characterized with the parameters: Chemical Oxygen Demand (COD), Biochemical Oxygen Demand (BOD_5), Color, alkalinity total, electrical conductivity, pH and heavy metals (Cd, Ni, Cr, Pb, and Zn). The COD was quantified via the closed reflux micromethod, digesting the sample at 150 °C for 2 h, and subsequently read in an HACH © DR-5000 spectrophotometer at 620 nm. The BOD_5 was quantified by determining the difference between the initial dissolved oxygen concentration and the concentration after five days of incubation at 20 ± 1 °C, using the DBOTrak II © respirometric BOD_5 equipment. Regarding Color determination, a HACH DR/890 colorimeter was used. Total alkalinity was calculated via the volumetric method, where 0.02 N sulfuric acid was used for titrating. The pH and electrical conductivity were measured with an EXTECH © EC-150 conductivity meter. All the analyses were developed by following standardized methods (APHA, 2012) that were adapted to the particularities of the leachate. The determination of heavy metals was determined by Flame Atomic Absorption Spectrophotometry (EPA, method 7000B) and according to the Mexican Standard NMX - AA - 051 - SCFI - 2001, adapting the procedure to the leachate samples. Finally, samples were analyzed on a Flame Atomic Absorption Spectrophotometer (Thermo Scientific © Ice 3000).

2.2 Collection and characterization of stabilized materials (SM)

The SMs used for packing the bioreactors were excavated from two closed FDSs. The old SM (SM-O) of around 11 years old was obtained from the open-air dump of the city of Tuxtla Gutiérrez and the young SM (SM-Y) of approximately 7 years old, was extracted from a localized open-air dump in the municipality of Berriozábal, Chiapas, Mexico. SM samples were taken in triplicate at a depth of 1.5 m measured after removing the final cover material. Samples were spread over canvases for 1 week and kept in the shade at room temperature to reduce their humidity and to facilitate cleaning and characterization. During the drying process in the shade, remains of larger materials such as cloth, glass, cardboard, stones, plastics, among others, were removed. Subsequently, a sieve granulometric analysis was performed to define particle sizes <15 mm. The characterization of the SM was carried out according to the techniques defined in the Mexican regulations for the parameters of moisture content (NMX - AA - 016 - 1984), pH (NMX - AA - 025 - 1984), volatile solids and fixed solids (NMX - AA - 018 - 1984).

2.3 Construction of Bioreactors Packed with Stabilized Material (BPSM)

Four laboratory-scale reactors were built with polyvinylchloride tubes (15 cm in diameter and 65 cm in height), similar to those reported by other authors (Bautista-Ramírez *et al*., 2018; Erabee *et al*., 2018; Li *et al*., 2010; Zhao *et al*., 2002), but modified in size to adapt to laboratory conditions. The lower part was packed with support material (0.35 "gravel and 0.55" gravel) and then SM with particle size minor than 15 mm was introduced, leaving 1 cm of free edge in the upper part, for feeding (Figure 1). To avoid the loss of SM, a mesh membrane with 3 mm spaces was placed between the support material and the SM. For the effluent outlet, a perforated cap was placed at the lower end of the tube, connected to a hose directed towards the effluent tank. Two reactors were packed with SM-Y from young open dump and two were packed with SM-O from old open dump. All reactors were supported on a metallic iron base.

2.4 Feeding and process monitoring

The feeding of the bioreactors was performed by spraying the upper area of the BPSM with leachates at room temperature (22.5 ± 3.2 °C) and the monitoring was carried out in two stages. Stage I was evaluated based on the hydraulic load (HL), with a low hydraulic load (HL-L) and a high hydraulic load (HL-H), which were 25 and 40 L/m^{3}d, respectively. This was done accordingly to what was reported in previous studies (Bautista-Ramírez *et al*., 2018; Han *et al*., 2013) with continuous feeding.

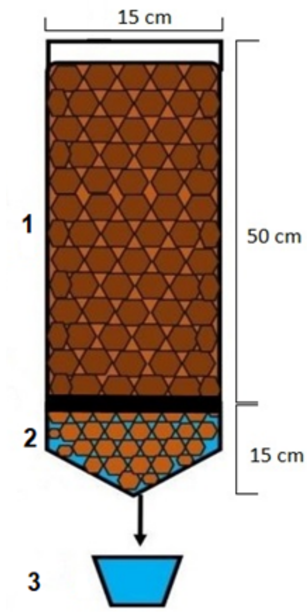

Fig. 1. Unitary structure of the BPSM. 1) Stabilized Materials (SM). 2) Support Material (gravel 0.55 cm and 0.35 cm). 3) Effluent.

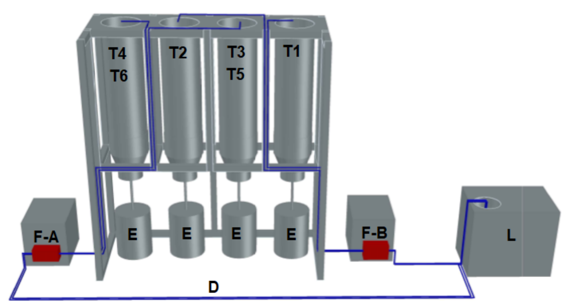

Fig 2. Bioreactor in operation. Where: (T1, T2, T3 y T4) treatments under Stage I conditions. (T5 y T6) treatments under Stage II conditions; (L) Influent; (E) Efluents; (F-B y F-A) Peristaltic pumps with con HL of 25 and 40 L/m3d, respectively; and (D) Influent distribution through masterflex pipes.

Based on the yields obtained from stage I, stage II was evaluated, considering the type of feed (TF): continuous (CT) and semi-continuous (SC), under a hydraulic load of 25 L/m^{3}d (figure 2).

In the CT feed, the leachate flow was constant throughout the monitoring time and in the SC feed the leachate was pumped to the top of the reactor four times a day at six-hour intervals. For flow control, MasterFlex peristaltic pumps (model 7534-04) were used, automated by means of a Sonoff R2® switch.

Table 1. Experimental design 2^2 stage I.

		Hydraulic Load (L/m^3d)	
		HL-L: 25	**HL-H: 40**
Age SM (years)	**SM-Y: 7**	T1	T3
	SM-O: 11	T2	T4

Table 2. Experimental design 2^2 stage II.

		Alimentation type	
		CT	**SC**
Age SM (years)	**SM-Y: 7**	T1	T5
	SM-O: 11	T2	T6

A 2^2 factorial design was used for both stages of the study. Tables 1 and 2 show the operating conditions of each treatment, and figure 2 shows the distribution of the treatments. The process evaluated the COD, BOD_5, and Color parameters, in addition to other control parameters such as pH, total alkalinity and electrical conductivity.

COD, Color and control parameters were measured once a week and BOD_5 measurements were carried out twice a month. Each treatment was monitored for 15 weeks except for T1 and T2, which were monitored for 30 weeks in total, which provided estimates on the life span of the bioreactor packaging.

The efficiency of the bioreactors was determined by estimating the removal percentage of COD, BOD_5 and Color, applying Eq. 1, as reported by Puentes-Morales *et al*., (2021).

$$\%Removal = \frac{Ci - Cf}{Ci} \times 100 \tag{1}$$

Where: Ci: Initial concentration; Cf: Final concentration.

At the end of the monitoring of each treatment, a characterization of the effluent was carried out with the parameters: COD, BOD_5, Color, total alkalinity, electrical conductivity, pH and heavy metals, following the same methodology as that of point 2.1.

2.5 *Statistical analysis*

The results were analyzed statistically by use of one-way ANOVA tests, with a significance level of 0.05, using the STATgraphics Centurion XVI.II software.

3 Results and discussion

3.1 *Collection and characterization of leachates*

The leachate characterization results are shown in Table 3, where the average concentrations and the range of the determined parameters is presented, as well as their standard deviation.

The average values of organic matter in terms of COD and BOD_5 were 4394 ± 167 and 443 ± 10 mg/L, respectively. According to Yao (2017), these values are classified within the typical ranges for an intermediate leachate. However, the BI that represents the proportion of biodegradable organic pollutants in the leachate was only 0.1. (Contreras *et al*., 2018, Foul *et al*., 2009) the BI for mature leachates is found in the range of 0.05 - 0.2. This indicates that the leachates used in this study was stabilized. Stabilized leachates are hardly biodegradable due to their content of humic and fulvic acids, as well as other recalcitrant organic materials that are partially stable and biologically resistant (Contrera *et al*., 2018; Brennan *et al*., 2017).

A high concentration of color (12501 ± 125 Pt-Co) was found in the range of typical values for mature leachates, which can oscillate between 1000 - 13000 Pt-Co units (Sánchez *et al*., 2012; San-Pedro *et al*., 2021). A large part of the color is provided mainly by dissolved organic compounds, refractory compounds such as humic and fulvic acids and humate (Foul *et al*., 2009; Artiola and Fuller, 1982). Humic substances are natural organic compounds that have a complex structure of polymerized organic acids, carboxylic acids, and carbohydrates (Edward and Amirtharajah, 1985).

Table 3. Characterization of the leachate used.

Parameter	Average	Concentration Range
COD (mg/L)	4394 ± 167	4276 - 4512
BOD_5 (mg/L)	443 ± 10	436 - 450
BOD_5/COD	0.10 ± 0.01	0.09 - 0.10
Color (Pt Co)	12501 ± 125	12412 - 12589
pH	8.6 ± 0.1	8.6 - 8.7
Alkalinity (mg $CaCO_3$/L)	4475 ± 931	3170-5134
Conductividad (mS/cm)	6.09 ± 2.9	6.11 - 6.07
Cadmium (mg/L)	0.0340 ± 0.0012	0.0331 - 0.0348
Lead (mg/L)	0.0463 ± 0.0005	0.0459 - 0.0466
Copper (mg/L)	0.0889 ± 0.0141	0.0789 - 0.0989

The pH value found in this study (8.6) is also characteristic of mature leachates, as their values can range between 7.5 - 9 (Zamri *et al*., 2017). Also, the electrical conductivity was 6.09 ± 0.9 mS/cm, which is an expected value in leachates from mature landfills. As the age of the leachates increases, the presence of bicarbonate, carbonate, magnesium, and calcium ions is reduced, which decreases the ionic mobility. This is reflected in lower conductivity values (Torres *et al*., 2014). The alkalinity of 3817 - 5134 mg/L of $CaCO_3$ is in the range of 1020 - 12300 mg/L of $CaCO_3$, corresponding to a mature leachate (Wang *et al*., 2003). Concentrations of some heavy metals (Cd, Pb and Cu) are also observed, but are below typical levels in mature leachates (2 mg/L) (Renou *et al*., 2008; Nájera-Aguilar *et al*., 2019). These results were similar to those found by Méndez *et al*., (2008) for the Mérida landfill, Yucatán, México, with respect to the values of heavy metals removed, although by an air flotation method.

3.2 Collection and characterization of stabilized materials

The SM excavated from both sites (SM-Y and SM-O) presented a slight odor, which disappeared quickly after the first 48 hours of drying. It is important to mention that, during the drying period, the presence of flies was never observed, contrary to what was reported in other studies (Bautista-Ramírez *et al*., 2018; Lozano *et al*., 2016). Table 4 shows the results of the physicochemical parameters after the excavation, as well as those reported in other works. The respective pH values for SM-O and SM-Y were 7.9 and 7.6, which are similar to those reported by Chen *et al*., (2020). Due to the type of leachate (mature) that percolates in the SM-Y, these present a slightly higher value than neutrality. Regarding the percentage of humidity, both sites present similar values (approximately 30%), while authors such as Chen *et al*., (2020) and Li *et al*., (2009) reported values at an estimated 34 - 35% humidity in SM with more than five years of being willing.

The results of fixed solids (FS) and volatile solids (VS) in the SM-O excavated materials remained at 89.3 and 10.7, respectively. As for the SM-Y samples, these solids were at 86.63 and 13.37%, respectively. This shows that both types of SM have reached a high degree of degradation of organic matter, as there is a minimum content of VS. These findings are close to those reported by Bautista-Ramírez *et al*., (2018). The concentration of heavy metals in SM was below the value of the concentrations of metals found in mature leachates that percolates through the residues (<2 mg/L) (Renou *et al*., 2008; Nájera-Aguilar *et al*., 2019).

3.3 Reduction of Chemical Oxygen Demand (COD)

The elimination of COD can be partially attributed to the adsorption of organic compounds by microparticles in the form of colloids, which are found in SM. Biodegradation of organic elements by microorganisms can also have an impact (Chen *et al*., 2020). Figure 3 shows a greater removal of COD (around 80%) during the first 5 weeks for treatments T1 and T3, with BPSM from SM-Y. However, in the last weeks of monitoring, treatment T3, containing higher HL, maintained an elimination of around 50 - 70% with a final concentration of 644 -2356 mg/L of COD, while treatment T1 maintained a stable elimination of 75 - 85% with a final concentration of 644-1296 mg/L of COD.

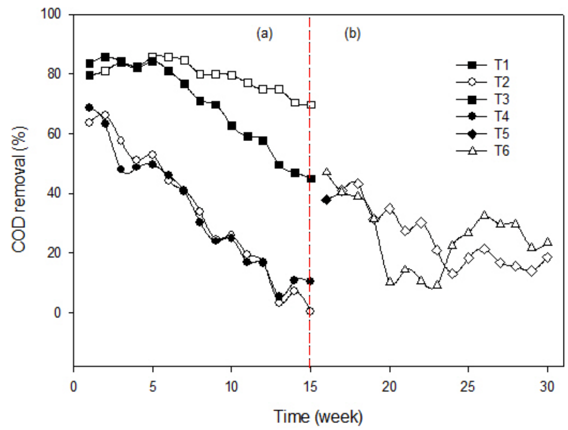

Fig. 3. Behavior of COD removal in mature leachates. Where: (a) stage I: treatments T1, T2, T3 and T4 with continuous alimentation and (b) stage II: treatments T5 and T6 with semi-continuous alimentation.

These differences in the elimination of COD between treatments could possibly be attributed to the fact that, as HL increases, there is a greater quantity of non-biodegradable substances, which leads to an increase in the COD of the effluent (Hassan & Xie, 2014). These results are like those obtained by Erabee and Ethaib (2018), who worked with intermediate leachates with an initial COD of 6400 mg/L and obtained a 75% decrease.

On the other hand, treatments with SM-O (treatments T2 and T4) achieved on average only a 34% elimination of COD in both cases. According to some authors, this low efficiency may be due to the fact that, in SM-O, a release and hydrolysis of complex organic compounds tend to increase the COD concentration in the effluent leachate (Chen *et al*., 2009; Erses *et al*., 2008).

In stage II (Figure 3.b), under a semi-continuous feeding system, a more stable behavior is observed in general, although with very low removal efficiencies (around 20%). This reflects high concentrations of COD in the effluents, with values between 2.52 - 2.99 mg/L. These lower efficiencies could be related to a saturation of stabilized materials due to the accumulation of recalcitrant contaminants, considering that according to Chen *et al*., (2020). The operation of a BPSM can reduce its treatment capacity after a long time of operation, which is a consequence of the accumulation of biorefractory organic

Table 4. Characterization of stabilized materials.

Parameter	This study		References	
	SM-O	**SM-Y**	**Ranges found**	**Authors**
Humidity (%)	32.75±5.5	30.22±5.3	24.26 - 35.3	(Chen et al., 2019; Li et al., 2019; Erabee y Ethaib, 2018; Han et al., 2013)
VS (%)	10.5±3.3	13.37±2.7	3.5 - 45.5	(Peng et al., 2019; Bautista-Ramírez et al., 2018; Han et al., 2013; Pellera et al., 2016)
FS (%)	89.25±12.1	86.63±13	42.4 - 94.7	
pH	7.9±0.8	7.6±0.5	6.20 - 8.07	(Chen et al., 2019; Feng et al., 2019; Han et al., 2010; Li et al., 2009)
EC (mS/cm)	5.44±0.68	5.07±0.55	0.76 - 0.95	(Chen et al., 2019; Li et al., 2009)
Density g/cm3	0.84±0.06	1.0±0.06	0.80 - 0.96	(Chen et al., 2019; Feng et al., 2019; Ziyang et al., 2015; Li et al., 2009;)
Cadmium (mg/L)	0.0272	0.0308	ND	ND
Lead (mg/L)	0.4159	0.0679	ND	ND
Copper (mg/L)	0.0599	0.0965	ND	ND
Zinc (mg/L)	0.0859	0.0567	ND	ND

VS: volatile solids, FS: fixed solids, EC: electric conductivity, ND: no data.

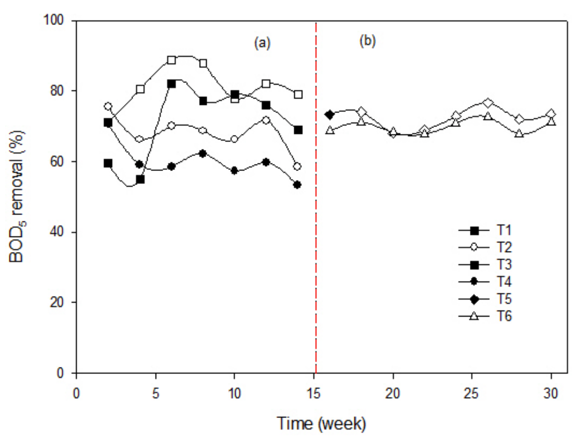

Fig. 4. Behavior of BOD_5 removal in mature leachates. Where: (a) stage I: continuous alimentation and (b) stage II: semi-continuous alimentation.

compounds found in mature leachates. Upon adsorption, a decrease or an inhibition of microbial activity was observed and, to recover the lost treatment capacity, they reported that washing with domestic wastewater is beneficial in the operation of a BPSM.

3.4 Reduction of Biochemical Oxygen Demand (BOD_5)

BPSM´s have been considered efficient in removing biodegradable organic compounds from leachates, because different types of biological reactions are promoted through aerobic, anoxic, and anaerobic zones, as leachate flows through bioreactors (Xie *et al*., 2012; Han *et al*., 2011). Figure 4 shows the elimination behavior of the biodegradable matter measured as BOD_5 in the present study. In stage I, it is observed that the elimination of BOD_5 remained in the order of 70 - 80% in general and exceeded the removal percentages achieved in the elimination of COD, achieving a greater stabilization after week 4. Similarly, with the COD parameter, the BPSM with SM-Y had better efficiency in the elimination of BOD_5. When testing the low hydraulic head (T1), the effluent had a concentration of 50 - 130 mg/L, which on average represented 81% removal, whereas for a high hydraulic head (T3), the average removal percentage was 79%, having a final concentration of 94 - 202 mg/L. For their part, the BPSM with SM-O (T2 and T4) maintained a stable behavior with efficiencies of up to 60 - 70%, but slightly lower than that achieved by BPSM with SM-Y.

In stage II (Figure 4.b), under continuous feeding conditions, both treatments had stable removal efficiencies throughout the fifteen weeks of monitoring. In the BPSM with SM-O (T5), an effluent of 105 - 144 mg/L was obtained, removing 72% of BOD_5. For BPSM with SM-Y (T6), the effluent decreased its concentration to 123 - 144 mg/L, representing 70% removal.

Regarding the elimination of the biodegradable fraction, results indicate that the BPSM were not affected significantly by the increase in HL or by the type of feeding. Thus, they provide insight into the high biological capacity of the system by eliminating more than 79% of BOD_5 from mature leachates that are considered as having very low biodegradability. Other studies have reported similar values with an estimated 89 and 86% (Nájera-Aguilar *et al*., 2019; Erabee and Ethaib, 2018). Likewise, the degradation of biodegradable compounds in this study, measured as BOD_5, is considered important as most of the effluents reported comply with the wastewater discharge regulations in Mexico (NOM - 001 - SEMARNAT - 1996).

Table 5. Heavy metal concentration in influent/effluent.

			Efluents (flowing)						MAL (Mexican regulation)
Parameter	Unit	Influent	E* T1	E* T2	E* T3	E* T4	E* T5	E* T6	NOM - 001 -SEMARNAT - 1996
Cd	mg/L	0.034	0.037	0.0375	0.0363	0.0367	0.0352	0.0337	0.1
Pb	mg/L	0.0463	0.0316	0.0443	0.0196	0.0359	0.0128	0.0599	0.2
Cu	mg/L	0.0889	0.0197	0.0348	0.043	0.025	0.0456	0.069	4

MAL: Maximum Allowable Limits

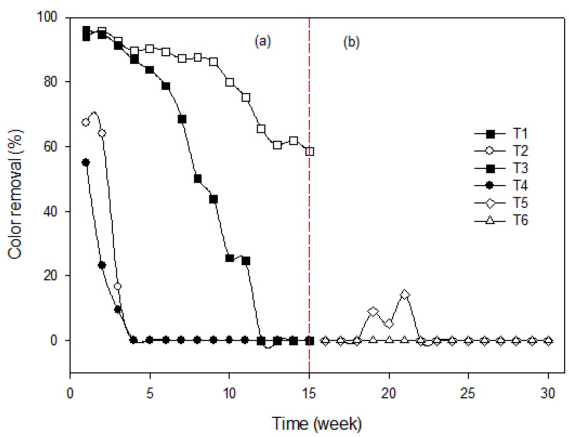

Fig. 5. Behavior of Color removal in mature leachates. Where: (a) stage I: continuous alimentation and (b) stage II: semi-continuous alimentation.

3.5 *Color reduction*

The Color in the mature leachates is closely related to the humic fractions. These recalcitrant components are responsible in inducing a yellow or brown color to the leachates. Additionally, they have chelating properties that allow them to bind to different metals (Show *et al*., 2019; León *et al*., 2007; Schnitzer *et al*., 1978), such as iron, which creates a black color in the water after generating iron sulfide. These humic materials are presented as negatively charged macromolecules, which result from the presence of functional groups such as carboxyls and phenols. As pH increases, the color molecules achieve greater stability, which is a phenomenon that results from the dissociation of functional groups, increasing the magnitude of negative charges (Edwards and Amirtharajah, 1985).

In this study, the results in the elimination of Color are practically imperceptible. In figure 5 it is observed that during the two stages, only treatment T1 maintained stability with around 60 - 80% of Color removal with a concentration in the effluent of 2.39 Pt-Co. As for stage I, the effluent persisted with the same initial concentration of Color in treatments T2 and T4, but without the characteristic smell of mature leachates. These results are similar to those found by Bautista-Ramírez *et al*., (2018) and Lozano *et al*., (2016) who obtained a removal of around 60 - 80% with hydraulic loads of the order of 10 - 18 L/m^{3}d. The lack of Color elimination in stage II in the BPSM's with SM-O (T5 and T6) could be attributed to the fact that these materials possibly had a low absorption, adsorption and desorption capacity, similar to what happened during the elimination of COD. These two parameters are highly related when quantifying the presence of organic substances (Bashir *et al*., 2009). Some authors have reported significant reductions in Color, odor and suspended solids, mainly attributed to the filtration and absorption effect of SM (Peng 2019; Hassan & Xie, 2014). However, the observed resistance to microbial degradation of humic materials appears to be largely due to the formation of stable organic metal and/or clay complexes (Schnitzer *et al*., 1978).

3.6 *Heavy metal removal*

In these studies, the concentration of elements such as cadmium, lead and copper were determined (Table 5). The concentration in the influent was low to begin with, which is characteristic of mature leachates that are in the methanogenic stage (<2 mg/L). Values found in the effluents varied very little with respect to the initial concentration, except for Cu in the effluent from treatments T1 - T5, where a reduction of around 50 - 70% is observed. In general, the concentration of elements was below the maximum permissible limits established in the Mexican regulations (NOM - 001 - SEMARNAT - 1996). According to Olivero *et al*., (2008), it is possible that Cd is found to form complexes with humic substances present in stabilized materials, which could explain the lack of color elimination in this study.

Conclusions

The characterization of the stabilized materials (young and old) showed a high degree of degradation of organic matter presenting a reduction a range of 86 - 89% of fixed solids, in addition to having pH values of 7.6 - 7.9. The leachate used in this study was characterized as a mature leachate, due to its low biodegradability (BI = 0.1) and high pH values (8.6). In this study, it was found that there was a significant statistical difference between the treatments (p value), finding that the best treatment was T1 (young, stabilized material, continuous feeding, hydraulic load of 25 L/m^{3}d) with an average removal of 79% of COD, and 81% in BOD_5 and 81% in Color. The final effluent complies with the permissible values of the Mexican regulations (NOM

- 001 - SEMARNAT - 1996) in relation to BOD_5 and the concentrations of heavy metals (Cd, Pb and Cu). The results of this study showed that bioreactors packed with stabilized materials extracted from open dumps are capable of removing a significant percentage of the organic fraction in leachates of low biodegradability.

It is considered important to be able to obtain results from the application of a Fenton-type chemical treatment to the effluent obtained, in order to know what the percentages of pollutant removal may be; or otherwise a Fenton pretreatment of the influent and subsequent treatment in the BPSM.

Acknowledgements

The authors are grateful for the support received from Tecnológico Nacional de México (TecNM) and its Project Number 5310.19-P. Teresa de Jesús Sánchez-Sánchez received scholarship (code 725366) from the Consejo Nacional de Ciencia y Tecnología (CONACYT) to pursue her master's degree.

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