REMOVAL OF NON-BIODEGRADABLE ORGANIC MATTER FROM LANDFILL LEACHATES BY ADSORPTION

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Abstract - Leachates produced at the La Zoreda landfill in Asturias, Spain, were recirculated through a simulated landfill pilot plant. Prior to recirculation, three loads of different amounts of Municipal Solid Waste (MSW) were added to the plant, forming in this way consecutive layers. When anaerobic digestion was almost completed, the leachates from the landfill were recirculated. After recirculation, a new load of MSW was added and two new recirculations were carried out. The organic load of the three landfill leachates recirculated through the anaerobic pilot plant decreased from initial values of 5108, 3782 and 2560 mg/l to values of between 1500 and 1600 mg/l. Despite achieving reductions in the organic load of the leachate, a residual organic load still remained that was composed of non-biodegradable organic constituents such as humic substances. Similar values of the COD were obtained when the landfill leachate was treated by a pressurised anoxic-aerobic process followed by ultrafiltration. After recirculation through the pilot plant, physico-chemical treatment was carried out to reduce the COD of the leachate. The pH of the leachate was decreased to a value of 1.5 to precipitate the humic fraction, obtaining a reduction in COD of about 13.5%. The supernatant liquid was treated with activated carbon and different resins, XAD-8, XAD-4 and IR-120. Activated carbon presented the highest adsorption capacities, obtaining COD values for the treated leachate in the order of 200 mg/l. Similar results were obtained when treating with activated carbon, the leachate from the biological treatment plant at the La Zoreda landfill; in this case without decreasing the pH.

Key words - Municipal Solid Waste (MSW), Landfill, Leachates, Recirculation, Refractory Organic Matter, Adsorption.

INTRODUCTION

Of the different alternatives for the disposal or treatment of MSW, sanitary landfilling is currently the most widely employed due to its economic advantages. However, this situation will change in the near future. The degradation of the organic fraction of the waste in the landfill in combination with the percolation of rainwater (Ehrig, 1983; Andreottola and Cannas, 1992; Clement, 1995) produces a liquid called "leachate". The composition of this leachate depends on a variety of parameters, such as the type of waste, climatic conditions, mode of operation and age of the landfill (Nanny and Ratasuck, 2002). The pollutant load of the leachate generally reaches maximum values during the first years of operation of a landfill and then gradually decreases over subsequent years. This trend is applicable to organic compounds, the main indicators of organic pollutants being COD (Chemical Oxygen Demand) and BOD (Biochemical Oxygen Demand).

Alternative treatments have been reviewed (Lema *et al*., 1988). Briefly, leachates can be recirculated to the same landfill (Yuen *et al*., 1995, Pohland and Al-Yousfi, 1994; De Rome and Gronow, 1995; Tittlebaum, 1982; Brown and Maunder, 1994; Barber and Maris, 1992) or treated by different methods: biological methods (aerobic, anaerobic) (Berrueta and Castrillón, 1992, Kennedy and Lentz, 2000, Hoilijoki et al., 2000, Im et al, 2001) to remove organic matter and ammonium nitrogen; and physico-chemical methods: precipitation, oxidation, adsorption, stripping, reverse osmosis, etc. (Cossu et al., 1992, Chianese et al., 1999, Li et al, 1999, Lin and Chang, 2000, Trebouet et al., 2001). Biological treatments of landfill leachates have been shown to be very effective in removing organic matter in the early stages (Berrueta and Castrillón, 1992) when the BOD/COD ratio of the leachate has a high value, but this ratio decreases with the age of the landfill (Rodríguez et al. 2000) and the process is less effective with time (Mendez et al., 1989), due to the major presence of refractory organic matter. Accordingly, a variety of physico-chemical processes have been used to treat leachates with this type of matter.

The purpose of the present research work was firstly to study the decrease in the pollutant load of the leachates from the La Zoreda landfill (old landfill) by means of their recirculation through a MSW anaerobic plant. At the same time, we compare the results obtained by means of this recirculation with the results obtained in the leachate treatment plant of the La Zoreda landfill, where purification of the leachate is carried out by means of a pressurised aerobic-anoxic process followed by ultrafiltration for the separation of biomass. Given that the COD values of the final effluent in both proceses are above the limits permitted by the legislation currently in force in Spain (500 mg O_2/l discharged into a public watercourse), these effluents must be treated yet again, so that they can de directly discharged. With the aim of studying the possibility of a final treatment for the leachates, these were treated by adsorption, studying different adsorbent materials, such as Amberlite XAD 4, Amberlite XAD 8, Amberlite IR-120 and Granular Activated Carbon.

METHODS

Pilot plant

The pilot plant was constructed in opaque PVC, the diameter and height being 0.5 and 3.6 m respectively. At the bottom of the plant, there is a system for collecting the leachates and at the top an exit for gas together with a water distribution device for simulating rainfall and recirculating the leachates. The leachates were collected in a closed container and a circuit enabled their recirculation by pumping. The operating temperature of the reactor was kept constant at 36 ± 1ºC by means of an external water jacket (Rodríguez Iglesias et al., 2000).

Landfill

The wastes generated in the Principality of Asturias (Spain) are deposited in a Central Landfill at La Zoreda, which started operating in January 1986. This landfill is managed by the Consortium for the Management of Solid Waste, COGERSA. The amount of MSW disposal has increased with time up to the current level of around 550000 t/year.

The volume of leachate generated has increased with time, reaching levels of around 600 m^3/day during periods of heavy rainfall. The COD of the leachate has decreased from 80000 mg/l in 1986, when waste disposal started, to current values of approximately 3000 mg/l. The leachate produced (without recirculation) is collected at the bottom of the landfill and subsequently transferred to a treatment plant. The treatment system employed at the landfill consists of a pressurised nitrification-denitrification process, which is characterised by high volatile solids content (14 g/l) and increased oxygen solubility as a consequence of the elevated pressure (2.5-3.0 bars). The biomass is subsequently separated by means of ultrafiltration. The plant was designed to treat a daily flow of 400 m^3. The plant was enlarged in 2001 so as to treat 550 m^3/day.

Chemical Analyses

The parameters analysed in the leachates were Chemical Oxygen Demand (COD), Suspended Solids (SS), Volatile Suspended Solids (VSS), Total Alkalinity (TA), Total Volatile Acids (VA), Kjeldahl Nitrogen, ammonium nitrogen, nitrates and metals. *Standard Methods* (APHA, 1989) were employed with the exception of volatile acids, which were measured following Degremont (1979).

Selected metals were determined by atomic absorption spectrophotometry. Samples of homogenised leachate were treated with mixtures of $HClO_4$ and HNO_3 in a proportion of 1/10 in volume until a colourless residue was obtained. The equipment used was a Perkin Elmer Mod. 3110 spectrophotometer equipped with a FIAS system.

Experimental procedure

Successive amounts of MSW were introduced into the pilot plant: initially, 48.5 kg of MSW (first cell); after one year, when the COD of the leachates presented constant values (around 2 g/l), 66 kg of MSW were added on top of this first cell; five months later, 59 kg of MSW were added on top of the other two layers, thus constituting the third cell. As a way of simulating the rainfall at the landfill, water was introduced into the pilot plant in a discontinuous way; the amount added each time corresponding to the total amount of daily rainfall in the area, according to data from the meteorological services. The average rainfall in Asturias is 900 mm/year. From day 120 onwards, recirculation of the leachates commenced and this operation was carried out regularly until the end of the study. The characteristics of the leachate generated and of the biogas produced in the three previous cells are shown in Rodriguez et al. (2000).

After stabilisation of the third cell (low constant values of the COD of the leachate, around 1700 mg/l, and low levels of gas production), the leachate still remaining in the plant was extracted from the bottom. This effluent was then recirculated through the anaerobic plant so as to study the decrease in COD of the leachate from the La Zoreda landfill.

For the recirculation experiments, 20 litres of leachate from the landfill were added at the top of the plant, collected at the bottom and recirculated (Rec-1) twice a day for 12 days (the volume recirculated was practically the same as that introduced, around 20 litres). Daily samples were taken and analysed. When the analytical parameters of the recirculated leachate remained constant, recirculation was stopped.

Subsequently, a fourth cell of 40.5 kg of MSW was added on top of the previously digested cells, and after stabilization of this MSW, the reactor was kept functioning at the same working temperature without recirculation of the leachate or addition of water. The aim was to obtain a digested residue inside the reactor with the least amount of water possible, eliminating in this way all the leachate generated at the bottom of the reactor. Subsequently, 20 litres of landfill leachate were introduced and recirculated for a period of 9 days (Rec-2) until achieving constant values of the analytical parameters, following the same procedure as above. Several months after this second recirculation and having eliminated the liquid from the reactor, another recirculation of leachate (Rec-3) was commenced with the aim of testing the existence of active biomass within the reactor. 20 litres of landfill leachate were recirculated for 12 days, following the same procedure as on the two previous occasions.

Treatment of the effluents resulting from the biological processes

The effluents obtained, both in the recirculation process as well as in the treatment at the landfill leachate plant, have COD values of around 1500 mg/l (which are above the permitted values for discharge into a public watercourse) containing dissolved substances that confer a strong colouring (yellowy-brown) to the liquid, which were thought to possibly be humic substances. Humic substances have been classified into three fractions based on water "solubility": (i) humin is the fraction not soluble in water at any pH value; (ii) humic acid is not soluble under acidic conditions ($pH<2$), but becomes soluble at higher pH; and fulvic acids, soluble at all pH conditions (APHA, 1989).

Following a similar procedure to that employed by Christensen et al. (1998) for the characterisation of the dissolved organic carbon in landfill leachate polluted groundwater, nitric acid was added to the recirculated leachate (Rec-2) until reaching a pH value of 1.5, obtaining a precipitate that was separated by centrifugation at 4000 rpm for 20 minutes. This precipitate corresponds to humic acids.

The supernatant, with a pH 1.5, was treated in a stirred tank with Amberlite XAD-8. Amberlite XAD-8 is a macroporous methylmethacrylate copolymer adsorbent resin, which according to Christensen et al. (1998) adsorbs fulvic acids after prior acidification to a pH value of 1.5. The residual COD not sorbed onto the XAD-8 resin is called the "hydrophilic fraction".

Besides this adsorbent, other adsorbents were also tested for treating the supernatant, such as Amberlite XAD-4, Amberlite IR-120 and Granular Activated Carbon (GAC-40, specific surface of 1000 m^2/g, particle size in the range of 0.4-1.6 mm).

The XAD-4 resin is an adsorbent resin with a polystyrene-divinylbencene matrix. Published reports (Malcolm and Hayes, 1994, Rodríguez Vidal et al. 1999) describe the isolation and purification of the hydrophilic acid fraction using this resin. However, Christensen et al. (1998) reported that it only retains a minimum fraction of what remains after having previously removed humic and fulvic acids (4.4% of the total COD, leaving 24% of the total accounted for).

Amberlite IR-120 is a strongly acidic cation exchange resin that uptakes hydrophilic bases: aminoacids, puric and pyrimidinic bases, low molecular weight aliphatic amines (Rodríguez Vidal et al. 1999). 3 g of adsorbent in 100 ml of leachate were employed in all the experiments.

Considering the better results obtained with activated carbon than with the other resins tested, this adsorbent was used for the final treatment of the effluent from the landfill leachate biological treatment plant using a dose of 20 g of activated carbon per litre of treated leachate. This experiment was carried out at the landfill leachate pH (around 7).

RESULTS AND DISCUSSION

Composition of the leachates generated in the pilot plant and in the Central Landfill of Asturias

The composition of the leachate generated during the functioning of the reactor varies for the four cells. The initial COD of the leachate in the first cell was very high (around 90 g O_2/l) and subsequently decreased until day 375 to a level of around 2 g O_2/l. The initial COD of the leachate generated in the second cell was around 23 g O_2/l, after which it fell to values of around 1.5 g O_2/l. In the third cell, the initial COD was lower, descending until the end of the experiment to similar values to those of the second cell. The composition of the leachates produced in municipal solid waste was different, depending on the number of digested layers or cells that the leachates had to pass through. A more detailed description may be found in Rodríguez et al., 2000.

Table 1 shows the physico-chemical composition of the leachates generated in the pilot plant corresponding to the final phase of the third and the fourth cells, prior to the process of recirculation of the landfill leachate through the plant. These leachates may be classified as leachates generated in an old landfill, with a low COD and high amounts of ammonium nitrogen.

Table 1 also presents the physico-chemical characteristics of the leachates taken from the landfill leachate treatment plant for the recirculation experiments. When collecting the leachates from the landfill, care had been taken for the samples to be representative of the composition of the leachates in the three selected periods. The first sample collected from the landfill, which was recirculated over the third cell, had a COD of 5108 mg/l. Ten months later, another sample was collected that had a COD of 3782 mg/l. This second sample was recirculated over the fourth, previously digested cell. Several months later, another representative sample of leachate, with a COD of 2560 mg/l, was collected from the landfill and was recirculated over the fourth cell. As can be expected, the COD of the landfill leachate decreased with time.

The three samples from the landfill that were recirculated presented a slightly alkaline pH, mainly due to the high ammonium content, around 1900 mg/l. The total volatile acidity (VA) was strongly related to the COD. In the first recirculated leachate, the values were close to 1000 mg acetic acid/l, indicating the presence of intermediate products in the anaerobic process produced in the landfill itself. The total volatile acidity in the second and third leachates recirculated was lower, 456 and 290 mg acetic acid/l respectively, which indicated a greater degree of stabilization.

The concentration of metals in the leachates was generally low, as can be seen in Table 1.

Effects of recirculation of the landfill leachate through the pilot plant

The COD and volatile acidity of the leachate recirculated through the pilot plant over time are closely related, decreasing rapidly when the leachate is recirculated. In the case of the leachate recirculated over the third cell (Rec-1), the COD decreased from 5000 mg/l to 2600 mg/l after only one day of recirculation. The COD subsequently decreased slightly until levelling off at approximately 1500 mg/l on the 8th day of recirculation (total decrease in COD of about 70%).

Similar behaviour was observed in the first recirculation over the fourth cell (Rec-2). Even though the initial COD was lower, the COD levelled off at the same value as after the recirculation over the third cell. The COD decreased rapidly from 3782 to 2260 mg/l after only one day of recirculation, which represents 40% elimination of organic substances. Subsequently, the COD underwent a slight decrease down to values of approximately 1500 mg/l on day 12 (a total decrease of 59%). The final COD values obtained for the second recirculation over the fourth cell (Rec-3) are similar to those reported above. The fact that, in this last case, recirculation had been carried out months later without having introduced neither new cells nor rain water and without having recirculated leachate during this time would imply that the amount of water in the waste (field capacity) within the plant was minimum, and therefore the dilution effect was also minimum. These results indicate that an adequate recirculation of leachate can greatly decrease the COD of the leachate.

The volatile acidity behaves similarly to COD, decreasing to values of between 200 and 90 mg acetic acid, approximately.

With respect to the concentrations of $NH4^{+}$-N a decrease is produced in the first recirculation period (Rec-1) to values of 1400 mg/l, possibly due in part to a initial dilution, while in the other two recirculations (Rec-2 and 3), the concentration of ammonium hardly varied with the recirculations, ranging between approximately 1700 and 2050 mg/l, depending on the different values of the ammonium in the recirculated leachate.

This fact may be an indicator that in these last two cases a dilution of the leachate was not produced when it was made to pass through the pilot plant; the percentage of COD removed thus being due to the selfsame degradation of the leachate and not to a phenomenon of dilution.

The metals concentration in the leachates was low, and with the exception of iron, was scarcely influenced by their recirculation through the pilot plant containing digested MSW. In the case of the second recirculation over the fourth cell (Rec-3), a decrease in the iron concentration from 10.22 to 1.97 mg/l was found at the end of the study, with a mean value of 3.62 mg/l (Table 2). In all cases, the minimum values corresponded to the results obtained at the end of the recirculation period.

The total alkalinity (TA) values of the leachates remained quite high in all cases. In the recirculation through the third cell, the alkalinity decreased from an initial value of 9.34 g $CaCO_3$/l to a final value of 6.7 g $CaCO_3$/l. In the recirculation through the fourth cell, the alkalinity decreased from 9.42 g $CaCO_3$/l to 7.7 g $CaCO_3$/l in one case, and in the other remained practically constant at values of around 8 g $CaCO_3$/l. The fact that the total alkalinity/volatile acidity ratio is very high indicates that the process of anaerobic degradation is highly stable (Metcalf & Eddy, 1998).

The fact that the organic pollutant load only decreased to values ranging between 1300 and 1500 mg/l in spite of recirculating the leachate through the plant for a considerable number of days leads to the supposition that there is a non biodegradable organic fraction present in the leachate that would need subsequent physico-chemical treatment in order to be eliminated. This fact is corroborated by the data obtained in the landfill leachate treatment plant at La Zoreda, the results of which we present below.

Characteristics of the leachate from the landfill

As mentioned above, the leachates generated in the landfill are treated by anoxic-aerobic conditions in pressurised bioreactors followed by ultrafiltration to separate the biomass. Table 3 shows the results obtained at the La Zoreda landfill leachate plant in four different periods of time. The amount of ammonium present in the leachate is considerably reduced by means of this treatment, as is the BOD_5. However, the effluent resulting from the treatment presents values of COD equal to or higher than 1000 mg/l, indicating that there exists a certain amount of matter that is refractory to biological degradation.

Physico-chemical treatment of the leachates

When the effluent obtained by recirculating the landfill leachate through the pilot plant with a COD of around 1500 mg/l undergoes acidification to pH 1.5, a precipitate is produced that separates by means of centrifugation. The supernatant liquid presents a COD of 1300 mg/l, which represents 13.5% removal of COD, corresponding to humic acids. These results are in agreement with those obtained by Christensen et al. (1998), which were in the order of 10%.

Figure 1 shows the results obtained when placing the supernatant liquid (COD: 1300 mg/l, pH: 1.5) in contact with activated carbon and the different resins in a stirring tank. Likewise, Table 4 shows the amount of organic matter retained by the adsorbents in mg COD/mg adsorbent after two hours of contact.

After 20 minutes of contact, the activated carbon GAC-40 is the adsorbent that presents the best behaviour in the removal of organic compounds from the leachates, followed by the adsorbent resin XAD-8 (Figure 1). For this resin, the percentages of reduction in COD are approximately 59%, which may correspond to the fraction of fulvic acids in the leachate, much higher than that corresponding to humic acids, obtained as a result of acidification.

According to Cossu, et al. (1992), the organic fraction preferentially removed by activated carbon is the fulvic one with a molecular weight of 100-10000. Organic substances characterised by a lower or higher molecular weight than this range are not efficiently retained; the former probably due to their high polarity (volatile acids, hydroxilated acids, sugars, etc) and the latter due to the large sizes of their molecules, which could clog the pores and decrease adsorption capacity for other molecules.

Although both adsorbents, XAD-8 and activated carbon, as mentioned above retain fulvic acids, the latter appears to be able to adsorb other types of compounds.

Employing the resin XAD-4, reductions in COD of around 48% were obtained after 2 hours of contact. However, in the case of the leachate treatment being carried out with this resin after pre-treatment with the resin XAD-8, only around 9% of the total COD was removed, thus producing a similar behaviour to that found by Christensen et al. (1998). The resin IR-120 is the one that presents the lowest removal capacity for organic matter (35%).

Given that GAC 40 is the one that presents the best behaviour, the removal of organic matter from the final effluent from the landfill leachate treatment plant by means of this adsorbent was studied. The effluent of the leachate treatment plant used in our study presented a COD of 1100 mg/l, a BOD_5 of 30 mg/l and a pH value of around 7. The BOD/COD ratio of this leachate was below 0.1, which excluded the possibility of biological treatment.

The results obtained are shown in Figure 2, the final COD being around 200 mg/l, values that were also achieved in the case of treating the recirculated leachate (Figure 1). However, when the leachate from the landfill biological plant was treated, a greater contact time was required (2 hours) to reach this minimum value of COD. In kinetic and equilibrium studies of adsorption using CAG 40 of the refractory organic matter of landfill leachate carried out by the authors, in which the influence of the dose of activated carbon in the treatment was studied, the conclusion reached was that even if the dose of activated carbon were increased, it would not be possible to reduce the COD below values of 191 mg/l.

CONCLUSIONS

Recirculation through an anaerobic pilot plant of the leachate generated at La Zoreda landfill (which possesses a low COD for this type of effluent, from around 5000 to 2500 mg O_2/l, a pH of around 8, and not very high volatile acidity) reduces its organic pollutant load. This reduction in the organic content of the leachate is quite similar to those obtained by means of the pressurised biological treatment followed by ultrafiltration carried out at the landfill. However, the effluent resulting from both treatments presents values of COD equal to or higher than 1000 mg/l, which indicates that a residual non-biodegradable organic matter remains that must undergo physico-chemical treatment.

The decrease in pH of the leachate pre-treated by means of recirculation to values of 1.5 gave rise to the precipitation of a solid, corresponding to humic acids, which may be removed by centrifugation, and which corresponds to 13.5% of the initial COD.

Of the adsorbents studied to remove the COD of the supernatant after reduction of the pH, granular activated carbon is the one that produces the greatest reduction in COD, followed by the resin Amberlite XAD-8. The residual COD obtained when using activated carbon was 200 mg/l. The COD removed by the resin Amberlite XAD-8, which may correspond to fulvic acids, was 59% of the initial COD.

After treating the effluent from the landfill leachate treatment plant with activated carbon, minimum values of COD of approximately 200 mg O_2/l were also achieved.

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Table 1. Physico-chemical characteristics of the leachates generated in the pilot plant (prior to the addition of the landfill leachate) and the leachates from the landfill used in the experiments

Parameter	Pilot plant leachate		Landfill leachate		
	3rd cell	4th cell	Rec-1	Rec-2	Rec-3
pH	7.60	7.58	8.00	8.43	8.26
COD (mgO_2/l)	1765	716	5108	3782	2560
NH_4^+-N (mg/l)	1521	1131	1876	1904	1904
TA (g/l $CaCO_3$)	8.27	5.41	9.34	9.42	7.90
VA (mg/l AcH)	150.6	65	912	456	290
Fe (mg/l)	9.32	2.5	0.835	-	10.22
Cu (mg/l)	0.21	0.16	0.41	-	0.15
Zn (mg/l)	0.75	0.18	0.28	-	0.42
Ni (mg/l)	0.53	0.34	0.69	-	0.17
Pb (mg/l)	0.12	0.33	0.37	-	<0.05
Cd (mg/l)	<0.01	0.03	0.05	-	0.02

Table 2. Metals content of the second leachate recirculated through the fourth cell

Metal	Maximum	Minimum	Mean	Standard deviation
Fe (mg/l)	10.22	1.97	3.62	2.05
Cu (mg/l)	0.31	<0.02	0.06	0.09
Ni (mg/l)	0.23	<0.04	0.09	0.08
Pb (mg/l)	<0.05	<0.05	<0.05	<0.05
Zn (mg/l)	0.42	0.08	0.17	0.09
Cd (mg/l)	0.03	0.02	0.02	0.00
Cr (mg/l)	0.43	0.08	0.18	0.08
Mn (mg/l)	0.45	0.18	0.23	0.06
Hg (μg/l)	11.00	0.15	4.38	3.63

Table 3. Physico-chemical characteristics of the leachates before and after treatment in the biological plant

Parameter	Sample 1		Sample 2		Sample 3		Sample 4	
	Influent	Effluent	Influent	Effluent	Influent	Effluent	Influent	Effluent
pH	8.3	7.0	8.3	6.8	8.4	6.9	8.3	7.0
BOD_5 (mg/l)	1025	79	950	-	724	89	1025	59
COD (mg/l)	5099	1510	4213	1406	3503	1215	2766	1017
KTN (mg/l)	2207	90.2	2322	76.6	2256	87	2068	80
N-NH_4^+ (mg/l)	2001	44.3	2200	33.8	2045	47.8	1805	46.8
N, NO_3^- (mg/l)	38.7	593	26.4	600	23.4	470	16.4	330

Table 4. Organic matter adsorption capacities of the adsorbents employed (mg COD/mg adsorbent)

Time (minutes)	GAC	XAD-8	XAD-4	IR-120
5	15.41	18.94	8.33	6.05
10	22.75	21.48	9.10	6.51
15	24.59	22.63	9.71	8.36
30	32.16	33.33	14.33	11.13
60	36.06	23.56	19.87	13.89
120	38.12	24.94	20.33	14.82

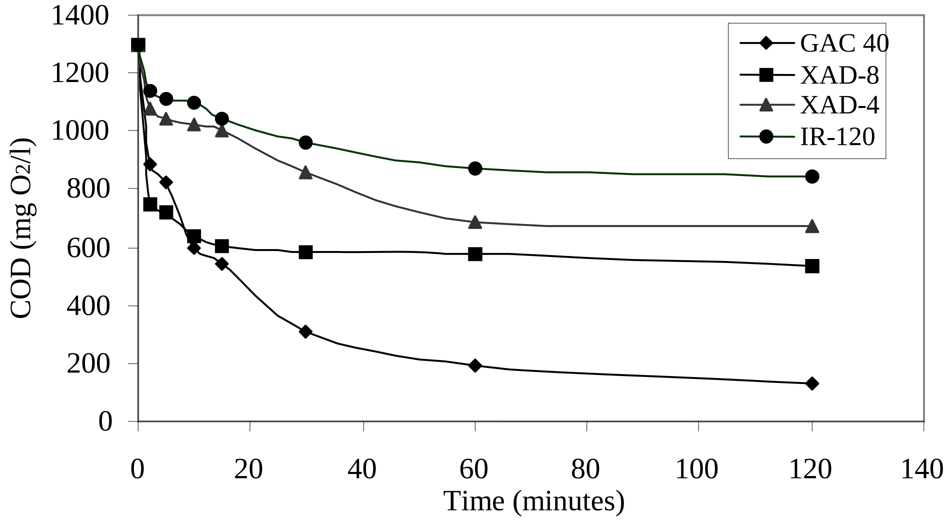

Figure 1. Kinetics of the adsorption of organic matter from previously recirculated and acidified pilot plant leachates (pH 1.5) onto different adsorbents

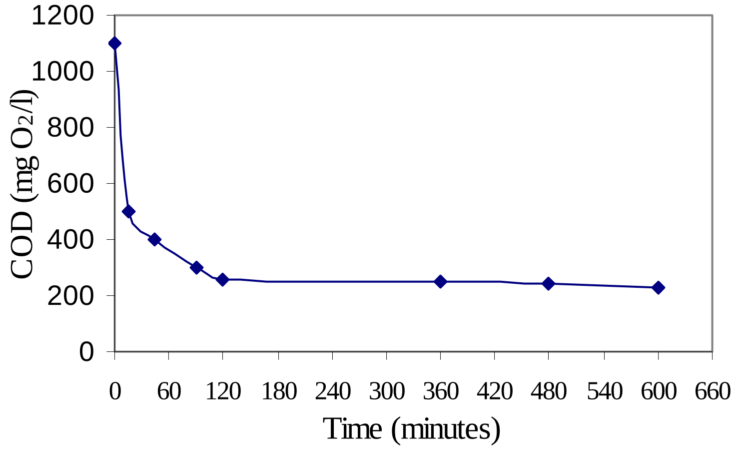

Figure 2. Kinetics of the adsorption of organic matter from biologically treated landfill leachates (pH 7) onto GAC-40

Table 1. Physico-chemical characteristics of the leachates generated in the pilot plant (prior to the addition of the landfill leachate) and the leachates from the landfill used in the experiments

Table 2. Metals content of the second leachate recirculated through the fourth cell

Table 3. Physico-chemical characteristics of the leachates before and after treatment in the biological plant

Table 4. Organic matter adsorption capacities of the adsorbents employed (mg COD/mg adsorbent)

Figure 1. Kinetics of the adsorption of organic matter from previously recirculated and acidified leachates (pH 1.5) onto different adsorbents

Figure 2. Kinetics of the adsorption of organic matter from biologically treated landfill leachates (pH 7) onto GAC- 40