The Effect of Packing Hydrophilization on Bacterial Attachment and the Relationship With the Performance of Biotrickling Filters

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ABSTRACT: Many bioprocesses depend on the effective formation of a biofilm on a solid support. In the present study, three different surface treatments (sandblasting, pure-O_2 plasma, and He–O_2 plasma treatments) were conducted on polypropylene (PP) Pall rings used as a support in biotrickling filters for air pollution control. The intent was to modify the ring surface and/or electrochemical properties in order to possibly improve cell adhesion, wetting properties, and possibly reduce the start-up time and increase the performance of the biotrickling filters. The surface treatments were found to generally increase the hydrophilicity and the zeta potential of the surfaces. However, the startup and performance of lab-scale biotrickling filters packed with treated Pall rings were not significantly different than the control with untreated rings. Cell and colloid deposition experiments conducted in flow cells showed that the treated surfaces and the hydrodynamic conditions were not favorable for cell deposition indicating that there could be significant opportunities for improving packings used in environmental bioprocess applications.
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KEYWORDS: biofilm formation; surface properties; plasma treatment; fixed-film bioreactors; biotrickling filter; cell deposition

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Additional Supporting Information may be found in the online version of this article.

Introduction

A large number of engineered bioprocesses rely on the effective attachment of microorganisms and the establishment of a thriving biofilm on some kind of support, membrane, or packing material. The phenomena involved in the formation of an effective biofilm are complex and depend on a number of factors, including biological, chemical, and hydrodynamic factors (Characklis and Marshall, 1990; Davies et al., 1998). While the importance of these factors relative to one another depends on the specific bioprocess being considered, there is ample evidence that process performance is linked to the successful adhesion of microorganisms and subsequent growth of a dense biofilm on the support medium. Thus, factors that affect cell deposition and attachment to surfaces as well as biofilm growth should be important for process design and in the selection of optimum operating conditions.

One type of bioreactors in which biofilm development is particularly important is bioreactors for air pollution control. In the past decade, there has been major progress on the development of high-performance bioreactors for air pollution control, in particular the so-called biotrickling filters. In these bioreactors, the use of synthetic packings together with the continuous recirculation of an aqueous nutrient solution has allowed greater air throughput and treatment performance than in conventional biofilters (Cox and Deshusses, 1998; Devinny et al., 1999; Gabriel and Deshusses, 2003). Even so, biotrickling filters can sometimes experience long start-up times, usually when poor attachment of bacteria to the packing results in slow biofilm

growth (Fortin and Deshusses, 1999; Kazenski and Kinney, 2000).

In one example, poor performance was observed in a full-scale biotrickling filter degrading styrene vapors at a bathtub manufacturing facility (Webster et al., 1999). A substandard packing material, and low pollutant loadings combined with periodical periods of starvation led to insufficient cells adhering to the packing. This prevented the establishment of a dense and effective population of pollutant degrading bacteria and resulted in low pollutant removal rates. Prado et al. (2009) recently reported that a chemical scrubber converted to a biotrickling filter packed with Pall rings only had a 10–25% removal of the target compounds (at 0.9 s gas residence time), despite inoculating the bed three times over a period of 1 year. The performance was likely due to the low surface area of the packing and insufficient cell adhesion and slow biofilm growth onto the packing surface. The importance of the packing surface properties was highlighted in a study conducted concurrently with the one reported in this article. Goncalves and Govind (2009) demonstrated that a faster startup, a greater biomass density, and a better H$_2$S long-term treatment performance could be achieved in a biotrickling filter packed with polyurethane foam coated with polyethyleneimine, a positively charged polymer. In the area of wastewater treatment, Show and Tay (1999) studied the influence of the surface texture and other surface physical properties on the performance of anaerobic filters for wastewater treatment. They observed that the COD removal efficiency of bioreactors packed with smooth PVC rings system was around 20% lower that that of bioreactors packed with open-pore glass rings. After 8 months of operation, the reactor packed with smooth rings had accumulated 7% less biomass than the one packed with rough rings, suggesting that reactor performance was linked to effective biomass attachment to the support.

There has been major progress on understanding fundamental aspects of attachment of microorganisms to surfaces and their ultimate development into biofilms. In particular, biofilm research has focused on how microorganisms interact with each other to form communities and the role of quorum sensing molecules in biofilm formation (Dunny and Leonard, 1997; Miller and Bassler, 2001), what kind of surface properties promote initial attachment of microbes (Chen et al., 2009; Walker et al., 2004) and development of biofilms (Harkes et al., 1991; Mozes et al., 1987; Mills et al., 1994; Walker, 2005), how biofilm grow on surfaces (Bryers and Characklis, 1982; Characklis and Marshall, 1990), and how hydrodynamics affect the rate of adhesion of microbes and subsequent shearing from surfaces (Chang et al., 1991; Stoodley et al., 1994). Even so, to date, there has been little connection between the above-mentioned advanced biofilm studies and the macroscale behavior of engineered systems, in particular in the area of biological waste treatment in biofilm reactors. Many bioprocesses for waste treatment rely on microorganisms, which are attached to some kind of support (Scott, 1987). Therefore, linking new knowledge on support materials and attachment of bacteria has the potential to help optimize such treatment systems.

Thus, the objective of this study was to determine the influence of synthetic packing material preparation and of selected surface modifications on the performance of biotrickling filters used for air pollution control and identify whether certain packing surface properties correlated with the performance of the bioreactors.

Materials and Methods

Packing Material and Surface Treatments

Polypropylene (PP) Pall rings with a size of 1.6 cm (Tecnium S.A., Barcelona, Spain) were selected as a model packing material. The PP rings were used in the biotrickling filters either in a pristine form or after treatment by one of three methods: sandblasting, pure oxygen plasma (pure-O$_2$ plasma), and helium–oxygen plasma (He–O$_2$ plasma). Pristine rings were used as is after being rinsed with deionized water. Sandblasting on the PP rings was performed in a SM20BM pressure blast cabinet (Trinity Tool Co., Fraser, MI). The rings were directly sprayed with sand (density 1.46 kg L^{-1}) for 10 min at a pressure of 2.4 bar. A set of rings was plasma treated in a FEMTO low-pressure plasma system (Diener Electronic North America, Reading, PA). Treatment lasted 1 h in a 100% oxygen atmosphere at a power of 50 W and with a chamber pressure of 0.35 mbar. These rings are thereafter referred to as pure-O$_2$ plasma-treated rings. Another set of rings was treated in an Atomflo^{TM} plasma system (SurfX Technologies, Culver City, CA). In this case, the rings were treated for 1.3–1.5 s each. The plasma was produced by mixing a pure helium stream at a flow rate of 30 L min^{-1} with a pure oxygen stream at a flow rate of 0.75 L min^{-1}. Plasma treatment was conducted at atmospheric pressure using a power of 180 W. Previous tests by SurfX Technologies (unpublished results) had shown that these were the most suitable conditions to increase the hydrophilicity of the rings. These rings are thereafter referred to as He–O$_2$ plasma-treated rings.

Some surface characterization techniques (zeta potential and cell deposition studies) required a planar surface, hence a series of PP flat coupons were prepared with the same treatments as the PP rings (pristine, sandblasted, or plasma treated). In all cases, great care was taken to ensure equal and uniform surface treatment.

Surface Characterization

The hydrophobicity of the treated rings was determined by contact angle measurements using a VCA-Optima Surface Analysis System (AST Products, Inc., Billerica, MA) using a 0.5 μL water droplet. The small size of the droplet enabled using the rings, as the ring curvature was large compared to the diameter of the droplet. The electrokinetic properties of

the different treated coupons were determined using an electrokinetic analyzer streaming potential analyzer (EKA, Brookhaven Instruments Corp., Holtsville, NY, with an asymmetric clamping cell). The zeta potential was calculated from the measured streaming potential as described elsewhere (Walker et al., 2002). Measurements were conducted using a background solution of the mineral medium, also used in the biotrickling filters (see composition below). Additionally, SEM images of the different treated coupons were also taken (see details of SEM method in the Supplementary Material).

Inoculum Characterization

A mixed culture of toluene-degrading organisms grown in a bubble column was selected as inoculum for the biotrickling filters (Kan and Deshusses, 2003). Volatile and total suspended solids analyses for the inoculum were performed according to Standard Methods 2540E and 2540D (APHA, 1998), respectively. Bacterial cell concentrations were measured by directly visualizing and enumerating cells in a Bürker–Türk counting chamber (Marienfeld Laboratory Glassware, Lauda-Königshofen, Germany), using an optical microscope. Toluene-induced oxygen uptake rate (OUR) for the inoculum was determined as per previously reported (Kan and Deshusses, 2005). Six liters of cell suspension (VSS $0.49 \, g \, L^{-1}$; TSS $1.38 \, g \, L^{-1}$; 4.5×10^8 cells mL^{-1}; toluene-induced OUR of $9.3 \, mg \, O_2 \, L^{-1} \, h^{-1}$) was used to inoculate the reactors on day 0. The cell suspension was recycled in a closed loop through the bed for 24 h to promote attachment to the packing, after which time, the toluene vapor feed was started. Air was supplied from day 0.

The electrophoretic mobility of the bacterial cells was determined using a ZetaPALS analyzer (Brookhaven Instruments Corp.) and a cell suspension of 4.5×10^8 cells L^{-1} in mineral medium at $25^\circ C$. The zeta potential of bacterial cells was obtained from the experimentally determined electrophoretic mobility values by means of the Smoluchowski equation (Elimelech et al., 1995).

Reactor Set-Up and Analysis

The reactor studies were performed in a laboratory-scale system comprising four biotrickling filters (referred as reactors 1–4) made of clear PVC pipe run in parallel. The bioreactors were 50 cm high by 7.7 cm (internal diameter) and operated in a down-flow mode, and packed with 175 rings each with an effective volume of 1.1 L. The corresponding bed height was about 23 cm. Reactor 1 served as a control and was packed with pristine rings, reactor 2 was packed with sandblasted rings, reactor 3 with pure-O_2 plasma-treated rings, and reactor 4 with He–O_2 plasma-treated rings. The biotrickling filters were fed toluene vapors (15.5 ppm_v) in dry air at a flow rate of 480 L h^{-1} per reactor resulting in an empty bed gas residence time of 8.2 s. The conditions (short residence time and low inlet concentration

of toluene) were selected to be representative of a possible field application for a high throughput biotrickling filter. The conditions were also chosen such that toluene removal would be less than 100% so that possible differences in the performance between the biotrickling filters could be observed. To ensure consistency between the four reactors, one single stream (1,920 L h^{-1}) of contaminated air was produced and split into the different reactors. Air pressure and airflow rate were regulated by means of manometers and flowmeters, respectively. A mineral medium containing $1 \, g \, L^{-1}$ KH_2PO_4, $1 \, g \, L^{-1}$ K_2HPO_4, $1 \, g \, L^{-1}$ KNO_3, $1 \, g \, L^{-1}$ NaCl, $0.2 \, g \, L^{-1}$ $MgSO_4$, $0.02 \, g \, L^{-1}$ $CaCl_2$, and $1 \, mL \, L^{-1}$ solution of trace elements (Pfenning et al., 1981; Trotsenko, 1976) was stored in a common vessel and continuously recirculated through all the bioreactors. A common sump was used to recirculate the liquid in each reactor, thereby allowing to isolate the effects of the packing material and of its surface properties on the process. A constant liquid flow rate of 43 mL min^{-1}, corresponding to a liquid linear velocity of 0.6 m h^{-1} was established. From day 7 of operation, fresh mineral medium was continuously added to the sump container at a rate of 60 mL h^{-1}.

Toluene concentration in the inlet and outlet streams of each of the four biotrickling filters were determined using an HP 5890 Series II gas chromatograph (Agilent Technologies, Wilmington, DE) fitted with an HP-5 column and a flame ionization detector. CO_2 concentrations were measured using an infrared sensor (Vernier Technologies, Beaverton, OR). The pressure drop across the reactor beds was measured by means of a U-tube water manometer.

Deposition Studies

Deposition studies were conducted in a rectangular parallel plate flow system (see Fig. S2 in Supplementary Material) installed on the stage of a BX-52 upright fluorescent microscope (Olympus, Tokyo, Japan). The dimensions of the chamber were 6 cm × 1 cm × 0.0762 cm. The chamber included a slot (9 mm × 20 mm in size) where coupons of pristine PP or treated PP were fitted (see Chen et al., 2009 for details). Mineral medium with suspended bacterial cells (5.5×10^7 cells L^{-1}) from the same source as the inoculum was injected in the axial direction through the chamber at a flow rate of 2.4 mL min^{-1}. This flow rate was selected to achieve an average velocity within the chamber matching that of the average trickling velocity in the wetted region in the biotrickling filters considering a 3% liquid holdup. Images of the PP coupon surfaces were taken every minute over the course of the 30 min experiment utilizing a 40× objective focused on a 209.0 μm × 166.3 μm area of the coupon surface. The flux of cells deposited on the surface was enumerated. The transfer rate coefficient for the bacteria was then calculated using this bacterial flux, as previously reported (Chen et al., 2009). Deposition experiments were also conducted using 1-μm fluorescent carboxylate-modified latex polystyrene particles (Invitrogen, Carlsbad,

CA) and transfer rate coefficients for the colloids were calculated with the same method. Experiments with latex colloids utilized 4×10^7 particles L^{-1} and a simple background electrolyte (KCl) at 60 and 200 mM. For observation of the colloids, an appropriate fluorescence filter (Olympus) was used in the same microscope system.

Results and Discussion

Bacterial Cell and Coupon Surface Characterization

Figure 1 shows the contact angles of water on the different treated rings. The contact angle is a measure of the hydrophobicity of the materials (Wu et al., 2005) with a greater angle corresponding to enhanced hydrophobicity. Previous studies have shown that cell adhesion to surfaces can be influenced by the hydrophobic nature of the material. Increasing contact angle and hydrophobicity has been been reported to increase cell adhesion by some authors (An and Friedman, 1998; Flemming and Schaule, 1991; Subramani and Hoek, 2008) while others have observed a decrease of cell adhesion (Sasai et al., 2008; Zelzer et al., 2008). These conflicting observations illustrate that hydrophobicity alone is not sufficient to explain adhesion trends (An and Friedman, 1998; Flemming and Schaule, 1991). In all cases, the water contact angle on the treated rings was lower than on pristine rings $(92.8 \pm 0.8°)$, demonstrating that the modifications of the PP surface that were selected resulted in greater hydrophilicity. The He–O_2 plasma-treated rings were the most hydrophilic, with a contact angle of $40.6 \pm 2.3°$, while the sandblasted rings showed only marginal difference with the pristine rings $(84.5 \pm 1.1°)$.
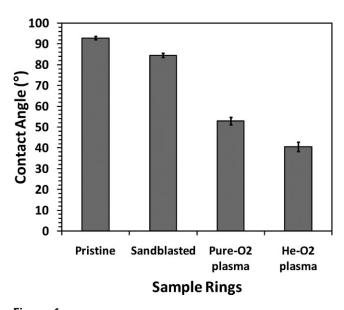

Figure 1. Contact angle with water for the different rings. The error bars show the standard error.
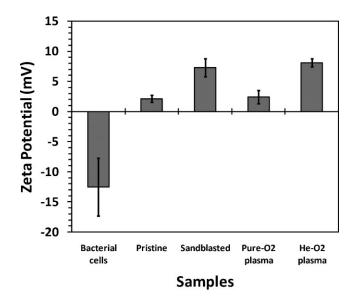

Figure 2. Zeta potential in (60 mM ionic strength) mineral medium solution of the bacterial cells used as reactor inoculum and of the different flat coupons. The error bars show the standard error.

As will be discussed later in the Deposition Studies Section, hydrophobic interactions were not the dominant mechanism by which the cells were retained on the packing material.

Figure 2 shows the zeta potentials of the four sample materials in mineral medium. Zeta potential has been shown to play a significant role in bacterial adhesion to inert matrices (Chen et al., 2009; Tsuneda et al., 2003; Walker, 2005). In particular, it has been demonstrated that the adhesion of bacteria to surfaces is largely governed by the electrostatic interactions resulting in part from the difference in surface charges, as indicated by zeta potentials (Jacobs et al., 2007). The PP test surfaces were all found to be positively charged under the solution conditions used in the biotrickling filter. The treatments led to the zeta potential for sandblasted and He–O_2 plasma-treated surfaces to become slightly more positively charged, while pure-O_2 plasma treatment did not significantly change the zeta potential. Other studies have shown that zeta potentials became more negative for plasma-treated materials (Frank et al., 1999; Khorasani and Mirzadeh, 2007); however, these tests were in different solution chemistry conditions. It is believed that opposite behavior observed in our study may be due in part to the specific surface treatment conditions and background mineral media utilized in this study.

The zeta potential of the reactor inoculum had a moderately negative value of -12.5 mV. This value falls in the upper tier in the range of -0.5 to -57 mV reported previously for pure bacterial cultures (Jacobs et al., 2007; Li and Logan, 2004). As the packing surfaces and bacterial cells were oppositely charged, electrostatic interactions were anticipated to contribute to cell adhesion and subsequent biofilm development on the packing, leading to enhanced

performance of the biotrickling filters. Hence, the performance of the bioreactors was compared as a function of the surface modifications of the packing material.

Reactors Performance

The performance of the bioreactors was evaluated during the initial stage of microbial colonization of the different packed beds. Hence, the biotrickling filters were only operated for 3 weeks, that is, a time representative of the initial acclimation phase. Figure 3 shows the removal efficiency of the four bioreactors during the startup. During the first 72 h of operation, initial adaptation of the microorganisms to the bioreactors conditions occurred and little activity was observed. Thereafter, a quasi-linear increase in removal efficiency was observed over time. Most importantly, no significant differences were observed between the four bioreactors, with all biotrickling filters reaching a toluene removal of 40–50% after 18 days of operation. As mentioned in the Materials and Methods Section, reaching only partial removal was expected and desired in order to observe possible differences between the bioreactors. Mineralization of the toluene removed was confirmed by analysis of CO_2 in the effluent stream, which also showed no major differences between the bioreactors. No significant pressure drop was observed in any of the biotrickling filters during the experimental period. This was expected as biomass growth was minimal as confirmed by visual observation during the relatively short duration of the experiment.

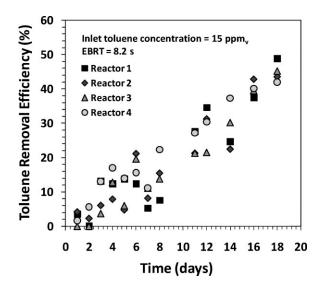The similarity in the behavior and performance of the four biotrickling filters was unexpected as it was anticipated that the different surface treatments of the PP rings would influence the biofilm development and hence the removal efficiency of toluene. Possible explanations are a combination of physical and chemical interactions. The packing surface treatments affected the water contact angle and thus the hydrophobicity of the packing. However, deposition studies (see next section) showed that hydrophobic interactions were not a dominating interaction and therefore the changes in the hydrophobicity of the packings had a negligible effect on biofilm formation. Next, there was no major difference in the zeta potential of the different treated surfaces; hence, the electrostatic forces occurring between cells and the various PP rings were effectively the same. This could in part explain the virtually identical behavior of the biofilters (Fig. 3), even if electrostatic interactions were critical to initial colonization of cells on the packing and formation of biofilm.

Surface roughness is another relevant factor that has been observed to possibly play a role in bacterial adhesion (An and Friedman, 1998; Chen et al., 2009; Show and Tay, 1999; Shellenberger and Logan, 2002). A cursory assessment of surface roughness can be made looking at SEM images of the different treated coupons (see Figs. S1 and S2 in Supplementary Material), which revealed some differences. Contrary to the common belief that plasma treatment only affects surface chemistry, both plasma treatments (pure-O_2 and He–O_2) were visually confirmed to have altered the surface topology. Logically, the sandblasted rings appeared to be the roughest; however, as was shown in Figure 3, the differences in surface roughness did not markedly affect the performance of the reactors. Therefore, no further determination of roughness parameters was conducted.

Hydrodynamic forces also play a major role in the rate of bacterial attachment and shearing from surfaces (Torkzaban et al., 2007, 2008). The trickling rate of $0.6 \, m \, h^{-1}$ that was selected for this study is a relatively standard condition for biotrickling filters used in air pollution control, and is similar to trickling filters in water treatment applications. Enhanced localized hydrodynamic shear may occur at the interface of the packing material and solution, and possibly reduced the extent of deposition and retention of cells on the surface during the experiments. This phenomenon has not been quantitatively evaluated in biotrickling filters used for air pollution control previously, as it is a major experimental challenge to determine the effect of fluid velocity and shear forces on cell deposition in a partially wetted trickling filter (Kim and Deshusses, 2008). However, it has been studied theoretically and experimentally for fully saturated conditions in flow cells and in solid porous media and it was shown to be a critical factor in the overall adhesion of cells (Purevdorj et al., 2002; Torkzaban et al., 2007, 2008). Hence, cell deposition onto the test surfaces was investigated in a flow cell under controlled conditions to identify the influence of surface properties on cell deposition and possibly explain toluene treatment performance in the biotrickling filters.

Figure 3. Start-up performance of the reactors packed with different materials. Reactor 1 was packed with pristine rings, reactor 2 with sandblasted rings, reactor 3 with pure-O_2 plasma-treated rings, and reactor 4 with He–O_2 plasma-treated rings. EBRT, empty bed gas residence time.

Deposition Studies

The first set of deposition experiments focused on evaluating the transfer rate coefficient for the different treated PP coupons using bacterial cells suspended in the same mineral medium solution used in the biotrickling filters. The main parameters of the deposition experiments are presented in Table I. The experiments revealed that bacterial deposition and adhesion to the PP coupons was poor, with less than five cells depositing within 1 h. Hence, a meaningful transfer rate coefficient could not be calculated. This demonstrated that the physical and chemical conditions within the system (i.e., chemistry of the coupons and hydrodynamics) were both unfavorable for cell attachment.

To further investigate the chemical contribution to cell retention, bacterial adhesion was measured for cells at a significantly higher ionic strength (360 mM mineral medium) than the solution used in the reactors. Bacterial adhesion improved to about 10 cells depositing within 1 h, which is still not enough to statistically determine differences between the various surfaces. Under these conditions, the bacterial transfer rate coefficient for all the materials was about 10^{-10} m s^{-1}, a very low value as compared to previously reported bacterial transfer rates at similar ionic strength conditions (Chen et al., 2009).

Further experiments were conducted with a colloidal suspension in a simple salt solution (KCl). As the colloids are notably more negatively charged than the cell inoculum, these conditions should be more favorable for deposition based upon electrostatic interaction forces (see Table I). Figure 4 shows the transfer rate coefficients determined for the colloids onto the different coupons. For all surfaces, the colloidal transfer rate coefficients ranged between 1×10^{-8} and 1.5×10^{-8} m s^{-1}, with statistically insignificant differences between them. Interestingly, the colloidal deposition coefficient was about two orders of magnitude greater than that of the bacteria. This suggests deposition is in fact enhanced with greater electrostatic attraction, although not sensitive to the subtle differences between the coupons.

Further insight into the mechanisms involved in adhesion to packing materials can be gained by the consideration of DLVO theory, which predicts the total interaction forces between surfaces as a function of the electrostatic interactions and van der Waals forces (Derjaguin and Landau, 1941; Verwey and Overbeek, 1948). Recently, this theory has
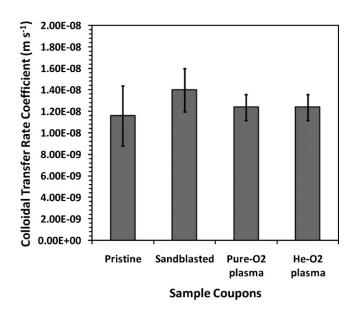

Figure 4. Colloidal transfer rate coefficients in 200 mM KCl for the different flat coupons. The error bars show the standard error.

been applied to bacterial systems (Redman et al., 2004). As the bacteria, colloids, and PP coupons are charged, electrical double layers of counterions exist around their surfaces. The thickness of these electrical double layers is a function of the solution ionic strength. At 60 mM, the DLVO theory indicates (see sample interaction energy profile in Supplementary Material) that the combination of electrostatic and van der Waals forces results in no energy barrier between either the bacteria or colloids and the coupons. This would suggest that under any of the chemical conditions tested, effective adhesion should occur. However, this was not the case for the bacteria, as compared to the more negatively charged colloids. Under the conditions of these deposition experiments, bacteria required a considerably higher ionic strength for adhesion to be quantifiable, despite the fact that the DLVO theory suggests that the chemical interactions are favorable. One possible explanation for the low deposition is that hydrodynamic forces may have reduced cell retention on the coupon surface. However, the Peclet number in the flow cell was 0.023 which indicates a diffusion-dominated

Table I. Characteristics of the reactor inoculum and the bacterial and colloidal solutions used in the deposition studies.

		Deposition studies			
	Reactor inoculum (bacterial cells)	Bacterial cells		Polystyrene colloids	
Solution	Mineral medium	Mineral medium	Mineral medium 6×[a]	KCl, 60 mM	KCl, 200 mM
Solution ionic strength (mM)	60	60	360	60	200
Concentration (particles mL^{-1})	4.5×10^8	5.5×10^7	5.5×10^7	4×10^7	4×10^7
Zeta potential (mV)	-12.5 ± 4.8	-12.5 ± 4.8	ND[b]	-32.0 ± 2	-42.7 ± 6.7

[a]Six times the concentration of the standard mineral medium.
[b]Not measurable due to limitations of the instrument at ionic strengths >200 mM.

regime with low shear. Thus, other factors not yet identified contributed to the low cell deposition.

Overall, the results from the deposition studies demonstrate that the operating conditions selected for the biotrickling filters were greatly unfavorable for cell adhesion, both due to the low ionic strength of the trickling solution leading to minimal bacterial-packing media interactions and to the liquid trickling rates at which the biological filters are maintained. The operating conditions of biotrickling filters have been selected for economical reasons and to limit excessive growth of biomass (Cox et al., 2000). However, deposition and biotreatment results highlight that while hydrophilicity and surface roughness are relevant parameters, hydrodynamic and electrostatic interaction forces are mostly likely the dominating factors controlling the extent of initial cell deposition and possibly the performance of the filters during the early phases of operation.

As the surface treatments tested in this study primarily affected the hydrophobicity of the materials and not the electrostatic conditions, the performance observed in the biotrickling filters and deposition rates for all the materials were very similar. Even so, this study highlights the needs for detailed research on the development of suitable surface properties for packing materials and on defining optimum operating conditions (solution chemistry and liquid flowrates) that will enhance bacterial deposition and biofilm growth during startup, and may ultimately result in more effective bioprocesses.

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