Wastewater from petroleum refining may contain a number of undesirable contaminants including sulfides, phenolic compounds, and ammonia. The concentrations of these compounds must be reduced to acceptable levels before discharge. Sulfur formation and the effect of selected phenolic compounds on the sulfide oxidation were studied in autotrophic aerobic cultures. A recirculation reactor system was implemented to improve the elemental sulfur recovery. The relation between oxygen and sulfide was determined calculating the O₂/S²⁻ loading rates (QO₂/QS₂⁻ = Rmt), which adequately defined the operation conditions to control the sulfide oxidation. Sulfur-producing steady states were achieved at Rmt ranging from 0.5 to 1.5. The maximum sulfur formation occurred at Rmt of 0.5 where 85% of the total sulfur added to the reactor as sulfide was transformed to elemental sulfur and 90% of it was recovered from the bottom of the reactor. Sulfide was completely oxidized to sulfate (Rmt of 2) in a stirred tank reactor, even when a mixture of phenolic compounds was present in the medium. Microcosm experiments showed that carbon dioxide production increased in the presence of the phenols, suggesting that these compounds were oxidized and that they may have been used as carbon and energy source by heterotrophic microorganisms present in the consortium.

Introduction

A petroleum refinery is a complex combination of interdependent industrial processes that generate effluents containing both organic and inorganic compounds. The term “sour” was originated to describe a waste contaminated with sulfide (1). Sour water streams in the refineries are generated from sour steam condensates from distillation, thermal or hydrogen cracking operations, and product heating process (2). Depending on where the sour condensates are produced, the sulfide, phenols, and ammonia concentrations (mg L⁻¹) present in these streams can range from 10 to 5000, from 5 to 300, and from 10 to 3000, respectively. Because of its high sulfide, phenols, and ammonia content, the sour water stream must be treated before its release into the environment.

Sour waste streams, including sour water, sour gases, and refinery spent-sulfidic caustics, have been successfully treated using Thiobacillus denitrificans, while organic compounds such as benzene, toluene, and phenol are biodegraded by heterotrophic bacteria grown in co-culture with T. denitrificans (1, 3). T. denitrificans strain F, isolated by Sublette and Woolsey (4), was used to treat sour effluents because of its higher sulfide tolerance in comparison with other facultative strains. Strain F tolerates sulfide concentrations up to 56 mg L⁻¹. Recently McComas et al. (5) characterized a novel system for sulfide oxidation using an enrichment culture dominated by Thiomicrospira sp. The consortium showed similar oxidation activities as compared to T. denitrificans under anaerobic conditions; however, it was more tolerant to extreme culture conditions such as pH (5.6–10.4), temperature (up to 46°C), and salt concentration (30% of NaCl). The authors concluded that the process described was shown to be a more robust biocatalyst system for sulfide oxidation than the systems using T. denitrificans.

Other species of thiobacilli have been studied to promote the sulfur production from partially reduced sulfur compounds oxidation (6–8). Sulfur production (eq 1) from the partial oxidation of sulfide instead of a complete oxidation to sulfate (eq 2) presents environmental implications as elemental sulfur can be removed by sedimentation. Additionally, lower energy consumption is required because the oxidation to sulfur requires 4-fold less oxygen:

\[
2HS^- + O_2 \rightarrow S^0 + 2OH^- \\
\Delta G^- = -129.50 \text{kJ mol}^{-1}
\]

\[
2HS^- + 4O_2 \rightarrow 2SO_4^{2-} + 2H^+ \\
\Delta G^+ = -732.58 \text{kJ mol}^{-1}
\]

According to the stoichiometry of the aerobic biological sulfide oxidation, oxygen is the key parameter that controls the level of oxidation (7). Buisman et al. (9) reported that, at sulfide concentrations below 20 mg L⁻¹, the oxygen concentration should be kept low (below of 1 mg L⁻¹) to limit the sulfur oxidation to sulfate. Thereby at sulfide concentrations higher than 20 mg L⁻¹, the sulfur formation is independent of the oxygen concentration. According to these data, Janssen et al. (10) found that the optimal oxygen to sulfide molar ratio to improve the sulfur production was about 0.7. The same authors described the performance of a sulfide-oxidizing expanded-bed reactor that was designed for elemental sulfur formation (7). In this reactor, the aeration of the liquid phase and the oxidation of sulfide were spatially separated. Sulfur sludge with good settling properties, which consisted mainly of elemental sulfur (92%) and biomass (2%), was obtained. Steffes et al. (11) reported that Thiobacillus o and Thiobacillus neapolitanus produced elemental sulfur from partial oxidation of hydrogen sulfide or thiosulfate. They also found that elemental sulfur was formed under oxygen limitation (0.1% saturation) or at high substrate loading rates (Q = 18 mmol L⁻¹ h⁻¹). Sulfide and thiosulfate thus proved to be interchangeable substrates for chemolithotrophic bacteria producing sulfur and sulfate. In the same way, Visser et al. (8) reported that sulfur formation in a Thiobacillus sp.
strain W5 was directly related to its maximum electron-transferring capacity or oxygen consumption rate. Consequently, sulfur formation was shown to occur when the maximum oxidative capacity of the culture was approached, indicating that if the sulfide concentration was increased, the organism had to convert part of the sulfide to sulfur instead of to sulfate.

The purpose of this work was to study the parameters that control the hydrogen sulfide oxidation using an aerobic sulfide-oxidizing consortium. Special emphasis was put on both the elemental sulfur-producing conditions and the effect of selected phenolic compounds usually present in sour water on the autotrophic sulfide oxidation under steady state.

Materials and Methods

Microorganisms and Culture Medium. The sulfide-oxidizing consortium was obtained from a pilot plant trickling biofilter used for the elimination of CS₂ and H₂S in waste gas. The consortium was obtained from a pilot plant trickling biofilter Microorganisms and Culture Medium.

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tion of phenol and the cresols by the consortium. Serum bottles (100 mL) containing 18 mL of mineral medium without sulfide and carbonates and 2 mL of inoculum were used. The inoculum was obtained from 1.8 L of culture at steady-state conditions and centrifuged (15300g) for 20 min. The pellet was washed and suspended in 50 mL of 0.85% NaCl. The protein was quantified to calculate the specific degradation rate. Duplicate microcosms were then amended to a final concentration of 25, 50, 100, and 200 mg of phenol L\(^{-1}\) and 12.5, 25, and 50 mg of cresol isomers (o-, m-, and p-cresol) L\(^{-1}\). Serum bottles containing mineral medium and inoculum were used as controls. The serum bottles were sealed with Teflon caps and then incubated with continuous agitation on an orbital shaker (180 rpm) at 30 °C. During incubation (16 h), CO\(_2\) production was measured from the headspace by gas chromatography. Additional 0.5-mL aliquots were taken to measure the phenolic compounds consumption by GC.

The sulfide-oxidizing activity of the mixed community was measured by the method proposed by Buisman et al. (6) used with free cells. The method is based on the O\(_2\) uptake rate measurement and was corrected for chemical oxidation and endogenous respiration. The oxygen concentration in the liquid was measured with an oximeter YSI (5300 Biological Oxygen Monitor, YSI Co.). The values were reported as mg of HS\(^{-}\) \(\text{g protein}^{-1}\) min\(^{-1}\).

**Analyses.** Thiosulfate, sulfate, and sulfite were analyzed by HPLC (Waters-Millipore model 600, Milford, Ma) using a photodiode array detector at 308 nm. A ChromSep IonoSphere 5A (200 × 3 mm) (Varian Inc., Palo Alto, CA) column was used. Potassium hydrogen phthalate (0.04 M at pH 4) was used as mobile phase. Sulfur content in the sediment was measured following the procedure of Bartlett and Skoog (14), and the Cord-Ruwisch (15) method was used to quantify sulfide. Biomass was estimated through protein measurement by the Lowry method. Phenol and cresol isomers were measured using a GC (HP, 6890, Hewlett-Packard Co., Avondale, PA) with a flame ionization detector. A capillary column (50 m × 0.25 mm) AT-1000 (Alltech, USA) was used. The injector temperature was 250 °C, and the temperature gradient started at 180 °C. The temperature increased at a rate of 2 °C min\(^{-1}\) to 275 °C. Carbon dioxide concentration was evaluated in a TCD-GC (Gow-Mac Instrument Co., Madison, NJ) equipped with a CTR-1 concentric column (Alltech, USA). The operating conditions were as follows: injector 70 °C, oven 30 °C, detector 60 °C, and helium was used as the carrier gas at 65 mL min\(^{-1}\).

**Results and Discussion**

**Sulfide Oxidation and Sulfur Production under Different \(R_{\text{ext}}\).** The effect of oxygen on the sulfide oxidation was investigated for \(R_{\text{ext}}\) values ranging from 0.15 to 2.0 under steady-state conditions at a dilution rate of 1.0 d\(^{-1}\) and sulfide loading rate of 2 g L\(^{-1}\) d\(^{-1}\). The stages describing the sulfide oxidation were (a) a partial sulfide oxidation stage producing elemental sulfur at ratios ranging from 0.5 to 1.5; (b) a complete sulfide oxidation to sulfate stage under ratios from 1.5 to 2, and (c) low sulfide oxidation at ratio lower than 0.5. The three stages observed for sulfide oxidation as a function of the \(R_{\text{ext}}\) are depicted in Figure 2.

As shown in Figure 2, an elemental sulfur-producing stage was observed at \(R_{\text{ext}}\) range from 0.5 to 1.5. The maximum sulfur production was observed at \(R_{\text{ext}}\) of 0.5, where 85% of the sulfide in the influent was recovered as elemental sulfur, while less sulfur accumulation was found as \(R_{\text{ext}}\) was increased to 1.5. When a \(R_{\text{ext}}\) of 2.0 was applied to the system, a complete oxidation of sulfide to sulfate was observed. The results are in agreement with data reported by Janssen et al. (7) under transient state conditions. The design of the reactor allowed recovering a maximum of 90% of the produced elemental sulfur through the bottom of the reactor, whereas the rest left the reactor with the effluent.

Finally, at \(R_{\text{ext}}\) lower than 0.5, both the sulfide oxidation and the microbial growth were affected. The sulfide-oxidizing activity was strongly impacted at a ratio of 0.15, and cell washout conditions were initiated at \(R_{\text{ext}}\) lower than 0.5. The effect observed at low \(R_{\text{ext}}\) was related to an oxygen limitation in the culture that promoted the sulfide accumulation in the reactor. The accumulation of sulfide attained toxic levels for the microorganisms as has been reported previously (5). Under these conditions, thiosulfate was detected in the culture at ratios between 0.25 and 0.35 (10% of total sulfur species, Figure 2).

The results showed that the microbial protein concentration in the reactor increased from 100 mg L\(^{-1}\) at total sulfate conversion conditions to 270 mg L\(^{-1}\) when elemental sulfur was produced. It has been suggested (7) that the formation of the elemental sulfur provides a surface for attachment of the cells that favor the retention of biomass inside the reactor.

**Sulfide Oxidation and Sulfur Production under Different Dilution Rates.** The sulfide oxidation was studied under different dilution rates at steady-state conditions of 0.5, 1, 1.5, 2, and 3 d\(^{-1}\) maintaining a constant sulfide concentration in the feed solution at 4.0 g L\(^{-1}\). The reactor was operated for more than 100 d, and the results are shown in Table 1. Elemental sulfur was produced at dilution rates of 0.5, 1, 1.5, and 2. Similarly to the results described in the previous section, the maximum sulfur formation occurred at \(R_{\text{ext}}\) of 0.5, accounting for 75% of the total sulfur added to the reactor. However, the elemental sulfur production was affected by the dilution rate applied to the system. When the system operated at \(R_{\text{ext}}\) for sulfide production (0.5 and 0.75) and dilution rates of 0.5, 1, and 2, the elemental sulfur produced was higher than 60%, while washout conditions were observed when the dilution rate was increased from 2 to 3 at a \(R_{\text{ext}}\) of 0.75.

Sulfide was completely oxidized to sulfate at dilution rates of 0.5 and 1.0 d\(^{-1}\) and \(R_{\text{ext}}\) of 2. However, when the dilution rate was increased at values of 1.5 and 2 d\(^{-1}\), the sulfide-oxidizing activity was affected. Possibly, the culture was washed out due to the high recirculation flow (500 and 666 L h\(^{-1}\), respectively) required to reach the set \(R_{\text{ext}}\). To confirm this hypothesis, the recirculation flow rates applied during the experiments were compared. For example, when the reactor was operated at a dilution rate of 2.0 d\(^{-1}\) and \(R_{\text{ext}}\) of 0.75 and 1.0, the recirculation flow rates were 250 and 333 L h\(^{-1}\), respectively. Under these conditions, the results showed

![Figure 2: Sulfur species and protein produced during the sulfide oxidation in the recirculation reactor operated at sequential O\(_2/S\)\(^2\) molar ratios under steady-state conditions at a dilution rate of 1.0 d\(^{-1}\) and sulfide loading rate of 2 g L\(^{-1}\) d\(^{-1}\). Sulfide (●), sulfate (○), elemental sulfur recovered from the bottom of the reactor (▲), thiosulfate (◇), and protein (◆).](image-url)
that approximately 92% of sulfide was oxidized to sulfate and sulfur, whereas the rest of sulfide was detected in the effluent. When the \( R_{\text{net}} \) was increased to 1.5 (recirculation flow rate of 500 L h\(^{-1}\)), washout conditions were again observed, confirming the proposed hypothesis. Finally, when a dilution rate of 3 d\(^{-1}\) and \( R_{\text{net}} \) of 0.75 (flow rate of 375 L h\(^{-1}\)) were applied, the sulfide removal efficiency was zero and the microbial culture was washed out.

According to the results, it can be suggested that the critical circulation flow was found between 333 and 375 L h\(^{-1}\). Consequently, the circulation flow is an important parameter that has to be considered to develop this kind of reactor. In this form, under the culture conditions evaluated, a sulfide loading rate of 2 g L\(^{-1}\) d\(^{-1}\) was reached with 100% of sulfide oxidation either to sulfate or elemental sulfur and sulfate, whereas 4 g of sulfide L\(^{-1}\) d\(^{-1}\) could be oxidized with 92% of conversion of sulfide to sulfur and sulfate. According to Janssen et al. (7), it was possible to oxidize 6 g L\(^{-1}\) d\(^{-1}\) in an expanded-bed reactor operated under transient-state conditions.

An average growth yield of 2.85 g protein mol\(_{\text{sulfide}}\)^{-1} was found for the consortium at the dilution rates evaluated, which is comparable with data reported for pure cultures of Thiobacillus species. For Thiobacillus thioparus ATCC in continuous culture at \( D = 0.7 \text{ d}^{-1} \), de Zwart et al. (16) reported a growth yield of 3.1 g protein mol\(_{\text{sulfide}}\)^{-1}, whereas, Sublette (17) reported a growth yield of 5.8 g protein mol\(_{\text{sulfide}}\)^{-1} for T. denitrificans ATCC 23642 grown under aerobic conditions in batch cultures. Cadenville and Sublette (18) compared the sulfide oxidation ability of other thiobacilli species and observed similar growth values. These authors reported growth yields for Thiobacillus thioparus ATCC 23647 of 2.57 g protein mol\(_{\text{sulfide}}\)^{-1}, for Thiobacillus versatilis ATCC 25364 of 3.8 g protein mol\(_{\text{sulfide}}\)^{-1}, for Thiobacillus thiooxidans ATCC 19377 of 3.2 g protein mol\(_{\text{sulfide}}\)^{-1}, and for Thiobacillus neapolitanus ATCC 23641 of 4.85 g protein mol\(_{\text{sulfide}}\)^{-1}. These data showed that the thiobacilli examined exhibited lower biomass yields than those found for T. denitrificans.

**Sulfide Oxidation Rate by the Consortium.** To evaluate the maximum sulfide oxidation rate, respirometric tests were performed at optimal temperature (30°C), pH (7), and sulfide concentrations between 0 and 256 mg L\(^{-1}\) (0–8 mM). Biomass obtained from the reactor at steady-state conditions under a sulfate-producing phase was used for these studies. By adjusting the saturation model reported by Han and Levenspiel (19) to the data (results not shown) and using the stoichiometry of sulfide oxidation, a maximum sulfide oxidation rate of 22.4 mg of HS\(^{-}\) g\(_{\text{protein}}\) min\(^{-1}\) and a saturation constant (\( K_s \)) of 8.96 mg L\(^{-1}\) (0.28 mM) were obtained. At sulfide concentrations above 32 mg L\(^{-1}\) (1 mM) inhibition of the sulfide oxidation activity was observed. In biological systems, sulfide oxidation rates between 1.1 and 61.7 mg of HS\(^{-}\) g\(_{\text{protein}}\) min\(^{-1}\) have been reported (20).

Table 1. Sulfur Balances in Steady-State Continuous Cultures of Bacterial Consortium at Different Dilution Rates and R\(_{\text{net}}\)\(^{a}\)

<table>
<thead>
<tr>
<th>( D ) (d(^{-1}))</th>
<th>( Q_{\text{S}2}^{-}) ( R_{\text{net}} ) (g L(^{-1}) d(^{-1}))</th>
<th>( Q_{\text{S}2}^{-}) (out) (g L(^{-1}) d(^{-1}))</th>
<th>( Q_{\text{SO}_4}^{-}) (out) (g L(^{-1}) d(^{-1}))</th>
<th>( S_{\text{S}2}^{-}) (out) (g L(^{-1}) d(^{-1}))</th>
<th>( O_2) (out) (g L(^{-1}) d(^{-1}))</th>
<th>Protein (mg L(^{-1}))</th>
<th>Sulfide removal (%)</th>
<th>Elemental sulfur recovered (%) (^{b})</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>0.5</td>
<td>1</td>
<td>1</td>
<td>0.5</td>
<td>1.5</td>
<td>0.75</td>
<td>208</td>
<td>100</td>
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<tr>
<td>0.5</td>
<td>0.25</td>
<td>2</td>
<td>5.8</td>
<td>0.9</td>
<td>1.1</td>
<td>1.5</td>
<td>60</td>
<td>75</td>
</tr>
<tr>
<td>0.75</td>
<td>0.75</td>
<td>2</td>
<td>2.3</td>
<td>2.3</td>
<td>1.25</td>
<td>1.5</td>
<td>270</td>
<td>100</td>
</tr>
<tr>
<td>1.0</td>
<td>1.0</td>
<td>2</td>
<td>3.8</td>
<td>3.8</td>
<td>0.6</td>
<td>0.6</td>
<td>167</td>
<td>100</td>
</tr>
<tr>
<td>1.5</td>
<td>1.5</td>
<td>2</td>
<td>4.7</td>
<td>4.7</td>
<td>0.3</td>
<td>0.3</td>
<td>140</td>
<td>100</td>
</tr>
<tr>
<td>2.0</td>
<td>2.0</td>
<td>2</td>
<td>5.9</td>
<td>5.9</td>
<td>0</td>
<td>0</td>
<td>105</td>
<td>100</td>
</tr>
<tr>
<td>1.5</td>
<td>2.0</td>
<td>3</td>
<td>2.3</td>
<td>2.3</td>
<td>1.25</td>
<td>0.6</td>
<td>105</td>
<td>100</td>
</tr>
<tr>
<td>2.0</td>
<td>2.0</td>
<td>4</td>
<td>2.3</td>
<td>4.0</td>
<td>1.2</td>
<td>1.5</td>
<td>138</td>
<td>93</td>
</tr>
<tr>
<td>3.0</td>
<td>3.0</td>
<td>4</td>
<td>2.8</td>
<td>5.0</td>
<td>1.0</td>
<td>2.0</td>
<td>155</td>
<td>91</td>
</tr>
</tbody>
</table>

\(^{a}\) Cultures were grown with 30 g of Na\textsubscript{2}S\textsubscript{2}·9H\textsubscript{2}O L\textsuperscript{-1}. Sulfide and medium were fed individually. \(^{b}\) Total sulfur added to reactor as sulfide transformed to elemental sulfur and recovered from the bottom of the reactor.

Effect of Selected Phenolic Compounds on the Sulfide-Oxidizing Consortium. As phenolic compounds are present in sour water effluents, it is of the utmost importance to know the effect of these compounds on the autotrophic sulfide oxidation under steady-state conditions. Consequently, a sulfide-oxidizing stirred tank reactor with a recirculation device was operated at a dilution rate of 1.0 d\(^{-1}\) and a sulfide loading rate of 2.0 g L\(^{-1}\) d\(^{-1}\). To avoid possible oxygen limitation and the inhibition on the autotrophic consortium by both sulfide and phenolic compounds, an oxygen-rich \( R_{\text{net}} \) of 2.0 was selected for operation of the reactor. The concentrations of the phenolic compounds evaluated were similar to those present in sour water effluents from Mexican refineries. Phenol was evaluated at OLR range from 25 to 200 mg L\(^{-1}\) d\(^{-1}\) (Figure 3A).

Before phenol was amended, the microbial cell concentration was 140 mg g\(_{\text{protein}}\) L\(^{-1}\), and when a OLR of 25 mg of phenol L\(^{-1}\) d\(^{-1}\) was used, the consortium growth was affected and protein concentration decreased to 100 mg g\(_{\text{protein}}\) L\(^{-1}\) (Figure 3B). However, the sulfide oxidation was not affected, and 100% of sulfide was oxidized to sulfate. The protein concentration increased to 120 mg g\(_{\text{protein}}\) L\(^{-1}\) when the OLR reached 200 mg of phenol L\(^{-1}\) d\(^{-1}\). At OLR below 200 mg L\(^{-1}\) d\(^{-1}\), phenol was not detected in the medium, while at OLR of 200 mg L\(^{-1}\) d\(^{-1}\) about 5% of phenol added was present in the reactor (Figure 3B).

Cresol isomers were also amended at several OLR, together with phenol (100 mg L\(^{-1}\) d\(^{-1}\), and steady-state conditions...
Microcosms experiments were performed to evaluate the utilization of phenol and cresols and to obtain kinetic assessments at 30 °C and 180 rpm. (B) Background-corrected CO₂ (μmol) from phenol oxidation at 25 (●), 50 (○), 75 (△), 100 (□), and 200 (●) mg L⁻¹, which corresponded to 5.3, 10.6, 15.9, 21.2, and 42.4 μmol of compound in 20 mL of culture medium evaluated in microcosm assessments.

**FIGURE 4.** (A) Phenol consumption evaluated in microcosm assessments. (B) CO₂ production (μmol) from phenol oxidation at 25 (●), 50 (○), 75 (△), 100 (□), and 200 (●) mg L⁻¹, which corresponded to 5.3, 10.6, 15.9, 21.2, and 42.4 μmol of compound in 20 mL of culture medium evaluated in microcosm assessments.

**TABLE 2.** Kinetic Parameters from Degradation of Phenolic Compounds in Microcosm Experiments Performed at 30 °C

<table>
<thead>
<tr>
<th>Phenolic compound</th>
<th>Degradation rate (μmol g⁻¹ h⁻¹)</th>
<th>Kᵣ (mg L⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phenol</td>
<td>0.308</td>
<td>14</td>
</tr>
<tr>
<td>p-Cresol</td>
<td>0.129</td>
<td>18</td>
</tr>
<tr>
<td>o-Cresol</td>
<td>0.123</td>
<td>20</td>
</tr>
<tr>
<td>m-Cresol</td>
<td>0.123</td>
<td>16</td>
</tr>
</tbody>
</table>

The use of aerobic and anaerobic heterothrophic bacteria to treat phenolic compounds has been extensively reported, and a review over the biodegradative limitations was made by Field et al. (21). With regard to chemolithotrophic bacteria, strict chemolithotrophic, mixotrophic, and chemorganotrophic bacteria have been found, and the negative effect of organic compounds on the strict chemolithotrophic has been reported (22). Nevertheless, the fate of phenolic compounds with chemolithotrophic oxidizing bacteria has been investigated.
been poorly studied. In a previous work, Alcántara et al. (12) reported that a consortium grown in a bioscrubber that treated effluents with carbon bisulfide and hydrogen sulfide was composed of heterotrophic and chemolithotrophic microorganisms. The chemolithotrophic bacteria were responsible for the reduced sulfur compounds oxidation. For this work a Thiobacillus sp. strain A1 isolated from the sulfide-oxidizing consortium was used to evaluate the phenolic compounds oxidation of chemolithotrophic bacteria. The activity of the isolated Thiobacillus sp. strain A1 was evaluated in the presence of 25 and 50 mg L\(^{-1}\) and was compared with the activity of the consortium. Figure 5 shows that Thiobacillus sp. strain A1 did not use phenol while the compound was completely oxidized by the consortium. Consequently, it seems that other heterotrophic microorganisms were responsible of the phenolic compounds degradation while chemolithotrophic bacteria oxidized the inorganic compound. The coexistence of both populations in the sulfide-oxidizing consortium was probably favored by the mild pH conditions preferred by this Thiobacillus sp. strain A1, and most probably the heterotrophic microorganisms survived in the consortium on microbial excretion or lysis products. As previously mentioned, the consortium growth under steady-state and autotrophic conditions was 140 mg\(_{protein}\) L\(^{-1}\) while 100 mg L\(^{-1}\) was detected at a phenol loading rate of 25 mg L\(^{-1}\)d\(^{-1}\). After approximately 180 d of reactor operation, the protein increased reaching almost 140 mg L\(^{-1}\), most probably because of the use of phenolic compounds by heterotrophic microorganisms.

Similar studies conducted with T. denitrificans have shown that sulfide was completely oxidized to sulfate by the chemolithotrophic bacteria and that heterotrophic microorganisms were responsible of phenolic compounds degradation (1, 3). No reports were found for the treatment of sour effluents by sulfide-oxidizing consortia under aerobic conditions.

The results showed that complex effluents, such as sour water streams from petrochemical industries, could be treated using the system evaluated allowing elemental sulfur recovery, thus sequestering the element from the geochemical cycle.

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**Literature Cited**


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