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Some recent advances in the bioprocessing of bauxite

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Abstract

This paper describes some of the important microbiological and engineering challenges in scaling up biobeneficiation of bauxite. A soil bacterium *Paenibacillus polymyxa* was recently shown to selectively remove calcium and iron impurities from low grade bauxite ($< 50\%$ Al), for abrasive and refractory applications, respectively. An industrial scale formulation of Bromfield medium (called ISF-2), based on cane sugar and tap/mine water, is developed to successfully culture *P. polymyxa* under septic conditions. The culture is found to be efficient in removing calcium from bauxite ore, carried out as cascade operations in total recycle slurry reactors. In cascade leaching experiments with pre-grown culture, calcium removal was observed to occur solely by indirect mechanism in an initial rapid phase lasting few minutes, followed by a gradual phase comprising of direct attack as well as indirect mechanisms. An alternative mechanism of indirect leaching is proposed based on solubilisation of accessible calcium in the culture metabolite, up to a saturation solubility limit. The saturation solubility theory gives an explanation for the need to perform cascade experiments, and also successfully predicts the possibility of pulse leaching experiments. Some of these recent advances are likely to enable successful commercialisation of bauxite biobeneficiation.

Keywords: bauxite; biobeneficiation; bioleaching; Bromfield medium; cascade; *Paenibacillus polymyxa*; solubilisation mechanism; solubility limit

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1. Introduction

The use of microorganisms in leaching and beneficiation of lean grade ores and minerals is widely considered an efficient, economical and environmentally benign alternative to conventional hydrometallurgical operations. Biohydrometallurgy is commercially exploited in the recovery of copper and uranium, and is also used for increasing the recovery of finely disseminated gold from refractory ores like pyrite and arsenopyrite (Rawlings, 1998; Natarajan, 1998). Bacterial oxidation of sulphide ores using chemoautotrophic bacteria such as *Thiobacillus ferrooxidans* and *Thiobacillus thiooxidans* is a well-known process in biohydrometallurgy, and thought to occur by a combination of direct and indirect mechanisms (Ehrlich, 1992). These bacteria attach themselves to the sulphide ore particles and form etch patterns on the mineral surface. This is known as direct attack mechanism. *Thiobacillus* also oxidises ferrous ions in the solution to produce ferric ions, which indirectly oxidises the sulphides. This is called indirect mechanism because the bacterium is not directly involved in the leaching process. Biohydrometallurgy of non-sulphidic minerals has received little attention in the past, compared to bioleaching of sulphidic minerals by *Thiobacilli* that dominates the literature. There are several examples of such microbe-mineral systems in which selective degradation of mineral component(s) have been found to occur through the action of metabolic products, e.g., bioleaching of aluminium from alumino-silicates (Groudev et al., 1982), biological removal of iron from sands, kaolins (Groudev et al., 1983, 1985), china clay (Chaudhury and Das, 1990), bioleaching of nickel from laterites (Bosecker, 1985; McKenzie et al., 1987), and biobeneficiation of bauxite to remove impurities like silica (Groudeva and Groudev, 1983), calcium (Modak et al., 1999), iron (Deo et al., 1999), etc. Biobeneficiation differs from bioleaching in that it refers to the selective dissolution of undesirable mineral component(s) from the ore by direct or indirect action of the microbes, thereby enriching the desirable mineral content in the ore.

Bauxite is the main source of the world's most abundant metal aluminium, and low-grade bauxite ($< 50\%$ Al) is used in the manufacture of alumina-based abrasives and refractories. Abrasive applications require that calcium content in the bauxite ore should not exceed 0.5% (expressed as %CaO), and refractory applications require that Fe_2O_3 should be as low as 1%. Several physico-chemical processes such as froth floatation, gravity separation, reduction roasting and magnetic separation are available for beneficiation of bauxite. However, these methods are energy and cost intensive, less flexible and pose environmental problems. Therefore, biotechnological solutions have been attempted for processing bauxite. Removal of silica from bauxite by using *Bacillus circulans* (Groudeva and Groudev, 1983) and *Bacillus mucilaginosus* (Karavaiko et al., 1989; Ogurtsova et al., 1990), and solubilisation of aluminium from alumino-silicates by *Aspergillus niger* (Groudev et al., 1982) were reported in the 1980s. In their paper, Groudeva and Groudev reported continuous leaching operation for alumnio-silicate biodegradation in five stirred vessels of 5-l capacity each. The leaching took place for 5 days, and each day the slurry from the last vessel was filtered, and 1 l of filtrate (containing bacteria) recycled to the first vessel in the series. It was also suggested by Karavaiko et al., 1989 that alumnio-goethite can be treated with microorganisms to

increase the extraction of aluminium by Bayer's process, but none of these ideas could be commercially exploited. Recently, the microbial ecology of bauxite ore and water samples from Jamnagar mines (India) was reported (Natarajan et al., 1997), and preliminary investigations showed that beneficiation of bauxite using *Bacillus polymyxa* can selectively remove calcium and iron impurities for abrasive and refractory applications, respectively (Anand et al., 1996).

B. polymyxa is an N_2-fixing chemoorganotroph and a facultative anaerobe. It is known to produce metabolites such as acetic, formic, lactic, succinic acids, besides ethanol, and 2,3-Butanediol (2,3-Butyleneglycol) and/or acetoin (Roberts, 1947; Groudev and Groudeva, 1986; Gottschalk, 1989; Mankad and Nauman, 1992). It also produces extra-cellular polysaccharides (ECP) such as levan (Anand et al., 1996), that forms the capsule of the organism (Murphy, 1952). *B. polymyxa* has a calcium-dependent metabolism; Ca is required for the production of enzymes like amylases and proteases (Gottschalk, 1989), for the synthesis of Ca-dipicolinate, an essential component of its endospores, and also for the production of slime (or *myxa*) (Wilkinson, 1958). *B. polymyxa* can utilize calcite in the ore to meet its calcium requirements, and its metabolic products can solubilise calcium from the ore, resulting in beneficiation of bauxite. Keeping in tune with the recent change of appellation (Ash et al., 1993), *B. polymyxa* is referred to in this work as *Paenibacillus polymyxa*.

We have recently reported scaling up of bauxite biobeneficiation from shake flask experiments to demonstration bioreactors, designed for flexibility of operation and easy adaptability by the mining industry (Modak et al., 1999). This paper describes some of the important microbiological and chemical engineering challenges encountered in the scale up of bauxite biobeneficiation. As the focus of this work is on abrasive applications, the removal of calcium is given priority over iron removal. Besides, excessive iron removal is not very beneficial for abrasive applications because iron is externally added to remove silica from bauxite as ferro-silicon (Khanna, 1997).

2. Materials and methods

2.1. Ore

Bauxite ore samples were obtained from Orient Abrasives from their Jamnagar mines in Gujarat, India. The raw bauxite was crushed, ground and screened to select the $-200+300$ mesh (53–74 μm) size fraction, with the chemical and mineralogical composition shown in Table 1.

2.2. Microorganism and growth medium

The Bromfield medium (Bromfield, 1954) used to culture *Bacillus* species contains 0.5% sucrose, essential salts, yeast extract as nitrogen source, and up to 5 g/l (or 5000 ppm) of $CaCO_3$. However, it would typically take about 2 days under optimal growth

Table 1
Chemical and mineralogical composition of $-200+300$ mesh bauxite ore

Chemical composition	wt.%	Mineralogical composition	wt.%
Al_2O_3	58.6	Cliachite	75–80
Fe_2O_3	2.32	Goethite	10–15
		Hematite	1–2
CaO	2.8	Calcite	5–7
SiO_2	3	Quartz	Traces
TiO_2	2.2		

conditions, for a 10% active inoculum of *P. polymyxa* to generate sufficient metabolites to solubilise only about 500 ppm of $CaCO_3$ (Vasan, 1998; Vasan et al., 1999). The Bromfield medium was earlier modified to substitute $CaCO_3$ with the ore (to enable beneficiation), and the optimal sucrose content was found to be 2% (Anand et al., 1996). However, the modified Bromfield medium (MBM) used in their studies is expensive, prepared with double distilled water, and sterilised in an autoclave before use. Therefore, it is neither economical nor practical for use in large-scale biobeneficiation studies.

Two industrial scale formulations (ISFs) of Bromfield medium were developed to commercialise the biobeneficiation process. The expensive carbon source in MBM, analytical grade sucrose, was replaced with a cheaper equivalent, viz. molasses in ISF-1 and cane sugar in ISF-2. In their paper, Anand et al. (1996) observed that 2% sucrose is the best composition for obtaining optimal growth and also the maximum production of ECP. It has been shown by Deo et al. (1999) (with a different bauxite ore and MBM in controlled shake flask experiments) that 2% is also the optimal composition of sucrose for the sake of calcium and iron removal from the ore. As calcium removal was not significantly enhanced beyond 2% sucrose in MBM, it was decided to retain 2% sucrose (or equivalent) in the ISFs, to optimise the cost/benefit ratio. ISF-1 was prepared out of molasses containing 45% (w/w) sucrose (gift from Khoday's Distillery, Bangalore, India). It was analysed by EDTA titration and found to contain a large amount of calcium by itself and was abandoned. ISF-2 was found to be satisfactory because it did not have any calcium, and the growth rate of *P. polymyxa* was found to be close to that in MBM. Besides, cane sugar is readily available, easy to store and the cost is comparable to molasses. Water from Jamnagar mines (Gujarat, India) was analysed for microorganisms by standard isolation techniques and was found to predominantly contain *P. polymyxa*, and also other species like *Micrococcus luteus*, *Pseudomonas fluorescens* and *Cladosporium* species. All our studies were conducted with ISF-2 prepared with tap water to eliminate background leaching by native organisms (in mine water), albeit future industrial applications will have to be conducted with mine water. Moreover, ISF-2 was not sterilised (unlike MBM), so adequate care was taken in minimising external contamination wherever possible. A pure strain of *P. polymyxa NCIM 2539* was subcultured everytime and used as inoculum in all the experiments. After addition of the medium ingredients in tap water, the pH was immediately adjusted to 7 by adding drops of 15 N NaOH, and the inoculation instantly done with a 10% (v/v) inoculum containing around 10^9 cells/ml of the pure strain. In order to

characterise the extent of contamination in the culture, a Dominance Index (DI) was monitored everyday as follows

$$\mathrm{DI} = \log_{10}[\text{Number of desirable cells}/\text{Number of contaminant cells}]. \quad (1)$$

Typically, a well-grown culture in ISF-2 (under septic conditions described above) was found to have an initial value of DI around 3. A value of $\mathrm{DI} > 2$ throughout the course of biobeneficiation was considered acceptable in these studies. *P. polymyxa* has a relatively small generation time, and produces Polymyxin A, B, C, D, E (Colistin), M, which are known to kill potential contaminants like *Pseudomonas* and Gram-negative bacteria. Besides, some of its metabolic products like ethanol and organic acids act as weak anti-fungal agents to slow down contamination. All these collectively contributed to successfully conducting biobeneficiation without sterilisation of the medium.

A minimal selective Bromfield agar/medium (MSBA) was also developed in this study to sub-culture the pure strain of *P. polymyxa*. The composition of MSBA is similar to MBM, except that it contains minimal amounts (500 ppm) of $CaCO_3$, and optional anti-fungal agents to improve selectivity. The prescribed minimal amount (500 ppm) of $CaCO_3$ is 10% of Bromfield's original composition (Bromfield, 1954), and is based on our observation that typically about 500 ppm $CaCO_3$ can be solubilised by a fully grown culture metabolite (Vasan, 1998; Vasan et al., 1999). Anti-fungal agents such as Clotrimazole, 2% (w/v) Miconazole nitrate +0.01% (w/v) Fluocinolone acetonide, etc., can be optionally added in small quantities to improve selectivity, but their actual composition should be decided on a case by case basis. The compositions of different media are summarised in Table 2.

2.3. Growth of microorganism

Ten percent of an active inoculum (from the late exponential phase) containing at least 10^9 cells/ml was added to a flask containing modified Bromfield medium at pH 7.

Table 2
Composition of Bromfield medium and its modifications (g/l)

Composition	BM	MBM	MSBA	ISF-1	ISF-2
Carbon Source	Sucrose 5	Sucrose 20	Sucrose 20	Molasses 20[a]	Cane sugar 20
$CaCO_3$	5	–	0.5	–	–
KH_2PO_4	0.5	0.5	0.5	0.5	0.5
$(NH_4)_2SO_4$	1	1	1	1	1
$MgSO_4 \cdot 7H_2O$	0.2	0.2	0.2	0.2	0.2
Yeast extract	0.15	0.15	0.15	0.15	0.15
Agar-agar	–	–	2[b]	–	–
Water type	Distilled	Distilled	Distilled	Tap	Tap/Mine
Sterilisation	Required	Required	Required	Not required	Not required

BM = Bromfield medium; MBM = Modified Bromfield medium; MSBA = Minimal selective Bromfield agar; ISF = Industrial scale formulation.

[a] 44.44 g of molasses containing 0.45% (w/w) sucrose.

[b] Not required for MSB medium; addition of anti-fungal agents optional.

The flask was incubated on a rotary shaker operated at 240 rpm and 30°C. The growth of the microorganism was monitored by measuring the dry weight and the pH of the growing culture. As a crosscheck, cells were also counted using a Petroff–Hausser counter (employing phase contrast microscopy), but the results are not reported separately because the cell counts with both these techniques were found to be within $\pm 10\%$. Fig. 1 shows a typical growth profile of *P. polymyxa* inoculated in ISF-2, without any bauxite added. After a lag phase of about 45 min, cells start growing rapidly and enter a logarithmic growth phase. This phase lasts for about 1 day beyond which cell growth is very slow. The sucrose concentration decreases sharply in first day and thereafter, sucrose consumption rate also slows down significantly. The cell growth is accompanied by a decrease in the pH of the culture due to production of organic acid metabolites. The optimal pH for the growth of *P. polymyxa* is in the range of 4–7. When pH of the culture decreases below 4, the growth of the bacteria is severely hindered, and therefore, growth ceases beyond 1 day albeit there is sufficient carbon source available in the system.

2.4. Bioreactor design

A 4-l column glass bioreactor (ID 48 mm and length 1.2 m) was designed to demonstrate bioleaching and biobeneficiation experiments in a larger scale, as shown in

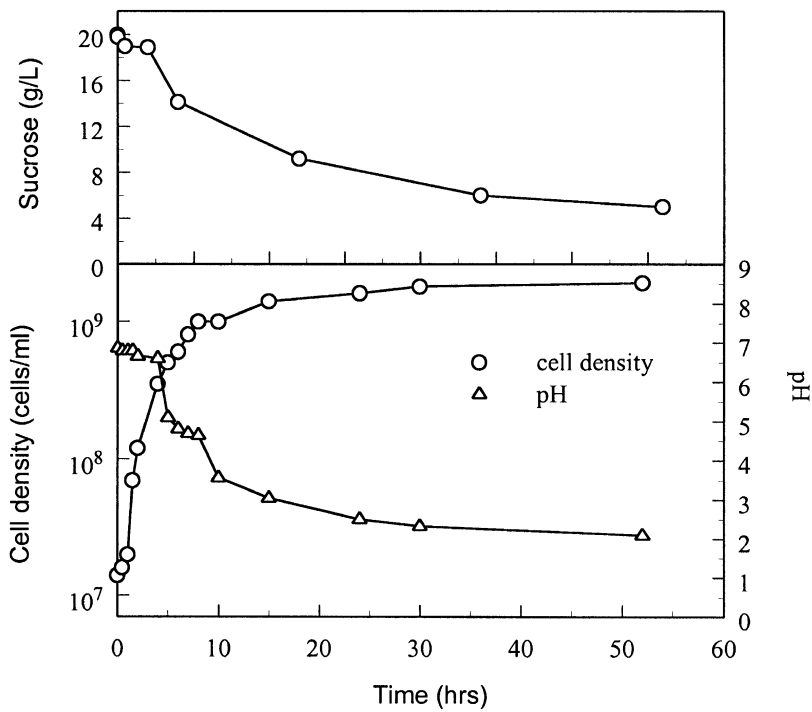

Fig. 1. Growth characteristics of *P. polymyxa* in ISF-2.

Fig. 2. The bauxite ore and a grown culture of *P. polymyxa* (in ISF-2) were added to a 15 l autoclavable plastic storage tank, and up to 20% (w/v) slurry was pumped from the storage tank to the bottom of the reactor, using a monoblock centripetal pump with ratings 0.18 kW and 0.25 hp. The slurry coming out of the reactor from the top of the column was fed back to the storage tank, thereby, making it a total recycle slurry (TRS) reactor. An optional air vent tube (1 m), tall enough to avoid spillage of circulating slurry was also provided at the top of the bioreactor. Due to pressure gradient in the column, the pressure at the top of the bioreactor is lower than the atmospheric pressure. As a result, air was continuously sucked in the bioreactor through the air vent tube. Thus, the aeration was achieved without sparging the air at the bottom of the reactor, as typically done in stirred tank bioreactors. Furthermore, uniform suspension of particles was achieved by the action of circulating liquid without the use of an agitator. The mechanical design aspects of the bioreactor and operation of the reactor in fluidized flood/drain mode (for processing coarser particles) are reported elsewhere in detail (Modak et al., 1999).

2.5. Biobeneficiation of bauxite ore

It has been reported (Modak et al., 1999) that considerable saving in grinding costs can be achieved if coarser particles are treated, but leaching time required with coarser

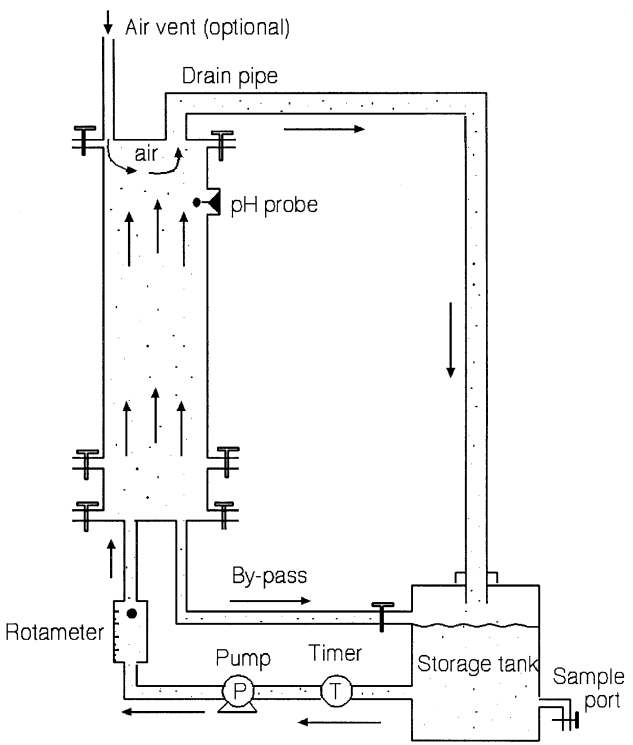

Fig. 2. Schematic representation of demonstration bioreactor used for biobeneficiation.

particles was also shown to be higher. Besides, processing of bauxite of abrasive grade material requires the particle size to be $-200+300$ mesh (Khanna, 1997). Thus grinding to finer sizes is an inevitable step even if coarser particle sizes are used for biobeneficiation of bauxite. Therefore experiments reported in this work have been conducted with $-200+300$ mesh size bauxite. Two types of beneficiation were attempted in TRS bioreactors: cascade and uncascade operation. The results of Fig. 1 clearly show that the growth of the bacteria ceases after about 24 h. Therefore, a culture grown for 24 h in ISF-2 was used as leaching medium in cascade experiments, with a contact time of up to 24 h in each cascade. After 24 h, the pump was stopped and the slurry was allowed to drain in the storage tank. The bauxite ore was allowed to settle at the bottom of the storage tank (about half-hour) and leached liquor was decanted. Fresh pre-grown culture was added to the storage tank and the pumping was restarted. The entire operation was repeated four times. In uncascade leaching experiments, bauxite ore was added at the time of inoculation so that bacterial growth and calcium leaching occurred simultaneously, and the whole operation was carried out by continuously pumping the slurry for 4 days. Experiments were conducted with 5% as well as 10% (w/v) pulp density. The solid residues were analysed for calcium remaining in the residue, to calculate %Ca removal.

3. Results and discussion

3.1. Bacterial growth characteristics with respect to media pH and calcium solubility

The leached residues of uncascade operations contain 2.24% CaO and 2.5% CaO, for experiments conducted with 5% and 10% (w/v) pulp density respectively. As these results do not meet the requirements of the abrasive industries ($<0.5\%$), further improvement in calcium removal is sought by replacing the leaching medium periodically (cascade operation). The bacteria pre-grown in ISF-2 (in the absence of bauxite) are used as the leaching medium in cascade experiments. The target of 0.5% CaO in the leached ore is reached after four cascade operations, for the case of 5% pulp density. It is observed that beneficiation occurred in two distinct phases: the initial phase of rapid removal of calcium (Phase I) which lasts for a few minutes, followed by a gradual calcium removal phase (Phase II). The initial rapid phase (less than few minutes) is too short for any direct attack mechanism to take place, and it results from the action of a well-grown culture ($\mathrm{pH}\approx 2$) coming into contact with the ore. The instantaneous dissolution of calcium in the metabolite causes the rapid removal of calcium from the ore, and the pH of the leach liquor shoots from 2 to about 5.5 (typically). The ability of metabolite to dissolve calcium reduces as pH rises to near neutral levels. However, higher pH favours bacterial growth in the culture (in spite of some growth inhibition due to the ore), as it still has about 10 g/l of sugar available as carbon source (as shown in Fig. 1). The growth of the bacteria in Phase II, along with weathering effects, leads to some more removal of calcium over the next 24 h. This results in a gradual decrease in calcium content of the ore, as well as an accompanying pH increase from 5.5 to about

6.5 (typically). Phase II has the combined contribution of direct mechanism involving the cells, as well as indirect leaching by metabolites produced by the cells. The leaching in Phase II is observed to be significant in second and third cascades, probably due to cells attached from earlier cascades. The inability to remove about 20% of the leach liquor at the end of each cascade (by settling and decantation) contributes to lower driving force for calcium removal in the fourth cascade. Besides, most of the calcium in the ore that is accessible to the action of lixiviant is leached out by the end of the third cascade, for the case of 5% pulp density. Therefore, calcium removal decreases in general in the last cascade(s). These results are reported in detail elsewhere (Modak et al., 1999).

Fig. 3a shows the total %Ca removed in uncascade operations for 5% and 10% pulp densities, after 4 days of operation. It is seen that 21.4% Ca is removed with 5% pulp density, nearly twice the removal with 10% pulp density, viz. 10.4% Ca removal. Fig. 3b shows the average calcium removal in Phase I of corresponding cascade operation, for 5% and 10% pulp densities. An interesting observation is that the amount of calcium removed in Phase I of each cascade is approximately the same, viz. 200 ppm as Ca. Thus, the mean removal in Phase I for 5% pulp density, is approximately twice that for 10% pulp density. Fig. 3c shows the average value of calcium removal in Phase II, and it is seen that the contribution of Phase II is slightly better with 10% pulp density. It is also observed that the synergy of Phase I and Phase II (cascade operation) is better than the corresponding uncascade operation, which may be due to possible re-precipitation of Ca with time in the latter. These experiments point to a saturation solubility of calcium in the 24-h grown culture, which results in approximately 180–200 ppm of Ca being leached in each Phase I operation, for 5% as well as 10% pulp densities. In order to confirm this conjecture and to throw more light on the mechanism of calcium removal, the following experiments are conducted. Known quantities of calcium carbonate are added to the metabolite (with the cells centrifuged out), and the calcium content is estimated by titration. The amount of calcium estimated by titration is found to be equal to the amount added, within 1% experimental error (data not shown). This shows that

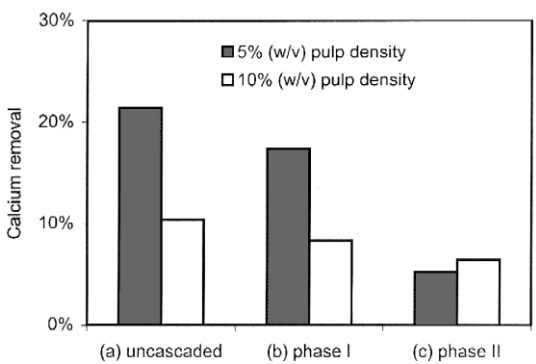

Fig. 3. (a) Total calcium removed in uncascaded operation. (b) Mean calcium removed/phase I of cascade operation. (c) Mean calcium removed/phase II of cascade operation.

the system has no significant complexation stronger than the calcium–EDTA complex. Therefore, it may be possible to remove all the free calcium by alkaline precipitation, and recycle the leached liquor after replenishing with fresh nutrients. This prospect has enormous potential to save water in an industrial scale operation. Besides, it may also be possible to make by-products (like chalk) out of the precipitated calcium. In another experiment, samples are periodically withdrawn from a shake flask culture of *P. polymyxa*, and after centrifuging the cells out, the cell-free metabolite samples are analysed for saturation solubility of calcium. Fig. 4 shows the estimated saturation solubility of calcium (denoted as Ca^*) of inoculated ISF-2, as a function of time. It is seen that it has a striking similarity with the Monod's growth curve shown in Fig. 1, with lag, exponential and saturation phases. In the initial lag phase, Ca^* decreases from 70 ppm (as Ca) to around 50 ppm, and then starts increasing to reach 70 ppm again at around 10 h. This behaviour may be explained on the basis of Table 3. It is seen that MBM (or ISF-2) has a value of Ca^* around 70 ppm (as Ca), with a substantial contribution from its nutrient salts. The lag phase of bacterial growth involves nutrient consumption (for growth and maintenance of cells) without substantial production of metabolites. This is seen in Fig. 1, when there is no appreciable change of pH in the first 4 h. So, the depletion of nutrients results in a slight decrease in Ca^* in the first few hours. However, as metabolites such as organic acids are being produced (as manifested in a sharp decrease of pH in Fig. 1), the saturation solubility Ca^* picks up to reach 70 ppm (as Ca) once again. This is followed by a rapid rise in Ca^* to a saturation value of 200–300 ppm (depending on the nature of culture and growth conditions) in 2–3 days. This is likely due to the exponential growth of bacteria, and growth-associated production of organic acids and other metabolites. Ca^* remains static for a while, but starts decreasing after 72 h, possibly due to depletion of nutrients and loss of cell growth and activity at acidic pH. Therefore the best strategy for cascade leaching is a 24-h culture (beyond which growth stops, cf. Fig. 1), with a contact time of 24 h corresponding to an optimal value of Ca^* around 48 h (cf. Fig. 4). This also means operating Phase I in the late exponential growth phase (Fig. 1), with excellent of bacterial growth and activity. A contact time of 24 h (Phase II) also ensures that there is adequate scope for direct attack mechanism to take place, albeit growth may be slightly retarded in the presence of ore.

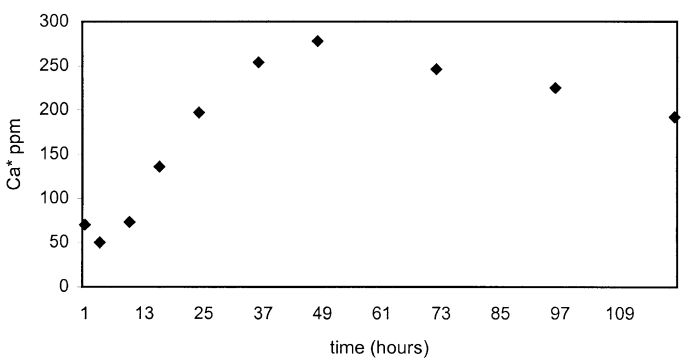

Fig. 4. Estimated saturation solubility of Calcium (Ca^*) in inoculated ISF-2 as a function of time.

Table 3
Estimated saturation solubility of calcium (Ca^*)

Composition	Ca^* ppm
Tap water in contact with ordinary air	20
Modified Bromfield Medium (MBM)	73
1 g $(NH_4)_2SO_4$ /l distilled water	45
0.5 g KH_2PO_4 /l distilled water	15
0.2 g $MgSO_4 \cdot 7H_2O$/l distilled water	15
0.2 g $MgSO_4 \cdot 7H_2O$/l distilled water	200–300

3.2. Biobeneficiation mechanisms

The mechanism of biobeneficiation is hitherto not well understood, and is generally thought to occur by a combination of direct attack and indirect mechanisms (Ehrlich, 1992). The indirect mechanism is often based on the acidolysis and complexation mechanisms of leaching of sulphidic minerals. In the light of our solubility studies on the metabolite, the entire process of (indirect) biobeneficiation of bauxite can be alternatively viewed as that of increasing solubility of the lixiviant

$$\text{MBM (or) ISF-2}(Ca^* = 70\ \text{ppm as Ca}) \rightarrow \text{Well grown culture with cells and metabolites}(Ca^* \approx 200\text{–}300\ \text{ppm as Ca}) \quad (2)$$

without going into the details of indirect mechanism, such as acidolysis or complexation. So long as the calcium in the ore that is accessible to the action of lixiviant is more than that of the solubility limit Ca^*, the "weathering effect" of direct attack mechanism has only got a less significant role to play. This is evident from the fact that the Phase I leaching in the first few cascades have almost resulted from instantaneous solubilisation of accessible calcium, and have all resulted in approximately the same amount of calcium removal (200 ppm) irrespective of the pulp density. Reducing the calcium content from 2.8% (as CaO) to 0.5% (as CaO) in 5% (w/v) pulp density of bauxite amounts to solubilising 820 ppm of calcium (as Ca) in the lixiviant culture. As a well-grown culture metabolite can solubilise only about 200–300 ppm (as Ca), the necessity of having cascades is evident. The solubilisation mechanism also enables to predict the number of cascades required, in the of 5% pulp density, four cascades are required with a mean Ca^* value of 200 ppm (as Ca). Therefore, 10% pulp density would require six to eight cascades to achieve the target of 0.5% (as CaO), if the lixiviant culture has a Ca^* value of 200–300 ppm (as Ca). As higher pulp densities are preferred in industrial scale operations, biobeneficiation looks promising to give good results with higher slurry concentrations as well, even though the number of cascades required will increase as the pulp density is increased.

3.3. Comparison of cascade and uncascade operations

An enormous saving in time is possible by assembling a series of Phase I cascades (without Phase II), to achieve the result almost completely due to solubilisation (indirect

leaching) mechanism. This is called pulse leaching experiment, and Modak et al. (1999) have reported that CaO in 20% pulp density of bauxite ore can be brought down from 2.8% to 0.5% after 13 cascades, by treating it with a culture at pH 2.1 for 10 min per cascade. The decrease in calcium content reported is almost linear (correlation coefficient 0.98) with the number of cascades. This implies that the calcium leached in each cascade is almost constant (about 234 ppm Ca/cascade), confirming the mechanism of solubilisation of calcium up to a saturation solubility limit, Ca^*. The whole operation lasts only for a couple of hours and the contribution of direct attack mechanism can be neglected. However, the contribution of direct leaching per se cannot be totally neglected. The production of levan and other exopolysaccharides that can complex calcium and the gradual weathering of the ore to expose the hitherto inaccessible calcium to the action of lixiviant are equally crucial to get as close to the target (100% removal) as possible. Besides, the saving in operating time with pulse leaching experiments is at the cost of increase in the volume of grown culture required. This also points to the need to recycle the spent liquor for feasibility of the operation in an industrial scale. The increase in alkalinity during biobeneficiation has been correlated with the calcium coming into the solution. Different correlations have been reported for Phase I and Phase II (Modak et al., 1999). When a bauxite ore has both calcium and iron impurities, it is generally a good strategy to remove calcium first and/or simultaneously. This is because the leaching of iron is not optimal in non-acidic pH caused by calcium dissolution into the lixiviant. Thus, the removal of calcium from bauxite is a crucial step, and some of the recent advances reported in this paper are likely to enable successful commercialisation of bauxite biobeneficiation in the future.

4. Conclusions

The following major conclusions could be made based on this study.

1. An industrial scale formulation of Bromfield medium based on cane sugar and tap/mine water (ISF-2), can be successfully used to culture the soil bacterium, *P. polymyxa* under septic conditions.
2. The above culture is found to be efficient in the removal of calcium from bauxite ore in large-scale biobeneficiation experiments, carried out in total recycle slurry reactors.
3. Cascade leaching experiments are found to be necessary to achieve the target of 0.5% CaO in bauxite ore.
4. In cascade leaching experiments with pre-grown culture, calcium removal is observed to occur solely by indirect mechanism in an initial rapid phase lasting few minutes, followed by a gradual phase comprising of direct attack as well as indirect mechanisms.
5. The indirect mechanism of biobeneficiation can be alternatively interpreted on the basis of solubilisation of accessible calcium in the culture metabolite, up to a saturation solubility limit, Ca^*.

6. The saturation solubility theory also gives an explanation for the need to perform cascade experiments and successfully predicts the possibility of pulse leaching experiments.

It is essential to scale-up the laboratory process with respect to various parameters for possible commercial utilization. For this purpose, it becomes essential to isolate the microorganisms from the ore deposits and water sources in the mines for large-scale cultivation.

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