MICROPLASTIC POLLUTANTS IN TERRESTRIAL AND AQUATIC ENVIRONMENT



Indium extraction from nitrate medium using Cyphos ionic liquid 104 and its mathematical modeling

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Abstract

The treatment and recovery of pollutants in aquatic system is one of the greatest challenges for environmentalists throughout the world. In this study, solvent extraction of indium using phosphonium ionic liquid (Cyphos IL 104) as an extractant and its mathematical model was proposed for prediction of In(III) ion transport across a FSSLM (flat-sheet-supported liquid membrane). Solvent extraction experiments on indium have been carried out under various experimental conditions in order to assert some fundamental parameters using mathematical analysis for mass transfer process. Diffusion is the process which facilitates metal ion transport across liquid membrane, indicating the applicability of Fick's law of diffusion in model formulation. The influence of different parameters like composition of diluent, feed acidity, and ligand concentration on In(III) ion transport rate has been reported. At different extractant concentrations, the modeling outputs and experimental indium extraction were observed to be in reasonably good agreement.

Keywords Diffusion · FSSLM · Cyphos IL 104 · Solvent extraction · Indium transport

Introduction

The treatment and recovery of pollutants in aquatic system is one of the greatest challenges for environmentalists throughout the world. The treatment of pollutants from water has been reported in literature using conventional techniques (Kumar and Gupta 2020; Singh et al. 2020). The impact of microplastic pollutants and other water quality drivers on lake and riverine system has also been reported (Kumar et al. 2022a, b; Barya et al. 2022). Modern technologies have showed a wide range of applications for the metal indium, which is also a precious metal and quite scarce in abundance. A few of the advanced technologies with high applicability of indium are manufacture of solar panels, flat-panel

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¹ Department of Chemistry, School of Sciences, IFTM University, Lodhipur Rajput, Uttar Pradesh 244102 Moradabad, India

² Department of Biochemical Engineering and Biotechnology, Indian Institute of Technology Delhi, New Delhi, India screens, and LCD lighting. The discarded waste devices are significant raw materials for indium, but the market demand of indium has been increased drastically (Liu et al. 2009; Fan et al. 2010). In order to comply with the market demand, the other sources of indium must be investigated. A low concentration of indium is available in lead, copper, and zinc ores, whereas residues or sludge of zinc melting processes may also be used to recover indium (Kai et al. 2010; Deferm et al. 2016). Therefore, it becomes necessary to develop a suitable methodology to separate indium from base metals like iron, lead, copper, and zinc. Secondary sources such as electronic or industrial wastes may also be employed to recover indium, which act as economic and eco-friendly technique with complete resource utilization (Silveira et al. 2015). The recovery of indium from various waste matrices has been reported in literature using different hydrometallurgical routes like solvent extraction, adsorption, precipitation, and ion exchange (Virolainen et al. 2011; Akama et al. 2016; Jiang et al. 2011; Nguyen and Lee 2019). Among them, solvent extraction is considered more advantageous due to its low energy consumption, rapidness, simple equipment, high selectivity, and metal recovery in highly pure form (Akama and Ito 2000; Jahroni et al. 2007). The reagents applied for solvent extraction are organophosphorus compounds (Iyer and Dhadke 2001; Jha et al. 2013; Padhan and Sarangi 2014), chelating

agents (Nusen et al. 2015; Cheng 2006), and high-molecularweight amines (Nayl 2010; Mishra et al. 2011). A number of problems have been encountered during application of these extractants in extraction process. The problems are limited selectivity, emulsion formation, extractant loss, and other hydrometallurgical considerations (Wilson et al. 2014). At the later stage, the environmentalists intend towards the application of "greener and safer" extractants in place of conventionally used organic solvents. In the recent research articles, the researchers have focused on the application of prominent extractants, phosphonium ionic liquids (PILs), due to their specific features. PILs have good extraction power, non-flammability, negligible vapor pressure, high thermal stability, and recyclability. PILs do not release any H⁺ ion in the media, which eliminates the requirement of neutralization of released acid (Fraser and MacFarlane 2009; Ferreira et al. 2012).

PILs are formulated by Cytec Industry and commercialized as Cyphos ionic liquids (ILs). Among a variety of PILs, Cyphos IL 101 and 104 have been applied to extract various metals such as Ge, Cd, In, Ga, Fe, Ni, Co, Ru, Rh, Au, Pd, and Zn from chloride media (Zhu et al. 2017; Cieszynska and Wisniewski 2012; Rzelewska et al. 2017; Regel-Rosocka et al. 2012; Dhiman and Gupta 2020a, b; Nayak and Devi 2017; Cui et al. 2015; Alguacil 2017).

The separation or removal of different low concentrated species from water has been performed alternatively using liquid membrane techniques, besides solvent extraction (Koter et al. 2013; Haghighi et al. 2018). The separation of indium has been reported using emulated and hollow fibersupported liquid membranes (SLM) (Teramoto et al. 1993; Alguacil. 2020; Yen et al. 2016). In order to control the process, mathematical modeling was implemented. Mathematical modeling combined with mass transfer phenomena develops facilitated transport models which may be applied experimentally in designing and developing of further methods. In the development of model showing facilitated species transport using SLM, a few assumptions are made (Ramkumar and Chandramouleeswaran 2015). In one assumption, the base of model is the diffusion through liquid membrane. With efficient stirring on both SLM sides and tending to zero thickness of interfacial layers, the desired results can be obtained (Ramkumar and Chandramouleeswaran 2015; Zantea et al. 2020). The application of Cyphos IL 104 as carrier has been reported in various studies to develop model for transport of various metals (Bonggotgetsakul et al. 2016; Baczynska et al. 2016; Pospiech 2015; Regel-Rosocka et al. 2012). Based on the available reports, no study involving methodical investigation for Cyphos IL 104 in order to transport indium through FSSLM has been carried out. Therefore, the present study provides the first detailed report on Cyphos IL 104 to extract and separate indium from nitrate medium. The influence of different experimental parameters on indium extraction with Cyphos IL 104 was investigated. On the basis of optimized results, the extraction mechanism for indium extraction through Cyphos IL 104 has been proposed and equilibrium extraction constant has also been calculated. The experimental results have also been verified with simulation studies.

Experimental method

Materials

Analytical grade chemicals for the study were supplied by Thomas Baker, Merck, and Sigma-Aldrich. Ultrapure water was applied for dissolution of salts of metal ions to prepare stock solutions. Cytec Industry Inc., Netherlands, supplied Cyphos IL 104 as gift sample which was employed in the present study without any treatment. Figure 1 shows the structure of Cyphos IL 104.

Filters of PTFE membrane (diameter 47 mm) were used for transport studies of In(III) ion as a membrane support with the following specifications: 64% porosity, 85μ m thickness, and 0.45μ m pore size (verified using Mitutoyo digital micrometer and Hg porosimetry). The experimental set-up consists of membrane with 3.14 cm^2 as effective surface area. It was evaluated using membrane porosity and geometrical area (Sriram et al. 2000).

Distribution measurements

Extraction studies were carried out in batch mode. Equal volumes (unless mentioned otherwise) of aqueous phase (metal in appropriate acid) and organic phase (Cyphos IL 104 in toluene) were mechanically shaken at room temperature to ensure complete equilibration and allowed to stand for phase separation. After phase disengagement, the aqueous phase was properly diluted and the metal contents were measured using a microplasma atomic emission spectrometer (MP-AES). The concentration of metal ions in the IL phase was calculated by mass balance as follows [1]:



Fig. 1 Cyphos IL 104 in chemically stable state

 $[Metal]_{organic} = [Metal]_{aqueous \ before \ extraction} - [Metal]_{aqueous \ after \ extraction}$ (1)

The distribution ratio (D) and extraction efficiency (% E) were calculated using the following equations:

$$D = \frac{[\text{Metal}]_{\text{organic}}}{[\text{Metal}]_{\text{aqueous}}}$$

$$%E = \frac{[\text{Metal}]_{\text{B}.\text{E}} - [\text{Metal}]_{\text{A}.\text{E}}}{[\text{Metal}]_{\text{B}.\text{E}}} \times 100$$

 $[Metal]_{B,E}$ and $[Metal]_{A,E}$ are the concentration of metal ion before and after extraction. Triplicate analysis was performed for all solvent extraction experiments, and the relative standard deviation is $\pm 5\%$.

Mathematical modeling for mass transfer through flat-sheet-supported liquid membrane

In the point of view of application, the prediction of mass transfer mechanism of supported liquid membrane (SLM) is an important aspect. The diverse research studies on mathematical modeling of SLMs using different extractants have been reported in the previous studies.

The mathematical modeling facilitates the application of minimum experiments to optimize the experimental parameters. In the mass transfer process, the combination of several formulations derives a model equation and its solution is achieved using time-dependent variation in species concentration. The present study demonstrates the derivation of model equation for the prediction of In(III) transport through flat-sheet-supported liquid membrane (FSSLM) under different experimental conditions. The assumptions to derive the model equation are summarized below:

- (i) Linearity of the concentration gradient with membrane phase and feed-membrane boundary layer interface.
- (ii) The metal ions are diffused through membrane as per Fick's law.
- (iii) Membrane interfaces shows pseudo-equilibrium existence on its both sides.
- (iv) In the membrane surface, no mass is accumulated due to boundary layer diffusion of metal ions.

Model development

The following extraction reaction has been given to represent the neutralization of charge on complex and equilibrium (Deferm et al. 2016) by co-transportation of counter anion with metal ion using Cyphos IL 104.

$$\mathrm{In}^{3+} + \mathrm{NO}_{3}^{-} + E_{\mathrm{(org)}} \leftrightarrow \left[\mathrm{In}(\mathrm{NO}_{3})_{2}(\mathrm{E})\right]_{\mathrm{(org)}}$$
(2)

Here, NO₃⁻ is counter-anion; $[In(NO_3)_2(E)]_{(org)}$ and $E_{(org)}$ refer to metal–ligand complex and Cyphos IL 104 ligand, respectively. The equilibrium constant (K_{eq}) is given by

$$K_{\rm eq} = \frac{\overline{C_{\rm i}}}{C_{\rm i}N_{\rm f}^2 E} = \frac{K_{\rm d}}{N_{\rm f}^2 E}$$
(3)

where $\overline{C}_{f,i}$ denotes the extraction species $[In(NO_3)_2(E)]_{(org)}$ in organic phase, whereas $C_{f,i}$ shows concentration of In(III) in aqueous phase at interface of feed membrane while *E* is the freeligand concentration in membrane phase; N_f represents nitrate ion activity in the feed solution (activity=activity coefficient×molality of nitric acid); distribution ratio (K_d) may be given as

Distribution ratio
$$\left(K_{\rm d}\right) = \frac{\left[\ln({\rm NO}_3)_2(E)\right]_{\rm (org)}}{{\rm In}^{3+}_{\rm (aq)}} = \frac{\overline{C}_{\rm f,i}}{C_{\rm f,I}}$$
 (4)

Figure 2 gives the concentration profile of metal ion in different regions of FSSLM configuration. As it can be seen in Fig. 2, the diffusion of metal ion to bulk strip phase from the bulk feed phase is always favored.

According to Fick's law, the mass transfer flux may be represented by the following equation:

$$J = -D \ dC/dx \tag{5}$$

Hence, mass flux (J) through feed and membrane phase may be given as

$$J_{\rm aq} = \frac{D_{\rm aq}}{d_{\rm aq}} \cdot (C_{\rm B} - C_{\rm f,i}) \tag{6}$$



Fig. 2 Schematic description of metal ion concentration profiles in different SLM regions, *C* represents concentration of various species in respective regions. $C_{\rm B} = \ln(\mathrm{III})$ concentration in bulk feed solution; $C_{\rm f,i} =$ concentration of $\ln(\mathrm{III})$ in aqueous phase; $\overline{C}_{\rm f,i} =$ concentration of extraction species $\left[\ln(\mathrm{NO}_3)_2(E)\right]_{(\mathrm{org})}$ at feed membrane interface; $\overline{C}_{\rm s,i} =$ concentration of extraction species $\left[\ln(\mathrm{NO}_3)_2(E)\right]_{(\mathrm{org})}$ at membrane-strip interface; $C_{\rm s,t} =$ concentration of $\ln(\mathrm{III})$ in strip phase

$$J_{\rm org} = \frac{D_{\rm org}}{d_{\rm org}} \cdot (\overline{C}_{\rm f,i} - \overline{C}_{\rm s,i}) \tag{7}$$

where $C_{\rm B}$ represents In(III) concentration in bulk feed solution, $\overline{C}_{\rm f,i}$ and $\overline{C}_{\rm s,i}$ represent $\left[{\rm In}({\rm NO}_3)_2(E) \right]_{\rm (org)}$ concentration at feed-membrane and membrane-strip interfaces, respectively, *d* represents diffusing path length, and *D* denotes diffusivity. Considering the distribution coefficient of metal ion is much lower at membrane-strip interface than that at feed-membrane interface, Eq. (6) can be modified as

$$J_{\rm org} = \frac{D_{\rm org}}{d_{\rm org}} \cdot \overline{C}_{\rm f,i} \tag{8}$$

$$J_{\text{org}} = \frac{D_{\text{org}}}{d_{\text{org}}} \cdot (C_{\text{f,i}} \cdot K_{\text{d}}) \left(K_{\text{d}} = \frac{\overline{C}_{\text{f,i}}}{C_{\text{f,i}}} \right)$$
$$J_{\text{org}} \frac{d_{\text{org}}}{D_{\text{org}} \cdot K_{\text{d}}} = C_{\text{f,i}}$$
(6)

On adding Eqs.
$$(5)$$
 and (8) , one can get

$$C_{\rm B} = J_{\rm aq} \frac{d_{\rm aq}}{D_{\rm aq}} + J_{\rm org} \frac{d_{\rm org}}{D_{\rm org} \cdot K_{\rm d}}$$
(10)

According to assumption (iii), pseudo-equilibrium exists, i.e., $J_{aq} = J_{org} = J$ (say), one can get

$$C_{\rm B} = J \left[\frac{d_{\rm aq}}{D_{\rm aq}} + \frac{d_{\rm org}}{D_{\rm org} \cdot K_{\rm d}} \right]$$

Since $d_{\text{org}} = d_{\text{m}} \cdot \tau$, where d_{m} is the thickness of membrane, one can write

$$C_{\rm B} = J \left[\frac{d_{\rm aq}}{D_{\rm aq}} + \frac{d_{\rm m} \cdot \tau}{D_{\rm org} \cdot K_{\rm d}} \right]$$
(11)

Organic mass transfer resistance (membrane phase) is defined as $R_{\text{org}} = \frac{d_{\text{m}} \tau}{D_{\text{org}}}$ and aqueous mass transfer resistance (feed phase) is defined as $R_{\text{aq}} = \frac{d_{\text{aq}}}{D_{\text{org}}}$, where τ is tortuosity of the membrane material. Therefore, Eq. (10) can be rewritten as

$$J = \frac{C_{\rm B} \cdot K_{\rm d}}{R_{\rm org} + K_{\rm d} \cdot R_{\rm aq}}$$
(12)

Now, if *J* represents overall feed phase metal ion flux, we may write

$$Q \cdot J = -V \frac{dC_{\rm B}}{dt} \tag{13}$$

Here, Q represents effective membrane area and V represents total aqueous feed solution volume. Or one can write $J = -\frac{V}{Q} \frac{dC_{\rm B}}{dt} = \frac{C_{\rm B} \cdot K_{\rm d}}{R_{\rm org} + K_{\rm d} \cdot R_{\rm aq}}$ (using Eqs. (11) and (12)), or

$$\frac{dC_{\rm B}}{dt} = -\frac{Q}{V} \frac{C_{\rm B} \cdot K_{\rm d}}{R_{\rm org} + K_{\rm d} \cdot R_{\rm aq}}$$
(14)

Considering the equilibrium (3), one ligand molecule is combined with one In(III) metal ion forming the metal–ligand complex. The equation for mass-balance of ligand in the membrane phase is denoted by

$$E_{\text{free}} + E_{\text{complexed}} = E_{\text{T}}$$

$$E_{\text{free}} + \overline{C}_{\text{f,i}} = E_{\text{T}}$$
(15)

where, in membrane phase, E_{free} represents free carrier concentration and E_{T} represents total carrier concentration. Using Eqs. (8) and (13) in Eq. (14), one can obtain

$$\frac{R_{\rm org} \cdot C_{\rm B} \cdot K_{\rm d}}{R_{\rm org} + K_{\rm d} \cdot R_{\rm aq}} + \frac{K_{\rm d}}{N_{\rm f} \cdot K_{\rm eq}} - E_{\rm T} = 0$$
(16)

In order to transport one mole of In(III) metal ion, two NO_3^- ions are transported to strip phase from feed for maintenance of electrical neutrality. Hence, total feed concentration of NO_3^- may be expressed with the reduction of In(III) ion concentration in feed, and we may write

$$N_{\rm f} = [N_{\rm f,0} - 2(C_{\rm f,0} - C_{\rm B})]$$

(9)

where $N_{\rm f,o}$ represents nitrate ion in bulk feed solution and $C_{\rm f,o}$ refers to initial In(III) ion concentrations and placing $N_{\rm f}$ value in Eq. (16).

$$\frac{R_{\rm org} \cdot C_{\rm B} \cdot K_{\rm d}}{R_{\rm org} + K_{\rm d} \cdot R_{\rm aq}} + \frac{K_{\rm d}}{[N_{\rm f,0} - 2(C_{\rm f,0} - C_{\rm B})]^2 \cdot K_{\rm eq}} - E_{\rm T} = 0$$
(17)

Differentiating Eq. (16) w.r.t. time (t) and coupling to Eq. (13) gives two differential equations as $dC_{\rm B}/dt$ and $dK_{\rm d}/dt$ which were solved simultaneously by applying MATLAB. The values of mass transfer resistances were determined experimentally and also taken from literature. The mass transfer resistances were estimated as $R_{\rm aq}$ =420 s/cm and $R_{\rm org}$ =10,200 s/cm. Figure 2 gives a comparison of calculated and experimental data for the transport of In(III) by ligand in the present work. The simulated results were in good agreement to experimental data, which validates the applicability of model.

Calculation of mass transfer resistances

The metal ion permeability (*P*) through flat-sheet SLM was evaluated by plotting the graph $\ln\left(\frac{C_t}{C_0}\right)$ versus time (*t*) using the following equation (Danesi et al. 1983):

$$-\ln\left(\frac{C_{\rm t}}{C_0}\right) = \left(\frac{Q}{V}\right) \times P \times t \tag{18}$$

where *P* represents metal ion permeability (cm/s), *V* represents total feed volume (mL), *Q* denotes membrane surface area (3.14 cm²), and C_0 and C_t represent feed concentration of metal ion at t = 0 and t = t.

The mass transfer resistances (R_{org} and R_{aq}) were experimentally measured by plotting 1/P vs. $1/K_d$, as per the following equation:

$$\frac{1}{P} = R_{\rm aq} + \frac{R_{\rm org}}{K_{\rm d}} \tag{19}$$

Using experimentally obtained graph, a linear data fitting gives value of $R_{aq} = 420$ s/cm and $R_{org} = 10,200$ s/cm, which may be applied in further calculations.

Results and discussion

Batch extraction of indium through Cyphos IL 104

Effect of HNO₃ concentration

Extraction behavior of indium from nitric acid media was investigated with toluene-diluted Cyphos IL 104 (0.01 mol/L). The variation range of acid molarity was 0.0001 to 1 mol/L (Fig. 3). At low acidity, In(III) was extracted quantitatively and its extraction diminishes with rise in nitric acid molarity (0.001–0.05 mol/L) and is negligible beyond 1 mol/L HNO₃. The extraction of cationic



Fig. 3 Effect of HNO_3 concentration on In(III) extraction. Conditions: [In(III)] = 100 mg/L, [Cyphos IL 104] = 0.01 mol/L

indium species at low nitric acid molarity is probably responsible for high indium extraction. At high nitric acid molarity, extraction of acid may compete with indium extraction. Various researchers reported the similar observation for indium extraction (Sato and Sato 1992, Paiva 2001; Tsai and Tsai 2013). In their reports, In(III) was extracted using different extractants from H_2SO_4 , HNO₃, and HCl media. At higher acid concentration, indium extraction followed the order HCl > H_2SO_4 > HNO₃, whereas, at low acid concentration, the order becomes reversed.

Effect of Cyphos IL 104 concentration

The influence of Cyphos IL 104 concentration on indium extraction has been examined by varying the extractant concentration in the range 0.001 to 0.05 mol/L at In(III) concentration of 100 mg/L and 0.1 mol/L nitric acid concentration (Fig. 4). The indium extraction into organic phase from aqueous solution was enhanced by increase in extractant concentration. The enhancement is due to increase in indium distribution coefficient with rising extractant concentration (Dhiman and Gupta 2020b). Tsai and Tsai 2012 studied the indium extraction through D2EHPA in nitrate medium. The results indicated that InR_3 (where R = D2EHPA) concentration increased as the total concentration of D2EHPA increased, while the concentrations of In³⁺ decreased. Figure 4 depicts the log-log plot of distribution coefficient and extractant. The plot shows 0.83 as the slope value, which indicates that in order to form the extracting species, one mole metal ion requires one mole of extractant.



Fig. 4 Effect of Cyphos IL 104 concentration on In(III) extraction. Conditions: $[In(III)] = 100 \text{ mg/L}, [HNO_3] = 0.1 \text{ mol/L}$

Non-dispersive solvent extraction

Ligand concentration variation

The concentration of ligand (ionic liquid) was varied from 0.0001 M to 0.1 M to examine the effect of concentration of ligand. The results reveal that, with the enhancement in carrier concentration, the rise in transport rate of In(III) ion took place. With an increase in carrier concentration, the metal ion distribution ratio and extraction percentage were increased (Table 1). Therefore, at higher ligand concentration, the transport of In(III) ion in feed was increased (Fig. 5).

In order to predict the model, the trend observed may be described by Eq. (13). The distribution ratio (K_d) for indium becomes higher with an increase in ligand concentration, which cause Eq. (13) more negative on the right side. Therefore, at higher ligand concentration, the rate of decrease of metal concentration becomes much faster.

Table 1 At varying ligand concentrations, experimental values of distribution ratios (K_d) of In(III); aqueous phase: 0.1 M HNO₃; organic phase: 0.001 M–0.1 M Cyphos IL 104 in toluene

[Cyphos IL 104], M	$K_{\rm d}$, In(III)	%E (extraction)
0.001	0.60	37.4
0.005	1.72	63.2
0.008	2.50	71.4
0.01	3.29	76.7
0.05	11.74	92.15
0.1	82.33	98.8



Feed acidity variation

The nitrate ion concentration increases with an increase in feed acidity, resulting in the enhancement of metal extraction (Table 2). Further, transport rate enhancement is expected with the rise in counter anion concentration. Therefore, all parameters were kept constant and feed nitric acid concentration was varied to carry out the indium transport experiments.

Figure 4 illustrates the results of simulation, which indicate that with rise in feed acidity, transport rate of indium from feed solution also increases. In an organic membrane, the mass transfer resistance (R_{org}) mainly governs the denominator of Eq. (13) as the product $(K_d \times Raq) < < R_{org}$. As per Eq. (10), the transport rate of indium increases at high acidity of feed phase. Figure 6 predicts outcomes of indium transport. The H⁺ ion is also increased in feed phase due to increase in feed acidity, which affect transport of acid to strip phase from feed phase to inhibit the stripping efficiency. Hence, during comparison with experimental data,

Table 2 Distribution ratio (K_d) of In(III) with variation in HNO₃ concentration; organic phase: 0.01 M Cyphos IL 104 in toluene

[HNO ₃], M	$K_{\rm d}$, In(III)	%E (extraction)
0.0001	0.85	45.9
0.001	8.26	89.2
0.01	70.43	98.6
0.05	65.67	98.5
0.1	3.39	77.2
0.5	0.40	28.6



Fig. 5 Simulation for transport of In(III) with varying ligand concentrations. Strip: distilled water, feed: 0.1 M nitric acid, ligand: Cyphos IL 104 in toluene (0.0001–0.1 M). C_0 =feed concentration of metal ion at t=0; C_t =feed concentration of metal ion at t = t

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Fig. 6 Feed acidity variation study. Feed: $0.0001-0.5 \text{ M HNO}_3$, strip: distilled water, ligand: Cyphos IL 104 in toluene (0.01 M). C_0 = feed concentration of metal ion at t=0; C_t = feed concentration of metal ion at t = t

the simulated curve in the later part is expected to show some off-results.

Diluent concentration variation

Extraction studies with Cyphos IL 104 solution were carried out in different diluents. The results reveal that the variation in diluent nature causes variation in partition of indium (Table 3). Diluents like n-butyl alcohol and cyclohexanone with higher dielectric constants show lower extraction percentage. It may be attributed to the stronger interactions among phosphonium extractants and diluents with high dielectric constants, leading to lower metal ion extraction (El-Nadi 2010). The diluents with dielectric constants nearly two do not show any particular trend. Therefore, on the basis of cost-effectiveness as well as observed results, toluene was employed for further studies.

This simulation optimization was used to investigate the effect of diluent concentration variation on transport of In(III) ion through flat-sheet SLM. The results suggest that the distribution ratio of metal ion with ligand was not affected, indicating no effect on indium transport rate in feed. As per obtained results, no effect was seen on transport of In(III) ion with diluent variation in Cyphos IL 104 ligand (Fig. 7).

Conclusion

The present study shows the development of a mathematical model in order to transport metal ion, indium, through the membrane using Cyphos IL 104 as ligand. The experimental conditions which are suitable for effective In(III) transport through FSSLM are predicted by the developed model. Indium is quantitatively extracted at low acidity and becomes negligible beyond 1 mol/L HNO₃. The results suggest that, in order to form the extracting species, one mole metal ion requires one mole of extractant. Diluents like n-butyl alcohol and cyclohexanone with

Table 3 Distribution ratio (K_d) of In(III) with Cyphos IL 104(0.01 M) at varying (%) diluent concentrations; aqueous phase: 0.1 MHNO3

Ligand	Diluent	$K_{\rm d}$, In(III)	%E (extrac- tion)
0.1 M HNO ₃ in varied	n-Hexane	3.50	77.8
diluents	Kerosene	3.63	78.4
	Xylene	3.50	77.8
	Benzene	3.48	77.7
	Toluene	3.59	78.2
	Butyl alcohol	0.01	0.9



Fig. 7 Diluent concentration variation. Ligand: Cyphos IL 104 in toluene (0.01 M), strip: distilled water, feed: 0.1 M HNO₃. C_0 = feed concentration of metal ion at t = 0; C_t = feed concentration of metal ion at t = t

higher dielectric constants show lower extraction percentage. The simulation optimization was used to investigate the effect of diluent concentration variation on transport of In(III) ion through flat-sheet SLM. The results suggest that the distribution ratio of metal ion with ligand was not affected, indicating no effect on indium transport rate in feed. As per obtained results, no effect was seen on transport of In(III) ion with diluent variation in Cyphos IL 104 ligand. On the basis of cost-effectiveness as well as observed results, toluene was employed for the present study. With an increase in carrier concentration, the metal ion distribution ratio and extraction percentage were increased. The transport rate of indium increases at high acidity of feed phase.

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Author contribution All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by Rohit Kumar, Soniya Dhiman, and Himanshu Gupta. The first draft of the manuscript was written by Soniya Dhiman and Rohit Kumar, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Data availability All data are true and valid and can be available.

Declarations

Consent to participate All the authors listed consent to participate.

Consent for publication All the authors listed have approved the manuscript that is enclosed.

Competing interests The authors declare no competing interests.

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