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Mathematical modeling of facilitated transport of Fe(III) using Cyanex 923 through supported liquid membrane

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Abstract

One of the most significant challenges facing environmentalist worldwide is the treatment and recovery of substances in aquatic environments. In this present, the transport of Fe(III) ions across a flat sheet supported liquid membrane immersed in Cyanex 923 as an extractant was predicted using a mathematical modeling. In order to establish certain fundamental parameters of the mathematical assessment for the mass transfer procedure, solvent extraction experiments were conducted on ferric ions under a variety of experimental conditions. The development of models is regulated by Fick's law of diffusion, which makes it easier for metal ions to diffuse across supported liquid membranes. It has been expected that a number of factors, including feed acidity and variations in ligand concentration, will have an effect on the transport rate of ferric ions.

Keywords Cyanex 923 · Supported liquid membrane · Diffusion · Transport · Extraction

Introduction

In lab-scale metal ion separations, liquid membranes have been used for a variety of initiatives, including organic's removal from waste streams, hazardous/toxic metal ion removal from nuclear waste, and the removal of metals (such as Cr, Zn, Pd, Fe, In, Hg, and As) from water-waste streams. Supported liquid membrane (SLM) offers significant advantages over other liquid membrane such as emulsion liquid membrane (ELM) and bulk liquid membrane (BLM) in terms of stability and ease of handling, ongoing research focuses on addressing its limitations. Future applications of SLM will likely benefit from advancements in material science, membrane engineering, and process optimization to enhance performance and broaden its industrial applicability. Amongst several methods of separation, the liquid membrane has been found quite attractive because of several advantages over other method (Danesi 1984, Kandwal et al. 2011, Dworzak and Naser 1987, Guerriero et al. 1988, Kopunec and Ngo Manh 1994, Meares 1994), which include (i) low operating and capital cost, (ii) less possibility of third phase formation, (iii) instantaneous removal and stripping, (iv) possibility of easy scale-up, etc. Membranes have been used extensively in a variety of industries, including medical research, processing of food, wastewater treatment, separation of gases, etc., and their processing development has shown promise. However, before attempting to scale-up a process, a number of experiments must be conducted in order to determine the best experimental conditions, which would obviously involve a significant financial and human resource commitment. Consequently, comprehension of an assortment of chemical equilibrium processes and also it is imperative to complete the transport procedure before attempting any expansion.

The research studies were carried out through various researchers on the separation of heavy and hazardous metal ions. Weize Wang et al. (2019) investigated the selective sensing of Fe^{3+} ions and the separation of C_2H_2/CH_4. These stable terbium-organic frameworks consisted of on predesigned functionalized ligands. (Wang et al. 2019), Narayanan and Palantavida (2021) examined a solid-state complexation of iron(III) by bis(β-diketone) extractor and specific extraction of iron(III) (Narayanan and Palantavida 2021), while Yi et al. (2020) researched the separation of Fe (III) from Ni–Co–Fe solutions containing chloride utilizing solvent

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Rohit Kumar and Shubhangee Agarwal have contributed equally to this work.

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extraction with TBP (Yi et al. 2020). The selective extraction of iron(III) from extensively salted chloride acidic solutions by solvent extraction through di(2-ethylhexyl) phosphate has been examined by Hu et al. (2021a, b) (Hu et al. 2021a, b), and Hu et al. (2021b) explored the solvent extraction effectiveness and mechanism by which TBP extracts Fe^{3+} from phosphoric acid by wet processing.

The removal of iron(III) and utilizing a synthetically produced wet phosphoric acid solution, rare earth element recovery through solvent extraction was examined by Sandra Pavón et al. in 2022 (Pavón et al. 2022). Titanium solvent extraction from ilmenite as hydrochloric acid was investigated by Zhu et al. (2022). Assessing the extraction processes of all encompassed metal ions is part of wastewater and optimization (Zhu and Keyu et al. 2022). A research investigation on the separation of iron (III) using nickel chloride solutions through combinations of ketone and alcohol with aliphatic groups was conducted by Alexander Kasikov (2022) (Kasikov et al. 2022). Investigation on separation of Fe(III)-Mn(II) using trialkylphosphine oxide (Cyanex 923) through supported liquid membrane in the processing of participated for alkaline batteries was researched by Alguacil and Lopez (2021). Ebaa Adnan Azooz et al. (2023) investigated the pre-concentration of Fe(III) ions in water and fruit samples before spectroscopic inspection using the displacement cloud point extraction approach (Azooz et al. 2023). Highly effective bio-polymeric membranes composed of chitosan, which contain incorporated alongside green solvent-encapsulated MIL-53(Fe) for the pervaporation-based process for separating methanol and MTBE, have been researched by Kachhadiya and Murthy et al. in 2023 (Kachhadiya and Murthy 2023).

Further, the optimization of processes is able to be accomplished with fewer human facilities in addition to fewer experimental trials by using mathematical modeling of the process. Additionally, it aids in a deeper comprehension of the mass transfer mechanism. Therefore, it was necessary to create a mass transfer model for liquid membranes that can reasonably predict, with mild approximations, the transportation of metal ions leaking from side to side membranes and produce results with a respectable degree of accuracy. A few systems under various experimental conditions have been evaluated with the model. The model is simple, but it accurately predicts the experimental results within reasonable error bounds is researched by Kandwal et al. (2011) and Kumar and Kandwal (2021) (Kandwal et al. 2011, Kumar et. al 2021). The disregard of model for strip phase resistance prevents us from seeing how the strip composition affects things. The deficiency of acidic cotransport, which be able to be included through presuming that the acid (H_3O^+) complexes by way of the transporter molecule, is another drawback of the model. Therefore, the present work reports the first detailed study on extraction and partition or transport of Fe(III) of hydrochloric acid (HCl) medium using Cyanex 923 as an extractant. The impact of several basic parameters on the process of extraction of ferric ions by Cyanex 923 has been analyzed. Under optimal circumstances, the process for influence of ligand concentration and influence of feed acidity on extraction and transport of ferric ions using Cyanex 923 has also been assessed, along with the equilibrium extraction constant. Additionally, modeling studies have been used to validate the experimental results.

Experimental method

Chemicals & materials

The analytical high-quality components used in all the compounds were acquired concerning Thomas Baker (India) and The Modern Scientific Industries, Meerut (India). The investigations were conducted using ultrapure water that was procured from URO Techno System, Ahmadabad, Gujarat (India). The metal ions were dissolved in their salts in ultrapure water with a minimal amount of the matching mineral acid to generate stock solutions. Without any additional purification, Cyanex 923 also known as **trialkylphosphine oxide** was utilized, and structural composition of extractant shows in Fig. 1.

The following parameters were reached by the polytetrafluoroethylene (PTFE) membrane filters (47 mm diameter) utilized as a membrane support for the transport experiments of Fe(III) ions: 64% porosity, 0.45 µm pore size (established using Hg porosiometry), and 85 µm thickness (as determined using Mitutoya digital micrometer). In the case of our experimental establishing, effective surface area of the membrane was determined through the multiplication of estimated geometrical area through membrane porosity that produces 3.14 cm^2 (S. Sriram et al. 2000).

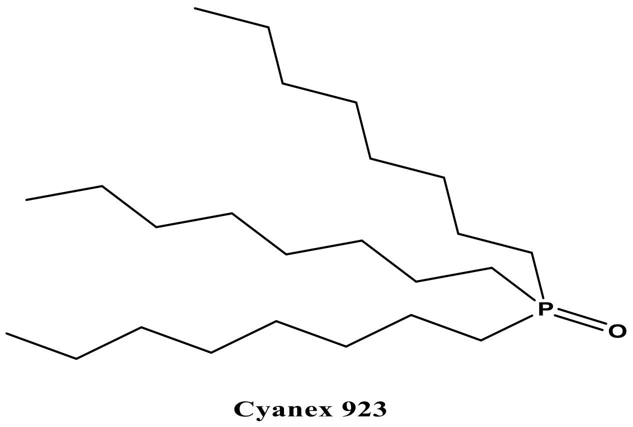

Fig. 1 Chemical Structure of Cyanex 923

Distribution studies

In equal amounts (1 ml) of an organic phase consisting of the ligand concentration solution (1 M Cyanex 923 in solvesso 100) and an aqueous phase carrying the iron tracer at a specified pH. The two phases were granted the opportunity to adjust in a stopper glass tube with rotational thermostated waters that was kept at a constant 25 ± 0.1 °C. This time was found sufficient for attaining the equilibrium condition. The two phases were then centrifuged for 2–5 min followed by taking suitable aliquots (0.1 ml) of the aqueous phase and organic phases; the metal contents were measured using a microplasma atomic emission spectrometer (MP-AES). The combination of the ratio of the entire activity of the Fe(III) sample within organic phase compared with the activity for the equivalent volume of aqueous phase resulting in the pattern of distribution ratio (K_d). Generally, solvent extraction studies were typically carried out in triple quantities, and the approved results remained within the range of ± 5% relative standard deviation (RSD) error limitations.

Model development

Mass transport process

The process of mass transfer is composed of various steps in supported liquid membranes (particularly through flat sheet supported liquid membrane [FSSLM] and hollow fiber supported liquid membrane [HFSLM]), which are illustrated in Fig. 2.

- Diffusion of metal ions takes place at feed-membrane interface through high portion of feed solution.
- At feed-membrane contact, metal ion complexes by extractant molecule and transfers keen on membrane phase.
- The diffusion of metal-extractant complex across membrane achieves the strip-membrane interface as a result of the concentration gradient.
- Metal-extractant complex de-complexes on strip-membrane interaction, discharging metal ion in strip phase.
- Released extractant diffuses reverse toward feed side, where it recombines with the metal to complete the process.

Proposed model and assumptions

The present model was developed for prediction of mass transfer through liquid membrane, which is based on the diffusive mass transport phenomena. Some of the parameters were assumed, and the dependence of the assumed parameter on the system is also integrated into the model. The approach to model development depends on the following assumptions:

1. Linear concentration gradients through the membrane and boundary layer
2. As interface reactions typically occur more quickly than diffusion across boundary layers, reaction resistances are regarded as insignificant.
3. Instantaneously stripping at the interface indicates that the membrane phase does not contain mass accumulation.
4. Steady-state (pseudo-equilibrium) exists.

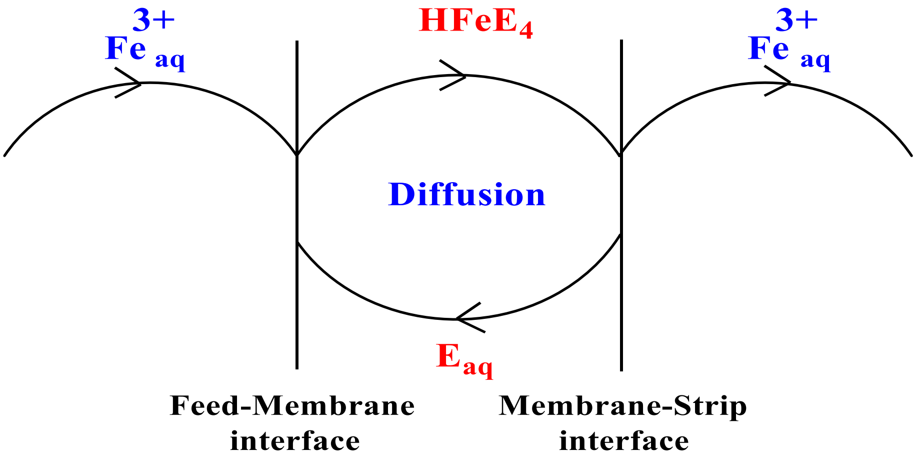

Fig. 2 A simplified viewpoints on the mechanism of transport of ferric ions across supported liquid membranes

Where, Fe^{3+} = *Concentration of ferric ions in feed side and strip side*
E = *Concentration of extractant/ligand*
E_{aq} = *Concentration of extractant nearly to feed side*
$HFeE_4$ = *Concentration of metal-extractant inside membrane*

5. The process that limits the rate is the diffusion process through the membrane phase.

Based on these assumptions, a set of mathematical equations is formed describing mass transport across liquid membrane. The mathematical equations are solved using MATLAB ODE solver. Then, by compared the simulated result with that of the experimental data, the model generated is verified.

Expansion of mathematical model

To neutralize the charge on the complex with instruct of ligand (E), metal ion as well as a counter anion is cotransported. The extraction reaction that follows represents the equilibrium.

$$\mathrm{Fe}^{3+} + 4\mathrm{Cl}^{-1} + \mathrm{H}^{+}_{(aq)} + 4E_{(org)} \leftrightarrow \left[\mathrm{HFe(Cl)}_4(E)_4\right]_{(\mathrm{org})}$$

where, $E_{(\mathrm{org})}$ and $\left[\mathrm{HFe(Cl)}_4(E)_4\right]_{(\mathrm{org})}$ denote extractantand metal-extractant complex, respectively, Cl^- is a counter anion; subscripts “org” and “aq” stand for species inorganic phase and aqueous phase in that order. The equilibrium constant (K_{eq}) specified by;

$$K_{\mathrm{eq}} = \frac{\overline{C}_{f,\,i}}{C_{f,\,i} X_f^4 E^4} = \frac{K_d}{X_f^4 E^4} \tag{1}$$

where, $\overline{C}_{f,i}$ denotes the extracted species $\left[\mathrm{HFe}^{3+}(\mathrm{Cl})_4(E)_4\right]_{(\mathrm{org})}$ in organic phase at feed-membrane interface and E stand for concentration of unbound ligand inside the membrane phase, $C_{f,i}$ denotes concentration of metal ion (Fe^{3+}) in feed phase, and X_f denotes the concentration of chloride ion in feed phase (Fig. 3). The scientific term of distribution ratio (K_d) is;

$$\text{Distribution ratio, } \left(K_d\right) = \frac{\left[\mathrm{HFe}^{3+}(\mathrm{Cl})_4(E)_4\right]_{(\mathrm{org})}}{[\mathrm{Fe}^{3+}]_{(\mathrm{aq})}} = \frac{\overline{C}_{f,\,i}}{C_{f,\,i}}$$

Given the assumption that Fick’s first rule of diffusion may be used to determine the flux (J_a) at aqueous feed side departing across membrane have flux (J_o) for Fe(III) ion [Fig. 2],

$$J = -D\frac{\mathrm{d}c}{\mathrm{d}x} \tag{2}$$

Using Eq. (2)

$$J_a = \frac{D_{\mathrm{aq}}}{d_{\mathrm{aq}}}.\left(C_B - C_{f,\,i}\right) \tag{3}$$

$$J_o = \frac{D_{\mathrm{org}}}{d_{\mathrm{org}}}.\left(\overline{C}_{f,\,i} - \overline{C}_{s,\,i}\right) \tag{4}$$

where, C_B indicates concentration of Fe(III) ion in bulk feed solution, whereas $C_{f,i}$ denote the concentration of $\left[\mathrm{HFe}^{3+}(\mathrm{Cl})_4(E)_4\right]_{(\mathrm{org})}$ at membrane-strip interface (Fig. 3), D indicates the diffusion coefficient, and d represents diffusion path length, we define k = (Diffusion coefficient)/(thickness of layer), where k is mass transfer coefficients. Considering the fact that distribution ratio of metal ions is lower at the membrane-strip interface compared with feed-membrane interface, Eq. (4) is able to be modified as.

Using assumption 3

$$J_o = \frac{D_{\mathrm{org}}}{d_{\mathrm{org}}}\overline{C}_{f,\,i}$$

$$J_o = \frac{D_{\mathrm{org}}}{d_{\mathrm{org}}}\left(C_{f,\,i}K_d\right) \text{ because, } K_d = \frac{\overline{C}_{f,\,i}}{C_{f,\,i}}$$

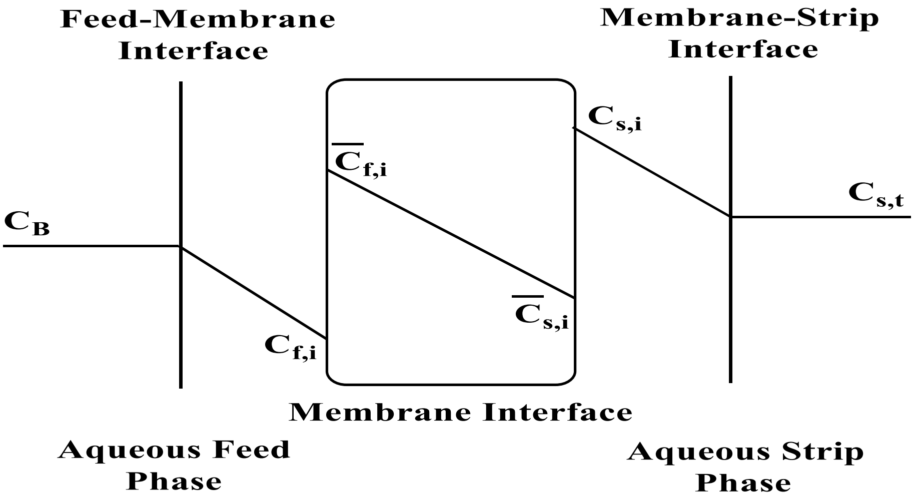

Fig. 3 Schematic illustration showing the profiles of metal ion concentrations in various portions of the supported liquid membrane; *C* is a representation of the metal ion concentration in various portions

$$J_o \frac{d_{\mathrm{org}}}{D_{\mathrm{org}} K_d} = C_{f,i} \tag{5}$$

Adding Eq. (3) and Eq. (5)

$$C_B = J_a \frac{d_{\mathrm{aq}}}{D_{\mathrm{aq}}} + J_o \frac{d_{\mathrm{org}}}{D_{\mathrm{org}} K_d}$$

From assumption 4, at pseudo-equilibrium, we have $J_a = J_o = J$

$$C_B = J\left[\frac{d_{\mathrm{aq}}}{D_{\mathrm{aq}}} + \frac{d_{\mathrm{org}}}{D_{\mathrm{org}} K_d}\right]$$

$$(\because d_{\mathrm{org}} = d_m \cdot \tau)$$

$$C_B = J\left[\frac{d_{\mathrm{aq}}}{D_{\mathrm{aq}}} + \frac{d_m \tau}{D_{\mathrm{org}} \cdot K_d}\right]$$

We define,

$$\Delta_o = \frac{d_m \tau}{D_{\mathrm{org}}} \quad \text{and} \quad \Delta_a = \frac{d_{\mathrm{aq}}}{D_{\mathrm{org}}}$$

Given the assumption that carrier of membrane is not saturated with Fe^{3+} ion according to $K_{\mathrm{eq}} = \frac{\overline{C_i}}{C_I}$, Tortuosity ($\tau$) > 1 and mass transfer resistance of the appropriate boundary layer is represented by ($\Delta = 1/k$), flux expression for Fe^{3+} be able to be write as,

$$J = \frac{C_B K_d}{\Delta_o + K_d \Delta_a} \tag{6}$$

where, Δ_a and Δ_o indicate the mass transfer resistances in feed-membrane interface and in organic phase in membrane phase, respectively. We also have

$$J = P C_B \tag{7}$$

Comparing Eq. (6) and Eq. (7)

$$\text{Permeability } (P) = \frac{K_d}{\Delta_o + K_d \Delta_a} \tag{8}$$

The expressions for mass flux for metal ion may be derived as follows,

$$QJ = -V \frac{\mathrm{d}C_B}{\mathrm{d}t} \tag{9}$$

Using Eq. (7) and Eq. (9), one can deduce that,

$$J = -\frac{V}{Q} \frac{\mathrm{d}C_B}{\mathrm{d}t} = \frac{C_B K_d}{\Delta o + K_d \, \Delta a}$$

or,

$$\frac{\mathrm{d}C_B}{\mathrm{d}t} = -\frac{Q}{V} \frac{C_B \cdot K_d}{\Delta o + K_d \, \Delta a} \tag{10}$$

The effective surface area (Q) of the membrane can be determined by multiplying the geometrical area (A) by the porosity (ε) of membrane, while the volume of aqueous feed solution (V) additionally demonstrated. Metal-carrier complex is formed when one molecule of Fe(III) ion (C) is associated to ligand molecules (E). Consequently, the ligand mass balance inside the membrane phase is expressed as,

$$E_{\mathrm{free}} + 4\overline{C}_{f,i} = E_T \tag{11}$$

where, in the membrane phase, the letters E and E_T stand for the concentration of free carriers and total extractant, respectively, combining Eq. (1), (5), (10) & (11), one can finally obtain,

$$\frac{4 C_B K_d}{\Delta_o + K_d \Delta_a} + \left[\frac{K_d}{X_f K_{\mathrm{eq}}}\right]^{\frac{1}{4}} - E_T = 0 \tag{12}$$

In order to preserve electrical neutrality, x mole of counter anions is transmitted from the feed side to strip side for each mole of Fe^{3+} transference. In order to decrease the concentration of metal in feed and overall concentration of Cl$^-$ in feed can be expressed, then

$$X_f = [X_{f,o} - 4(C_{\mathrm{BO}} - C_B)] \tag{13}$$

where, initial concentrations of metal ion is represented by C_{BO}, and initial concentrations of nitrate ions in the bulk solution are indicated by $X_{f,o}$, substituting the value of X_f in Eq. (12), one can write,

$$\frac{4 \Delta_o C_B K_d}{\Delta_o + K_d \cdot \Delta_a} + \left[\frac{K_d}{[X_{f,o} - 4(C_{\mathrm{Bo}} - C_B)]^4 \cdot K_{\mathrm{eq}}}\right]^{\frac{1}{4}} - E_T = 0 \tag{14}$$

Now, rearranging Eq. 14, then

$$\frac{4 \Delta_o C_B K_d}{\Delta_o + K_d \Delta_a} + \left[\frac{K_d^{\frac{1}{4}}}{[X_{f,o} - 4(C_{\mathrm{Bo}} - C_B)] K_{\mathrm{eq}}^{\frac{1}{4}}}\right] - E_T = 0 \tag{15}$$

After differentiating Eq. (15) with respect to time (t), Eq. (10) takes on associated. Using mathematical techniques such as those accessible with MATLAB, two differential equations $\mathrm{d}C_B/\mathrm{d}t$ and $\mathrm{d}K_d/\mathrm{d}t$ are obtained by this process and solved simultaneously.

Mass transfer resistance calculation

The permeability (P) of metal ions across flat sheet supported liquid membrane (FSSLM) is obtained via generating the diagram $\ln\left(\frac{C_{f,t}}{C_{f,0}}\right)$ versus time (t) by way of support of given procedure as,

$$-\ln\left(\frac{C_{f,t}}{C_{f,0}}\right) = \left(\frac{Q}{V}\right) \times P \times t \qquad (16)$$

where, P, V, and Q are represented as permeability of metal ion (cm/s), total volume of feed solution (ml), and surface area of membrane (3.14 cm^2), and $C_{f,o}$ and $C_{f,t}$ indicated ferric ions concentrations in feed side at $t = 0$ and time t, correspondingly.

The mass transfer resistances ($\Delta_a \& \Delta_o$) was experimentally calculated with graphing $1/P$ versus $1/K_d$, in accordance with the relevant following calculation, gets linearly filled

$$\frac{1}{P} = \Delta_a + \frac{\Delta_o}{K_d} \qquad (17)$$

The values of $\Delta_a = 169$ s/cm and $\Delta_o = 398$ s/cm can be derived using a linear proper of the data from empirically acquired graph. These values are able to be utilized as input into additional analyses.

Results and discussion

Influence of HCl concentration

Extraction studies of ferric ions/Fe(III) from hydrochloric acid medium were examined using 1 M Cyanex 923 in solvesso 100. Acid molarity was performed in the range of 1–8 M (Fig. 4), and ferric ions is quantitatively extracted at 1–5 M acidity. This can be attributed to the formation of more soluble metal chloride complexes that are readily extracted by Cyanex 923. At moderate acidities, the protonation of Cyanex 923 might facilitate the formation of more stable complexes with ferric ions, enhancing extraction efficiency. Higher concentrations of HCl (6–8 M) could lead to competitive complexation or increased solvation of ferric ions in the aqueous phase, reducing their availability for extraction by Cyanex 923 and higher acidity may also affect the solubility or stability of Cyanex 923, potentially leading to reduced extraction efficiency due to changes in its chemical environment.

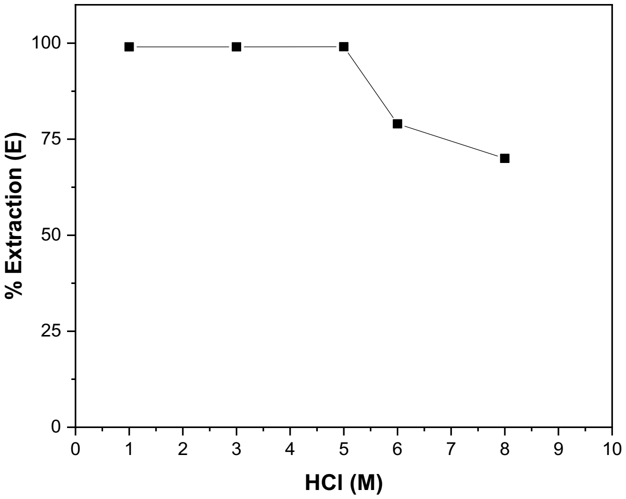

Fig. 4 Influence of concentration of hydrochloric acid (HCl) on extraction of Fe(III) at conditions of 100 mg/L Fe(III) and 1 M Cyanex 923

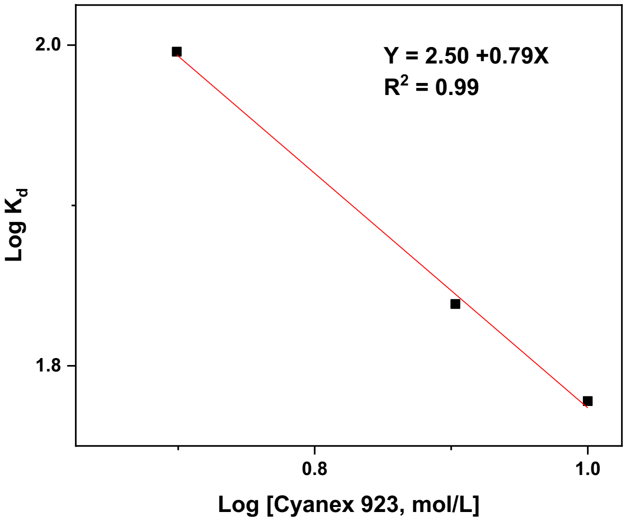

Fig. 5 Influence of concentration of Cyanex 923 on extraction of Fe(III) ions at conditions of 100 mg/L Fe(III) and 1 M HCl

Influence of Cyanex 923 concentration

An investigation was performed to examine the influence of various concentrations of (1–10 M) Cyanex 923 extractant on the extraction of Fe(III) ions. The concentration of ferric ions was preset at 100 mg/L with a 1 M HCl concentration. The distribution ratio and concentration of extractant (Cyanex 923), log-log plot of the tentative results are given away in Figure 5. A slope value of 0.79 was found, when comparing log K_d versus log [Cyanex 923], representing that one mole of extractant was concerned in generating of extracting species for every one mole of the ferric ions.

Variation of ligand concentration

The influence of concentration of ligand (Cyanex 923) was investigated in the concentration series of 1–10 M Cyanex 923. It has been determined that the transport rate of Fe(III) ions increases by way of growing carrier/ligand concentration at 1–5 M. The key reason behind this increase is the higher distribution ratio of Fe(III) ions at the interface between the feed solution and the membrane. Cyanex 923 forms complexes with Fe(III) ions, which facilitate their transport through the membrane (Table 1).

However, as the concentration of Cyanex 923 was further increased to 8 M and 10 M, the transport rate of Fe(III) ions started to decrease. This decrease is attributed to the formation of excessive complexes between Cyanex 923 and Fe(III) ions at these higher concentrations. These complexes might hinder the transport process rather than facilitating it (Fig. 6).

To come to point, the concentration of Cyanex 923 significantly impacts the transport of Fe(III) ions across the membrane. Moderate concentrations enhance transport by increasing the distribution ratio, whereas very high concentrations lead to reduced efficiency due to complex formation. This highlights the importance of optimizing ligand concentration in membrane processes for efficient metal ion extraction.

Examining Eq. (10), the observed trend may be readily explained in terms of the prediction of model. The right part of Eq. 10 grows increasingly negative as a result of a greater distribution ratio value (K_d) for Fe(III) caused by an increase in ligand concentration. Therefore, with greater ligand concentrations, the metal concentration decreases significantly more quickly.

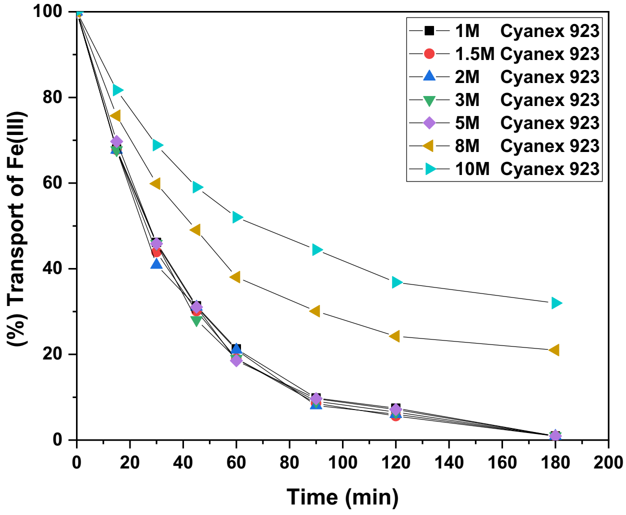

Fig. 6 Simulation of transport of Fe(III) ions for various ligand concentrations (feed: 1 M HCl, strip: distilled water, ligand: 1–10 M Cyanex in solvesso 100)

Feed acidity variation

A higher HCl concentration is generated by increasing the feed acidity, which increases the extraction of metal ion (Table 2). As a result, it stands to reason that the transport rate will rise as the counter anion concentration while maintaining the other parameter's constant, and the transport of ferric ions experiment were conducted at varying nitric acid concentrations in feed. Transport rate of Fe(III) ions out of feed solution increases with feed acidity, as demonstrated by simulation results shown in Fig. 7. The common factor of Eq. 10 mainly determines by mass transfer resistance in organic phase (Δ_o), in view of the fact that result of K_d, $\Delta_a << \Delta_o$. Therefore, according to Eq. 10, the transport of ferric ions increased at higher feed phase acidity. The rate of transport of Fe(III) ion results shown in Fig. 7 is predicted by the model. It deserves to be eminent that growing the acidity of the feed also raises H^+ ion content on feed side. Since that this is compared to the actual data, it additionally influences the feed acidity from the side that receives feed side to strip side. This is anticipated to reduce the performance of stripping and produce some odd results in the later portion of the simulated curve.

Table 1 The value of experimentation of distribution ratio (K_d) of Fe(III)/ferric ions at varying ligand concentration; aqueous phase: 1 M HCl; organic phase: 1–10 M Cyanex 923 in solvesso 100

[Cyanex 923], *M*	K_d, Fe(III)	% *E* (Extraction)
1	0.83	99.04
1.5	1.62	99.05
2	1.95	99.06
5	2.39	99.07
8	3.21	68.94
10	3.46	59.97

Table 2 Distribution ratio (K_d) of Fe(III)/ferric ions at varying the concentration of hydrochloric acid; organic phase: 1 M Cyanex 923 in solvesso 100

[HCl], *M*	K_d, Fe(III)	% *E* (Extraction)
1	0.08	99.04
2	1.56	99.27
3	2.59	99.05
4	3.67	99.06
5	3.89	99.07
6	3.28	79.01
8	2.29	70.01

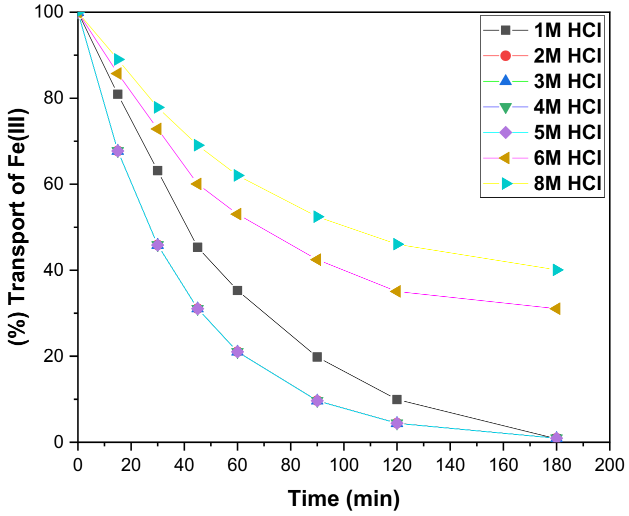

Fig. 7 Study on variations in feed acidity (ligand: 1 M Cyanex 923 in solvesso 100, feed: 1–8 M HCl, strip: distilled water)

Conclusion

In the present work, mathematical model using the Cyanex 923 ligand develops to clarify the transport of ferric ions through membranes. The model predictions optimum experimental parameters for ferric ion's transport from FSSLM that is both effective and efficient. A quantitative extraction of ferric ions is possible at 1–5 M HCl and decreases to 6–8 M HCl. The distribution of metal ion ratios and extraction percentage increased and decreases at 8–10 M ligand concentrations, respectively. Transport rate of ferric ions were increased at highly feed acidity (1–5 M) and decreased at 6–8 M HCl. Furthermore, our earlier findings demonstrated the suitability of model for the system. More comprehensive verification of the model on various systems is necessary before applying it to unidentified systems. Subsequent investigations will do a comprehensive evaluation of the model's suitability and begin making the necessary modifications to faithfully represent the mass transfer process.

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Author contributions The authors contributed the study of conception and design, preparation of material, data collection, and analysis were performed by Rohit Kumar and Shubhangee Agarwal. The first draft of manuscript was written by Rohit Kumar and Shubhangee Agarwal, and all authors commented on previous versions of the manuscript. Rohit Kumar and Shubhangee Agarwal read and approved the final manuscript.

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

Declarations

Conflict of interest The authors have no relevant financial or nonfinancial interests to disclose.

Ethics approval I would like to declare on behalf of my coauthors that the work described was original research that has not been published previously.

Consent to participate All the authors consent to participate.

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

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