Effects of process factors on performances of liquid membrane-based transfer of indole-3-acetic acid

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The paper has aimed at studying the transfer of indole 3-acetic acid (IAA) from a feed aqueous solution to a stripping aqueous solution of NaOH using a chloroform bulk liquid membrane and trioctylamine (TOA) as a ligand (L). Initial molar concentrations of IAA in the feed phase, \(c_{IAA,F0}\) (10\(^{-4}\)–10\(^{-3}\) kmol/m\(^3\)), of TOA in the membrane phase, \(c_{L,M0}\) (10\(^{-2}\) and 10\(^{-1}\) kmol/m\(^3\)), and of NaOH in the stripping phase, \(c_{NaOH,S0}\) (10\(^{-2}\) and 1 kmol/m\(^3\)), were selected as process factors. Their effects on the final values of IAA concentration in the feed phase, \(c_{IAA,Ff}\), and stripping solution, \(c_{IAA,Sf}\), extraction efficiency, \(EF\), distribution coefficient, \(KD\), and recovery efficiency, \(ER\), were quantified using multiple regression equations. Regression coefficients were determined from experimental data, i.e.,

\[
c_{IAA,Ff,ex} = 0.02–1 \times 10^{-4} \text{ kmol/m}^3, \\
c_{IAA,Sf,ex} = 0.22–2.58 \times 10^{-3} \text{ kmol/m}^3, \\
EF,ex = 90.0–97.9\%, \\
KD,ex = 9.0–46.6, \\
ER,ex = 66.5–94.2\%.
\]

It was found that \(c_{IAA,F0}\) had the most significant positive effect on \(c_{IAA,Ff}\) and \(c_{IAA,Sf}\), whereas \(c_{NaOH,S0}\) had a major positive effect on \(EF\), \(KD\), and \(ER\). A deterministic model based on mass transfer of IAA was developed and its parameters, i.e., mass transfer coefficient of IAA-L complex in the liquid membrane (0.82–11.5 \(\times\) 10\(^{-7}\) m/s) and extraction constant (1033.9–1779.7 m\(^3\)/kmol), were regressed from experimental data. The effect of \(c_{L,M0}\) on both parameters was significant.

Phytohormones are a group of natural substances found in plants with the role of regulating plant growth and development. The main classes of phytohormones are auxins, abscisic acids, gibberellins, ethylene, and cytokinins. Indole 3-acetic acid (IAA) is an auxin which has an important role in various plant physiological processes, e.g., cell elongation, division, and differentiation, flowering, fruit development. IAA-based biofertilizers and biostimulants can heavily improve soil fertility and crop production. Phytohormones are synthesized by plants at very low levels (0.1–50 ng/g fresh weight basis) and the plants contain many other compounds with similar structure. Accordingly, finding simple, fast, and efficient methods for their separation and analysis is a very important task as well as a challenge.

Several analytical techniques were developed for phytohormone analysis, e.g., gas chromatography (GC), GC coupled with mass spectrometry (GC–MS), spectrophotometry, high performance liquid chromatography (HPLC), HPLC coupled with mass spectrometry (HPLC–MS), ultraviolet (HPLC–UV) or fluorescence detection (HPLC–FD). A preliminary stage of sample pretreatment before the instrumental analysis is commonly necessary to purify and concentrate the target phytohormone(s). Due to the low phytohormone concentration in the plants as well as to the presence of other compounds with a similar structure, sample pretreatment is a critical stage. In addition to the significant loss of analyte mass, this stage can be time-consuming and introduce errors in subsequent quantification.

Solid phase extraction (SPE) is the most common pretreatment technique applied before the quantification of phytohormone content by instrumental analysis. SPE is simple, fast, but commonly has a low selectivity as well as it requires a large solvent volume, resulting in a limited enrichment factor. Solid phase microextraction (SPME) allows simultaneous extraction and concentration of analytes. SPME is characterized by a low solvent consumption and a high enrichment factor, but requires specialized equipment and usually has low selectivity and efficiency.
Selection of efficient methods for the separation and purification of IAA carboxylic acid has become a major research aim. Various techniques for the separation of carboxylic acids from aqueous solutions, including liquid–liquid extraction, adsorption, nanofiltration, ultrafiltration, ion exchange, electrodialysis, reverse osmosis, distillation, liquid membrane separation (LMS), have been intensively studied. LMS has a series of advantages, e.g., fast and selective separation of target compounds, high transport efficiency, recovery of different compounds with low concentrations, low cost compared to other methods of separation, simple handling, easy to scale up. Accordingly, LMS could be an efficient sample pretreatment applied before instrumental analysis of IAA.

Liquid membranes are semi-permeable barriers that separate two aqueous phases, i.e., feed (source or donor) and stripping (receiving or acceptor) phases. Techniques based on bulk liquid membranes (BLMs), emulsion liquid membranes (ELMs), and supported liquid membranes (SLMs) have been widely used to separate organic compounds and metal ions from aqueous solutions. BLM-based separation technique is the most simple and efficient among them. BLMs have been extensively used in the separation of carboxylic acids, e.g., formic, acetic, propionic, butyric, levulinic acids, and metal ions through liquid membranes.

Solute transfer through systems containing liquid membranes can be significantly enhanced by adding different carriers (ligands or extraction reagents) in the liquid membrane. Mass transfer assisted by a carrier takes place as follows: (1) the carrier reacts with the target compound (solute) at the interface between feed phase and membrane phase forming a chemical complex; (2) solute–carrier complex diffuses through liquid membrane and reaches the interface between membrane and stripping phase, where the decomposition occurs; (3) the solute is released into the stripping phase, whereas the carrier diffuses back through membrane. A suitable carrier facilitates the solute extraction (from feed phase) and transport (through membrane phase) as well as determines its purification.

Neutral, acidic (anionic), and basic (cationic) carriers have been extensively used in different applications both on a laboratory and industrial scale. Tri-n-butyl-phosphate (TBP) and tri-n-octyl phosphine oxide (TOPO) are neutral carriers widely applied to transport organic compounds (e.g., formic, acetic, propionic, butyric, acrylic, levulinic, hippuric, and mandelic acids, vanillin, catechol) and metal ions through liquid membranes.

Acetic carriers such as di-(2-ethylhexyl)phosphoric acid (D2EHPA), bis(2,4,4-trimethylpentyl)phosphonic acid (Cyaxen 272), and derivatives of Cyanex 272 have been used to extract and transport amino acids, peptides, and metal ions. Tri-octylamine (TOA) and N-methyl-N,N,N-tri-octylammonium chloride (Aliquat 336) are basic carriers commonly involved in liquid membrane-based separations. TOA has been extensively applied to separate carboxylic acids (e.g., acetic, propionic, and lactic acids) and metals, whereas Aliquat 336 to extract phenolic compounds, antibiotics, and metals. Selecting suitable liquid membranes and carriers, BLM-based separation could be successfully applied to isolate and concentrate IAA in a single step.

Mathematical modelling is an effective tool used to predict the performances of liquid membrane-based separation. Process performances depend on different factors, e.g., type and initial concentration of separating species in the feed phase, type of organic solvent in the membrane phase, type and concentration of carrier in the membrane phase, type and concentration of stripping agent in the stripping phase, type of separation equipment, stirring speed, temperature, pH of feed and stripping phases, volumes of feed, membrane, and stripping phases and their contact surface areas.

The transport of IAA through a chloroform BLM using TOA as a basic (cationic) carrier was studied in this paper. Statistical models based on a 2³ factorial plan and a deterministic model based on mass transfer of IAA were used to predict the process performances under different operation conditions. Chloroform is widely used as BLM. It has a lower viscosity (η = 0.58 cP) than other solvents, e.g., 1,2-dichloroethane (η = 0.73 cP), nitrobenzene (η = 1.62 cP), resulting in a faster mass transfer. TOA carrier can heavily improve the separation efficiency. TBP, TOPO, and TOA carriers and chloroform BLM were used in a previous study to separate IAA from dilute aqueous solutions. Separation efficiency was higher for TOA carrier, due to stronger donor–acceptor interactions between IAA and TOA, as opposed to weaker hydrogen bonds between IAA and the other two carriers.

**Materials and methods**

**Materials.** IAA, chloroform, TOA, and NaOH, which were provided by Merck (Germany), were analytical grade reagents used without further purification. Three-phase system involved in the mass transfer process consists of: (1) a feed (F) aqueous solution of IAA; (2) a membrane (M) phase consisting of a chloroform BLM and TOA as a ligand (L); (3) a stripping (S) aqueous solution of NaOH.

**Experimental setup and process parameters.** A scheme of experimental setup used to study the transfer of IAA from the feed phase to stripping phase is shown in Fig. 1. The tube in tube setup consists of an outer glass tube, containing the feed solution (at the upper part) and membrane phase (at the bottom part), and an inner glass tube, containing the stripping solution. The internal diameter of outer tube was D = 0.042 m, whereas the external and internal diameters of inner tube were d = 0.021 m and d = 0.019 m, respectively. The values of phase volumes were V_F = 20 × 10⁻⁶ m³, V_M = 50 × 10⁻⁶ m³, and V_S = 70 × 10⁻⁶ m³.

According to the schematic representation in Fig. 1, the mass transfer process in the experimental setup occurs as follows: (1) IAA diffuses through F phase towards interface between F and M phases; (2) TOA (L) diffuses through M phase towards F-M interface; (3) IAA reacts with L at the interface forming the IAA-L complex; (4) IAA-L complex diffuses through M phase and reaches the interface between M and S phases, where the decomposition takes place; (5) IAA is released into S phase and L diffuses back through M phase.

Initial molar concentrations of IAA, TOA, and NaOH in F, M, and S phase, namely C_IAA,F, C_TOA,F, and C_NaOH,S were selected as process independent variables (factors). Twenty experimental runs were conducted at different
levels of \( c_{\text{IAA,F}} \) (10\(^{-4}\)–10\(^{-3}\) kmol/m\(^3\)), \( c_{\text{L,M}} \) (10\(^{-2}\) and 10\(^{-1}\) kmol/m\(^3\)), and \( c_{\text{NaOH,S}} \) (10\(^{-2}\) and 1 kmol/m\(^3\)). Each experiment was performed for 4 h, at ambient temperature, under mechanical stirring (200 rpm) of inner tube.

Final \((f)\) values of molar concentration of IAA in the feed \((c_{\text{IAA,F},f,ex})\) and stripping solution \((c_{\text{IAA,S},f,ex})\), corresponding to \( \tau_f = 14,400 \) s, were determined experimentally using a LAMBDA 750 spectrophotometer (PerkinElmer, USA). Extraction efficiency \((E_{F,ex})\), distribution coefficient \((K_{D,ex})\), and recovery efficiency \((E_{R,ex})\) are defined by Eqs. (1)–(3)\(^{10-12,18,30}\).

\[
E_{F,ex} = 100 \frac{c_{\text{IAA,F},0} - c_{\text{IAA,F},f,ex}}{c_{\text{IAA,F},0}} \tag{1}
\]

\[
K_{D,ex} = \frac{c_{\text{IAA,F},0} - c_{\text{IAA,F},f,ex}}{c_{\text{IAA,F},f,ex}} \tag{2}
\]

\[
E_{R,ex} = 100 \frac{c_{\text{IAA,F},f,ex}}{c_{\text{IAA,F},0}} \tag{3}
\]

**Statistical analysis.** Multiple regression analysis and correlation analysis were performed using XLSTAT 2019.1 (Excel).

**Mathematical modelling. Statistical models.** The effects of process factors \((c_{\text{IAA,F0}}, c_{\text{NaOH,S0}}, \text{and } c_{\text{L,M0}})\) on dependent variables (responses), i.e., \( c_{\text{IAA,F}}, c_{\text{IAA,S}}, E_p, K_D, \text{and } E_R \), were quantified using statistical models based on a 2\(^3\) factorial plan\(^{35,36}\). According to a 2\(^3\) factorial plan, 8 experimental runs (1–8 in Table 1) were conducted at 2 levels (inferior and superior) of process factors. Dimensionless values of process factors are given by Eqs. (4)–(6), where \( c_{\text{L,M0},p} = 0.00055 \) kmol/m\(^3\), \( c_{\text{NaOH,S0},p} = 0.505 \) kmol/m\(^3\), and \( c_{\text{L,M0},p} = 0.055 \) kmol/m\(^3\) are centre-points.

\[
x_1 = \frac{c_{\text{IAA,F0}} - 0.00055}{0.00045} \tag{4}
\]

\[
x_2 = \frac{c_{\text{NaOH,S0}} - 0.505}{0.495} \tag{5}
\]

\[
x_3 = \frac{c_{\text{L,M0}} - 0.055}{0.045} \tag{6}
\]
Table 1. Experimentation matrix for 2^4 factorial experiment.

| Run | $c_{IAA,F} \times 10^3$ (kmol/m³) | $c_{SNaOH,S} \times 10^3$ (kmol/m³) | $c_{IAA,F,ex} \times 10^4$ (kmol/m³) | $c_{IAA,F,ex} \times 10^4$ (kmol/m³) | $E_{tot}$ (%) | $K_{ex}$ | $E_{ex}$ (%) |
|-----|----------------------------------|----------------------------------|----------------------------------|----------------------------------|-------------|----------|-------------|
| 1   | 0.1                              | 10                               | 10                               | 0                               | 0.07        | 0.22     | 93.0        |
| 2   | 1                                | 10                               | 10                               | 0                               | 1.00        | 1.99     | 90.0        |
| 3   | 0.1                              | 1000                             | 10                               | 0                               | 0.03        | 0.26     | 97.0        |
| 4   | 1                                | 1000                             | 10                               | 0                               | 0.42        | 2.58     | 95.8        |
| 5   | 0.1                              | 10                               | 100                              | 1                               | 0.04        | 0.24     | 96.0        |
| 6   | 1                                | 10                               | 100                              | 1                               | 0.50        | 2.00     | 95.0        |
| 7   | 0.1                              | 1000                             | 10                               | 1                               | 0.02        | 0.27     | 97.9        |
| 8   | 1                                | 1000                             | 10                               | 1                               | 0.28        | 2.37     | 97.2        |
| 9   | 0.55                             | 505                              | 55                               | 0                               | 0.25        | 1.11     | 11.5        |
| 10  | 0.55                             | 505                              | 55                               | 0                               | 0.26        | 1.08     | 95.3        |
| 11  | 0.55                             | 505                              | 55                               | 0                               | 0.23        | 1.15     | 95.8        |
| 12  | 0.55                             | 505                              | 55                               | 0                               | 0.24        | 1.13     | 95.7        |

Moreover, 4 centre-point runs (9–12 in Table 1) were performed. Statistical models described by Eq. (7) link the process dimensionless factors, $x_j$ ($j = 1..3$), and their interactions ($x_j x_k$, $x_j x_k x_l$, and $x_j x_k x_l x_m$) to the process responses, $y_i$ ($i = 1..5$), i.e., $y_i = c_{IAA,F} \times 10^4$, $y_2 = c_{IAA,F} \times 10^4$, $y_3 = E_{tot}$, $y_4 = K_{ex}$ and $y_5 = E_{ex}$. Regression coefficients, $\beta_{jk}$ ($k = 1..8$, $i = 1..5$), were determined based on experimental data summarized in Table 1.

$$ y_i = \beta_{1i} + \beta_{2i} x_1 + \beta_{3i} x_2 + \beta_{4i} x_3 + \beta_{5i} x_1 x_2 + \beta_{6i} x_1 x_3 + \beta_{7i} x_2 x_3 + \beta_{8i} x_1 x_2 x_3 $$

**Mass transfer-based model.** Some characteristic parameters of mass transfer process in the three-phase system, i.e., association constants in membrane phase ($K_{as,M}$) and feed solution ($K_{as,F}$), repartition constants of species IAA and $L$ (TOA) between membrane and feed solution ($R_{IAA,M/F}$ and $R_{L,M/F}$), repartition constant of species $L$ between membrane and stripping solution ($R_{L,M/S}$), and extraction constant ($K_{ex}$), are defined by Eqs. (8)–(11), where $c_p$ (kmol/m³) represents the molar concentration of $s$ (IAA, $L$, IAA-$L$) species in the $p$ ($F$, $M$, $S$) phase.

$$ K_{as,p} = \frac{c_{IAA\rightarrow L} \cdot c_{IAA,F}}{c_{IAA,F} \cdot c_{L,F}}, p = F, M $$

$$ R_{IAA,M/F} = \frac{c_{IAA,M}}{c_{IAA,F}} $$

$$ R_{L,M/F} = \frac{c_{L,M}}{c_{L,F}}, p = F, S $$

$$ K_{ext} = \frac{c_{IAA\rightarrow L,M}}{c_{IAA,F} \cdot c_{L,M}} $$

The partial mass balance of $L$ species in the three-phase system, considering perfectly mixed phases, is given by Eq. (12), where $V_p$ (m³) is the volume of $p$ ($F$, $M$, $S$) phase and $c_{L,M0}$ (kmol/m³) the initial molar concentration of $L$ species in the membrane phase. Dividing the terms of Eq. (12) to $V_M$, Eq. (13) was obtained, where $r_{M/p}$ ($p = F, S$) volume ratios are defined by Eq. (14).

$$ c_{L,M0} V_M = (c_{L,M} + c_{IAA\rightarrow L,M}) V_M + (c_{L,F} + c_{IAA\rightarrow L,F}) V_F + c_{LS} V_S $$

$$ c_{L,M0} = (c_{L,M} + c_{IAA\rightarrow L,M}) + \frac{(c_{L,F} + c_{IAA\rightarrow L,F})}{r_{M/F}} + \frac{c_{LS}}{r_{M/S}} $$

$$ r_{M/p} = \frac{V_M}{V_p}, p = F, S $$

Substituting Eqs. (8)–(11) into Eq. (13), $c_{L,M0}$ is given by Eq. (15), where $H$ is defined by Eq. (16). Assuming $H = 1$ ($R_{L,M/F} M/F$ and $R_{L,M/S} M/S$), $c_{IAA\rightarrow L,F}$ can be expressed depending on $c_{L,M0}, c_{IAA,F}$ and $K_{ex}$ using Eq. (17).

$$ c_{L,M0} = c_{IAA\rightarrow L,M} \left(1 + \frac{H}{K_{ex} c_{IAA,F}}\right) $$
The parameters $c_{IAA,F} \approx c_{K_1}$ for the concentration of $c_{NaOH,S}$ from the intercept and slope of the straight line given by a plot of $c_{NAOH,S}$ extraction and recovery efficiencies with an increase in $c_{NaOH,S}$, and, except for runs 4 and 8, at superior levels of $c_{L,M}$ being significant (8.2–9.9 times); (3) higher values of $c_{L,M}$ at inferior level of $c_{L,M}$, $k_{IAA-L,M}$ and $k_{L}$ were determined based on experimental data obtained in 16 experimental units (1–8 and 13–20 in Table 2), which were performed at different levels of $c_{L,M}$ (0.0001, 0.0003, 0.0006, and 0.001 kmol/m$^3$), $c_{NaOH,S}$ (0.01 and 1 kmol/m$^3$), and $c_{L,M}$ (0.01 and 0.1 kmol/m$^3$).

$$H = 1 + \frac{K_{ext}c_{IAA,F}}{R_{LM/FTM/F}} + \frac{1}{R_{LM/FTM/F}} + \frac{1}{R_{LM/STM/S}}$$  \hspace{1cm} (16)

$$c_{IAA-L,M} = \frac{c_{L,M0}}{1 + \frac{1}{k_{L,ext}c_{IAA,F}}}$$  \hspace{1cm} (17)

Total molar flux of $IAA$ ($J_{IAA,L}$) is defined by Eq. (18) as sum of molar flux of free $IAA$ ($J_{IAA}$) and molar flux of associated $IAA$ ($J_{IAA,L}$). Assuming $J_{IAA} \approx J_{IAA,L}$, $J_{IAA,L}$ can be expressed by Eq. (19), where $k_{IAA-L,M}$ represents the mass transfer coefficient of $IAA-L$ complex in the membrane phase. Substituting Eq. (17) into Eq. (19) and considering a stationary state characterized by a mean flux $j_{IAA,d}$. Eq. (20) was obtained, where $c_{IAA,F,m}$ is a mean concentration of $IAA$ in the feed phase. According to Eq. (20), $k_{IAA-L,M}$ and $k_{ext}$ can be estimated from the intercept and slope of the straight line given by a plot of $c_{IAA,F,m}$ vs. $J_{IAA,L}$. The parameters $k_{IAA-L,M}$ and $k_{L}$ determined based on experimental data obtained in 16 experimental units (1–8 and 13–20 in Table 2), which were performed at different levels of $c_{L,M}$ (0.0001, 0.0003, 0.0006, and 0.001 kmol/m$^3$), $c_{NaOH,S}$ (0.01 and 1 kmol/m$^3$), and $c_{L,M0}$ (0.01 and 0.1 kmol/m$^3$).

$$J_{IAA,tot} = J_{IAA} + J_{IAA-L}$$  \hspace{1cm} (18)

$$J_{IAA,tot} \approx J_{IAA-L} = k_{IAA-L,M}c_{IAA-L,M}$$  \hspace{1cm} (19)

$$\frac{c_{L,M0}}{J_{IAA,tot,m}} = \frac{1}{k_{IAA-L,M}K_{ext}} + \frac{1}{c_{IAA,F,m}}$$  \hspace{1cm} (20)

### Results and discussions

**Statistical models.** The values of dimensional and dimensionless factors and those of process responses determined experimentally, i.e., $c_{IAA,F,tot} = 0.02–1 \times 10^{-4}$ kmol/m$^3$, $c_{IAA,\text{Tot},S} = 0.22–2.58 \times 10^{-3}$ kmol/m$^3$, $E_{F,ext} = 90.0–97.9\%$, $K_{D,ext} = 9.0–46.6$, and $E_{R,ext} = 66.5–94.2\%$, are summarized in Table 1. Tabulated data (runs 1–8) highlight the following issues: (1) lower values of $c_{IAA,L,F,tot}$ at inferior levels of $c_{L,M}$ and superior levels of $c_{NaOH,S}$ and $c_{L,M0}$, the effect of $c_{IAA,F,tot}$ being significant (12.5–14.3 times); (2) higher values of $c_{IAA,F,tot}$ at superior levels of $c_{L,M}$ and $c_{NaOH,S}$, the effect of $c_{IAA,F,tot}$ being significant (8.2–9.9 times); (3) higher values of $E_{F,ext}$ and $K_{D,ext}$ at inferior level of $c_{IAA,\text{Tot},S}$ and superior levels of $c_{NaOH,S}$ and $c_{L,M0}$; (4) higher values of $E_{R,ext}$ at inferior level of $c_{IAA,L,M}$ superior level of $c_{NaOH,S}$ and, except for runs 4 and 8, at superior level of $c_{L,M0}$.

An increase in extraction and recovery efficiencies and distribution coefficient with an increase in $c_{L,M0}$ and $c_{NaOH,S}$ was reported in the related literature. A higher level of $c_{L,M0}$ leads to an increase in the concentration of $IAA-L$ complex in the membrane phase, resulting in enhanced mass transfer of this complex. On the other hand, a higher value of $c_{NaOH,S}$ determines enhanced mass transfer of $IAA-L$ complex by increasing the concentration of $L$ released in the membrane phase after decomplexation. Moreover, a decrease in extraction and recovery efficiencies with an increase in $c_{L,M0}$ was found by other researchers.

| No. | Run | $c_{IAA,L,F,tot}$ $\times 10^3$ (kmol/m$^3$) | $c_{IAA,F,tot}$ $\times 10^3$ (kmol/m$^3$) | $c_{L,M}$ $\times 10^3$ (kmol/m$^3$) | $c_{IAA,L,M}$ $\times 10^3$ (kmol/m$^3$) | $J_{IAA,tot,m}$ $\times 10^3$ (kmol/(m$^2$·s)) |
|-----|-----|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| 1   | 1   | 1.0                            | 10.0                            | 10.0                            | 0.22                            | 0.035                           | 0.382                           |
| 2   | 2   | 1.0                            | 10.0                            | 10.0                            | 0.63                            | 0.109                           | 1.087                           |
| 3   | 3   | 0.6                            | 10.0                            | 10.0                            | 1.20                            | 0.223                           | 2.057                           |
| 4   | 4   | 1.0                            | 10.0                            | 1.0                             | 1.90                            | 0.391                           | 3.258                           |
| 5   | 5   | 0.1                            | 1000                            | 10.0                            | 0.26                            | 0.038                           | 0.446                           |
| 6   | 6   | 0.3                            | 1000                            | 10.0                            | 0.75                            | 0.128                           | 1.279                           |
| 7   | 7   | 0.6                            | 1000                            | 10.0                            | 1.42                            | 0.281                           | 2.439                           |
| 8   | 8   | 1.0                            | 1000                            | 10.0                            | 2.58                            | 0.388                           | 4.418                           |
| 9   | 9   | 0.1                            | 1000                            | 100                             | 0.24                            | 0.045                           | 0.416                           |
| 10  | 10  | 0.3                            | 1000                            | 100                             | 0.69                            | 0.146                           | 1.190                           |
| 11  | 11  | 0.6                            | 1000                            | 100                             | 1.30                            | 0.320                           | 2.234                           |
| 12  | 12  | 1.0                            | 1000                            | 100                             | 2.00                            | 0.581                           | 3.429                           |
| 13  | 13  | 0.1                            | 1000                            | 100                             | 0.27                            | 0.033                           | 0.460                           |
| 14  | 14  | 0.3                            | 1000                            | 100                             | 0.77                            | 0.117                           | 1.323                           |
| 15  | 15  | 0.6                            | 1000                            | 100                             | 1.51                            | 0.249                           | 2.586                           |
| 16  | 16  | 1.0                            | 1000                            | 100                             | 2.37                            | 0.468                           | 4.066                           |
Statistical models given by Eqs. (21)–(25) express the process responses depending on dimensionless factors and their interactions. Regression coefficients, $\hat{\beta}_i$, (k = 1.8, l = 1.5), which were determined by processing the experimental data presented in Table 1, are summarized in Supplementary Tables S1–S5 along with their corresponding values of standard errors ($SE_{ki}$), t statistics ($t_k$), and p-values ($p_k$). The coefficients that are statistically significant ($p_k \leq \alpha = 0.05$, where $\alpha$ is the significance level) are written in bold. Supplementary Tables S1–S5 contain also the values of multiple determination coefficient ($R^2$), adjusted $R^2$ ($R^2_{adj}$), regression standard error (RSE), F statistic (F), and significance F (p-value for F).

Tabulated results indicate that Eqs. (21)–(24) fit the data very well ($R^2 \geq 0.966$, $R^2_{adj} \geq 0.906$, RSE $\leq 3.050$, $F \geq 16.13$, $p \leq 0.009$), whereas Eq. (25) does not fit the data well ($R^2 = 0.674$, $R^2_{adj} = 0.104$, RSE = 9.233, $F = 1.182$, $p = 0.462$). Moreover, all factors and their binary and ternary interactions in Eq. (25) (Supplementary Table S5) are statistically non-significant, i.e., $p_{f,s} > 0.05$ (k = 2.8). Quadratic regression Eq. (26), where $\hat{\beta}_{ij}$ (k = 1..10) are regression coefficients, was selected to express $y_5 = E_R$. The results of multiple regression analysis, which are given in Supplementary Table S6, highlight that the model is statistically significant ($F = 35.20$, $p = 0.028$). Moreover, $R^2 = 0.984$, $R^2_{adj} = 0.456$, RSE = 2.044 as well as $x_1$, $x_2$, and $x_3$ have statistically significant effects on $E_R$.

$$y_1 = c_{IAA,Ff} \times 10^6 = 0.278 + 0.255x_1 - 0.107x_2 - 0.085x_3 - 0.093x_1x_2 - 0.075x_1x_3 + 0.048x_2x_3 + 0.042x_1x_2x_3$$

(21)

$$y_2 = c_{IAA,Sf} \times 10^6 = 1.193 + 0.982x_1 + 0.139x_2 - 0.010x_2 + 0.123x_1x_2 + 0.017x_1x_3 - 0.040x_2x_3 - 0.037x_1x_2x_3$$

(22)

$$y_3 = E_F = 95.35 - 0.737 x_1 + 1.738x_2 + 1.288x_3 + 0.262x_1x_2 + 0.313x_1x_3 - 0.712x_2x_3 - 0.188x_1x_2x_3$$

(23)

$$y_4 = K_D = 24.04 - 3.839x_1 + 8.899x_2 + 5.863x_3 - 1.518x_1x_2 - 0.387x_1x_3 + 0.685x_2x_3 - 0.208x_1x_2x_3$$

(24)

$$y_5 = E_R = 78.53 - 4.821x_1 + 7.341x_2 + 0.805x_3 + 1.829x_1x_2 - 1.733x_1x_3 - 1.820x_2x_3 - 0.834x_1x_2x_3$$

(25)

$$y_5 = E_R = \beta_{15} + \beta_{25}x_1 + \beta_{35}x_2 + \beta_{45}x_1 + \beta_{55}x_1 + \beta_{65}x_1 + \beta_{75}x_1 + \beta_{85}x_1 + \beta_{95}x_1 + \beta_{105}x_1$$

(26)

Statistical models expressed by Eq. (21) and Eqs. (27)–(30), obtained after removing statistically non-significant terms in Eqs. (22)–(24) and (26), along with their corresponding results of multiple regression analysis (Supplementary Tables S1, S7–S10) indicate the following aspects: (1) $c_{IAA,Ff}$ decreases with a decrease in $x_1$, $x_2$, $x_3$, and $x_1x_3$, as well as with an increase in $x_2$, $x_3$; (2) $c_{IAA,Sf}$ increases with an increase in $x_1$, $x_2$, and $x_1x_2$; (3) $E_F$ increases with a decrease in $x_1$ and $x_2x_3$, as well as with an increase in $x_2$ and $x_3$; (4) higher levels of $K_D$ correspond to lower values of $x_1$ and higher values of $x_2$ and $x_3$; (5) higher levels of $E_R$ correspond to lower values of $x_1$ and higher values of $x_1$ and $x_2$; (6) $x_1$ has the most significant influence on $c_{IAA,Ff}$ and $c_{IAA,Sf}$ whereas $x_3$ has a major effect on $E_F$, $K_D$, and $E_R$; (7) Eq. (21) and Eqs. (27)–(30) fit the data very well ($R^2 \geq 0.905$, $R^2_{adj} \geq 0.870$, RSE $\leq 3.521$, $F = 25.47$, $p \leq 3.9E-04$).

$$y_2 = c_{IAA,Sf} \times 10^6 = 1.193 + 0.982x_1 + 0.139x_2 + 0.123x_1x_2$$

(27)

$$y_3 = E_F = 95.35 - 0.737 x_1 + 1.738x_2 + 1.288x_3 - 0.712x_2x_3$$

(28)

$$y_4 = K_D = 24.04 - 3.839x_1 + 8.899x_2 + 5.863x_3$$

(29)

$$y_5 = E_R = 71.11 - 4.821x_1 + 7.341x_2 + 11.13x_3^2$$

(30)

Regression Eqs. (21) and (27)–(30) could be applied to estimate the process performances for factor levels within the ranges considered in the statistical analysis, i.e., $c_{IAA,Ff} = 10^{-3} - 10^{-1}$ kmol/m$^3$, $c_{IAA,Sf} = 10^{-7} - 1$ kmol/m$^3$, and $c_{NaOH} = 10^{-7} - 10^{-1}$ kmol/m$^3$.

Correlation coefficients ($r$) summarized in Supplementary Table S11 indicate: (1) very strong positive correlation between $E_F$ and $K_D$ ($r = 0.95$); (2) strong positive correlations between $c_{IAA,Ff}$ and $c_{IAA,Sf}$ ($r = 0.70$), $K_D$ and $E_F$ ($r = 0.68$), and $E_F$ and $E_R$ ($r = 0.63$); (3) strong negative correlations between $c_{IAA,Ff}$ and $E_R$ ($r = - 0.68$), $c_{IAA,Ff}$ and $K_D$ ($r = - 0.67$), and $c_{IAA,Ff}$ and $E_R$ ($r = - 0.58$).

**Mass transfer-based model.** The values of $c_{IAA,Ff,eq}$, $c_{IAA,Sf,eq}$, and $I_{IAA,eq}$, at different levels of $c_{IAA,Ff}$ (0.0001, 0.0003, 0.0006, and 0.001 kmol/m$^3$), $c_{NaOH} (0.01$ and 1 kmol/m$^3$), and $c_{NaOH} (0.01$ and 1 kmol/m$^3$) are presented in Table 2. The mean logarithmic concentration of IAA in the feed phase, $c_{IAA,Ff}$, and mean total flux of IAA, $I_{IAA,eq,m}$, were calculated using Eqs. (31) and (32). Moreover, $c_{IAA,Ff}$ and $c_{IAA,Sf}$ predicted by Eqs. (21) and (22) can be used in Eqs. (31) and (32) instead of $c_{IAA,Ff,eq}$ and $c_{IAA,Sf,eq}$ (Equation (32) highlights that $I_{IAA,eq,m}$ [kmol/(m$^2$·s)]) is proportional with $c_{IAA,Ff}$ (kmol/m$^3$)), i.e., $I_{IAA,eq,m} = 1.71 \times 10^{-4} c_{IAA,Ff}$. Accordingly, taking into account Eq. (22), $x_1$ (dimensionless $c_{IAA,Ff}$), $x_2$ (dimensionless $c_{NaOH}$), and their interaction ($x_1x_2$) have positive effects on process kinetics (evaluated as $I_{IAA,eq,m}$), the effect of $x_2$ being higher. The values of $I_{IAA,eq,m}$ specified in Table 2, i.e., $0.382 - 4.418 \times 10^{-8}$ kmol/(m$^2$·s), are consistent with those estimated in other related studies.

$$c_{IAA,Ff,m} = \frac{c_{IAA,Ff} - c_{IAA,Ff,eq}}{\ln \left( \frac{c_{IAA,Ff}}{c_{IAA,Ff,eq}} \right)}$$

(31)
Figure 2. Variation of $c_{IAA,F} / J_{IAA,tot,m}$ depending on $1 / c_{IAA,F,m}$ under different operating conditions: (filled diamond) $c_{IAA,F} = 0.01$ kmol/m$^3$, $c_{NaOH,S} = 0.01$ kmol/m$^3$, (filled square) $c_{IAA,F} = 0.01$ kmol/m$^3$, $c_{NaOH,S} = 1$ kmol/m$^3$; (white diamond) $c_{IAA,F} = 0.1$ kmol/m$^3$, $c_{NaOH,S} = 0.01$ kmol/m$^3$; (white square) $c_{IAA,F} = 0.1$ kmol/m$^3$, $c_{NaOH,S} = 1$ kmol/m$^3$ ($c_{IAA,PD} = 10^{-4}-10^{-3}$ kmol/m$^3$, $\tau_f = 14,400$ s).

Table 3. Values of mass transfer coefficient of IAA-L complex in the liquid membrane and extraction constant at different levels of process factors.

| $c_{IAA,F}$ (kmol/m$^3$) | $c_{NaOH,S}$ (kmol/m$^3$) | $c_{IAA,F}$ (kmol/m$^3$) | $c_{NaOH,S}$ (kmol/m$^3$) | $x_1$ | $x_2$ | $J_{IAA,tot,m} \times 10^3$ (m$^3$/s) | $K_{ext}$ (m$^3$/kmol) |
|-------------------------|--------------------------|-------------------------|--------------------------|------|------|-----------------------------|-------------------------|
| $10^{-4}-10^{-3}$       | 0.01                     | 0.01                    | 1                        | 1    | 1    | 10.90                       | 1033.91                 |
| $10^{-4}-10^{-3}$       | 1                       | 0.01                    | 1                        | 1    | 1    | 11.50                       | 1064.14                 |
| $10^{-4}-10^{-3}$       | 0.01                     | 0.1                     | 1                        | 1    | 1    | 0.784                       | 1249.06                 |
| $10^{-4}-10^{-3}$       | 1                       | 0.1                     | 1                        | 1    | 1    | 0.816                       | 1779.66                 |

According to Eq. (20), the values of mass transfer coefficient of IAA-L complex in the liquid membrane, $k_{IAA,L,M} = 0.82-11.5 \times 10^{-7}$ m/s, and extraction constant, $K_{ext} = 1033.91-1779.66$ m$^3$/kmol, were obtained from the intercepts and the slopes of the straight lines given by the plots of $c_{IAA,F} / J_{IAA,tot,m}$ vs. $1 / c_{IAA,F,m}$ (Fig. 2). The levels of $k_{IAA,L,M}$ and $K_{ext}$ which are summarized in Table 3, indicate the following issues: (1) $k_{IAA,L,M}$ increases with an increase in $c_{NaOH,S}$ (up to 5%) and decreases with a decrease in $c_{IAA,F}$ (about 14 times); (2) $K_{ext}$ increases with an increase in $c_{NaOH,S}$ (up to 1.4 times) and $c_{IAA,F}$ (up to 1.7 times). The effect of $x_1$ and $x_2$ (dimensionless $c_{NaOH,S}$ and $c_{IAA,F}$) on mass transfer coefficient and extraction constant can be predicted using Eqs. (33) and (34) ($R^2 = 1$, RSE = 0), obtained based on data given in Table 3. Multiple regression Eq. (34) indicates an increase in extraction constant with an increase in $x_2$, $x_3$, and $x_4$, the effect of $x_1$ being higher. Multiple regression Eq. (33) highlights that the effect of $x_3$ on $y = k_{IAA,L,M,calc}$ is over 30 times higher than the effects of $x_1$ and $x_2$, $x_3$. Equation (35) was obtained by neglecting the contributions of $x_2$ and $x_3x_4$ in Eq. (33). Results specified in Supplementary Table S12 indicate that Eq. (35) fits very well the data presented in Table 3 ($R^2 = 0.998$, $R^2_{adj} = 0.998$, RSE = 0.300, $F = 1198.4$, $p = 8.3E-04$). According to Eq. (35), the mass transfer coefficient is higher at lower levels of initial molar concentration of TOA in the membrane phase.

$$y = k_{IAA,L,M,calc} \times 10^7 = 6.0 + 0.158x_2 - 5.2x_3 - 0.142x_2x_3$$  \hspace{1cm} (33)

$$K_{ext,calc} = 1281.69 + 140.21x_2 + 232.67x_3 + 125.09x_2x_3$$  \hspace{1cm} (34)

$$y = 6.0 - 5.2x_3$$  \hspace{1cm} (35)

Conclusions

IAA transport through a chloroform BLM using TOA as a ligand ($L$) was performed in a tube in tube equipment. The inner tube contained a stripping ($S$) aqueous solution of NaOH and the outer tube the membrane ($M$) phase and a feed ($F$) aqueous solution of IAA. Twenty experiments were performed at different levels of process factors in terms of initial molar concentrations of IAA in the feed phase, $c_{IAA,PD} (10^{-4}-10^{-3}$ kmol/m$^3$), of TOA in the membrane phase, $c_{IAA,F} (10^{-2}$ and $10^{-1}$ kmol/m$^3$), and of NaOH in the stripping phase, $c_{NaOH,S} (10^{-2}$ and 1 kmol/m$^3$). Each experimental run was conducted for 4 h, at ambient temperature, under mechanical stirring (200 rpm) of inner tube.
The effects of dimensionless factors on process responses, i.e., final values of molar concentration of IAA in the feed phase (c_{IAA,F}) and stripping solution (c_{IAA,S}), extraction efficiency (E_F), distribution coefficient (K_D), and recovery efficiency (E_S), were quantified using statistical models based on a 2^5 factorial plan. Experimental values of process responses were as follows: c_{IAA,F,ex} = 0.02–1 \times 10^{-4} \text{ mol/m}^3, c_{IAA,S} = 0.22–2.58 \times 10^{-5} \text{ mol/m}^3, E_F = 90.0–97.9, K_D = 9.0–46.6, and E_S = 66.5–94.2%. Taking into account the statistically significant factors and their interactions, the results of regression analysis indicated the following aspects: (1) all factors and their binary and ternary interactions influenced c_{IAA,F,ex} increased with an increase in c_{IAA,S} and c_{NaOH,S}, and their binary interaction; (3) higher levels of E_F and K_D were obtained at low values of c_{IAA,R} and high values of c_{L,M} and c_{NaOH,S}; (4) higher levels of E_S were obtained at low values of c_{IAA,A} and high values of c_{NaOH,S}; (5) c_{IAA,R} had the most significant (positive) effect on c_{IAA,F,ex} and c_{NaOH,S}; whereas c_{NaOH,S} had a major (positive) effect on E_F, K_D, and E_S. A very strong positive correlation (r = 0.95) was found between E_F and K_D. A deterministic model based on mass transfer of IAA in the system containing the BLM was developed and its parameters, i.e., mass transfer coefficient of IAA-L complex in the liquid membrane (k_{IAA,L-M} = 0.82–11.5 \times 10^{-5} \text{ m/s}) and extraction constant (K_{IAA,S} = 103.39–1779.66 \text{ m}^3/\text{mol}) were regressed from experimental data. The process factors in terms of c_{NaOH,S} and c_{L,M} had positive effects on K_{IAA,L-M}, whereas c_{L,M} had a major negative effect on K_{IAA,L-M}.

The results obtained in this study indicate that IAA was successfully transported through a chloroform BLM using TOA as a carrier. Mathematical models developed in the paper could be used to control and optimize the separation of IAA in systems containing liquid membranes.

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**Author contributions**

I.D. and O.C.P. wrote the main manuscript text; I.D. and S.L.T. performed the experimental runs; O.C.P. and T.D. had a substantial contribution to the conception of article, statistical analysis, and interpretation of results; all authors reviewed the manuscript.

**Competing interests**

The authors declare no competing interests.

**Additional information**

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