

Reverse Micellar Extraction of Copper Ions from Wastewater: Modelling and Simulation

Tarun Kumar Chaturvedi, Prabhat Pandit, Sushant Upadhyaya* and
Manish Vashishtha

Malaviya National Institute of Technology, Jaipur - 302017, India
✉ supadhyay.chem@mnit.ac.in

Received October 29, 2021; revised and accepted November 20, 2021

Abstract: The waste streams from various agencies like textile, leather, electroplating, and process industries are generating pollutants in the form of effluents or by products. These waste streams consist of various carcinogenic pollutants such as dyes and heavy metals above the permissible limits. Numerous effluent treatment techniques have been implemented for the removal of these pollutants before their discharge into the water body. In this work, reverse micellar extraction was used for the removal of copper ions (heavy metal ions) from the waste stream. Mathematical models namely, the ion exchange reaction model and electrostatic model were developed in order to compare the experimental data with model predictions with regard to the effect of process parameters such as initial metal ion concentration, sodium bis-2-ethyl hexyl sulphosuccinate (AOT) concentration, and organic to aqueous phase volume ratio on final copper ion concentration in the aqueous phase. The ion exchange reaction model was based on chemical and electrostatic interactions between heavy metal ions and the surfactant head groups at the reverse micellar interface, whereas the electrostatic model was based on the adsorption of metal ions on the reverse micellar interface due to electrostatic force of attraction with no chemical bonding. The developed mathematical models were found in close agreement with the experimental data. Atomic absorption spectroscopy (AAS) was used to measure the metal ion concentration in the aqueous phase.

Key words: Reverse micelle, ion exchange reaction model, electrostatic model, AOT, AAS.

Introduction

Industrial effluents contaminated with heavy metals have drawn considerable attention from researchers from all around the globe on account of being highly toxic at low concentrations (≥ 1 ppm) (Egorova & Ananikov, 2017), non-biodegradable, bio-accumulative, and inherently persistent. Copper was listed as a priority toxic metal among the various heavy metals by the U.S. Environmental Protection Agency (Halim et al., 2020). Cupric ($\text{Cu}[\text{II}]$) ions, in particular, were omnipresent in the effluents generated by a variety of industries such as electroplating, mining, printed circuit

board manufacturing, and metal finishing (Bilal et al., 2013). These ions had intensified various detrimental degradations towards the aquatic life because the effluents laden with $\text{Cu}(\text{II})$ ions were let off directly into the waterbodies. This was crucial to the areas where water resources might be deficient or sensitive to the maintenance of the biosphere (Pandit & Basu, 2004a). Therefore, the treatment of polluted industrial effluents has become an ultimate environmental challenge for the removal of toxic contaminants for researchers (Verma & Sarkar, 2017).

The conventional treatment techniques for the effluents containing heavy metals and other toxins

*Corresponding Author

comprised of chemical precipitation (Hu et al., 2017), coagulation-flocculation (Quiroz et al., 2017), membrane filtration (Camarillo et al., 2010), ion exchange (Siu et al., 2016), and adsorption (Bhatt et al., 2013; Goswami et al., 2020; Jain et al., 2014). However, each of these techniques had inherent drawbacks and none of them was found to show universal application in treating all kinds of industrial effluents (Halim et al., 2020). Industries are looking for competitive alternatives which could overcome some of the inherent disadvantages of these methods. Membrane separation processes like vacuum membrane distillation (Baghel et al., 2017, 2020; Upadhyaya et al., 2016a, 2016b, 2018), air gap membrane distillation (Kalla et al., 2019) using different types of membranes were advertised well in commercial applications.

For the past two decades, solvent extraction using reverse micelles (RMs) had been studied comprehensively as a separation method, owing to the fact that these systems could adapt to large scale applications. The partitioning tendency of many water-soluble solutes into reverse micellar organic phase had generated a lot of interest in using such systems in the extraction of protein, amino acids, enzymes, and dyes (Pandit & Basu, 2002). Solvent extraction using RMs tendered some rare features such as large interfacial area, less energy requirement, single-stage and continuous mode operation, low cost and easy scale up (Gangadharappa et al., 2017). Numerous researchers have examined RMs systems for the up-take of amino acids, proteins and enzymes for their substantial solubilising space (Cui et al., 2011) and some theoretical models have been presented. Whereas, little work has been published on the up-take of heavy metal ions by RMs.

RMs are spontaneously and reversibly formed nanometer-sized droplets of the aqueous phase stabilised by surfactant molecules surrounding microscopic water core in apolar solvents (Senske et al., 2018). Formation of the RMs occurred when an aqueous phase was interfaced with an immiscible organic phase containing surfactants (Sankaran et al., 2019). As opposed to the normal micelles in aqueous solution, the reverse micelles were inverted, wherein the polar head groups of the surfactant molecules constituted the core of the aggregates while their hydrophobic tails faced the apolar solvent (Gangadharappa et al., 2017). The polar heads remained dipped in the water pools thereby isolating inside the aggregates (Sankaran et al., 2019). The polar head groups of surfactant molecules were held by hydrogen bonding in the presence of the minimal

amount of water in the core formed by them and thus they were thermodynamically stable (Pandit & Basu, 2002, 2004b).

In this study, mathematical modelling of reverse micellar extraction of copper ions was done using ion-exchange reaction model and electrostatic model. The ion exchange reaction model was simulated using *ExcelSolver* and the electrostatic model was simulated using *fsolve* in *Matlab*. These models were validated with the experimental data taking various effects of different parameters.

Material and Methods

Reagents

Sodium bis-2-ethyl hexyl sulphosuccinate(AOT) supplied by Sigma as surfactant and Isooctane of spectroscopic grade, supplied by Fluka as solvent were used to prepare isooctane-AOT reverse micelles. All other chemicals used were of analytical grade.

Experimental Setup

As shown in Figure 1, a magnetic stirrer was used to agitate the solvent mixed with the surfactant and the metal ion solution. A separating funnel was used to separate the organic and aqueous phases by gravity. Atomic absorption spectroscopy (AAS) was used to measure the copper ions removed from the aqueous phase.

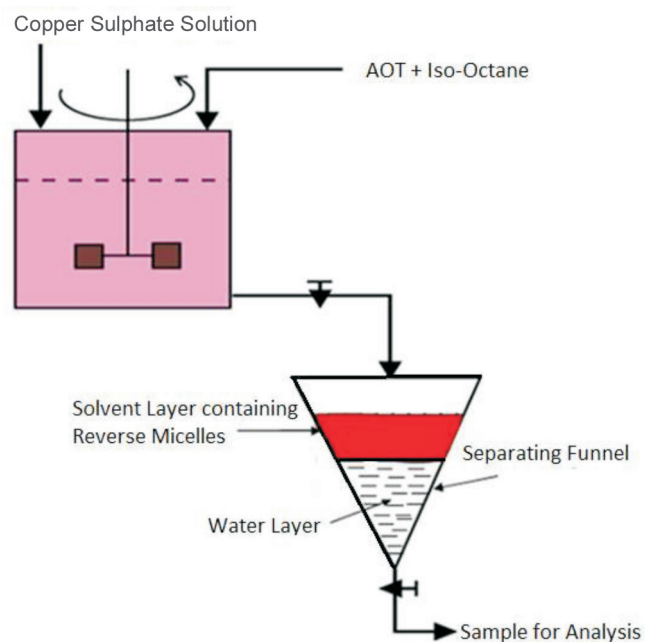


Figure 1: Schematic diagram of reverse micellar extraction.

Experimental Procedure

The metal ions removal using reverse micellar extraction consisted of two steps. In the first step, a given volume of the aqueous solution of known copper ion concentration was added to a known volume of the isooctane containing a known quantity of the AOT in a beaker. The range of AOT concentrations was kept around the critical micelle concentration (CMC). The entire content was agitated thoroughly on a magnetic stirrer at 400 rpm for 30 min and an equilibrium was attained during the stirring.

In the second step, the two-phase dispersion was transferred into a separating funnel for the gravitational separation of organic and aqueous phases. This resulted in the formation of two clear liquid phases, the organic phase containing the copper ions encapsulated in the reverse micellar core and the clear aqueous phase. The two-phase dispersion was allowed to settle for two days to ensure complete separation of the two immiscible phases. The samples were withdrawn from the aqueous phase at the bottom (water being of higher density than that of isooctane) and analysed for copper ion concentration by AAS in Material Research Centre, Jaipur to determine the amount of copper ions removal.

More experiments were done by changing parameters as necessitated while comparing the models' predictions with experimental data.

Mathematical Modelling

Ion-Exchange Reaction Model

In this model, it was considered that the reverse micellar interface was chemically active on account of being the strong electrostatic effect of surfactant head-groups. The solute molecules reacted with surfactant head-groups and complexes were produced. In the present model, one divalent metal ion reacted with two molecules of the oppositely charged surfactant to form a metal-surfactant complex, which on further dissociation released the counter-ions in the reverse micellar water core. It was assumed that all the surfactant molecules present in the organic phase participate in the formation of reverse micelles at equilibrium and surfactant concentration in the aqueous phase was negligible.

Ion-Exchange Reaction

The ion-exchange reaction between divalent metal and surfactant (AOT) is:



where one mole of heavy metal ion (M) formed a

complex S_2MCI_2 with two moles of surfactant, SCI . In the above equation, S represented the ionic head group and CI , the counter-ion of the surfactant.

The equilibrium constant for this reaction in terms of concentration was written as:

$$K_c = \frac{C_{S_2MCI_2}}{C_{CI,b}^2 C_M} \quad (2)$$

where $C_{S_2MCI_2}$ was the molar concentration of metal-surfactant-counter-ion complex at the reverse micellar interface and $C_{CI,b}$ was the molar concentration of counter-ion bound to the surfactant head-group at the reverse micellar interface. C_M was the concentration of a metal ion in the bulk aqueous phase, which was assumed to be the same as that in reverse micellar water pools. Further, it was assumed that this complex could be dissociated to release the counter-ion into the water pool leaving the metal-surfactant complex.



The dissociation constant for this reaction was

$$K_d = \frac{C_{S_2M} C_{CI}^2}{C_{S_2MCI_2}} \quad (4)$$

where C_{S_2M} is the molar concentration of the dissociated metal-surfactant complex at the reverse micellar interface, C_{CI} was the molar concentration of free counter-ion in the water pools of the reverse micelles, which was assumed to be the same as that in the bulk aqueous phase.

Mass Balance

The mass balance for the metal-ion was given by:

$$\begin{aligned} C_M^0 V_{ab} &= C_M V_{S_2MCI_2} V_{org} + C_{S_2M} V_{org} \\ \Rightarrow C_M + r C_{S_2MCI_2} + r C_{S_2M} &= C_M^0 \end{aligned} \quad (5)$$

The mass balance for the counter-ion was given by:

$$\begin{aligned} C_{CI}^0 V_{aq} + C_S^0 V_{org} &= C_{CI} V_{aq} + C_{CI,b} V_{org} + C_{S_2MCI_2} V_{org} \\ \Rightarrow C_{CI} + r C_{CI,b} + r C_{S_2MCI_2} &= C_{CI}^0 + r C_S^0 \end{aligned} \quad (6)$$

where C_{CI}^0 is the initial concentration of the counter-ion in the aqueous phase, ' r ' is the organic to aqueous phase volume ratio.

The concentration of bound counter-ion to the surfactant at the reverse micellar interface is written as:

$$C_{CI,b} = C_S^0 - 2 \frac{(C_M^0 - C_M)}{r} \quad (7)$$

On combining equations (5), (6) and (7) along with equations (2) and (4) for the equilibrium constants, the final model equation is obtained as

$$\frac{(C_M^0 - C_M)}{\frac{4K_c C_M}{r} \left\{ \frac{rC_S^0}{2} - C_M^0 + C_M \right\}^2} = 1 + \frac{K_d}{\left[C_{Cl}^0 + C_M^0 - C_M - \frac{4K_c C_M}{r} \left\{ \frac{rC_S^0}{2} - C_M^0 + C_M \right\}^2 \right]^2} \quad (8)$$

Model Solution

The metal-ion concentration in the aqueous phase C_M , after reverse micellar extraction was determined from equation (8) for known equilibrium constants, K_c , K_d , the initial metal-ion concentration in the aqueous phase C_M^0 , the initial surfactant concentration in the organic phase C_S^0 , and organic to aqueous phase volume ratio r . C_{Cl}^0 was zero in most of the cases. As the K_c and K_d values for different metal-surfactant combinations were not known, equation (8) could be transformed to a straight line equation of the form $y = mx + c$, where the slope $m = (K_c K_d)^{0.33}$, the intercept $c = K_c$,

$$y = \frac{(C_M^0 - C_M)}{\frac{4C_M}{r} \left\{ \frac{rC_S^0}{2} - C_M^0 + C_M \right\}^2} \quad \text{and} \\ x = \frac{1}{\left(\frac{4C_M}{r} \right)^{0.67} \left\{ \frac{rC_S^0}{2} - C_M^0 + C_M \right\}^{1.34}}.$$

By fitting the experimental data to a straight line and determining the slope and intercept, and values were estimated. Once the K_c and K_d were known, the model equation (8) was solved by *Excel Solver*.

Electrostatic Model

In this model, it was assumed that the surfactant molecules completely dissociated and the negatively charged heads of the ionised surfactants constituted an electric field inside the reverse micelles. The metal ions were adsorbed onto the anionic interface of the reverse micelles entirely by electrostatic force without involving any chemical bonding as opposed to the ion-exchange reaction model. The counter-ions of the surfactants existing in the water pools of reverse micelles did not strive with the metal ions for adsorption on the reverse micellar interface. Moreover, ions having polarity identical to that of surfactants did not contend with metal ions for adsorption.

Adsorption Isotherm

The Stern adsorption isotherm was used to determine the amount of metal ions adsorbed to the reverse micellar interface. This is written as:

$$\tau_i = \frac{\mu^\circ n_i \exp\left(\frac{-\phi_i - z_i e \psi_\delta}{kT}\right)}{1 + \mu^\circ n_i \exp\left(\frac{-\phi_i - z_i e \psi_\delta}{kT}\right)} \quad (9)$$

where τ_i is the surface coverage of the metal ion, n_i is bulk concentration of metal ion, μ° is the molar volume of solvent, ϕ_i is the specific non-electrostatic adsorption potential of one metal ion, k is the Boltzmann constant, T is the absolute temperature, z_i was the charge on metal ion, ' e ' is electronic charge, and ψ_δ is the electrostatic potential at the Stern plane. In this model, it was assumed that the electrostatic potential at the stern plane was equal to that at the surface, ψ_0 . The electrostatic potential declined to zero exponentially in the bulk of the reverse micellar pool. The non-electrostatic adsorption potential ϕ_i , of Vander Waals origin rationalised the existence of some amount of metal ions nearby the reverse micelles.

Potential Distribution

The potential distribution in the vicinity of an electrically charged surface was governed by one-dimensional planar Poisson-Boltzmann equation:

$$\frac{d^2 \psi}{dx^2} = \frac{-4\pi e n_i z_i}{\epsilon} \exp\left(\frac{z_i e \psi}{kT}\right) \quad (10)$$

subject to the boundary conditions, $\left(\frac{d\psi}{dx}\right)_{x=0} = -4\pi\sigma/\epsilon$,

$\psi(x)|_{x=0} = \psi_0$, and $\psi(x)|_{x \rightarrow \infty} = 0$, where ' ϵ ' was the dielectric constant of water and ' σ ' is the surface charge. Above second-order differential was integrated with the help of boundary conditions to give the following equation:

$$\left(\frac{4\pi\sigma}{\epsilon}\right)^2 = \left(\frac{8\pi kT}{\epsilon}\right) \left[n_i \exp\left(\frac{-z_i e \psi_0}{kT}\right) - n_i \right] \quad (11)$$

Being the reverse micelles were nanometric in size, it was safe to assume ϵ to remain constant throughout. This integrated form of the Poisson-Boltzmann equation was used to calculate the surface potential, ψ_0 . The surface charge is calculated as $\sigma = \epsilon \kappa \psi_0 / (4\pi)$, where κ is the Debye-Huckel function, which can be determined as, $\kappa = \sqrt{[4\pi e^2 \sum n_i z_i^2 / (\epsilon kT)]}$. The surface potential dropped exponentially to zero at a distance of $1/\kappa$ approximately, manifesting the thickness of the electric double layer equal to $1/\kappa$.

Mass Balance

The mass balance for the metal ion is calculated as:

$$n_i^0 V_0 = \tau_i N_S + n_i V_0 \quad (12)$$

where n_i^0 is the initial metal ion concentration in the aqueous phase, V_0 is the aqueous phase volume, and V_S is the initial number of moles of surfactant. The left hand side of equation (12) indicated the total metal ion present in the aqueous phase. The first term on the right hand side represented the metal ions adsorbed by the surfactant molecules present in the reverse micelle phase and the second term was the metal ions left in the bulk aqueous phase. It was presumed that all surfactant molecules participated in the synthesis of reverse micelles.

Model Solution

The non-linear equations were solved simultaneously for τ_i , $\frac{z_i e \Psi_0}{kT}$, and n_i by using *fsolve* in *Matlab*. n_i gave the final concentration of the metal ion in the aqueous phase. $\frac{z_i e \Psi_0}{kT}$ was the dimensionless group that signified the work done in bringing an ion from the bulk to the reverse micelle interface.

Result and Discussion

Ion-Exchange Reaction Model

Estimation of K_c and K_d

The experimental data were fitted with a straight line obtained from the transformation of model equation (8), using the least square fit method (average regression coefficient ~ 0.93). The K_c and K_d values, determined from the slopes and intercepts of the straight lines for metal-surfactant ion-exchange reactions are shown in Table 1. The different surfactants possessing the same number of charges for a particular metal (copper) had the same K_c and K_d values as the stoichiometric ratio in the ion-exchange reactions. There was no role of

Table 1: Equilibrium constant values in the ion exchange reaction model at 30°C temperature

Heavy metal	Surfactant	Solvent	K_c (mM) ⁻²	K_d (mM) ²
Copper	AOT	Iso-octane	0.132	0.287
	AOT	Amyl Alcohol		
	AOT	Benzyl Alcohol		
	SDBS	Iso-octane		
	SDBS	Amyl Alcohol		
	SDBS	Benzyl Alcohol		

solvent in the ion-exchange reaction model and hence the values of K_c and K_d did not depend upon the nature of the solvent.

Operating Parameters

Comparison of final copper ion concentration in the aqueous phase predicted by the ion exchange reaction model with that estimated from experimental data is represented in Figures 2-4. The model predictions are shown by the dotted lines, whereas, the experimental data by the symbols. Predictions of the ion-exchange reaction model were found to be in close agreement with experimental data for varying initial copper ion concentration, AOT concentration and organic to aqueous phase volume ratio. Figures 2 and 3 showed

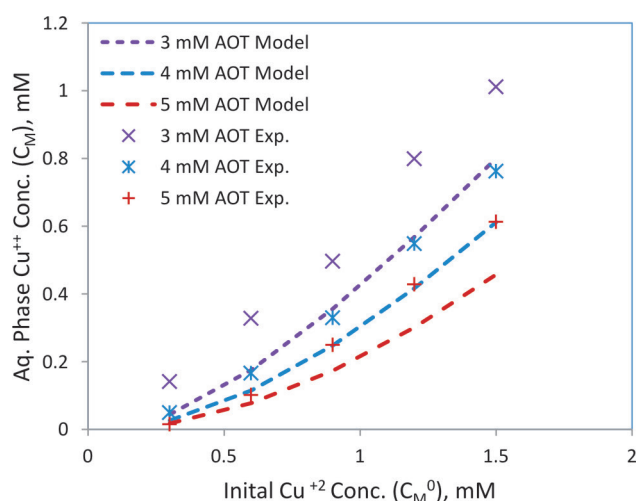


Figure 2: Effect of copper ion concentration—Experimental data and ion-exchange reaction model predictions for the removal of copper ions using iso-octane as solvent.

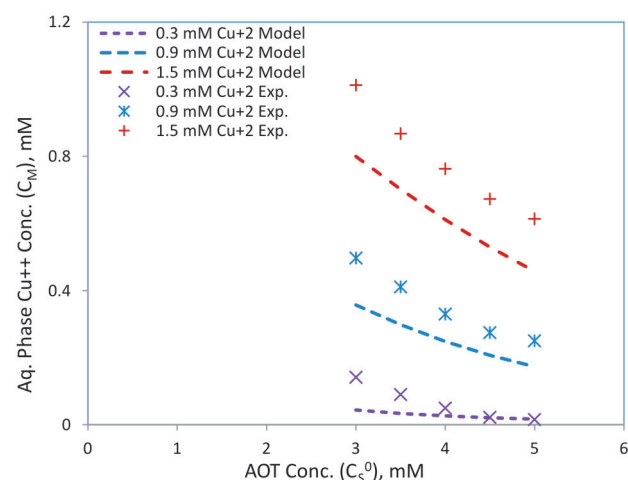


Figure 3: Effect of AOT concentration-- Experimental data and ion-exchange reaction model predictions for the removal of copper ions using iso-octane as solvent.

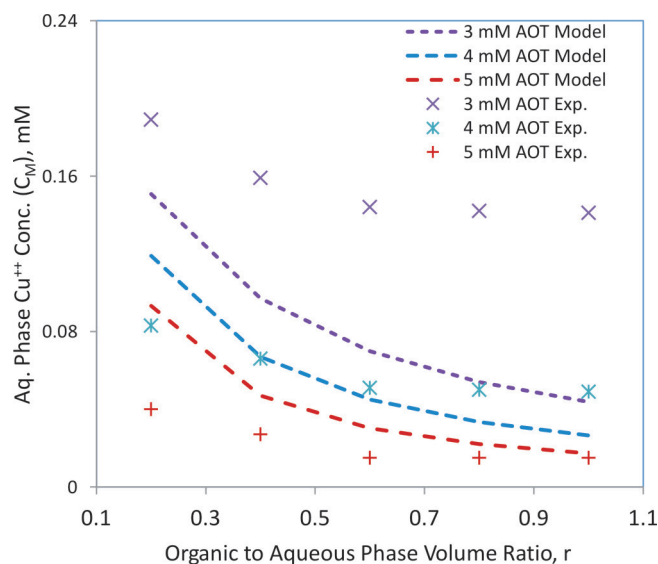


Figure 4: Effect of volume ratio—Experimental data and ion-exchange reaction model predictions for the removal of copper ions using iso-octane as solvent.

that both the model predictions and experimental data favoured increasing copper ion removal with the decrease in initial copper ion concentration; however, it increased with the rise in AOT concentration. Figure 4 exhibits both the model predictions and experimental data showing that the copper ion removal increased significantly with an increase in volume ratio from 0.1 to 0.6, thereafter no significant increase was noticed.

Electrostatic Model

Operating Parameters

Figures 5 and 6 showed the comparison of final copper ion concentration in the aqueous phase forecasted by the electrostatic model with that estimated from experimental data. Lines were used for the model predictions, whereas the symbols were for experimental data. Predictions of the electrostatic model were found to be aligned with experimental data for varying initial copper ion concentration and AOT concentration. It was clear from Figures 5 and 6 that both the model predictions and experimental data showed an increase in copper ion removal with the decrease in initial copper ion concentration, however, it increased with the rise in AOT concentration. This could also be understood from the material balance equation (Eq.12). The non-electrostatic adsorption potential ϕ_i was taken as zero since the surfactant molecule was assumed to be dissociated completely and all-metal ions were adsorbed

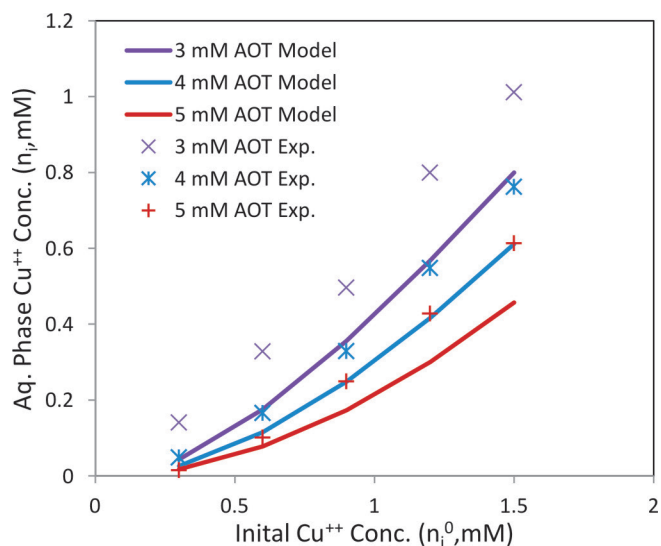


Figure 5: Effect of copper ion concentration—Experimental data and electrostatic model predictions for the removal of copper ions using iso-octane as solvent.

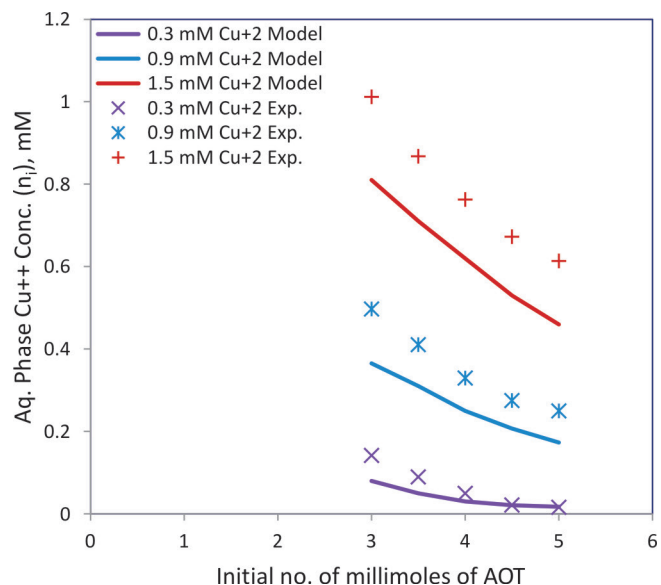


Figure 6: Effect of AOT concentration—Experimental data and electrostatic model predictions for the removal of copper ions using iso-octane as solvent.

at the reverse micellar interface primarily through electrostatic attraction. The fraction of surface coverage of metal ions got increased with rise in initial metal ion concentration. However, the percentage removal of metal ion declined with increase in initial metal ion concentration as the reverse micelle surface coverage increased.

Conclusions

The ion exchange reaction model based on chemical and electrostatic interaction between heavy metal ions and the surfactant head groups at the reverse micellar interface was tested against experimental data for copper ions removal. The experimental data were fitted to a straight line in accordance with the ion-exchange reaction model for divalent metal ions. The slope and intercept of straight-line obtained for copper ions had provided the values of equilibrium constants for the ion-exchange reaction between copper ion and surfactant molecules. The model equation could be fitted to data for varying surfactant, metal ion concentration and nature of the solvent. The predictions of the ion-exchange reaction model were in good agreement with experimental data within the considered range of metal ion and surfactant concentration.

The electrostatic model based on adsorption of metal ions on reverse micellar interface due to electrostatic attraction was tested with experimental data on metal ion removal from the aqueous phase. The electrostatic model predictions were in agreement with experimental data for an entire range of metal ion and surfactant concentration under consideration. The ion-exchange reaction model was simpler as compared to the electrostatic model, however, it required experimental data for the determination of equilibrium constants.

References

- Baghel, R., Kalla, S., Upadhyaya, S., Chaurasia, S.P. and K. Singh (2020). CFD modeling of vacuum membrane distillation for removal of Naphthol blue black dye from aqueous solution using COMSOL multiphysics. *Chemical Engineering Research and Design*, **158**: 77-88.
- Baghel, R., Upadhyaya, S., Singh, K., Chaurasia, S.P., Gupta, A.B. and R.K. Dohare (2017). A review on membrane applications and transport mechanisms in vacuum membrane distillation. *Reviews in Chemical Engineering*, **34(1)**: 73-106.
- Bhatt, P., Vyas, R.K., Pandit, P. and M. Sharma (2013). Adsorption of reactive blue and direct red dyes on powdered activated carbon (PAC) - Equilibrium, kinetics and thermodynamic studies. *Nature Environment and Pollution Technology*, **12(3)**: 397-405.
- Gangadharappa, B.S., Dammalli, M., Rajashekarappa, S., Pandurangappa, K.M.T. and G.B. Siddaiah. (2017). Reverse micelles as a bioseparation tool for enzymes. *Journal of Proteins and Proteomics*, **8**: 105-120.
- Bilal, M., Shah, J.A., Ashfaq, T., Gardazi, S.M.H., Tahir, A.A., Pervez, A., Haroon, H. and Q. Mahmood (2013). Waste biomass adsorbents for copper removal from industrial wastewater-A review. *Journal of Hazardous Materials*, **263**: 322-333.
- Camarillo, R., Llanos, J., García-Fernández, L., Pérez, Á. and P. Cañizares (2010). Treatment of copper (II)-loaded aqueous nitrate solutions by polymer enhanced ultrafiltration and electrodeposition. *Separation and Purification Technology*, **70(3)**: 320-328.
- Cui, K.L., Yuan, X.-Z., Zeng, G.-M., Liang, Y.-S., Han, Z.-H., Zhang, S. and X. Peng (2011). Application of biosurfactant on the construction of reversed micelle and the optimization of its microenvironment. *Zhongguo Huanjing Kexue/China Environmental Science*, **31(9)**: 1444-1450.
- Egorova, K.S. and V.P. Ananikov (2017). Toxicity of metal compounds: Knowledge and myths. *Organometallics*, **36(21)**: 4071-4090.
- Goswami, V., Upadhyaya, R. and S.K. Meher (2020). Column study for adsorption of methylene blue dye using *Azadirachta indica* adsorbent. *Asian Journal of Water, Environment and Pollution*, **17(4)**: 47-52.
- Halim, S.F.A., Chang, S.H. and N. Morad (2020). Extraction of Cu(II) ions from aqueous solutions by free fatty acid-rich oils as green extractants. *Journal of Water Process Engineering*, **33(September 2019)**: 100997.
- Hu, H., Li, X., Huang, P., Zhang, Q. and W. Yuan (2017). Efficient removal of copper from wastewater by using mechanically activated calcium carbonate. *Journal of Environmental Management*, **203**: 1-7.
- Jain, S., Vyas, R.K., Pandit, P. and A.K. Dalai (2014). Adsorption of antiviral drug, acyclovir from aqueous solution on powdered activated charcoal: Kinetics, equilibrium, and thermodynamic studies. *Desalination and Water Treatment*, **52(25-27)**: 4953-4968.
- Kalla, S., Upadhyaya, S., Singh, K. and R. Baghel (2019). Experimental and mathematical study of air gap membrane distillation for aqueous HCl azeotropic separation. *Journal of Chemical Technology and Biotechnology*, **94(1)**: 63-78.
- Quiroz, M.M., Maldonado, E.A.L., Terán, A.O., Guzman, M.T.O., Luis, G.E.P. and J.Z. Ramírez (2017). Innovative uses of carbamoyl benzoic acids in coagulation-flocculation's processes of wastewater. *Chemical Engineering Journal*, **307**: 981-988.
- Pandit, P. and S. Basu (2002). Removal of organic dyes from water by liquid-liquid extraction using reverse micelles. *Journal of Colloid and Interface Science*, **245(1)**: 208-214.
- Pandit, P. and S. Basu (2004a). Dye and solvent recovery in solvent extraction using reverse micelles for the removal of ionic dyes. *Industrial and Engineering Chemistry Research*, **43(24)**: 7861-7864.
- Pandit, P. and S. Basu (2004b). Removal of ionic dyes from water by solvent extraction using reverse micelles. *Environmental Science and Technology*, **38(8)**: 2435-2442.

- Sankaran, R., Bong, J.H., Chow, Y.H., Wong, F.W.F., Ling, T.C. and P.L. Show (2019). Reverse micellar system in protein recovery - A review of the latest developments. *Current Protein & Peptide Science*, **20(10)**: 1012-1026.
- Senske, M., Xu, Y., Bäumer, A., Schäfer, S., Wirtz, H., Savolainen, J., Weingärtner, H. and M. Havenith (2018). Local chemistry of the surfactant's head groups determines protein stability in reverse micelles. *Physical Chemistry Chemical Physics*, **20(13)**: 8515-8522.
- Siu, P., Koong, C.C., Saleem, L.F., Barford, J. and J.G. McKay (2016). Equilibrium and kinetics of copper ions removal from wastewater by ion exchange. *Chinese Journal of Chemical Engineering*, **24(1)**: 94-100.
- Upadhyaya, S., Singh, K., Chaurasia, S.P., Baghel, R., Singh, J.K. and R.K. Dohare (2018). Sensitivity analysis and Taguchi application in vacuum membrane distillation. *Membrane Water Treatment*, **9(6)**: 435-445.
- Upadhyaya, S., Singh, K., Chaurasia, S.P., Dohare, R.K. and M. Agarwal (2016a). Mathematical and CFD modeling of vacuum membrane distillation for desalination. *Desalination and Water Treatment*, **57(26)**: 11956-11971.
- Upadhyaya, S., Singh, K., Chaurasia, S.P., Dohare, R.K. and M. Agarwal (2016b). Recovery and development of correlations for heat and mass transfer in vacuum membrane distillation for desalination. *Desalination and Water Treatment*, **57(55)**: 26886-26898.
- Verma, S.P. and B. Sarkar (2017). Rhamnolipid based micellar-enhanced ultrafiltration for simultaneous removal of Cd(II) and phenolic compound from wastewater. *Chemical Engineering Journal*, **319**: 131-142.