

12-3-2019

## Acute Toxicity study of Choline Based Ionic Liquids Towards Danio rerio fish and the Aggregation Behavior of Their Binary Mixtures

Mansoor Ul Hassan Shah

*Department of Chemical Engineering, Universiti Teknologi PETRONAS, Bandar Seri Iskandar, Perak 32610, Malaysia*

Nasruddin Nasruddin

*Department of Mechanical Engineering, Faculty of Engineering, Universitas Indonesia, Depok 16424, Indonesia*

Suzana Bt Yusup

*Department of Chemical Engineering, Universiti Teknologi PETRONAS, Bandar Seri Iskandar, Perak 32610, Malaysia*

Muhammad Moniruzzaman

*Department of Chemical Engineering, Universiti Teknologi PETRONAS, Bandar Seri Iskandar, Perak 32610, Malaysia, m.moniruzzaman@utp.edu.my*

Follow this and additional works at: <https://scholarhub.ui.ac.id/mjt>



Part of the [Chemical Engineering Commons](#), [Civil Engineering Commons](#), [Computer Engineering Commons](#), [Electrical and Electronics Commons](#), [Metallurgy Commons](#), [Ocean Engineering Commons](#), and the [Structural Engineering Commons](#)

---

### Recommended Citation

Shah, Mansoor Ul Hassan; Nasruddin, Nasruddin; Yusup, Suzana Bt; and Moniruzzaman, Muhammad (2019) "Acute Toxicity study of Choline Based Ionic Liquids Towards Danio rerio fish and the Aggregation Behavior of Their Binary Mixtures," *Makara Journal of Technology*. Vol. 23: Iss. 3, Article 6.

DOI: 10.7454/mst.v23i3.3858

Available at: <https://scholarhub.ui.ac.id/mjt/vol23/iss3/6>

This Article is brought to you for free and open access by the Universitas Indonesia at UI Scholars Hub. It has been accepted for inclusion in Makara Journal of Technology by an authorized editor of UI Scholars Hub.

## Acute Toxicity study of Choline Based Ionic Liquids Towards *Danio rerio* fish and the Aggregation Behavior of Their Binary Mixtures

Mansoor Ul Hassan Shah<sup>1,2</sup>, Nasruddin<sup>3</sup>, Suzana Bt Yusup<sup>1</sup>, and Muhammad Moniruzzaman<sup>1,2\*</sup>

1. Department of Chemical Engineering, Universiti Teknologi PETRONAS, Bandar Seri Iskandar, Perak 32610, Malaysia

2. Centre of Research in Ionic Liquids (CORIL), Universiti Teknologi PETRONAS, Bandar Seri Iskandar, Perak 32610, Malaysia

3. Department of Mechanical Engineering, Faculty of Engineering, Universitas Indonesia, Depok 16424, Indonesia

\*e-mail: m.moniruzzaman@utp.edu.my

---

### Abstract

Marine oil spills are effectively controlled by chemical dispersants. However, the toxicity associated with it reduce its employment in marine environment. To overcome this limitation, the acute toxicity of choline based ionic liquids was evaluated as a potential low toxic variant for oil spill remediation. Further, the aggregation behavior of the individual as well as their binary mixtures was also evaluated by employing tensiometry technique. The half-lethal concentration,  $LC_{50}$  on zebrafish (*Danio rerio*) of three choline based ionic liquids showed that the studied ionic liquids (ILs) fall in the range of “practically nontoxic” ( $100-1000 \text{ mg L}^{-1}$ ). Various micellar properties showed that a synergistic interaction existed between all the binary mixtures ( $\beta < 0$ ,  $f_1$  and  $f_2 < 1$ ). Moreover, the produced micelles were found to be spontaneous and thermodynamically stable with respect to all the mole ratio of ILs. Overall, these results showed the safe nature of the studied ILs for various application including oil dispersants.

### Abstract

**Uji Toksisitas Akut dari Ionic Liquids (IL) Berbasis Kolin terhadap Ikan *Danio rerio* dan Perilaku Agresi dari Campuran Binernya.** Tumpahan minyak bumi di laut diatasi secara efektif dengan dispersan yang berasal dari bahan kimia. Namun, karena toksisitas yang ditimbulkan oleh dispersan tersebut, penggunaan dispersan tersebut dikurangi dalam lingkungan laut. Untuk mengatasi keterbatasan ini, uji toksisitas akut dari *ionic liquid* (IL) berbasis kolin dievaluasi sebagai potensial toksik varian rendah untuk remediasi tumpahan minyak bumi. Selanjutnya, perilaku agregasi individu serta campuran binernya juga dievaluasi menggunakan teknik tensiometri.  $LC_{50}$  dari *zebrafish* (*Danio rerio*) untuk tiga IL berbasis kolin menunjukkan bahwa cairan yang diteliti berada dalam kisaran “tidak beracun” ( $100-1000 \text{ mg L}^{-1}$ ). Sifat-sifat *micellar* menunjukkan bahwa interaksi sinergis terdapat pada semua campuran biner ( $\beta < 0$ ,  $f_1$  and  $f_2 < 1$ ). Selain itu, *micelle* yang diproduksi dengan semua rasio mol dari IL bersifat spontan dan stabil secara termodinamika. Secara keseluruhan, hasil ini menunjukkan bahwa IL yang diteliti bersifat aman untuk alam dan dapat digunakan dalam berbagai aplikasi termasuk dispersan untuk minyak bumi.

**Keywords:** *dispersant, ionic liquids, oil spill, toxicity*

---

### 1. Introduction

The transfer of crude oil and its treated products due to various activities adversely effected the marine environment [1]. Therefore, to reduce the impact of oil spill, several response measures were adopted and among them chemical dispersant is proved to be the most suitable response option [2]. Although it is well accepted that employment of chemical dispersants

reduce the damages of oil spill but still its use is restricted in marine environment by many governmental organizations due to toxicity issues [3]. For instance, Corexit<sup>®</sup>, the most well known chemical dispersant, used in huge amount (more than two million gallons) in Deepwater Horizon oil spill caused severe environmental concerns. This is because the solvent and the surfactants used in its formulation are mostly toxic and nonbiodegradable [3],[4]. Enhancement in environmental awareness and

strict governmental legislation has motivated the researchers to identify dispersants/formulations that are safe and environmentally benign [5],[6].

Ionic liquids (ILs) have garnered great attention as a sustainable material due to its fascinating properties e.g; low flammability, low volatility, and high surface activity [7],[8]. Recently, choline based ILs have gain more attraction due to its low toxicity and high biodegradable nature [9],[10]. These long chain environmentally benign surfactants utilized in different fields including; biomass pre-treatment, adsorption of carbon dioxide, demulsifying and emulsifying agents [9],[11],[12]. The ongoing development on the employment of choline based ILs in diverse fields embarks a better understanding about its impact on environment. Therefore, to further explore its safe nature in marine environment, in this study we evaluated the acute toxicity of three choline based ILs, choline laurate [Cho][Lau], choline myristate [Cho][Myr] and choline oleate [Cho][Ol] against the *Danio rerio* fish. Furthermore, to ensure its application for oil spill remediations the aggregation behaviour of ILs were also evaluated. However, it is reported that the micelles produced by a single IL surfactant require a high surfactant content to form a stable micelle [13]. Therefore, to overcome this limitation the aggregation behaviour of the binary mixtures was evaluated to enhance the target properties of the selected system.

## 2. Experimental

**Materials and synthesis of ILs.** Lauric acid (Merck,  $\geq 99\%$ ), Myristic acid (Sigma,  $\geq 99\%$ ), oleic acid (Sigma  $\geq 99\%$ ) and choline hydroxide (Sigma, 46 wt% water) were of analytical grade and used to synthesize the respective ILs.

The ILs were synthesized by a developed method [14]. Briefly, respective acids, were added to the choline hydroxide solution (1:1 molar ratio) under stirring. The

reaction mixture (under continuous stirring) was then refluxed at a temperature of 80 °C for a period of 24 h. Rotary evaporator (80 °C, 2 h) were applied to dry the synthesized ILs and their structure was confirmed by employing  $^1\text{H}$  NMR.

**Fish toxicity analyses.** A well known method accepted by Organization for Economic Co-operation and Development (OECD) [15] were employed to evaluate the acute toxicity towards zebra fish (*Danio rerio*). The *Danio rerio* were obtained from a fish hatchery (Perak, Malaysia) and screen having size  $\pm 2$  cm. Further, prior to the toxicity test, safe conditions of survival [16] were followed to ensure the optimum health of the fish as shown in Figure 1. The fish were then shifted to 5 L water tanks, connected with air pump that provide sufficient air ( $1.8 \text{ L min}^{-1}$ ) for fish survival.

Initially, the test were started with a  $100 \text{ mg L}^{-1}$  concentration of ILs (called limit test), to know whether the half lethal concentration at 50% mortality ( $\text{LC}_{50}$ ) falls below or above than this value ( $100 \text{ mg L}^{-1}$ ). According to the guidelines of OECD [15], the lack of mortality in the limit test depicts that full assay test can be waived. However, to evaluate the actual hazard value, a full test was conducted for ILs surfactants. The obtained  $\text{LC}_{50}$  values were then compared with a hazard ranking established by Passino and Smith [17].

**Surface tension measurements.** Surface tension measurements were carried out with high accuracy by employing the pendant drop technique (OCA20, Data Physics, Germany). The pure and mixed system surface tension was evaluated after appropriate mixing of the components. In all experiments, three measurements were carried out and the average value was then reported. The accuracy of the equipment was confirmed by evaluating the methanol and pure water surface tension at  $25 \pm 0.1$  °C. The uncertainty in achieved results were found to be  $\pm 0.1 \text{ mN m}^{-1}$ .



Figure 1. Acclimatization of Zebra Fish (*Danio rerio*) to Confirm Their Optimum Health

### 3. Results and Discussion

**Acute toxicity assessment.** Initially, the limit test were performed for all the ILs at a dose of 100 mg L<sup>-1</sup> for 96 h and it was noticed that LC<sub>50</sub> values (96 h) of all ILs were found to be higher than 100 mg L<sup>-1</sup>. The obtained results was then compared with the hazard toxicity ranking (Table 1) established by Passino and Smith [17].

Comparing with Table 1, it can be seen that all ILs were fall in ranking of “practically nontoxic” (LC<sub>50</sub> > 100 mg L<sup>-1</sup>) towards zebra fish and hence, the complete toxicity test can be waived. However, to strengthen these observations, the full test was carried out for all ILs, e-g; [Cho][Lau], [Cho][Mys] and [Cho][OI] to determine the exact LC<sub>50</sub> values after 96 h. The full test was started by selecting five different concentrations as fallows: 600, 700, 800, 850, and 900 mg L<sup>-1</sup> of [Cho][Lau]. Each dose was poured in separate tank holding 10 fishes. The parameters including: dissolved oxygen, pH and water temperature were measured after every 24 h in order to ensure that the abnormalites are caused by ILs only. The fish activity was checked after every day (24 h) and the number of mortalities were determined after four days (96 h). The LC<sub>50</sub> can be determined as the concentration at which 50% of the population (fish) died and was found to be 850 mg L<sup>-1</sup> (Table 2) for pure [Cho][Lau].

In similar way the LC<sub>50</sub> values of pure [Cho][Mys] and [Cho][OI] were also evaluated by taking five different concentrations as fallow: 450, 500, 550, 600 and 700 mg L<sup>-1</sup> and 250, 300, 400, 450 and 550 mg L<sup>-1</sup> for pure [Cho][Mys] and [Cho][OI] respectively.

The LC<sub>50</sub> at 50% mortality was determined to be 600 mg L<sup>-1</sup> for [Cho][Mys] and 450 mg L<sup>-1</sup> for [Cho][OI] (Table 2). This again illustrated that both ILs are classified as “practically nontoxic” according to hazard ranking as shown in Table 1. The above results showed that all three ILs fall in the range of “practically nontoxic” however, each ILs behave differently against the tested organism. Recently, the acute toxicity of [Cho][Lau] merg with biosurfactants against zebra fish was reported. The results illustrates that a practically nontoxic formulation were produced by combining both surfactants [8]. A study performed by Pretty *et al.* [18] observed that ILs

caused a different effect towards zebrafish depending on their chemical structure. A similar result was seen in our study where the toxicity of the ILs towards the fish increases by increasing the alkyl chain length of the introducing ILs. Hence, it can be seen that [Cho][OI] have higher toxicity as compared to the [Cho][Mys] and [Cho][Lau] towards the zebrafish.

**Aggregation behavior of mixture comprised of [Cho][Mys] and [Cho][OI].** The detail aggregation behavior of the binary mixture comprised of [Cho][Lau] and [Cho][OI] was investigated in our previous study [10] and it was observed that the micelle formed by the binary mixture was more stable as compared to the individual component. Therefore, in this study the aggregation behaviour of the binary mixture comprised of [Cho][Mys] and [Cho][OI] is investigated in order to check the possible synergism and stability of the mixed system micelles.

**Evaluation of critical micelle concentration.** The critical micelle concentration (CMC) values of the single components ([Cho][Mys] and [Cho][OI]) were evaluated and it was observed that the CMC of the single components are similar with those reported in literature [19],[20]. CMC values of the binary mixture with different mole ratios of the components were evaluated and presented in Table 3. The break points of the linear fitting lines of higher and lower concentration regions were used to determine the CMC of individual and mixed system. As depicted in Table 3 that by increasing the [Cho][OI] mole fraction ( $\alpha$ ), the values of CMC start decreases and ultimately reached near to the pure [Cho][OI] CMC value. In the process of micellization, two main factors play their role (i) the hydrophobic part interaction between the component molecules and (ii) the charged heads electrostatic interaction. In the present research study, it is the hydrophobic interaction between the tails of the component molecules that succeeds over the electrostatic interaction and causes micelle formation at lower concentration. Similar trend was observed previously [21], where the CMCs of the mixed anionic surfactants occurred between the pure components.

**Mixed system composition and Interaction parameters.** To check the syergism between the components and to investigate that either the mixed surfactant system interaction is ideal or not, several parameters were investigated and discussed in detail. The ideal mixed surfactant system critical micelle concentration can be find out from CMC<sub>1</sub> and CMC<sub>2</sub> of component 1([Cho][OI]) and component 2 ([Cho][Mys]), respectively by employing the Clint equation [22] as shown in Eq.(1).

$$\frac{1}{CMC^*} = \frac{\alpha}{CMC_1} + \frac{(1-\alpha)}{CMC_2} \quad (1)$$

**Table 1. Toxicity Ranking Established by Passino and Smith [17]**

Relative Toxicity	Aquatic LC <sub>50</sub> (mg/L)
Super Toxic	0.01-0.1
Highly Toxic	0.1-1
Moderately Toxic	1-10
Slightly Toxic	10-100
Practically Nontoxic	100-1000
Relatively Harmless	>1000

**Table 2.** Acute Toxicity Estimation of ILs, [Cho][Lau], [Cho][Mys] and [Cho][OI]

Concentration (mg L <sup>-1</sup> ) of ILs	Number of fish tested	Mortality (dead fish) after test	% mortality
[Cho][Lau]			
600	10	2	20
700	10	3	30
800	10	4	40
850	10	5	50
900	10	8	80
[Cho][Mys]			
450	10	2	20
500	10	3	30
550	10	4	40
600	10	5	50
700	10	9	90
[Cho][OI]			
250	10	2	20
300	10	3	30
400	10	4	40
450	10	5	50
550	10	9	90

**Table 3.** Experimental and Ideal Critical Micelle Concentration of Binary Mixture Comprised of [Cho][Mys] and [Cho][OI]

$\alpha$	CMC(mM)	CMC* (mM)	$\chi_{cmc}$ (mNm <sup>-1</sup> )
0	6.1	-	29.21
0.2	2.81	3.50	28.14
0.4	1.95	2.46	27.33
0.6	1.57	1.89	26.12
0.8	1.42	1.54	27.86
1.0	1.30	-	30.11

where CMC\* is the ideal mixed state CMC. The experimental CMC's values as shown in Table 3 for the mixed system are lower than the ideal CMC\* and illustrating negative deviation (Figure 2) as predicted by the Clint model. This trend shows that the micelle formed at a concentration lower than the ideal mixing state micelle formation, and further illustrates that the interactions between the components are supportive for mixed system micelle formation.

The [Cho][OI] mole fraction in ideal state ( $X_{ideal}$ ) of mixed surfactant system was determined using Eq.(2):

$$X_{ideal} = \frac{\alpha cmc_2}{\alpha cmc_2 + (1-\alpha)cmc_1} \quad (2)$$

Further, the mixed system non-ideal nature was also confirmed by Holland and Rubingh method [23]. The micellar mole fraction ( $X_1$ ) of first component ([Cho][OI]) and interaction parameter ( $\beta$ ) between the components was determined by using Eq.(3) and Eq.(4) respectively.

$$\left[ \frac{X_1^2 \ln\left(\frac{cmc\alpha}{cmc_1 X_1}\right)}{(1-X_1)^2 \ln\left(\frac{cmc(1-\alpha)}{cmc_2 (1-X_1)}\right)} \right] = 1 \quad (3)$$

$$\beta = \frac{\ln\left(\frac{cmc\alpha}{cmc_1 X_1}\right)}{(1-X_1)^2} \quad (4)$$

For the binary mixed system, all the calculated values of  $X_{ideal}$ ,  $X_1$ , and  $\beta$  are presented in Table 4. It can be seen (Table 4 and Figure 3) that both  $X_{ideal}$  and  $X_1$  values increases by increasing the [Cho][OI] mole fractions. The rise of  $X_1$  with [Cho][OI] concentration (Figure 3) provide an indication that the mixed system micelle formation is favored by enhancing the [Cho][OI] content.

The nature and extent of interaction between the mixed surfactant system components is evaluated by determining interacting parameter ( $\beta$ ) as depicted in Table 4. It is reported that a positive and negative value of  $\beta$  representing an antagonistic interaction, i.e., the molecules interaction are weak and synergistic interaction (strong interaction between molecules), whereas a zero value of  $\beta$  shows no interaction, illustrating ideal behavior [24]. In the present study, all the values of  $\beta$  are negative (Table 4) of the binary mixture, which shows synergistic interactions between the component molecules e-g; [Cho] [Mys] and [Cho][OI]. The results presented in this study are in line with previous study where the ILs mixed system showed synergism between the components [25].

The activity coefficients ( $f_1$  and  $f_2$ ) for the mixed surfactant systems were evaluated by using Rubingh [26] equations as stated below.

$$f_1 = \exp\{\beta(1 - X_1)\} \quad (5)$$

$$f_2 = \exp\{\beta X_1^2\} \quad (6)$$

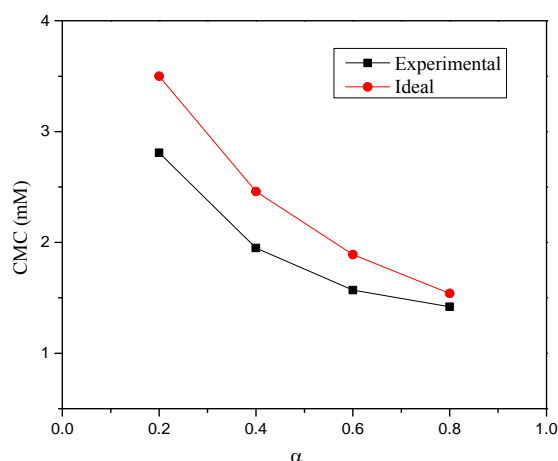


Figure 2. Comparison of Experimental and Ideal CMC values of Binary Mixtures

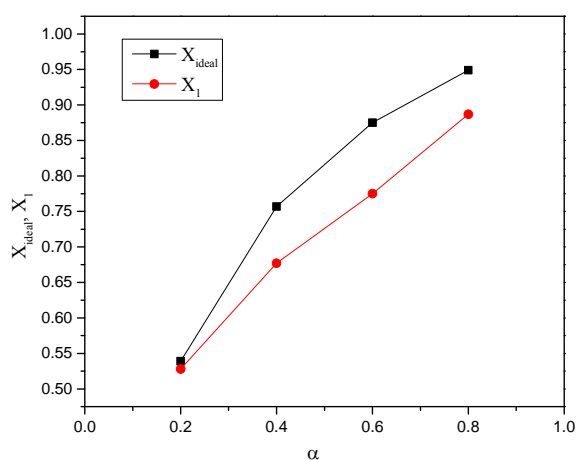


Figure 3. Variation of  $X_1$  and  $X_{ideal}$  with Different  $\beta$  Values

Table 4. Micellar Composition ( $X_1$  and  $X_{ideal}$ ), Activity Coefficients ( $f_1$  and  $f_2$ ) and Interacting Parameter ( $\beta$ ) of Binary Mixtures

$\alpha$	$X_{ideal}$	$X_1$	$\beta$	$f_1$	$f_2$
0.2	0.539	0.528	-0.897	0.818	0.778
0.4	0.757	0.677	-1.157	0.886	0.588
0.6	0.875	0.775	-1.327	0.935	0.450
0.8	0.949	0.887	-1.170	0.985	0.398

Table 5. Thermodynamic Parameters of Binary Mixture with Different  $\beta$  at a Temperature 25 °C

$\alpha$	$\Delta G_{mic}^0$ (kJ.mol <sup>-1</sup> )	$\Delta G_{ex}$ (kJ.mol <sup>-1</sup> )	$\pi_{cmc}$ (mNm <sup>-1</sup> )
0.2	-24.51	-0.556	43.96
0.4	-25.42	-0.628	44.77
0.6	-25.96	-0.574	45.98
0.8	-26.20	-0.291	44.24

The values of activity coefficients  $f_1$  and  $f_2$  less than unity illustrating the non-ideal system (synergistic behavior). In the existing study, all the values of  $f_1$  and  $f_2$  as shown in Table 4 are less than one for all ratios of mixed system, showing the attractive interaction (synergistic) between the component molecules, i.e., [Cho][Mys] and [Cho][OI]. All the above results i.e., negative  $\beta$  values and  $f_1$  and  $f_2$  values < unity representing the non ideal nature of the binary system.

**Thermodynamics of micellization.** Two important thermodynamic parameters including; standard Gibbs free energy of micellization ( $\Delta G_{mic}^0$ ) and excess free energy of micellization ( $\Delta G_{ex}$ ) were evaluated to get an idea about the thermodynamic stability of the micelle formed by the mixed system.

The  $\Delta G_{mic}^0$  was found out by using Eq.(7) [27].

$$\Delta G_{mic}^0 = RT \ln X_{cmc} \quad (7)$$

where  $X_{cmc}$  representing the  $cmc$  in mole fraction units. All the  $\Delta G_{mic}^0$  values as shown in Table 5 are negative and this negative trend increases by enhancing the mole ratio of [Cho][OI]. This further, depicts that the micelle formation is favored and the micellization process becomes more spontaneous by increasing the concentration of [Cho][OI]. A similar trend was also observed for the binary mixtures of anionic surfactants i.e; sodium dodecyl benzene sulfonate (SDBS) and sodium dodecylsulfate (SDS) [21].

The stability of micelles formed by the mixed system was also confirmed by determining the  $\Delta G_{ex}$  values using Eq.(8) [28].

$$\Delta G_{ex} = RT[X_1 \ln f_1 + (1 - X_1) \ln f_2] \quad (8)$$

It is well reported that for ideal mixing, the value of  $\Delta G_{ex}$  is zero [25], showing no interaction between the components. However, in current work, the values of  $\Delta G_{ex}$  as presented in Table 5 is not zero, showing the possible interactions between the components and their



stability can be confirmed by the negative value of  $\Delta G_{\text{ex}}$ . Hence, it can be seen (Table 5) that for all mole ratios, the negative  $\Delta G_{\text{ex}}$  values further, proves that the binary system micelles are more thermodynamically stable as compared to the micelle formed by the pure components. Recently, some researchers observed similar results, where thermodynamically stable micelles were noticed for the mixed surfactant system involving ILs [25, 29]. Moreover,  $\pi_{\text{cmc}}$ , which shows the reduction of surface tension at CMC, was also determined ( $\pi_{\text{cmc}} = \gamma_o - \gamma_{\text{cmc}}$ ), where  $\gamma_o$  and  $\gamma_{\text{cmc}}$  are surface tension of pure water and surface tension of mixture at CMC. It was observed that thermodynamically stable micelles are able to reduce the surface tension of solvent to lower values (Table 5).

#### 4. Conclusions

In this study the acute toxicity and aggregation behavior of choline-based surface active ILs were investigated. The toxicity study on zebra fish indicates that all the ILs could be classified as “practically nontoxic” with  $\text{LC}_{50}$  values greater than  $100 \text{ mg L}^{-1}$ . However, the full toxicity analysis on zebra fish indicated that the toxicity increases by increasing the anion chain length of the ILs. Therefore, [Cho][Lau] was observed to be least toxic ( $\text{LC}_{50} = 850 \text{ mg L}^{-1}$ ) where as [Cho][Ol] was the most toxic having  $\text{LC}_{50}$  values of  $450 \text{ mg L}^{-1}$ . The aggregation behavior of mixed system composed of [Cho][Mys] and [Cho][Ol] suggested strong synergism between the components and stable micelles produced by the binary surfactant system as compared to the micelles composed of pure components. Furthermore, thermodynamic studies showed spontaneous and thermodynamically stable micelles formation by the mixed surfactant system.

#### Acknowledgements

Mansoor Ul Hassan Shah acknowledges the Centre of Research in Ionic Liquids (CORIL), Universiti Teknologi PETRONAS for financial support (015 3AB A30) under the PRF project.

#### References

- [1] Z.H. Asadov, A.H. Tantawy, I.A. Zarbaliyeva, R.A. Rahimov, Egypt. J. Pet. 22 (2013) 261.
- [2] H. Chapman, K. Purnell, R.J. Law, M.F. Kirby, Mar. Pollut. Bull. 54 (2007) 827.
- [3] R. Almeda, C. Hyatt, E.J. Buskey, Ecotoxicology Environ Saf. 106 (2014) 76.
- [4] E. Nyankson, M.J. DeCuir, R.B. Gupta, ACS Sustain. Chem. Eng. 3 (2015) 920.
- [5] R. Maier, G. Soberon-Chavez, Appl. Microbiol. Biotechnol. 54 (2000) 625.
- [6] M.U.H. Shah, M. Sivapragasam, M. Moniruzzaman, M.M.R. Talukder, S.B. Yusup, M. Goto, Biochem. Eng. J. 127 (2017) 60.
- [7] A.M. Atta, H.A. Al-Lohedan, M.M. Abdullah, S.M. ElSaeed, J. Ind. Eng. Chem. 33 (2016) 122.
- [8] M.U.H. Shah, M. Moniruzzaman, M. Sivapragasam, M.M.R. Talukder, S.B. Yusup, M. Goto, J. Mol. Liq. 280 (2019) 111.
- [9] B.L. Gadilohar, G.S. Shankarling, J. Mol. Liq. 227 (2017) 234.
- [10] M.U.H. Shah, M. Sivapragasam, M. Moniruzzaman, M.M.R. Talukder, S.B. Yusup, M. Goto, J. Mol. Liq. 266 (2018) 568.
- [11] J. Aburto, D.M. Márquez, J.C. Navarro, R. Martínez-Palou, Tenside Surfactants Deterg. 51 (2014) 313.
- [12] M.U.H. Shah, M. Sivapragasam, M. Moniruzzaman, M.M.R. Talukder, S.B. Yusup, Mater. Today Proc. 5 (2018) 21661.
- [13] H. Niedermeyer, J.P. Hallett, I.J. Villar-Garcia, P.A. Hunt, T. Welton, Chem. Soc. Rev. 41 (2012) 7780.
- [14] M. Petkovic, J.L. Ferguson, H.N. Gunaratne, R. Ferreira, M.C. Leitao, K.R. Seddon, L.P.N. Rebelo, C.S. Pereira, Green Chem. 12 (2010) 643.
- [15] OECD-203 (Ed.), Fish acute toxicity test, in: Organisation for Economic Co-operation and Development, OECD Guidelines for Testing Chemicals, No. 203, 1992.
- [16] S.H. Baharuddin, N.A. Mustahil, A.A. Abdullah, M. Sivapragasam, M. Moniruzzaman, Proc. Eng. 148 (2016) 401.
- [17] D.R. Passino, S.B. Smith, Environ. Toxicol. Chem. 6 (1987) 901.
- [18] C. Pretti, C. Chiappe, D. Pieraccini, M. Gregori, F. Abramo, G. Monni, L. Intorre, Green Chem. 8 (2006) 238.
- [19] R. Klein, D. Touraud, W. Kunz, Green Chem. 10 (2008) 433.
- [20] D. Rengstl, B. Kraus, M. Van Vorst, G.D. Elliott, W. Kunz, Colloids Surf. B-Biointerfaces, 123 (2014) 575.
- [21] G.B. Ray, I. Chakraborty, S. Ghosh, S.P. Moulik, Colloid Polym. Sci. 285 (2007) 457.
- [22] J.H. Clint, J. Chem. Soc. 71 (1975) 1327.
- [23] P. Holland, D. Rubingh, J. Phys. Chem. 87 (1983) 1984.
- [24] N. Azum, A.Z. Naqvi, M. Akram, J. Colloid Interface Sci. 328 (2008) 429.
- [25] A. Ali, U. Farooq, S. Uzair, R. Patel, J. Mol. Liq. 223 (2016) 589.
- [26] D.N. Rubingh, Solut. Chem. Surfactants, Springer, 1979, p. 337.
- [27] K. Tsubone, Y. Arakawa, M.J. Rosen, J. Colloid Interface Sci. 262 (2003) 516.
- [28] N. Azum, M.A. Rub, A.M. Asiri, A.A.P. Khan, A. Khan, S.B. Khan, M.M. Rahman, A.O. Al-Youbi, J. Solut. Chem. 42 (2013) 1532.
- [29] R. Sharma, S. Mahajan, R.K. Mahajan, Colloids Surf. A-Physicochem. Eng. Asp. 427 (2013) 62.