



Separation of PCE via Liquid-Liquid Extraction and Reverse Micellar Extraction for Surfactant Recovery

Kuntida Krisorncharoen and Punjaporn Weschayanwiwat

Abstract— This study aimed to investigate two extraction techniques: liquid-liquid extraction (LLE) and reverse micellar extraction (RME) coupled with ultrafiltration (UF) for tetrachloroethylene (PCE) removal and surfactant recovery purposes. In this study, we imitated the surfactant solution similar to one pumped out of the contaminated site, which contains 4%AMA (anionic surfactant), 3%NaCl and 10,000 ppm solubilized PCE. The LLE using five extracting solvents varying the equivalent alkane carbon number (EACN) was investigated to determine the partitioning of PCE from surfactant solution into solvent phase and eventually the %PCE removal. The RME is another extraction technique based on Winsor type II microemulsion formation. The result showed that EACN of extracting solvent and the surfactant solution:solvent volumetric ratio were crucial parameters governing the extraction efficiency of LLE. Moreover, other parameters (molecular structure and functional groups, etc.) also affect the PCE partitioning and PCE removal in LLE. For RME, the surfactant solution: solvent volumetric ratio used in this study (ranged from 40:1 to 5:1) did not show significant effects on the surfactant removal (84.9-86.9%) and PCE removal (96.7-98.4%). Furthermore, an UF followed with RME was used as an additional downstream process to concentrate reversed surfactant micelles in retentate while passing PCE and solvent in permeate..

Keywords— Watershed, Wetland, Multiple Criteria Decision Making, MCDM.

1. INTRODUCTION

Tetrachloroethylene (PCE) is a volatile chlorinated hydrocarbon widely used as a solvent in the chemical industries, a dry-cleaning fluid in the textile industries, and a metal-degreasing agent in electroplating industries. Moreover, PCE is a nonflammable, colorless liquid that belongs to a class of chemicals known as volatile organic compounds (VOCs) meaning that PCE easily evaporates into the air. PCE moves easily through soil and ends up contaminating to the groundwater. PCE does not mix very well with water but over time may dissolve in sufficient amounts to become a health concern. PCE is denser than water and tends to sink to the bottom of aquifers [1]. PCE may stay in groundwater for several months without being broken down. Under some conditions, PCE may stick to the soil, present in surface water and contaminate into water sources, groundwater, and aquatic life. Thus, the clean-up activities tend to be more problematic as compared to clean-up of oil spills.

Surfactant-enhanced aquifer remediation (SEAR) is a promising technology using a surfactant solution to remedy the subsurface contaminated by nonaqueous

phase liquids (NAPLs). The term “surfactant” is a truncation of surface active agent. Surfactants can help the extraction of organic contaminants from an aquifer by reducing interfacial tension (IFT) between NAPLs and groundwater, and by increasing the solubility of the contaminants. Surfactants are molecules that consist of hydrophilic and hydrophobic moieties referred to as heads and tails, respectively as shown in Figure 1. The hydrophobic interior cores of surfactant micelle can promote the solubilization of NAPLs in the micelles leading to desorption of these compounds from soil media. The solution containing solubilized contaminants in surfactant micelles can then be treated to separate surfactants and contaminants [2]. Since surfactant costs are significant in large-scale implementation of SEAR, the decontamination and reuse of surfactant solutions are desirable [3]. Recovery of surfactant solution is very important in the development of the surfactant-based remediation. In addition, reducing the volume of wastewater, recycling of used surfactant solutions will reduce chemical costs for the treatment of hydrophobic organic contaminated soils and groundwater [2].

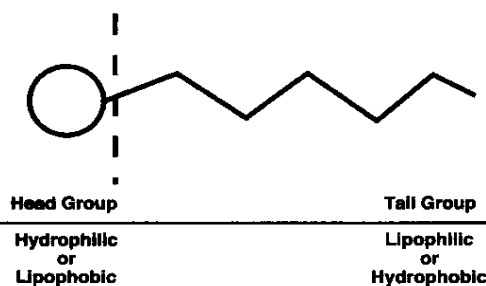


Fig. 1. General Representation of Surfactant Molecule.

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2. THEORETICAL BACKGROUND

2.1 Supersolubilization condition

The supersolubilization concept takes advantage of the fact that the interfacial tension (IFT) continually decreases and the solubility enhancement continually increases as suggested by the Chun Huh relationship [4]. Salinity scans are typically conducted to find the optimum electrolyte addition to maximize the contaminant solubilization. By operating near the Winsor type I-III microemulsion boundary, it is possible to maximize the solubility enhancement while minimizing the vertical migration potential [5]. The ionic surfactant solutions, which form the Winsor type I microemulsion at certain electrolyte concentrations closed to the Winsor type I-III transition boundary, show an ultralow IFTs without forming Winsor type III microemulsion. Such systems have extremely high contaminant solubilization capacities compared to solutions at lower electrolyte concentrations [3]. A generic diagram of Winsor type I-III-II microemulsion transition is shown in Figure 2.

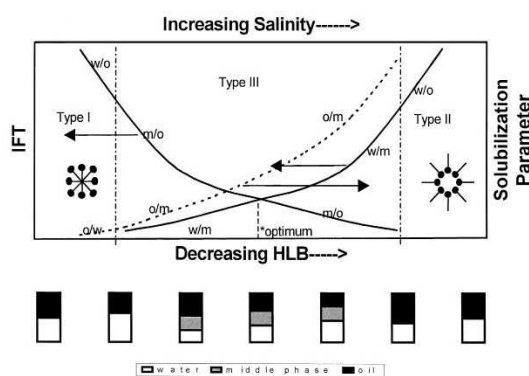


Fig. 2. Illustration of Phase Behavior and Interfacial Tension (IFT): oil is o; w is water; m is middle phase.

2.2 Liquid-liquid extraction

Liquid-liquid extraction (LLE), sometimes referred to as solvent extraction also has the potential to recover the surfactant for regeneration by removing contaminant into the solvent as the rule of thumb "like dissolve like". The driving force behind LLE is the equilibrium distribution coefficient (K_d) for the contaminant-aqueous-solvent solution [6]. Furthermore, the distribution of a solute depends on its preference for one or the other liquid, which is closely related to its solubility in each one of them. However, the disadvantage of LLE or solvent extraction technique is the high potential for the extracting solvent contamination in the aqueous stream. Hence, the utilization of the suitable solvent (i.e. nontoxic and low solubility solvent), the efficiency of the extraction column can be maximized.

2.3 Reverse micellar extraction (RME)

The hydrophile-lipophile balance (HLB) is a parameter that characterizes surfactants in terms of their abilities to produce optimum emulsions with given oil. As the surfactant HLB decreases, the transition of microemulsion system is induced in the order of Winsor

type I-III-II [7]. While an ionic surfactant possesses a certain HLB value, an electrolyte addition alters its effective HLB value and thus facilitate to the Winsor type II microemulsion formation.

A Winsor type II (water-in-oil) microemulsion will form when a low HLB surfactant system is in contact with a hydrophilic solvent. Micelles break up and migrate into solvent phase and re-aggregate into the reversed micelles, and the micellar-solubilized contaminant is released during the micelle breakup. The contaminant molecules will also be extracted into the solvent phase, promoted by both the disappearance of micelles and the high affinity of the solvent phase for the contaminants. A small amount of water with dissolved electrolyte will be accumulated in the reversed micelle interiors, and the contaminant concentration in the water will be its water solubility.

Therefore, the aqueous solution will be decontaminated of both contaminant and surfactant after RME, while electrolyte and some portions of solvent will be left in the aqueous phase [3].

2.4 Ultrafiltration process

The ultrafiltration (UF) membranes contain pores in the range 1-100 nm [8]. An UF is a relatively low pressure membrane process used in a water treatment. UF has rapidly increased in the last decade due to stricter regulations for water quality, decreased cost, improved membrane materials and modules, simplicity of installation and improved reliability when compared with conventional treatment process such as sedimentation and sand filtration. The principle application comprises the removal of undesirable products such as particles, colloids, high molecular weight materials, bacteria and viruses from an effluent stream in order to obtain more purified water [9]. It has been applied either to remove organic and inorganic solutes of environmental concern from aqueous wastes, as well as preconcentration step in some analytical determinations. The separation procedure is based on the association of solutes to added micellar aggregates, successively removed from the bulk solution through an UF membrane. The membrane pore-size has to be small enough to block the aggregates in the retentate, and large enough to allow acceptable flux rates in the system [10].

3. MATERIALS AND METHODS

3.1 Materials

The following surfactants were used without further purification, sodium dihexyl sulfosuccinate (trade name of Aerosal MA or AMA with 80% active) purchased from Fluka Company and sorbitan monolaurate (trade name of Span-20 with 100% active) supplied by East Asiatic (Thailand) Public Company Limited.

Tetrachloroethylene or PCE (EACN = 2.9) was used as contaminant with 95% purity and purchased from Aldrich Company.

Five extracting oils with different EACNs were used in this study as follows: 1) dodecane ($C_{12}H_{26}$, EACN = 12) purchased from Aldrich Company, 2) palm oil

(C₁₆H₃₂O₂, EACN = 13) purchased from Lamsoon (Thailand), 3) sunflower oil (C₁₈H₃₂O₂, EACN = 18) purchased from Healthymate (Thailand), 4) octadecane (C₁₈H₃₈, EACN = 18) and 5) squalane (C₃₀H₆₂, EACN = 30) purchased from Aldrich Company. All extracting oils have purity higher than 99% and were used as received.

3.2 The phase behavior studies

The phase behavior studies were conducted in 12 mL centrifuge tubes with teflon screw caps where equal volumes of aqueous surfactant solution and PCE was added into the tube. The concentration of AMA was held constant at 4 wt% and a salinity scan was conducted using NaCl. The phase transition of Winsor type I-III-II microemulsion was observed visually and confirmed by interfacial tension measurement (IFT). The NaCl concentration that causes the supersolubilization condition was determined. In addition, the concentration of solubilized PCE at the supersolubilization condition was analyzed by gas chromatography (GC) equipped with headspace autosampler.

3.3 Liquid-liquid extraction study (LLE)

Five extracting solvents varying EACNs were used including dodecane (EACN = 12), palm oil (EACN = 13), sunflower oil (EACN = 18), octadecane (EACN = 18) and squalane (EACN = 30). The surfactant solution with certain amount of solubilized PCE at supersolubilization condition as obtained from phase behavior study was prepared. The equilibrium time was determined using one solvent (palm oil) at the specific surfactant solution:solvent volumetric ratio (5:1). The concentration of PCE in both phases was analyzed by GC. The time at which the concentrations of PCE in both phases remain constant defined as the equilibrium time.

The surfactant solution was blended with pure extracting solvent at the volumetric ratios of 1:1, 5:1, 10:1, and 20:1 in the test tubes in such a way to minimize the headspace volume in order to avoid the loss of PCE into air phase. The concentration of PCE in aqueous and extracting solvent phases were analyzed using GC and the mass balance of PCE with the closer of material balance of PCE between phases of 10% were carried out to assure the reliability of experiment.

The PCE partitioning among phases and the PCE removal from surfactant aqueous solution to solvent phase could be revealed. The best surfactant solution:solvent volumetric ratio was determined and then applied to other types of extracting solvents. As a consequence, the relationship between the PCE removal and extracting solvents' EACN was investigated.

3.4 Reverse micellar extraction study (RME)

The RME was studied only with palm oil. The surfactant aqueous solution obtained from preliminary study in the presence of solubilized 10,000 ppm PCE at the fixed volumetric ratio of surfactant solution:solvent at 1:1 was used to form the Winsor Type II microemulsion by salinity scan with NaCl. If the Winsor type II microemulsion could not be formed solely by AMA, the second surfactant needed to be added to help reducing

the HLB of the system. The total amounts of surfactant(s) along with the extracting oil presenting in the aqueous phase were analyzed using total organic carbon analyzer (TOC). The suitable NaCl that can form Winsor type II microemulsion with the least amount of surfactant(s) was selected. The effect of surfactant solution:solvent volumetric ratio was studied and applied to the above surfactant(s)-oil-NaCl system at 4 ratios including 5:1, 10:1, 20:1, and 40:1. The selected volumetric ratio of surfactant solution:solvent was determined by considering the Winsor Type II microemulsion system that has the least amount of remaining surfactant(s) and PCE in the aqueous phase.

3.5 Ultrafiltration (UF)

The prepared palm oil solution at the same surfactant compositions with the best surfactant solution:solvent volumetric ratio as obtained from 3.4 with 50,000 ppm PCE. This solution was used as the palm oil feed solution for UF stirred cell unit (Amicon Stirred Ultrafiltration Cell, Model 8400). The regenerate cellulose membrane with 5,000 Dalton cutoff was used to block the passage of surfactant reversed micelles in the retentate stream. The effect of applied nitrogen (N₂) gas pressure on the UF cell was studied. The concentration of PCE in the permeate and retentate stream were analyzed and the percentage of PCE removal could then be evaluated.

4. RESULTS AND DISCUSSION

4.1 Phase behavior study

According to the visual observation of the phase transition between Winsor type I-III-II microemulsion, the 4%AMA/3%NaCl system was found to exhibit the Winsor type I microemulsion (oil in water) closed to a boundary of Winsor type I-III microemulsion prior to form the middle phase microemulsion at 4%NaCl. By the solution appearance as shown in Figure 3, it was found that the one before the Winsor type I-III transition showed the milky-like surfactant solution, which is generally used to identify that the surfactant system is at the supersolubilization region where the solubilization of solute in the surfactant micelles is maximum. This surfactant solution was corresponded to the work done by [11], which also used AMA as the surfactant in the field demonstration for surfactant-enhanced solubilization of DNAPL. In addition, the concentration of solubilized PCE at this supersolubilization condition was found to be about 12,000 ppm measured by GC. Consequently, this 4%AMA/3%NaCl system was used to represent the supersolubilization system for PCE and PCE at concentration of 10,000 ppm was applied throughout the experiment as a base PCE concentration.

4.2 Effect of EACN of solvent on liquid-liquid extraction

4.2.1 Equilibrium time determination

The concentration of PCE in solvent remained constantly at 4 days. Thus, 4 days was used as the equilibrium time for this liquid-liquid extraction and applied for the rest of the experiments.

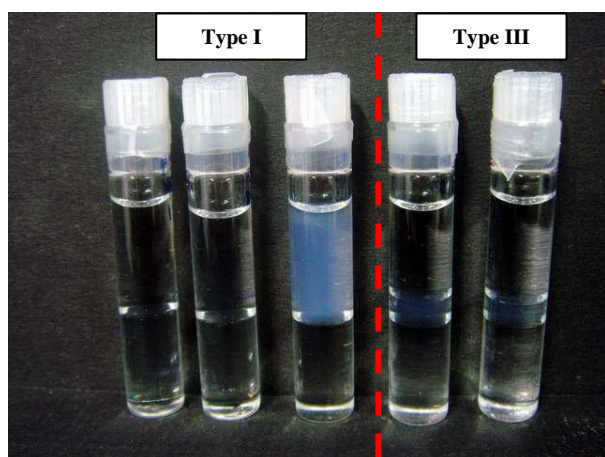


Fig. 3. The Phase Transition of Microemulsion Solution by Scanning with NaCl in the System Containing of 4%AMA.

4.2.2 Effect of surfactant solution:solvent volumetric ratios

Palm oil was used to determine the optimal surfactant solution:solvent volumetric ratio. At the equilibrium time (4 days), the concentration of the PCE in both palm oil and surfactant aqueous phases was analyzed and the material balance of PCE was carried out to assure the reliability of the data. The deviation of mass of PCE in material balance was less than 10%. The distribution of PCE between phases ($[PCE]_{\text{solvent}}/[PCE]_{\text{aqueous}}$) and %PCE removal from surfactant aqueous phase to extracting oil phase at different surfactant solution:solvent volumetric ratio were shown in Table 1.

Table 1. The Effect of the Surfactant Solution:Solvent Volumetric Ratios in Liquid-Liquid Extraction on %PCE Removal and Distribution Coefficient of PCE by Using Palm Oil as Extracting Solvent

Surfactant solution :solvent volumetric ratios	[PCE] initial (ppm)	[PCE] aqueous (ppm)	[PCE] solvent (ppm)	% PCE removal	$\frac{[PCE]_{\text{solvent}}}{[PCE]_{\text{aqueous}}}$
1:1	9,782	1,662	7,667	83.0	4.6
5:1	9,964	3,653	26,288	63.3	7.2
10:1	9,959	4,571	64,674	54.1	14.1
20:1	9,986	6,478	67,686	35.0	10.4

The results showed that PCE can partition from surfactant aqueous phase to extracting oil phase followed a rule of thumb “like dissolve like” but the partitioning ability depends greatly on the surfactant aqueous solution: solvent volumetric ratio used. The distribution coefficient of PCE ($[PCE]_{\text{solvent}}$ divided by $[PCE]_{\text{aqueous}}$) was found to increase with increasing surfactant aqueous solution: solvent volumetric ratio. In another word, the distribution coefficient of PCE increases with decreasing the volume of extracting oil used. In this case, a decrease in volume of extracting oil used caused a reduction in the %PCE removal, meanwhile increasing the concentration of PCE in the oil phase resulting in a greater PCE distribution coefficient. As the reduction of volume of extracting oil reached a certain point, the distribution

coefficient cannot be improved since the volume of extracting oil is inadequate to induce the PCE partitioning into the extracting oil phase.

From this study, the ratio of 10:1 was selected to be an optimal surfactant solution:solvent volumetric ratio using 3 main criteria including (1) the %PCE removal from surfactant solution to extracting solvent, (2) the used volume of extracting solvent and (3) the distribution coefficient of PCE. At the 10:1 ratio, although the %PCE removal from surfactant solution into the extracting solvent (palm oil) phase was not the highest (54.1%) but the highest PCE distribution coefficient of 14.1 was obtained at this ratio.

The greatest PCE removal of 83.0% was found at volumetric ratio of 1:1, which is about 30% higher than one obtained at 10:1 ratio. However, the 1:1 ratio used the volume of extracting oil 3 times greater that of 10:1 and yielded an obvious lower distribution coefficient of PCE. Consequently, the volumetric ratio of surfactant solution:solvent at 10:1 was further used to study the effect of EACNs of extracting solvent in LLE on PCE removal from surfactant aqueous solution.

4.2.3 Effect of EACNs of extracting solvents

Two groups of selected extracting solvents used in this study were vegetable oil (non-alkanes) and alkanes at varied EACN values as shown in Table 2. The results showed that alkane showed a greater extraction performance than the vegetable oil although having the similar EACN values as can be seen by a comparison between dodecane and palm oil (EACN = 12-13); and octadecane and sunflower oil (EACN = 18). This can be explained by even at the same EACN of extracting oils, the different functional groups of solvent are influential to the affinity of solvent to PCE. The vegetable oils are classified as fatty acids containing the carboxyl groups (-COOH) as the main functional group. Thus, the affinity of PCE to partition into these polar oils is less than that of straight chain hydrocarbon or n-alkane. Reference [12] stated that solutes have differing solubilities in different solvents due to variations in strength of the interaction of solute molecules with those solvents.

The significant improvement of the PCE distribution coefficient by EACN was found in the system of alkanes but a slight improvement was also evidenced in the system of vegetable oils. However, the result was not in agreement with squalane (straight chain hydrocarbon with EACN = 30) which was the extracting solvent having the highest EACN used in this study. It was possible that squalane has too high degree of hydrophobicity or in another word, too nonpolar for PCE to dissolve. Since PCE has low EACN value (EACN = 2.9) and $\log K_{ow}$ of 3.40, PCE was relatively non-polar compound if compared with water but quite polar if compared with squalane resulting in a less favorable in PCE partitioning into squalane solution. This finding also confirms the “like dissolve like” phenomenon.

Table 2. The Effect of the EACNs of Extracting Solvents in Liquid-Liquid Extraction on %PCE Removal and Distribution Coefficient of PCE with Constant Surfactant Solution:Solvent Volumetric Ratio of 10:1

Extracting solvents	EACN	[PCE] initial (ppm)	[PCE] aqueous (ppm)	[PCE] solvent (ppm)	%PCE removal	[PCE] solvent
						[PCE] aqueous
Dodecane	12	11,263	4,397	50,978	84.3	49.4
Palm oil	13	9,959	4,571	64,674	54.1	14.1
Sunflower oil	18	10,039	3,254	58,778	67.6	18.1
Octadecane	18	8,949	941	81,079	89.5	86.2
Squalane	30	10,263	3,805	50,978	57.2	11.6

Therefore, EACN solely cannot be used if solvents applied are not in the same homologous series. Thus, other physical-chemical properties of compounds, i.e., functional groups, water solubility, log K_{ow} , etc. should be considered. In addition, besides the extraction performance, other factors determining the suitability of compounds to be used as the extracting solvent should also be incorporated such as cost, availability, and toxicity of the solvents.

It should be noted that in this LLE, most of surfactant and electrolyte still remained in the aqueous solution, only PCE partitioned out of surfactant micellar aqueous solution and moved into the extracting solvent phase due to the affinity between PCE and extracting oil or "like dissolve like" rule as discussed in the section 4.2.2. So most of surfactant, electrolyte and some PCE were remained in the aqueous solution because HLB surfactant system with this extracting solvent was not low enough to force the transition from Winsor type I into type microemulsion II or reversed micelle where surfactant can move into the extracting solvent phase as already explained in section 2.1.

4.3 Reverse Micellar Extraction (RME)

4.3.1 Reverse micellar extraction with palm oil

Palm oil was used as the extracting solvent because of its non toxicity, cheap price, and it is environmentally friendly. Moreover working with palm oil as the extracting solvent in the area of microemulsion was challenging since very limited studies were done on palm oil due to its complexity in structure. So this step aimed to investigate the surfactant systems that can form the Winsor type II microemulsion with palm oil.

From the rule thumb of Winsor type II microemulsion, the surfactants with low HLB, more lipid loving, tend to make a water in oil microemulsion (Winsor type II microemulsion) while those with high HLB are more hydrophilic and tend to make an oil in water microemulsion (Winsor type I microemulsion).

In this study, we imitated the supersolubilization solution for PCE removal, the surfactant solution contained 4%AMA and 3%NaCl. However, this system

cannot form Winsor type II microemulsion with palm oil although the NaCl and $CaCl_2$ were added in help decreasing HLB of the system. The precipitation of salt in surfactant aqueous solution was observed if an excessive electrolyte concentration was used. In addition, the phase separation between surfactant and water can be observed in some cases because of the density of components in the system was altered resulted from the salt added. Thus, the HLB of AMA used in this system was too high to form Winsor type II microemulsion with palm oil since AMA is normally soluble with water with high degree of hydrophilicity. In many cases, a mixed surfactant system will produce better emulsification than a single surfactant [13].

From phase behavior study, the closest formula of surfactant system to the original formulation that can form the Winsor type II microemulsion with palm oils was 2%AMA/1%Span-20/20%NaCl with the surfactant solution:solvent volumetric ratio of 1:1. This formation of Winsor type II microemulsion was confirmed using TOC analyzer to assure the removal of surfactant from aqueous to oil phase.

4.3.2 Effect of surfactant solution:solvent volumetric ratios

In previous study (section 4.3.1), the system of 2%AMA/1%Span-20/20%NaCl at the surfactant solution:solvent volumetric ratio of 1:1 could form Winsor type II microemulsion with palm oil. This section aimed to study the effect of surfactant solution:solvent volumetric ratio on the percentages of PCE and surfactant removal from aqueous into palm oil phase and to investigate the best ratio suited for this reverse micellar extraction.

From the results, there was insignificant effect of surfactant solution:solvent volumetric ratio on both the %surfactant and %PCE removal from aqueous phase into the palm oil as shown in Figure 4.

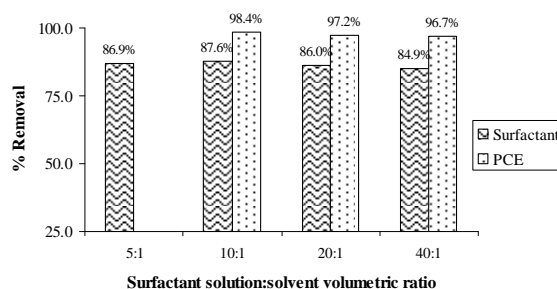


Figure 4. Effect of Surfactant Solution:Solvent Volumetric Ratio on %Surfactant and %PCE Removal in Reverse Micellar Extraction Using Palm Oil

Due to an almost independence of surfactant solution:solvent volumetric ratio, RME was proven to be very attractive extraction technique since high extraction efficiency can be achieved and remained although the least volume of extracting solvent was used, unlike the LLE where the volume of surfactant solution and extracting solvent was one of the main parameter governing the degree of extraction. This result agreed

with [3], since they stated that one advantage of RME over typical solvent extraction was that almost complete surfactant and contaminant removal achieved with formation of an ideal Winsor type II microemulsion with the least amount of solvent used. Therefore, the surfactant solution:solvent volumetric ratio of 40:1 was selected to further study in ultrafiltration process to separate surfactant reversed micelles from PCE and palm oil.

4.4 Effect of applied pressure on ultrafiltration (UF) for PCE removal

The main purpose of this study was to concentrate surfactant reversed micelles into the retentate stream while passing PCE and palm oil into the permeate stream. The applied pressure of N₂ gas was varied at 30, 40, 50, and 60 psi in the UF cell. The %PCE removal was evaluated as shown in Table 3. Moreover, the material balance of PCE where less than ±12% deviation of PCE mass was measured to assure the reliability of the experiment.

Table 3. The Percentage of PCE Removal at Various Applied Pressures

Pressure (psi)	Termination time (minute)	[PCE] initial (ppm)	[PCE] permeate (ppm)	[PCE] retentate (ppm)	%PCE removal
30	32.5	73,655	62,799	71,002	76.0
40	26.1	63,230	64,322	57,126	77.6
50	19.2	72,573	72,787	66,276	77.2
60	25.2	70,157	63,051	68,472	75.7

There was no significant change in %PCE removal upon altering applied pressure as illustrated in Table 3. Since more than 75% of PCE could separate from retentate into permeate phase for all applied pressures, while only 25% of PCE still remained in the retentate stream. Although the highest pressure utilized in this study (60 psi) which closed to the maximum allowable pressure for this Amicon stirred cell (70 psi), the performance of this separation process was the same as the lowest applied pressure (30 psi). This result was similar to ones obtained by [14]. They found that the degree of separation of organic polymer from wastewater water by UF process was insensitive to pressure if applied at the relatively low pressures (14.5, 29.0, and 43.5 psi, respectively).

5. CONCLUSIONS

The prediction of the LLE efficiency based on EACN may be acceptable for the same applied homologous series solvents. However caution should be taken if the differences of physical and chemical properties between solute and solvent are obvious. Since EACN solely cannot be used if the applied solvents are not in the same homologous series. Thus, other physical-chemical properties of compounds, i.e., functional groups, water solubility, log K_{ow}, etc. should be considered.

RME has high extraction efficiency even using small volume of the extracting solvent, thus receiving less volume of PCE waste production. Furthermore, the

environmentally friendly solvent (palm oil) applied here for the first time worked very successfully in the field of environmental management with consuming less time (only 1 day for equilibrium time). However, the complexity of surfactant preparation of Winsor type II microemulsion for RME technique and the additional separation process of PCE from surfactant were the main disadvantages.

In this study, UF process was proven to be an effective way to retain surfactant reversed micelles in the retentate stream. In this case, the UF unit was needed to fulfill the surfactant recovery purpose since without the decontamination of PCE from solvent, the surfactant solution was not ready to be reused. So, high operational costs may result from the complexity of that surfactant preparation and the downstream separation process. Unlike the LLE, PCE partition from surfactant aqueous solution to solvent phase, the surfactant was simultaneously decontaminated and ready to be reused. Thus, the extraction efficiency of the LLE can be increased by selecting a suitable type of solvent to have a high affinity to PCE but caution on toxicity of solvents needed to be considered. In summary, a trade-off decision process should be done by considering all involved advantages and disadvantages for extraction technique selection.

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