

Reactive Extraction Of Lactic Acid From An Alkaline Aqueous Solution With An Ammonium-Based Ionic Liquids

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ABSTRACT: Black liquor from the pulping process contains lactic acid, which is used in the chemical industry and especially as monomer for poly lactic acid production, in considerable amounts. However, the high pH of black liquor leads to the formation of the lactic acid salts which cannot be recovered with Lewis basic solvents. In the present work, the results of an investigation of the reactive extraction of lactic acid from an alkaline aqueous solution using an ammonium-based ionic liquid (Aliquat 336) and the carbonated thereof are reported. Data gained from the experiments show the carbonated Aliquat 336 enhances the extraction efficiency. The use of polar-aprotic solvents like MIBK, was significantly more effective in terms of lactic acid extraction than alcohol like 1-octanol or 1-heptanol. A successful attempt to improve the extraction efficiency was made by using solvent mixtures containing Aliquat 336 in the carbonate form and the modifier MIBK diluted in n-hexane. Back-extraction was performed with NaHCO₃, water and HCl, where NaHCO₃ lead to the best stripping results..

KEYWORDS: Lactate, lactic acid, ionic liquid, Aliquat 336, reactive extraction, anion extraction

Date of Submission: 06-09-2018

Date of acceptance: 22-09-2018

I. INTRODUCTION

The substitution of chemicals derived from petroleum with chemicals derived from biomass is receiving an increasing amount of attention. Lactic acid is one of these latter types of chemicals, as it can be converted into a large variety of materials that can be used as building blocks for other compounds. The rising demand for lactic acid and polylactic acid (PLA) has driven a market growth of around 20% per year. Biodegradable plastic which is synthesized from polylactic acid (PLA) is a significant part (59%) of the market segment [1–3].

According to this challenging paradigm change, the pulp and paper industry may serve as backbone of the biorefinery concept. Pulping mainly uses the Kraft process, which generates yearly 170 mio tons of black liquor globally. The black liquor contains 15-17% solids, which is made up of dissolved organic material from the wood and leftover pulping chemicals [4]. The main intermediate byproduct from pulping is lignin, hemicellulose and carboxylic acids are also present in remarkable amounts in the black liquor [5]. The composition of the black liquor varies with the feed and the cooking conditions. High kappa numbers are related to high lignin content in the pulp and vice versa. Regarding the acid content in black liquor, low kappa number corresponds to extended degradation of the hemicellulose and hence results in higher concentration of the carboxylic and hydroxy carboxylic acids [6].

In the chemical recovery cycle, the black liquor is incinerated in the recovery boiler after evaporation of the major amount of water in order to recover NaOH and Na₂S. Besides the chemical recovery, steam and electricity are produced. Lignin is the main fuel constituent. It has a heating value of 23.4 MJ/kg. The heating value of lactic acid is with 14.72 MJ/kg much lower. Due to the low heating value and the low concentration of lactic acid in the black liquor compared to lignin, alternatives to incineration of lactic acid offer a fascinating research challenge. Besides reactive extraction, membrane processes as well as crystallization are in discussion.

The separation of lactic acid from fermentation broth has been intensively studied. Different separation techniques such as electrodialysis [7], nanofiltration [8] and ion exchange [9] have been studied. Among these, reactive extraction is a promising approach in terms of selectivity and process costs. The aliphatic amine, tri-n-octylamine (TOA), is a well-established, highly efficient compound used to extract lactic acid. Amine extractants are usually highly efficient for the extraction of acids, because they form an acid-base complex with the non-dissociated acid [10,11]. Unlike studies on the fermentation broth, black liquor from Kraft pulping is a highly alkaline solution with a pH of ~13. For this reason, the acids are present as dissolved anions.

In the present study, therefore, the isolation of lactic acid from highly alkaline process effluents such as the black liquor from Kraft pulping is discussed. Liquid/liquid extraction may be used to selectively isolate lactic acid also from highly alkaline process streams. Most of the studies for lactic acid extraction are performed with acidic effluents, the reaction mechanism there is mostly a cation exchange or a chelation mechanism, when dealing with highly alkaline effluents an anion exchange can be performed, but in general this is a challenging task, because reactive extractants for lactate need be tailor made.

Therefore, ionic liquids are in discussion. Ionic liquids are salts that remain in a liquid state at room temperature and consist of an organic cation and an organic or inorganic anion with specific features (i.e., less or non-volatile, non-flammable, hydrophobic, or hydrophilic) [12]. Ionic liquids have received attention as extractants in hydrometallurgical processing for selective removal of various metals (i.e., copper, zinc). A variety of ionic liquids has recently been studied as extractants for their extraction performance in acid extraction. In particular, ammonium and phosphonium cation-based ionic liquids have showed potential performance for carboxylic acid extraction. Blahusiak et al. [13] investigated the extraction of butyric acid with an ammonium-based ionic liquid. The extraction of lactic acid with phosphonium-based ionic liquids (Cyphos 101, Cyphos 104) has been studied by Martak et al. [14]. The results of the study indicated that lactic acid could be effectively extracted at low acid concentrations.

Tri-octylmethylammonium chloride (Aliquat 336) has been reported to extract dissociated and the non-dissociated carboxylic acids. Acid anion extraction with Aliquat 336 is favored, but at elevated pH beyond pKa the extraction efficiency decreases [11,15]. Kyuchoukov et al. [16] studied the extraction of lactic acid by Aliquat 336 and its carbonated form. The results indicated that carbonated Aliquat had a higher potential to extract lactic acid than Aliquat 336 in the chloridated form, as usually delivered by the manufacturer. Aliquat 336 is expensive and its physical properties suffer from high viscosity and density. Therefore, admixture of diluents and modifiers to the reactive solvent is recommended. No study has yet been conducted on the influence of diluents on the reactive extraction process using the carbonated Aliquat 336. Furthermore, no suggestions for the back-extraction of acids from the laden amine based solvents have yet been made.

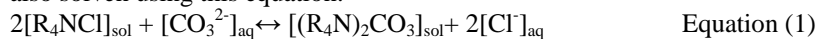
In the present work, an experimental study of lactic acid extraction from a highly alkaline aqueous solution with Aliquat 336 based solvents and the carbonated form thereof is presented. For comparison the commercial ionic liquids Cyphos 101 (tri-hexyltetradecylphosphonium chloride) and Cyphos 104 (tri-hexyltetradecylphosphoniumbis (2,4,4-trimethylpentyl) phosphinate) were investigated. The extraction equilibria were measured depending on the solvent used. In the study, three solvent categories were used: non-polar, polar-protic and polar-aprotic solvents which had alcohol, ketone, alkane and aromatic functional groups. The extraction efficiency was examined as a measure of the ability of each group to enhance the lactic acid extraction. In addition, the solvent composition was varied in both binary and ternary solvent systems, and the comparison thereof is discussed. The back-extraction process of the laden solvent was investigated by comparing the stripping agents NaHCO₃, de-ionized water and HCl. In the present study uses modeled solutions containing lactic acid in a concentration of 0.2 mol/L at a pH of 13 were used.

II. MATERIALS AND METHODS

2.1 Materials

The aqueous phase consisted of lactic acid (CAS 79-33-4), purchased from Carl Roth. The lactic acid concentration in the aqueous solution was 0.2 mol/L, similar to that in the black liquor [17]. The pH of the aqueous solution was adjusted to 13 by adding sodium hydroxide (CAS 1310-73-2), purchased from JT Baker. The extractants used in this study were tri-octylmethylammonium chloride (Aliquat 336), tri-hexyltetradecylphosphonium chloride (Cyphos101) and tri-hexyltetradecylphosphoniumbis 2,4,4-trimethylpentyl phosphinate (Cyphos 104) were all purchased from Sigma Aldrich. To decrease the viscosity, the reactive extractant was diluted with the following solvents. The solvents used were isobutyl methylketone (MIBK, CAS 108-10-1, Merck), toluene (CAS 108-88-3, Sigma Aldrich), 1-heptanol (CAS 111-70-6, Fluka AG), 1-octanol (CAS111-87-5, Sigma Aldrich) and methoxybenzene (anisole, CAS 100-66-3,Fluka AG). The solvent phase was prepared by mixing the components at room temperature.

Carbonated Aliquat 336 was prepared by mixing 100 mL of 1 mol/L sodium carbonate (CAS 497-19-8, Fluka AG) with 50 mL of Aliquat 336. The reaction follows an ion exchange reaction of chloride and carbonate. The conversion was determined by measuring the chloride concentration in the aqueous phase by ion chromatography (IC, DionexIonPac AS 11 column). The substitution follows equation 1, the mass balance is also solven using this equation.



The degree of conversion(X) was calculated to assess the concentration of chloride ions removed following equation 2 where $c_{\text{Cl},o}$ and $c_{\text{Cl},t}$ represent the initial chloride concentration and the chloride concentration at equilibrium, respectively and was determined to be 43%.

$$X = c_{\text{Cl},o} - c_{\text{Cl},t} / c_{\text{Cl},o} \quad \text{Equation (2)}$$

As a stripping solution, either deionized water, sodium hydrogen carbonate (CAS 144-55-8, Carl Roth), or hydrochloric acid (CAS 7647-01-0, Carl Roth) were used.

All chemicals were used as received except for the carbonated form of Aliquat 336.

2.2 Experimental procedure

The extraction of lactic acid was carried out by equilibrating equal mass of the aqueous solution containing lactic acid in a concentration of 0. mol/L at pH 13 and the solvent phase. The solvent phase contained an ionic liquid with a concentration in the range of 0-100 wt% diluted in different solvents. The experiments were carried out in 5 mL glass vials, and were mixed using a magnetic stirrer plate (Janke& Kunkel, ES5) at 1200 rpm for 2 hours at room temperature. The two phases were left for separation overnight. The lactic acid concentration in the aqueous phase was analyzed using high-performance liquid chromatography (HPLC). The next step targeted the back-extraction and, therefore, the laden solvent phase was transferred to a new vial. An equal mass of stripping phase was added. The procedure used for the back-extraction process was the same as was used for the extraction step.

2.3 Analysis

The lactic acid concentration in the aqueous phase was determined using HPLC (Dionex) at room temperature. The HPLC column used was a REZEX-ROA column equipped with an UV/VIS detector, detecting at a wavelength of 210 nm. As mobile phase, 0.005 mol/L H₂SO₄ in ultrapure water with a flow rate of 0.5 mL/min was used. The concentration of extracted acid in the solvent phase was calculated by determining the mass balance. The distribution coefficient (K_d) and the extraction efficiency (E) were calculated by applying the following equations:

$$K_d = c_{LA,sol} / c_{LA,aq} \quad \text{Equation (3)}$$

$$E = K_d / (1 + K_d) \times 100 \quad \text{Equation (4)}$$

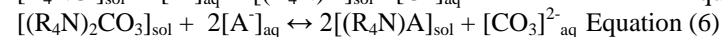
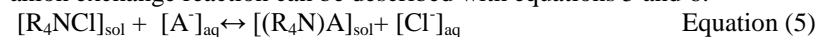
Where $c_{LA,sol}$ and $c_{LA,aq}$ are the equilibrium concentrations of lactic acid in the solvent phase and the aqueous phase, respectively.

III. RESULTS AND DISCUSSION

3.1 Extraction of lactic acid with Aliquat 336 and the carbonated form of Aliquat 336

The extraction of lactic acid with Aliquat 336 follows an ion exchange mechanism. Aliquat 336 has chloride ions as counterions, whereas the carbonated form thereof is prepared by exchanging the anions chloride and carbonate. Kyuchoukov et al. [16] reported that use of the carbonated form of Aliquat 336 increases the extraction efficiency of lactic acid. In this study, the extraction of lactic acid from an aqueous solution using commercially available Aliquat 336 and the carbonated form of Aliquat 336 was investigated. The solvent phase consisted of either Aliquat 336 or its carbonate form diluted in MIBK at a fixed ratio of 1:3 by weight. Since the dissociation of the acid is essential for the extraction by a quaternary amine, and specifically Aliquat 336[15], the pH in the aqueous solution was adjusted by addition of sodium hydroxide to pH 13.

The mechanism of lactate extraction follows an ion exchange mechanism, whereby either the chloride anion or the carbonate anion is exchanged by the lactate anion. The lactate is hence transferred into the solvent phase, the anion exchange reaction can be described with equations 5 and 6:



where R_4N represents Aliquat 336 and A^- represents the anion of lactic acid.

In Table 1, a comparison of the distribution coefficient (K_d) and the extraction efficiency (E) of Aliquat 336 and the carbonated form of Aliquat 336 is summarized. If the extraction efficiency using Aliquat 336 and the carbonated form thereof are compared, the data show that the use of the latter leads to an extraction efficiency of 62.2%, whereas the use of the commercially-available, chlorinated form leads to an extraction efficiency of 45.8%. This result indicates that the lactate anion replaces the carbonate anion more easily than the chloride anion. Furthermore, the results are in line with those presented in the study of Kyuchoukov et al.[16]. The replacement of chloride by monoacid anion leads to the formation of hydrochloric acid in the aqueous phase, leading to a drop of pH-value which in turn limits extraction of the target acid. Ion exchange using the carbonated form of Aliquat 336, releases CO_3^{2-} into the aqueous phase, which is a weak acid compared to the target acid, and hence decreases the pH, starting from a pH value of 8, HCO_3^- will liberate as CO_2 from the solution.

Table 1: Summary of the distribution coefficient and extraction efficiency for lactic acid. The solvent contains 33 wt% Aliquat 336 or the carbonated form Aliquat 336 diluted in MIBK. $c_{LA,ini}= 0.2 \text{ mol/L}$; pH 13; T= 25°C; ambient pressure.

Solvent	$c_{LA,ini}$ (mol/L)	$c_{LA,aq}$ (mol/L)	$c_{LA,sol}$ (mol/L)	K_d	E (%)
Commercial Aliquat 336	0.22	0.12	0.10	0.9	45.8
Carbonated Aliquat 336	0.21	0.08	0.13	1.6	62.2

The commercially available ionic liquids tri-hexyltetradecylphosponium chloride (Cyphos 101) and tri-hexyltetradecylphosponium bis-2,4,4-tri-methylpentylphosphinate (Cyphos 104) are known to extract carboxylic acids [14],[18] and were compared to the carbonated Aliquat 336. Fig. 1 shows the comparison of the extraction efficiency of lactic acid when the different extractants were used. The use of carbonated Aliquat 336 led to the highest extraction efficiency. The use of Aliquat 336 and Cyphos 101, both led to similar extraction efficiencies of 46% and 48%, respectively. Since the anion of both extractants is the chloride anion, similar behavior was expected. The difference observed in the extraction efficiency between Aliquat 336 and Cyphos 101 may be due to the steric hindrance related to the different alkyl chains present in the reactants.

The extraction efficiency of Cyphos 104 was determined with 19%. The difference between Cyphos 101 and Cyphos 104 is the counterion; while Cyphos 101 has a chloride anion, Cyphos 104 has the (bis-2,4,4-trimethylpentyl) phosphinate anion as counterion. The phosphinate anion is able to form hydrogen bonds with the non-dissociated lactic acid [14,19] while lactate anion assumingly results in poor extraction efficiency.

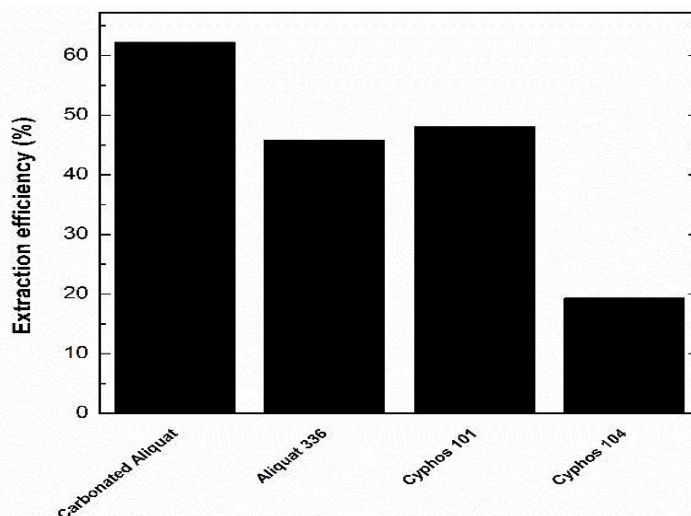


Figure1: Effect of the reactive extractant (33 wt% diluted in MIBK) on the extraction of lactic acid. $c_{LA,ini}= 0.2 \text{ mol/L}$; pH 13; T= 25°C; ambient pressure.

3.2 Effect of the solvent on the extraction of lactic acid

Typically, physical extraction of mono-carboxylic acids by low polar solvents can be improved by adding a polar modifier to the solvent. Because of limited water solubility long chain alcohols are recommended. The influence of different polar solvent classes on the extraction efficiency of lactate using an initial lactic acid concentration of 0.2 mol/L and a pH of 13 was investigated. To be able to select the appropriate solvent and attain the highest extraction efficiency, three solvent categories were considered: non-polar, polar-protic and polar-aprotic solvents. In each category, two representatives were investigated. The solvents chosen were toluene and n-hexane (non-polar), MIBK and anisole (polar-aprotic) and 1-heptanol and 1-octanol (polar-protic). The phase ratio of the extractant to the solvent was kept constant at 1:3 by weight. Table 2 summarizes the properties of the solvents used [20].

Table 2: physical properties of solvents [20].

Solvent class	Solvent	Properties				
		Molar mass (g/mol)	Density (g/mL)	Dielectric constant	Dipole moment (D)	Viscosity (mPa·s)
Polar-aprotic	MIBK	100.16	0.80	13.11	2.69	0.58
	Anisole	108.14	0.99	4.33	1.38	NA
Non-polar - aprotic	Toluene	92.14	0.87	2.38	0.31	0.64
	n-Hexane	86.18	0.65	1.88	0.08	0.3
Polar-protic	1-heptanol	116.2	0.82	12.1	1.71	5.97
	1-octanol	130.23	0.83	10.30	1.68	7.59

Due to the high dipole moment, aprotic solvents are expected to improve the solubility and the extraction efficiency of the lactate anion. The highest extraction efficiency was observed for the group of polar aprotic solvents (see Fig 2). The difference in the extraction efficiencies of MIBK and anisole can be attributed to their polarity; they dissolved the lactate anions as nucleophiles. While the Van der Waals forces and electrostatic affinity apply in a polar aprotic solvent, only Van der Waals forces are present in non-polar solvents, and both increase the solubility of the organic lactate salt. Polar-protic solvents are able to increase the solubility of substances that are able to dissociate, this effect is small compared to the effects of the Van der Waals and electrostatic forces. Clayden et al. [21] reported that polar-protic solvent solvates both, the cations and anions of a salt.

Examining the two non-polar solvents, the extraction ability of the lactate depends on the dipole moment. Toluene has a dipole moment of 0.31 and hexane, 0.08, the higher dipole moment leads to higher extraction efficiency. Similar observations have been obtained by Wasewar et al. [22]. They found that the higher dipole moment of ethyl acetate compared to kerosene and hexane enriches the solvation of the itaconic acid-amine complex.

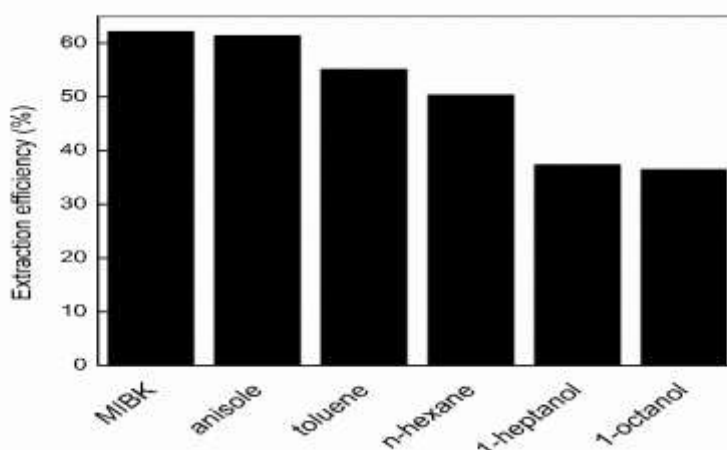


Figure 2: Effects of polar-aprotic (MIBK, anisole), polar-protic (1-heptanol, 1-octanol) and non-polar diluents (toluene, n-hexane) on the extraction efficiency of lactic acid. Reactive extractant: carbonated Aliquat 336, $c_{\text{Aliquat}} = 33 \text{ wt\%}$, $c_{\text{LA,ini}} = 0.2 \text{ mol/L}$; pH = 13; T = 25°C; ambient pressure.

The results contradict the outcome of lactic acid extraction by a tertiary amine from acidic solutions, whereby a polar-protic solvent such as octanol improves the phase transfer more than non-polar solvents. The polarity of the solvent, influenced by the alcohol side groups, promotes the solubility of the acid-amine complex and leads to higher extraction efficiency [23-25]. The extraction mechanism of lactic acid from acidic solutions involves the proton transfer of non-dissociated acid, which forms ion pairs in acidic environment or, more precisely, the acid-base reaction. The polar solvent affects the amine basicity and, thus, the stability of the acid-amine complex and its solvation [26].

3.3 Effect of extractant concentration on the lactic acid extraction

In the present study, the influence of the extractant concentration on the extraction efficiency of the lactate with an initial concentration of 0.2 mol/L and a pH of 13 was investigated. Based on the previous results,

the carbonated Aliquat 336 was diluted in MIBK. The concentration of carbonated Aliquat 336 was varied between 0 wt% and 100 wt%. Experiments were carried out following the procedure described in section 2.2.

Figure 3 depicts the influence of the extractant concentration on the extraction efficiency of lactic acid. A significant improvement in the extraction efficiency can be obtained when the carbonated Aliquat 336 was added to MIBK. The extraction efficiency increased from 28.5% when pure MIBK was used to 77.5% when pure carbonated Aliquat 336 was used. It clearly shows that the extraction efficiency increased with increasing extractant concentration of Aliquat 336, however, as known from extraction from acidic solutions, the extraction efficiency passes a maximum. Increasing the extractant concentration leads to an increase in the amount of lactic acid distributed. The solvent composition affects the hydrodynamic conditions. The high viscosity of the pure reactive extractant also has been shown to influence the settling behavior in liquid-liquid extraction [27]. In the latter experiments, the results showed that, the disperse droplet size decreased as the organic phase viscosity was increased, leading to longer settling time.

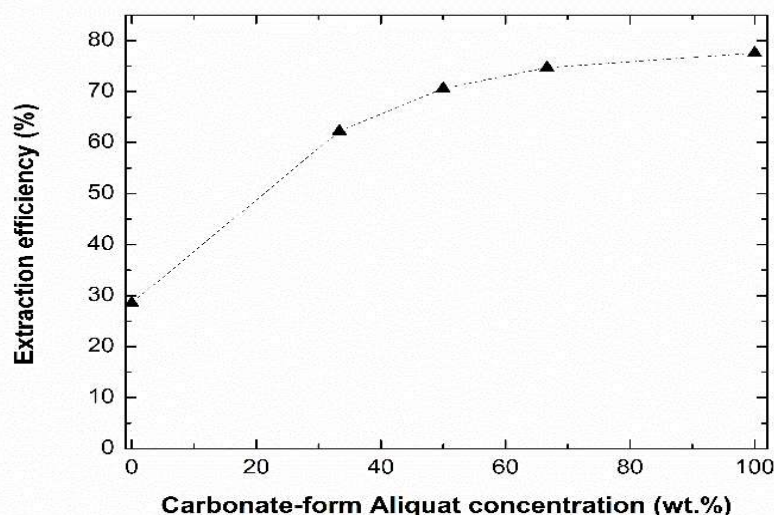


Figure 3: Effect of carbonated Aliquat 336 concentration (0-100 wt%) diluted in MIBK on the extraction efficiency. $c_{LA,ini} = 0.2 \text{ mol/L}$; $\text{pH} = 13$; $T = 25^\circ\text{C}$; ambient pressure.

3.4 Optimized extractant phase

All the extractants have a high viscosity and a high density. The viscosity of carbonated Aliquat 336 is 1450 mPa·s at 25°C. In order to reduce the viscosity and increase the diffusive mass transfer in extraction processes, diluents are usually used. The diluent affects the viscosity, the density and surface tension and, hence, it may influence the reactions at the interphase. The role of MIBK as a modifier in extraction has been described elsewhere [28]. This study provides data for the optimized composition of the extractant phase, whereby all three components are present. Therefore, the binary and the ternary compositions of the extractant phase were compared. In order to decrease the viscosity, carbonated Aliquat 336 mixed with MIBK was diluted with n-hexane. The composition of the ternary extractant phase consisted of an equal mass of carbonated Aliquat 336 and MIBK diluted with n-hexane. The concentrations of the extractant were varied in the range of 25-37.5 wt%. The feed solution consisted of lactic acid with an initial concentration of 0.2 mol/L and pH of 13. The phase ratio of the feed phase and the solvent phase was kept constant at one (by weight) in all experiments.

Figure 4 compares the extraction performance for lactic acid using a binary mixture of carbonated Aliquat 336 mixed with MIBK with a ternary mixture of carbonated Aliquat 336 and MIBK diluted in n-hexane. The results show that increasing the extractant concentration leads to an increase in the extraction efficiency for both the binary and ternary mixture. However, a significant difference in the extraction efficiency was observed above a concentration of 30 wt% carbonated Aliquat 336. The extraction efficiency was 62% for the binary and the ternary mixtures that had an extractant concentration of 33 wt%. With an extractant concentration of 37.5 wt%, the same extraction efficiency of 70% in the ternary system as compared to an extractant concentration of 50 wt% in the binary system was observed. In terms of costs, the results are promising, as the reactive extractants are more expensive than the modifier and diluents.

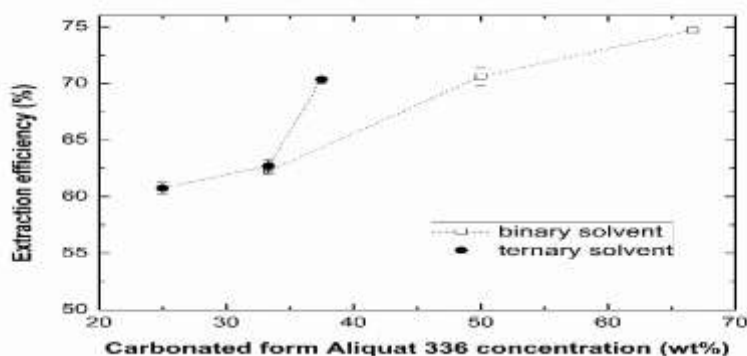


Figure 4: Influence of the solvent composition on the extraction efficiency. Binary and ternary system; the binary solvent refer to carbonated Aliquat 336 diluted in MIBK. Ternary solvent refer to an equal amount of carbonated Aliquat 336 and MIBK by weight diluted in n-hexane; $c_{LA,ini} = 0.2 \text{ mol/L}$; $\text{pH} = 13$; $T = 25^\circ\text{C}$; ambient pressure.

3.5 Back-extraction

To liberate the lactic acid from the laden solvent, back-extraction is needed. Three different stripping agents, de-ionized water, sodium hydrogen carbonate with concentrations of 1 mol/L and hydrochloric acid were tested in order to vary the pH value and the anions available for the ion exchange. The stripping solution was added together with the laden carbonated Aliquat 336 obtained from the extraction experiments and the same procedure as described in section 2.2 was applied. The phase ratio of both phases was kept constant at one by mass for all experiments. The back-extraction efficiency was calculated based on the lactate concentration released into the stripping solution during back-extraction. Figure 5 summarizes the back-extraction efficiency for de-ionized water, NaHCO_3 and HCl . The results clearly show that the use of NaHCO_3 leads to the highest amount of back-extraction compared to H_2O and HCl . These results are in accordance with the expectation according to equation 6. Back-extraction, respectively regeneration of the reactive extractant again requires an ionic exchange. According to the results described in section 3.1 the ionic exchange obtained using Aliquat 336 in the carbonated form was more effective than using Aliquat 336 in the chlorinated form. The results from the back-extraction confirm the data obtained during the lactate extraction. Although the efficiency of the back-extraction with NaHCO_3 was rather low (40%), the results are promising. To improve the back-extraction efficiency, Shi et al. [29] suggested increasing the number of back-extraction stages.

The basic properties of NaHCO_3 leads to an enhancement of the dissociation of lactic acid and promotes the solubility of the lactate in the stripping solution. Water, on the other hand, offers OH^- ions for the ion exchange reaction, but these are not able to act as counterions. Furthermore, the back-extraction efficiency using HCl was found to be 60% lower than that with NaHCO_3 . This confirms the results described in section 3.1, namely, that a carbonate anion replaces a lactate anion more easily than a chloride anion. Although the back-extraction process using NaHCO_3 gave not very sufficient results in terms of back-extraction efficiency at 40%, its use is beneficial in that it regenerates the solvent without conditioning.

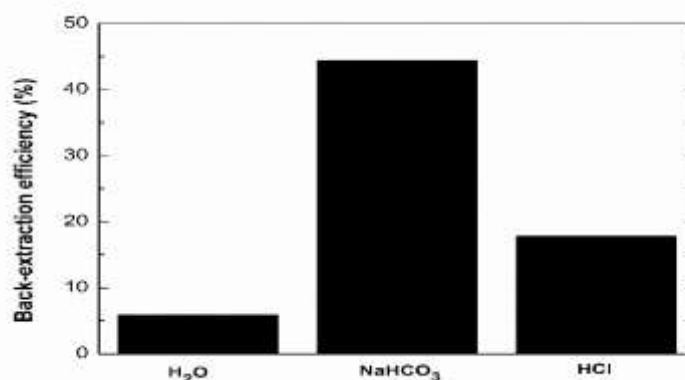


Figure 5: Back-extraction efficiency of lactic acid using H_2O , NaHCO_3 and HCl . The solvent contains 33 wt% carbonated Aliquat 336 in MIBK. $c_{LA,ini} = 0.13 \text{ mol/L}$; $\text{pH} = 13$; $T = 25^\circ\text{C}$; ambient pressure.

IV. CONCLUSION

In the present study, a focus was placed on the reactive extraction of lactic acid from highly alkaline aqueous feed. Therefore, an ammonium-based ionic liquid, Aliquat 336, and its carbonated form as well as the commercially-available ionic liquids, Cyphos 101 and Cyphos 104, were investigated. The carbonated form of Aliquat 336 turned out to be the most promising extractant providing an extraction efficiency of 62%. Following the design rules for solvent design for reactive liquid/liquid extraction, a modifier and a diluent were added to the extractant phase. During the investigation of the modifier, a focus was placed on three categories: polar-protic, polar-aprotic and non-polar-aprotic solvents. As expected, the polar-aprotic solvents MIBK and anisol improved transfer of lactic acid. The design of the extractant phase was modified to appropriate mixture viscosity and density by adding the diluent n-hexane. The results show that the use of a ternary composition of the extractant phase led to the highest extraction efficiency. For 50 wt% of extractant in binary and 37.5 wt% in the ternary system 70% extraction efficiency was obtained. Extraction always needs a second unit operation, the constituent isolation step.

Further, a focus was placed on the back-extraction, and three stripping solvents water, NaHCO₃ and HCl. With a back-extraction efficiency of 44% NaHCO₃ performed best in single step back-extraction. The extraction of lactic acid with Aliquat 336 follows an ion exchange reaction. Aliquat 336 has chloride ions as counterions, whereas the carbonated form of Aliquat 336 is prepared by exchanging the chloride anions by carbonate anions. Kyuchoukov et al. [16] reported that use of the carbonated form of Aliquat 336. The present study support this findings.

ACKNOWLEDGEMENT

Research reported in this publication was supported by the ASEAN-European Academic University Network (ASEA-UNET).

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Marlene Kienberger "Reactive Extraction Of Lactic Acid From An Alkaline Aqueous Solution With An Ammonium-Based Ionic Liquids "International Journal of Research in Engineering and Science (IJRES), vol. 06, no. 08, 2018, pp. 30-38