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3**Kinetic evaluation of simultaneous waste cooking oil hydrolysis and reactive liquid-liquid Cu extraction from synthetic Cu-containing wastewater: Effect of various co-contaminants**

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Hydrolysis Wastewater reuse Liquid-liquid extraction Heavy metal Waste cooking oil Fatty acids Subcritical water abstract Combination of

3**oil hydrolysis** reaction **and reactive liquid-liquid extraction** of Cu2+ **from wastewater**

offers economic and environmental advantage than running two processes separately. To give better insight on the application of the proposed process to treat real wastewater, the effects of other pollutants (acid/base, chelating agents, organic solvent, anions) present in the synthetic Cu-containing wastewater were stud- ied. The reaction was carried out in a batch reactor using a water/acylglycerides molar ratio of 30:1 at 225 °C up to 8 h to understand the effect of the studied parameters during the reaction time course. It was found that pH influenced acid/base balance, which governs catalysis and Cu-soap formation in sub- critical water. Chelating agents formed strong complexation with Cu2+ that changed Cu removal mecha- nism from cation exchange reaction to that of conventional solvent extraction. The presence of organic solvents affected the dielectric constant of water that shifted the equilibrium of cation exchange reaction towards lipophilic Cu soap formation. Different anion type produced different type of acid by means of the cation exchange mechanism that influenced acid catalysis and Cu-soap formation. Other heavy metal cations expressed the same cation exchange mechanism and catalysis ability as that of Cu2+. Ó 2017 Published by Elsevier B.V.

1. Introduction Among all waters in the world, fresh water only occupies 2.8% with only around 0.63% available as potable surface and ground waters [1]. Based on that fact, fresh water is a very limited resource for the increasing global population. Wastewater reuse and recy- cling are one way to alleviate the water shortage issue. Reuse and recycle of wastewater require a good understanding on the composition and characteristics of wastewater. Pollutants in wastewater are classified as organic and inorganic. Although both classes can impose certain level of hazard to the environment, a class of inorganic pollutants named heavy metals possess lethal toxicity and strong persistency to human, animals, and even microorganisms, which has to be removed before the ⇑

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recycle and reuse of wastewater [2]. Various techniques are avail- able for treating heavy metals in wastewater such as membrane fil- tration, solvent extraction, chemical precipitation, ion exchange, adsorption, and electrochemical deposition [3]. Nevertheless, all these methods are limited by some factors such as expensive cap- ital cost, material fabrication, and material regeneration, which overall hinders its application for treating large volume of indus- trial wastewater [3,4]. Copper (Cu) is a heavy metal that commonly exists in wastew- ater from various industries such as printed circuit board, metal plating, battery manufacturing, electronic, mining, and metallurgi- cal [3,5–7]. Moreover, the amount of Cu-containing wastewater generated is undoubtedly increasing with increasing production of electronics in this modern era. Other pollutants may exist in Cu-containing wastewater. For example, Fe, Zn and Ni may exist together with Cu in the drainage of acid-treatment of ores [8,9]. In the plating and printed circuit board manufacturing, chelating agent and organic solvents also are present [10]. The existence of those pollutants may inhibit the recovery and removal of Cu from the wastewater. Due to those contaminants, Cu removal was required to pass a series of

treatments, such as pH-controlled solvent extraction with different carrier agent [11], a combined microbial desalination cells and electro-dialysis system [12], and combination of advanced oxidation-chemical precipitation [7,13] to remove each pollutant separately allowing Cu to be removed effectively. Recently, a study reported the utilization of artificial Cu- containing wastewater for hydrolysis of waste cooking oil under subcritical water state, which offers a promising way to directly reuse wastewater [14]. Direct reuse of Cu-wastewater for waste cooking oil hydrolysis process also brings revenue by producing fatty acids (FAs) instead of simply remove Cu^{2+} and dispose the waste cooking oil. This strategy is critical to overcome the eco- nomic uncertainty in the realization of wastewater reuse [15]. Moreover, the process was demonstrated to possess remarkably higher Cu removal (5 times) from wastewater without adding car- rier agent compared to the use of refined vegetable oil alone in the solvent extraction process, which reflected high aspect of eco- nomic and environmental sustainability [16]. In that study, free Cu^{2+} was described to undergo an exchange with two in situ gener- ated FA molecules, producing a molecule of a mineral acid catalyst and Cu-soap, where the latter is soluble in the oil phase and pro- vides a slight degree of water-in-oil emulsification. However, the use of artificial wastewater in the previous studies often did not cover the effects of other organic and/or inorganic compounds that co-exist with Cu ion in the wastewater [11,14]. Overlooking the presence of these compounds may surprisingly alter the Cu exchange mechanism and catalysis of oil hydrolysis reaction, hence leading to the rising of uncontrolled aspects when real wastewater is dealt with. In this study, the effect of possible co-contaminants in the Cu-containing wastewater, such as acid-base, chelating agent, organic solvents, and anion type on FA concentration and Cu removal percentage was thoroughly evaluated by kinetic mod- eling developed from the previously studied basic reaction mecha- nism. Different divalent heavy metals sulfate salts were also assessed to illustrate the utilization of a wider range of heavy metal-containing wastewaters. 2. Experimental 2.1. Chemicals Waste cooking oil was donated by a local restaurant in Taipei, Taiwan. The oil was kept in a sealed amber glass bottle to avoid air oxidation. The oil was used without further pretreatment. KOH (85%, Acros Organics, USA) and HCl (37% purity, Acros Organ- ics, USA) were used for pH adjustment and acid-base titration anal- ysis. Anhydrous $CuSO_4$ (97%, Shimakyu, Japan), $CuNO_3$ $3H_2O$ (99%, Acros Organics, USA), $CuCl_2$ $2H_2O$ (Sigma Aldrich, USA), $Cu(CH_3\text{-}COO)_2$ H_2O (J.T. Baker, USA), $FeSO_4$ $7H_2O$ (99%, Shimakyu, Japan), $NiSO_4$ $6H_2O$ (99%, Shimakyu, Japan), $ZnSO_4$ $7H_2O$ (99% Sigma Aldrich, USA), H_2SO_4 (95–97%, Scharlau Chemical, Spain), ethanol (95%, Echo Chemical, Taiwan), and oxalic acid dihydrate (99%, Kokusan Chemical Co. Ltd., Japan) were reagent grade. Analytical reagent grade anhydrous citric acid (99.5%, Acros Organics, USA) and anhydrous ethylenediaminetetraacetic acid (EDTA, 98.5%, Sigma Aldrich, USA) were used in the experiment on chelating agent effect. Acid-base titration indicator used was phenolph- thalein (Sigma Aldrich, USA) dissolved in ethanol. All solutions were made by dissolving the corresponding salts with deionized water into a concentration of 25,000 mg metal (II)/kg. HNO_3 (90%, May and Baker, UK) was diluted by deionized water to form 10% v/v solution for copper ion extraction from the oil hydrolysate. A mixed standard solution (solution IV, 1000 mg/L, Merck Chemi- cals, USA) was used to obtain Cu, Fe, Ni, and Zn calibration curves in the inductively coupled plasma (ICP) measurement. 2.2. Waste cooking oil hydrolysis A mixture of waste cooking oil and $CuSO_4$ solution (500 mg $CuSO_4$/kg solution = 3.13 mmol Cu^{2+}/L, pH 5.0) with a triacylglyc- erides to water molar ratio of 1:30 was introduced into a stainless steel reactor. The reactor apparatus is comprised of a 200 mL glass chamber, a 316-grade stainless steel autoclave body, a K-type ther- mocouple, a PID temperature controller, a pressure gauge, a mag- netic stirrer, and an external electric heater (Fig. S1). After the reactor was closed tightly, trapped air was purged out by nitrogen. The reactor was then heated to 225 °C and held at that temperature to 8 h to reach equilibrium according to the previous study [14]. After the reaction, the reactor was cooled to 50 °C. Aqueous phase was separated prior to washing to remove trapped glycerol in the product for monitoring the change of aqueous pH. Washing step was carried out twice using warm deionized water. Separation was performed gravitationally in a separation funnel overnight. The recovered oil product was weighed and analyzed for its acid value (AV) and Cu content. The effect of the initial pH of the copper solution was studied at pH 4.0 and 6.0 by addition of 0.1 N of H_2SO_4 or KOH. Adjustment of pH by KOH was stopped at pH 6.0 to avoid Cu precipitation. EDTA and citric acid were introduced to the $CuSO_4$ solution (1:1 molar ratio) at pH 3.0–9.0 to study the effect of chelating agent. Mean- while, 0.25–1.0% aqueous ethanol or acetone solution was used to dissolve and dilute $CuSO_4$ to obtain 500 mg $CuSO_4$/kg solution used in the experiments on the effect of organic solvents. Ethanol and acetone were picked as the model solvents in cleaning metals with the concentration simulated based on total organic carbon content of printed circuit board wastewater in other studies [7,10]. Anion type was evaluated by changing $CuSO_4$ solution into $CuNO_3$, $CuCl_2$ or $Cu(CH_3COO)_2$ solution with an equimolar concen- tration of Cu^{2+} (3.13 mmol Cu^{2+}/L). Fe, Zn, and Ni solutions (3.13 mmol metal (II) ions/L) were also used to substitute $CuSO_4$ solution to study the effect of divalent metal types. Experiments involving different pH, chelating agents, organic solvents, anion, and other divalent metal cations were carried out at the same tem- perature and acylglycerides/water molar ratio. All experiments were performed in triplicate. 2.3. Oil analysis AV was analyzed by KOH titration according to ASTM D1980-87 method and calculated by using Eq. (1). AV ðmg KOH=g oilÞ ¼ VKOH ðmLÞ CKOH ðNÞ 56:1 wt: of sample ðgÞ ð1Þ Saponification value (SV) was determined titrimetrically (ASTM D5558-95) to know the maximum obtainable fatty acid from the waste cooking oil. SV was calculated by using Eq. (2). SV ðmg KOH=g oilÞ ¼ VHCl of blank ? sample ðmLÞ NHCl ðNÞ 56:1 wt: of sample ðgÞ ð2Þ Ester value (EV) and average molecular weight of waste cooking oil (MWav) as pure triacylglycerides can be calculated from Eqs. (3) and (4), respectively. MWav was used to estimate the amount of oil required to fulfill 30:1 water/triacylglycerides molar ratio. EV ðmg KOH=g oilÞ ¼ SV ðmg KOH=g oilÞ ? AV ðmg KOH=g oilÞ ð3Þ ¼ 1000 56:1 3 MWav EVoil feed ðmg KOH=g oilÞ ð4Þ To provide more detailed concentration profile of acylglycerides for kinetic evaluation purpose, gas chromatography (GC) analysis was carried out as described in the previous study [14]. The results were then used in Eqs. (5)–(8) to obtain average molecular

weight of triacylglycerides (TG), diacylglycerides (DG), monoacylglyc- erides (MG), and free fatty acids (FA). SV was defined as the total theoretical amount of saponifiable FA and the identity of acylglyc- erides as the ester of glycerol (G) and FA. SV ðmg KOH=g oilÞ ¼ mg oil MWKOH ¼ 1000 g oil 3 wt:% TG wt:% DG wt:% MG wt:% FA MWTG þ 2 MWDG MWMG MWFA þ þ ð5Þ MWTG ¼ MWG þ ð3 MWFAÞ ? ð3 MWDG ¼ MWG þ ð2 MWFAÞ ? ð2 MWMG ¼ MWG þ MWFA ? MWH2O MWH2OÞ MWH2OÞ ð6Þ ð7Þ ð8Þ Analysis results revealed that waste cooking oil comprised 84.1 ± 1.27 wt.% TG, 9.25 ± 0.67 wt.% DG, 0.29 ± 0.03 wt.% MG, and 6.29 ± 0.59 wt.% FA with SV and AV of 200.73 ± 2.70 and 13.58 ± 1.18 mg KOH/g oil, respectively. Molecular weights obtained were 839.66, 590.47, 341.28, 267.21, and 595.96 g/mol for TG, DG, MG, FA, and Cu(FA)2, respectively. The amount of metals transferred into the oil phase was deter- mined by acid extraction as reported in a previous study with slight modification [17]. Oil sample (5 g) was mixed with 20 mL 10% (v/v) HNO3 at 60 °C for 4 h under magnetic stirring (500 rpm). After the extraction was finished, the mixture was left to separate. The oil layer was cooled in a refrigerator and then fil- trated using a 5-mm filter paper (Advantec Grade No. 2). Aqueous layer was analyzed by an ICP-AES (Horiba Jobin Yvon 2000–2). Metal removal percentage was expressed as number of metal ions transferred into the oil phase to total metal ions put in the reaction system as showed in Eq. (9). 8.8 (Aspen Technology Inc., 2015). Due to high resemblance between the measured densities of oil and oleic-oil mixture at 25 °C (0.919 g/mL vs. 0.908 g/mL), the density of the studied waste cooking oil was predicted to be 0.807 g/mL at 225 °C (Fig. S2). Properties of pure water at the working temperature and pressure (225 °C and 2.94 MPa), particularly specific volume of water and steam was estimated from online calculator provided by Moscow Power Engineering Institute [20]. Liquid mass fraction (xl) of the total amount of water introduced into the reactor (V^) then can be found through calculations using Eqs. (10) and (12) [21]. V^ ðm3=kgÞ ¼ 2 10?4 ? mqooiill m aqueous ð10Þ V^ ðm3=kgÞ ¼ xv:V^v þ 1 ? xvÞ:V^l ð11Þ xl ¼ ð1 ? xv Þ ð12Þ where moil and maqueous are mass of oil and metal solution (assumed as pure water), respectively. Superscript v and l refer to the vapor and liquid phase of water in the reactor with a volume of 2 10?4 m3. For temperature and pressure used in the experi- ments, calculation showed that 95.24 wt.% of the aqueous phase remained as liquid. Initially H3O+ came from water self-ionization [22], unless the system was acidified by H2SO4. The added amount of H3O+ in moles can be traced by the difference of pOH to normalize the effect of metal ions as Lewis acid in the original Cu solution. In terms of base addition, added OH? appears to subtract the amount of H3O+ from water self-ionization. Initial concentration of H3O+ was calculated by Eq. (13) qffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffi added H3Oþ ½H3OþŠ ¼ V þ added H3Oþ þ 4 KW added OH? V 2 ? V ð13Þ where [H3O+] and KW are concentration of the liberated proton and the self-ionization constant of water, respectively. Removal ð%Þ ¼ Metaloil product ðmg=kgÞ oil product ðkgÞ ? Metaloil feed ðmg=kgÞ oil feed ðkgÞ m m Cmetal solution ðmg metal cations=kgÞ mmetal solution ðkgÞ 100% ð9Þ 2.4. Kinetic modeling In this study, several assumptions were made: Total volume of liquid water and oil was constant at the given temperature and pressure, which was the volume of the reac- tion system (V). Concentration of species was expressed as mol/L. Thermodynamic properties of metal solution can be approached by those of pure water. Density of oil and water were constant regardless of the transfer of glycerol and change of oil composition [18]. Reaction between diffusing metal ions and FA as the ion exchanger is instantaneous [19]. The reaction of metal ions and FA can be described as M2þ þ 2FA þ 2H2O $ MðFAÞ2þ 2H3Oþ, where M is the metal. Density of oil (mixture of TG, DG, MG and FA) was approached by the density of mixture of triolein, diolein, monoolein and oleic acid, which was simulated by NRTL-Rackett model in Aspen Plus Reaction rate equations can be expressed as follows: dTG dt ¼ ?kTG:TG:H2O þ k?TG:DG:HFA dDG dt ¼ kTG:TG:H2O ? k?TG:DG:FA ? kDG:DG:H2O þ k?DG:MG:FA dMG dt ¼ kDG:DG:H2O ? k?DG:MG:FA ? kMG:MG:H2O þ k?MG:G:FA dG dt ¼ kMG:MG:H2O ? k?MG:G:FA dCudðFtAÞ2 1 dHd3tOþ ¼ ? dCdut2þ ¼ 2 : ¼ kCuðCu2þ Cu2inþterfaceÞ ? Cu2inþterface ¼ KCCuuðFðAFÞ2A:ðþF2A:ðþH2:3ðOHþÞ2þO2Þ2 ð14Þ ð15Þ ð16Þ ð17Þ ð18Þ ð19Þ ? dH2O dFA dt ¼ dt ¼ kTG:TG:H2O ? k?TG:DG:HFA þ kDG:DG:H2O ? k?DG:MG:FA þ kMG:MG:H2O ? k?MG:G:FA ? 2:kCuðCu2þ ? Cu2inþterfaceÞ ð20Þ These equations were numerically solved using Euler method programmed in Excel (Microsoft Office 2007) with a step size of 0.5 min. All hydrolysis rate constants (L/moles.min), Cu2+ mass transfer coefficient (1/min), and apparent equilibrium constant of Cu-soap formation (L/moles) were estimated by the assistance of Solver Add-In to minimize the objective function (OF). Xn Yex ? Ycal ! 2 OF ¼ ¼ Y ex 100 ð21Þ i¼1 where Y is the data of AV and metal removal percentage found by experiments (ex) and fitting (cal), which are Eqs. (22) and (23) using concentrations found in the simulation. AVcal ðmg KOH=gÞ ¼ 1000 FA MWKOH FA MWFA þ MG MWMG þ DG MWDG þ TG MWTG þ CuðFAÞ2 MWCuðFAÞ2 ð22Þ Removalcal ð%Þ ¼ 100 1 ? Cu2þðat tÞ ! Cu2þðt ¼ 0Þ ð23Þ

3. Results and discussion 3.1. Effect of pH Acid **and**

base addition enhanced the reaction rate of FA produc- tion as showed in Fig. 1. Regardless of considerable difference in the formed Cu-soap amount, FA concentration of acidic system was found as high as that in the alkalinized Cu solution system, which suggests a unique catalysis by H2SO4 produced in the ion exchange reaction rather than the Cu-soap. Production of H2SO4 was confirmed in both acidified and alkalinized system from the final pH of the aqueous phase (2.4–2.6). Since the stoichiometric ratio of water to the acylglycerides in the system are fixed in this study, FA concentration obtained at equilibrium in the acidified and alkalinized system remained similar (approximately 170 mg KOH/g oil), which is also in agreement with the concept of cataly- sis, where the catalyst is unable to alter the reaction stoichiometry. Addition of base to CuSO4 solution was not simply spiking up Cu removal percentage by eliminating the net amount of protons in the reaction system. This enhancement was observed at the early stage of reaction since the amount of

KOH added was not enough to overcome the initial acidic species to form either K-soap or K2SO4 from the reaction between FA or CuSO4. Considering the effect of subcritical water, certain extent of OH? from self-ionization of water may be stabilized by the K+ present in the system [23]. A previous study showed a possible formation of soap with FA in the oil phase, which is called acid soap [24]. Similar mechanism to the cation exchange reaction between Cu2+ and FA [25] may explain the subcritical water effect to cause KOH forma- tion from K+, which further transformed into K-soap in the pres- ence of FA. K-soap tends to dissolve in the aqueous phase to form oil-in-water emulsion, which may help hydrolysis of non- polar compound such as TG. Kinetic rate constants in Table 1 show higher TG transformation rate in the acidified and alkalinized Cu solution system. The increase in the reverse reaction rate constant of MG hydrolysis indicates that acid and alkaline treatments are not selective towards FA formation. Remarkably high reverse reaction rate con- stant than that of the forward reaction can be explained by a lower water amount used in this study (oil:water = 2:1 v/v) than in the studies with a negligible reverse reaction that used oil:wa- ter = 1:1–1:4 v/v [26,27]. Although the molar amount of water was excessive, only certain excessive amount of water could suffi- ciently dilute the formed glycerol and gave an impression of no reverse reaction in the system. From the same theory on the pres- ence of K-soap, a higher reverse MG hydrolysis rate in the base- added system was due to the better transfer of glycerol from the aqueous phase in addition to the non-selectivity of H2SO4 catalysis. Table 1 Kinetic rate constants of waste cooking oil hydrolysis using Cu solution with different initial pH. Kinetic rate Initial pH constant 4.0 5.0 (original Cu 6.0 solution) kTG 9.72 kDG 9.98 kMG 1.82 k-TG 0 k-DG 0 k-MG 9.90 KCu(FA)2 1.66 kCu 3.80 10?4 7.94 10?3 9.98 10?3 9.55 0 0 10?3 7.94 10?10 2.16 10?3 3.74 10?4 1.00 10?3 9.98 10?4 1.91 0 0 10?3 1.05 10?9 2.93 10?1 5.69 10?3 10?3 10?3 10?2 10?8 10?3 A 180 AV (mg KOH/g oil) 160 140 120 100 80 60 pH 4.0 40 pH 5.0 pH 6.0 20 fitting 0 0 2 4 6 8 time (h) B 90 80 70 pH 4.0 pH 5.0 pH 6.0 fitting Removal (%) 60 50 40 30 20 10 0 0 2 4 6 8 time (h) Fig. 1.

> 8**Effect of initial pH** of Cu solution **on** the **(A)** AV **and (B)**

Cu removal percentage. For Cu2+ mass transfer, acid/base addition inhibited mass trans- fer through the formation of dense ionic barrier with a larger decrease of magnitude for more organized barrier of H+ in acidified system. Although cation exchange equilibrium constant (KCu(FA)2) is supposed to be independent of pH, it was found that the KCu (FA)2 in alkalinized system was higher than in acidified system. This indicates that the acquired constant is the apparent equilibrium constant. An investigation of the change in equilibrium constant resulted in surprisingly comparable results with initial pH differ- ence, which is about 10?1.11 and 101.13 for acid- and base-added system, respectively. This finding revealed a hidden mechanism involving HSO?4, a type of inorganic ligand that could inhibit ion exchange reaction. Accordingly, the possible reason for a higher apparent equilibrium constant in the alkalinized system is the sup- pressed SO24? protonation by KOH formed in subcritical water. Since K-soap formation also involved consumption of a proton from FA, the theory of ion exchange facilitation by K-soap is inter- changeable with the prevention of SO24? protonation. 3.2. Effect of chelating agent Chelating agent stabilizes metal ions to be precipitated in water by hindering metal-hydroxide precipitate formation. In the elec- troless Cu-plating, chelation of Cu is mandatory since the pH of the bath has to be adjusted to 13.5 for the oxidation of formalde- hyde to occur [28]. However, the presence of chelating agent leads to difficult heavy metal removal process since the stability of metal in wastewater becomes very high [29,30]. By observation, aqueous solution of Cu-EDTA and Cu-citric acid possessed an acidic pH of 3.0, which later changed into very slightly more acidic after reaction (pH 2.9–3.0). Interestingly, same pH value of 4.8 was observed in the aqueous phase of non-catalytic system (oil and water only) as well as Cu-EDTA and Cu-citric acid with an initial pH of 5.0–9.0. These indicate unchanging H+ concen- tration in the chelated-Cu system that further reflects different mechanism for Cu transportation. Rather than ion exchange mech- anism, van der Waals interaction of carbon backbone of chelating agents with oil phase may facilitate Cu-complex extraction to the oil phase in the form of dimer or polymer [31,32]. Since Cu-EDTA could form polymeric structure, removal percentage of Cu-EDTA complex was higher than dimeric Cu-citrate complex (Fig. 2B). This finding changed the model of Cu removal into Eq. (24). ? dCucodmtplex;aq ¼ kCu?complexðCucomplex;aq ? Cucomplex;lipÞ ð24Þ Cu-EDTA and Cu-citric acid complexes were found to be stable in subcritical water [33–35]. Hence, concentration of Cu-complex in the aqueous phase (Cucomplex,aq) was assumed to be the same as Cu2+ introduced into the system. Although some Cu2+ seen in Fig. S3 for Cu-citric acid system was at pH 3.0, the assumption still may be valid at high reaction temperature due to the increase of chelating stability of Cu-citrate complex, which has endothermic nature [36]. Fitting was employed to find mass transfer rate (kCu- complex) and maximum concentration of Cu complex in the oil phase (Cucomplex,lip). Surprisingly, FA concentration in the system with chelating agents was slightly higher than chelating agent-free system. With significantly lower Cu removal percentage, the results indicate that Cu complex also induced catalytic ability in the reaction system. Neevel [37] mentioned that metal complexes are able to catalyze the reaction as long as some coordination sites are free from the ligand blocking. Fully occupied structures of Cu complex with studied ligands are given in Fig. S4. Based on the speciation dia- gram in Fig. S3 [38,39], free coordination sites are available only at pH lower than 5.0 for Cu-EDTA system and in the whole studied pH range of this work (2.0–9.0) for Cu-citric acid complex. FAs deprotonation can provide slight acidification to pH 4.8 and possi- bly changed the Cu-complex species [40]. Moreover, exothermic nature of Cu[EDTA]2? complex as the fully occupied coordination complex of Cu with EDTA indicates its less proportion under high hydrolysis temperature [36]. On the other hand, dihydrate bridged Cu-complex structure could improve water transportation into the oil phase besides improving complex stability in the water [31,32]. Both Cu-EDTA and Cu-citrate have the same capability to form hydrogen

bonding, given that the ability comes from the metal ion nature and not the ligand. Double function of chelated-Cu as catalyst and water vehi- cle resulted in a comparable FA concentration in contrast to the combination of acid catalyst (H2SO4) and Cu(FA)2 as water-in-oil emulsifier in the free-chelating agent system [14] even with lim- ited amount of chelated-Cu in the oil phase. In contrast to the result of free-chelating agent system, chelated-Cu performed catalysis of TG hydrolysis better than H2SO4 produced from ion exchange of CuSO4 and FA (Table 2). While catalysis of forward and reverse MG hydrolysis were compa- rable to those in the free-chelating agent system, chelated-Cu sys- tem showed a slower rate of DG hydrolysis due to steric hindrance contribution of the confined structures of chelated Cu. Mass trans- fer of chelated-Cu was faster than free Cu2+ due to its lipophilicity. A 180 B 160 50 140 AV (mg KOH/g oil) 40 120 100 30 80 60 Removal (%) 20 EDTA 40 Chelator-free EDTA CA 10 Chelator-free 20 fitting CA fitting 0 0 0 2 4 6 0 2 4 6 8 time (h) time (h) Fig. 2. Effect of chelating agents on (A) FA yield and (B) Cu removal percentage in the Cu-catalyzed hydrolysis of waste cooking oil at 225 °C. Table 2 Kinetic rate constants obtained from experimental data fitting of waste cooking oil hydrolysis using chelated Cu solution at an initial pH of 5.0. Constants Chelating agent EDTA Citric acid kTG kDG kMG k-TG k-DG k-MG kCu-complex Cucomplex, lip 9.94 10?4 4.26 10?3 9.38 10?4 0 0 7.99 10?3 3.83 10?2 7.38 10?4 1.07 2.80 9.38 0 0 8.20 1.20 7.78 10?3 10?3 10?4 10?3 10?1 10?4 Compared to Cu-citrate complex, Cu-EDTA showed slower transfer due to its larger molecular size. This also explains a smaller kTG and a slightly lower saturation concentration of Cu-EDTA complex in EDTA system due to higher steric hindrance and larger spatial occupation of molecules in the oil phase. The possibility of K+ involvement in catalysis as occurred in the base addition was evaluated in the system with a lower pH (Table S1 and Fig. S5). Similar values of kTG and k-MG independent of pH indicate that K-soap did not form as significant as in the free- chelating agent system. Though the system also contained K+, the presence of negative-charged Cu-complex should be considered as the counter ion that inhibited K+ from being free in the aqueous phase. By varying pH, mass transfer of Cu-complex into the oil phase increased gradually due to less charge density of complex formed and more K+ available to neutralize complex charge at higher pH. Saturation concentration values were approximately constant with pH change since the space is limited by the fixed oil mass (volume) only. 3.3. Effect of organic solvent Organic solvent presents in wastewater may lower down the dielectric constant of water [41], which could affect the formation of Cu-soap [25]. The increase of obtained FA concentration and Cu removal was small since only very small amount of solvents was added. At a glance, Fig. 3 showed comparable effect of the presence of ethanol and acetone. At equilibrium, the effect of solvent con- centration on FA production was negligible (Fig. S6). Meanwhile, negligible increase on Cu removal percentage was observed, except for ethanol system at concentrations of 0.75 and 1 wt.%. Thus, in order to accentuate the effect of organic solvent presence, 1 wt.% solvent concentration was chosen for kinetic modeling. Due to better association of ethanol than acetone in water by means of the hydroxide group of ethanol, Cu2+ mass transfer (kCu) in aqueous ethanol is faster than that in water-acetone (Table 3). Lower polarity also slightly increased the apparent equi- librium constant of Cu-soap formation. Facilitated mixing between water and oil by solvents was obvious from higher kTG than that of pure CuSO4 solution. More non-polar acetone might give certain interference on the interaction between water and acylglycerides as observed in the slightly lower kTG, kMG, and k-MG than ethanol and pristine Cu solution. 3.4. Effect of anion types In the previous study, mineral acid was discussed as the main catalyst that increased FA yield significantly [14]. Thus, the anion species may also affect acid catalysis in subcritical water [25]. In this study, equimolar Cu systems with sulfate anion (SO24?) was compared with nitrate (NO?3), chloride (Cl?), and acetate (CH3- COO?), which are commonly found anions coupling with Cu in the wastewater. Overall, comparable FA yield and Cu removal were achieved for all anion systems (Fig. 4). A pH decrease to 2.3–2.5 was observed in all systems, except for the equilibrium pH of the aqueous phase in Cu-acetate system, which reached 3.63 due to lower deprotonation of acetic acid. As showed in Table 4, Cu-chloride surpassed the other anion systems in TG hydrolysis. Cu-acetate system was the least among all. In the meantime, Cu mass transfer increased in the following order: Cu-chloride, Cu-nitrate, Cu-sulfate, and Cu-acetate. Since Table 3 Reaction rate constants of waste cooking hydrolysis using 500 mg CuSO4 in 1 kg of 1 wt.% aqueous ethanol and acetone. Kinetic rate constant Aqueous organic solvent Ethanol (1 wt.%) Acetone (1 wt.%) kTG 9.36 kDG 9.98 kMG 9.55 k-TG 0 k-DG 0 k-MG 7.94 KCu(FA)2 2.80 kCu 3.83 10?4 9.34 10?3 9.98 10?4 9.16 0 0 10?3 7.25 10?9 2.81 10?1 3.69 10?4 10?3 10?4 10?3 10?9 10?1 A B 60 180 160 50 AV (mg KOH/g oil) 140 120 40 100 80 Removal (%) 30 60 1% Ethanol 20 40 Free organic solvent 1% Ethanol 1% Acetone 10 Free organic solvent 20 fitting 1% Acetone fitting 0 0 0 2 4 6 8 0 2 4 6 8 time (h) time (h) Fig. 3. Kinetic curves of (A) AV and (B) Cu removal percentage in the experiments using Cu solution contaminated with organic solvent. 180 160 50 AV (mg KOH/g oil) 140 120 100 80 60 40 20 Acetate Chloride Nitrate Sulfate fitting Removal (%) 40 30 20 10 Acetate Chloride Nitrate Sulfate fitting 0

11**0 2 4 time (h) 6 8 0 0 2 4 time (h) 6 8**

Fig. 4. FA yield and Cu removal percentage in the hydrolysis of waste cooking oil using various anion types. Table 4 Reaction rate constants of waste cooking hydrolysis using Cu solution with different anion type. Kinetic rate constant Anion Acetate Chloride Nitrate Sulfate kTG 7.34 kDG 9.58 kMG 8.65 k-TG 0 k-DG 0 k-MG 7.62 KCu(FA)2 2.16 kCu 3.75 10?4 8.24 10?3 9.99 10?4 9.84 0 0 10?3 8.01 10?9 2.16 10?1 3.64 10?4 8.04 10?3 9.98 10?4 9.55 0 0 10?3 7.91 10?9 2.16 10?1 3.68 10?4 7.94 10?3 9.98 10?4 9.55 0 0 10?3 7.94 10?9 2.16 10?1 3.74 10?4 10?3 10?4 10?3 10?9 10?1 an equimolar amount of Cu should produce the same amount of proton, this trend may be the results of the acids dissociation at higher temperature. Negative logarithm of the acid dissociation constant (pKa) and the enthalpy of acid dissociation are listed in

Table S2 [42–44]. HCl as the strongest acid demonstrated the highest hydrolysis rate constants among all acids formed in this study. As the weakest acid, acetic acid gave the lowest forward hydrolysis rate and the least inhibition of Cu^{2+} mass transfer by less ionic barrier made of hydrogen proton. In contrast with HNO_3, sulfuric acid has a smaller amount of proton since dissocia- tion occurs in two steps with considerable weak dissociation at the second step (dissociation of $HSO^?4$). With exothermic nature, $HSO^?4$ is less deprotonated at high temperature by van't Hoff correlation, which also proved its inhibiting effect on ion exchange reaction in acidified system. The same apparent equilibrium constants indi- cate the same degree of cation exchange. With unselective nature of the acid catalyst, faster reversible reaction rate of MG hydrolysis was also observed at higher acidity. 3.5. Application of other divalent heavy metal ions Substitution of $CuSO_4$ by other heavy metal sulfate salts at the same initial metal concentration showed the same equilibrium FA concentration (Fig. 5). Same low equilibrium aqueous phase AV (mg KOH/g oil) 180 160 140 120 100 80 60 40 20 Zn Fe Ni Cu fitting Removal (%) 70 60 50 40 30 20 10 Zn Fe Ni Cu fitting 0

10**0 2 4 time (h) 6** 0 **0 2 4 time (h) 6 8 Fig.** 5. Kinetic curves **of**

AV and removal percentage in the waste cooking hydrolysis using various metal sulfate solution (3.13 mmol metal (II) ions/L, initial pH 5.0). Table 5 Kinetic rate constants obtained from the hydrolysis experiments using various metal sulfate solution (3.13 mmol metal (II) ions/L, initial pH 5.0). Kinetic rate constants Metal (II) cation Zn Fe Ni Cu kTG 7.53 kDG 9.68 kMG 8.65 k-TG 0 k-DG 0 k-MG 6.75 KCu(FA)2 2.16 kCu 1.55 10?4 7.89 10?3 9.98 10?4 9.46 0 0 10?3 7.82 10?9 5.81 10?1 2.04 10?4 9.31 10?3 9.99 10?4 9.24 0 0 10?3 7.62 10?9 3.59 10?1 4.35 10?4 7.94 10?3 9.98 10?4 9.55 0 0 10?3 7.94 10?9 2.16 10?1 3.74 10?4 10?3 10?4 10?3 10?9 10?1 pH, all metals followed the same mechanism and sufficient catalyst was present in all systems. From the hydrolysis rate constants (Table 5), Ni gave the highest acylglycerides conversion. However, considering the same order of magnitude, all metals actually per- formed quite similar, indicating lower contribution of metal ions and soaps as catalyst species than the produced H_2SO_4. Apparent equilibrium constants revealed the order similar to the Irving-William series: Cu Zn < Ni < Fe, which also serves as a trend of Lewis acidity [45]. Higher Lewis acidity results in less cation exchange due to more solid hydration cage between metal ions and water ligand. However, since the acidity of metal ions is not as strong as the proton from the acid deprotonation, the mag- nitude of the constants remained similar. In the meantime, Cu^{2+} mass transfer coefficient increased with increasing electronegativ- ity: Ni (1.91) > Cu (1.9) > Fe (1.83) > Zn (1.65). This reflects metal ions attraction towards a free electron pair of species in the oil phase, either oxygen atom of the ester group in acylglycerides or oxygen atom of the deprotonated FA. Coincidentally, increasing TG hydrolysis rates were also showed by the same electronegativ- ity trend. As the miscibility of acylglycerides in water increases as in the case of DG and MG, this trend is diminished by overshadow- ing catalysis of H_3O^+. 4. Conclusion The effects of other contaminants in the Cu-containing wastew- ater on the hydrolysis of waste cooking oil were studied. Overall, the presence of contaminants did not give significant effect on the FA production. However, system acidification and chelating agents remarkably lowered down Cu removal percentage. More ionic species by acid and base addition disturbed Cu^{2+} transfer from aqueous to oil phase by providing ionic barrier at the inter- face. Subcritical water effect particularly self-dissociation of water molecules had a certain contribution to the enhancement of hydrolysis in the acidified and alkalinized system. Molecular inter- action between the organic solvent and water influenced the equi- librium and mass transfer of Cu^{2+} towards the oil phase. Different anions formed different acids by means of cation exchange mech- anism that determines the extent of cation exchange and hydroly- sis reaction. The studied process also can be applied to other heavy metal ions with removal efficiency depending on the Lewis acidity of the corresponding metal ion.

4**Appendix A. Supplementary material Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.seppur.**

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