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Synthesis of Ferric Citrate Complexes as Potential Draw Solutes for Forward Osmosis

Li H and Su J*

School of Life Sciences & Chemical Technology, Ngee Ann Polytechnic, 535 Clementi Road, Singapore

Abstract

In this study, ferric citrate complexes (Fe-Cit) have been successfully synthesized from citric acid monohydrate ($C_6H_8O_7 \cdot H_2O$) and Iron (III) nitrate nonahydrate ($Fe(NO_3)_3 \cdot 9H_2O$) in the basic solution at pH~8. Different ratios of the two precursors from 2:1, 5:1, 9:1 to 19:1 are used for the synthesis and the resultant samples are named as Fe-Cit-2, Fe-Cit-5, Fe-Cit-9, and Fe-Cit-19, respectively. The formation mechanism of Fe-Cit complexes are studied via spectrophotometric method, and the transition from polynuclear to mononuclear Fe-Cit structure is observed with excess citrate for Fe-Cit-9 and Fe-Cit-19 solutions. The intrinsic properties of the purified Fe-Cit compounds are systematically examined in terms of osmotic pressure, viscosity, thermal stability, and toxicity. The mononuclear Fe-Cit-9 structure outperforms the others, such as higher osmotic pressure, lower viscosity at similar concentrations, nontoxicity, and better thermal stability. These characteristics enable Fe-Cit-9 to be a very promising draw solute in forward osmosis (FO) applications.

Keywords: Ferric citrate complex; Reaction mechanism; Intrinsic properties; Draw solute; Forward osmosis

Introduction

Forward Osmosis (FO) is a process where there is net movement of water across a selectively permeable membrane from the feed solution to draw solution. The natural driving force is resulted from the osmotic pressure difference between the two solutions [1,2]. Compared with conventional pressure driven processes such as reverse osmosis (RO), FO has the merits of high water recovery rate, minimized brine discharge, low fouling propensity, and low energy requirements [3-5]. Thus, FO has been considered as a promising membrane technology for various disciplines, such as wastewater reclamation [6], seawater desalination [7], protein or pharmaceutical enrichment [8,9], and food processing [10]. In order to fulfill the above applications, many efforts have been put on FO research and remarkable progress has been made on the two essential components of FO, one being the semi permeable membrane which has excellent water permeability and rejection to any solutes and the other being the reagent named as draw solution (i.e., aqueous solution of draw solutes) which has high osmotic pressure [11,12].

An ideal draw solute is expected to have the following characteristics: 1) it is able to generate a high osmotic pressure when dissolved in water to form an aqueous solution; 2) it incurs negligible reverse permeation rate; 3) it is easy to be regenerated after its solution is diluted in the FO process; 4) it has small molecular weight and its aqueous solution has low viscosity; and 5) it is nontoxic and inexpensive.¹²In the past few decades, many types of draw solutes including responsive or non-responsive solutes have been developed and tested in FO processes but most of them could not offer satisfactory performances, i.e. low water flux and serious reversely permeation to the feed. The progress in draw solute research has been reviewed by Ge Q et al. [12] and Cai Y et al. [13]. From 2014, the elaborate coordination complexes have been explored as the new class of draw solutes due to their bulky configuration and attractive drawing ability in terms of high water fluxes and low reverse solute fluxes. Among these complexes, ferric citrate complex $Fe(Cit)_2$ has received great attention because it contains a number of hydrophilic groups and ionic species, which endow it good solubility and high osmotic pressure in aqueous solution [14,15]. Although the crucial role of iron citrate in the iron metabolism is well recognized, the coordination chemistry of iron and citrate is still the subject of debate and further discussion [16]. Early studies had indicated that various Fe-Cit structures might be formed based on different conditions. Lanford and co-workers reported oligomeric $Fe(Cit)$ complex obtained with a molar ratio of 1:1 for iron and citrate under low pH while Spiro reported the aggregates formed at equimolar citrate and iron via polymerization [17,18].

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*Correspondence:

J. Su, School of Life Sciences & Chemical Technology, Ngee Ann Polytechnic, 535 Clementi Road, Singapore.

E-mail: SU_Jincai@np.edu.sg

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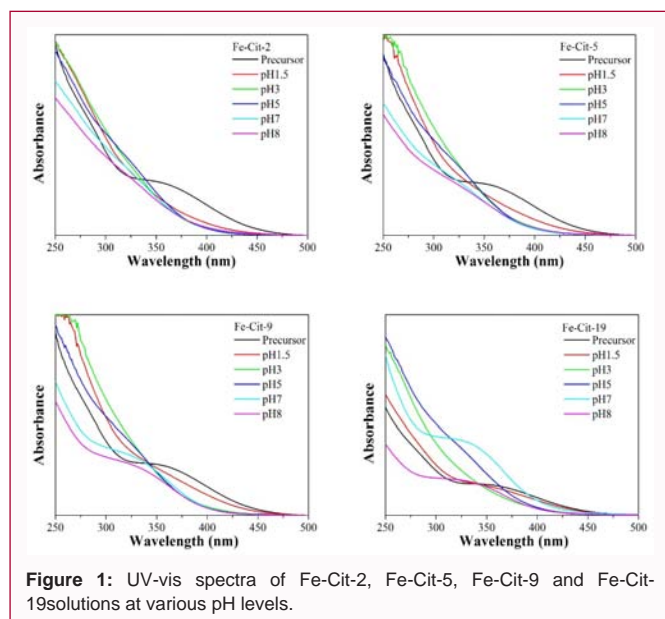


Figure 1: UV-vis spectra of Fe-Cit-2, Fe-Cit-5, Fe-Cit-9 and Fe-Cit-19 solutions at various pH levels.

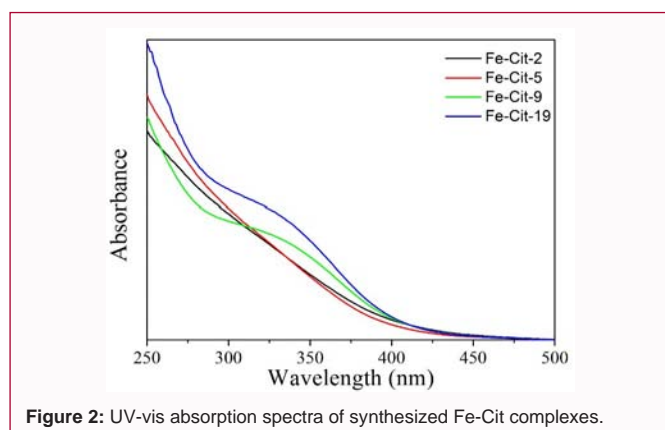


Figure 2: UV-vis absorption spectra of synthesized Fe-Cit complexes.

A $\text{Fe}_2(\text{Cit})_2$ complex was found by Timberlake due to the extent of hydrolysis occurring in the complex [19]. As well, $\text{Fe}_2(\text{Cit})_3$ or $\text{Fe}_3(\text{Cit})_2$ was proposed by Bobtelsky based on different ratio of iron and citrate in dilute solutions [20]. Recently, mono-nuclear $\text{Fe}(\text{Cit})_2^{5-}$ complex has been synthesized with the excess citrate in the chemical process [21]. Compared with multi-nuclear alternatives, mono-nuclear $\text{Fe}(\text{Cit})_2^{5-}$ complexes have higher solubility, lower molecular weight and better biological compatibility [22]. These characteristics allow them stand out among the Fe-Cit species and these characteristics make FO more realistic in many potential application areas and also stimulate scientists' interest to further investigate it. Therefore, it is necessary to particularly synthesize $\text{Fe}(\text{Cit})_2^{5-}$ with mono-nuclear configuration via carefully controlling the reaction condition. Some studies reported the relationship between the Fe-Cit structure and the ratio of iron and citrate, and emphasized the function of excess citrate in Fe-Cit coordination chemistry [23]. However, the conclusions are not convincing as the precursor contains chloride which also forms a complex with ferric ion [17,24]. Even if the effect of chloride is insignificant, the previous studies were only focused on the reaction mechanism of Fe-Cit while very few works mentioned their intrinsic property and their potential in FO applications.

The objective of this study was to develop novel mono-nuclear $\text{Fe}(\text{Cit})_2^{5-}$ complexes with bulky configuration and investigate their

potential as FO draw solutes. The effects of the molar ratio of iron and citrate on the Fe-Cit structures were firstly investigated. The intrinsic properties of the synthesized Fe-Cit complexes were subsequently examined.

Experimental

Materials

Iron(III) nitrate nonahydrate ($\text{Fe}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O} \geq 98\%$), citric acid monohydrate ($\text{C}_6\text{H}_8\text{O}_7 \cdot \text{H}_2\text{O} \geq 98\%$), and sodium hydroxide (NaOH , > 99%) purchased from Sigma-Aldrich were used for the synthesis. Denatured ethanol ($\text{CH}_3\text{CH}_2\text{OH}$, 96%) supplied by GCE® Laboratory Chemicals was used to crystallize the Fe-Cit complexes. All the chemicals above were used as received without further purification. Deionized (DI) water with conductivity $< 1.0 \mu\text{S}/\text{cm}$ was obtained from a Heal Force Water Purification System (NW20VF, Heal Force).

Synthesis of Fe-Cit complexes

In a typical procedure, precursor solutions were first prepared by mixing $\text{C}_6\text{H}_8\text{O}_7 \cdot \text{H}_2\text{O}$ (CA) and $\text{Fe}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$ (Fe) in 1.2 L DI water at various molar ratios (i.e. CA:Fe=1:2, 1:5, 1:9 or 1:19) with the overall quantity of $\text{Fe}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$ and $\text{C}_6\text{H}_8\text{O}_7 \cdot \text{H}_2\text{O}$ fixed at 1.2 mol. The mixtures were stirred at 25°C until clear solutions were obtained. Subsequently, 2.0M NaOH was added stepwise into the solutions under vigorous stirring to adjust the pH level to 8. The resultant solutions were further stirred for 3 hr and then concentrated separately to 400 ml under vacuum. Ethanol (96%) was added to each solution to induce precipitation. The precipitated solid product was further purified by repeating the dissolution and precipitation in H_2O and EtOH. After drying at 60°C overnight, the solid was ready for characterization and performance tests. The products were designated as Fe-Cit-2, Fe-Cit-5, Fe-Cit-9, and Fe-Cit-19, respectively, according to the molar ratio of $\text{Fe}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$ and $\text{C}_6\text{H}_8\text{O}_7 \cdot \text{H}_2\text{O}$ for the synthesis.

Characterizations

The pH values of Fe-Cit solutions were determined using a pH meter (Thermo Scientific Orion Star A215, USA). The functional groups of synthesized Fe-Cit complexes were studied by Fourier Transform Infrared (FT-IR, Shimadzu Irprestige-21, Japan) spectroscopy. Each FT-IR spectrum was collected after 64 scans in the wavelength range of 400 to 4000cm^{-1} . A series of Fe-Cit solutions were prepared by dissolving Fe-Cit complexes in DI water. The optical light-transmitting behavior of Fe-Cit solutions was measured by using UV-vis spectrophotometer (UV-1800, Shimadzu, Japan). The osmotic pressure of the Fe-Cit solutions was measured using an osmometer (Advanced Instruments, Inc. Model 3250, USA). The relative viscosity of the Fe-Cit solutions, μ_r , compared to DI water was calculated using the following equation [15]:

$$\mu_r = \frac{t\rho}{t_o\rho_o} \quad (1)$$

where t is the elution time of the Fe-Cit solution measured using a Cannon Ubbelohde Viscometer, ρ is density of the Fe-Cit solution measured using a density/specific gravity meter (DA-130N, KEM Kyoto Electronics), t_o is the elution time of DI water and ρ_o is the density of DI water.

Toxicology study

Fe-Cit-2 and Fe-Cit-9 compounds were subjected to toxicology study at Biomedical Sciences Institutes (A*Star, Singapore) using ICR female mice. The study was designed and carried out by up and

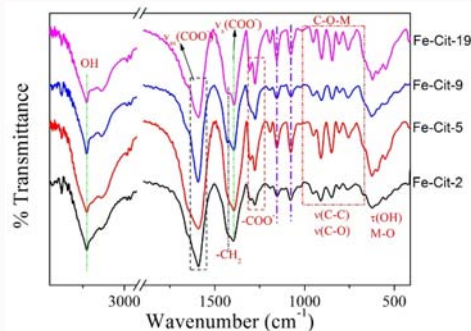


Figure 3: FTIR spectra of the synthesized Fe-Cit complexes.

down method as per OECD 425 and OECD 423 guide lines for acute oral toxicity. Dosing levels were selected by using AOT425Statpnm software from OECD and LD50 values calculated by probit analysis.

Results and Discussion

Reaction mechanism of ferric iron and citric acid to form Fe-Cit complexes

In previous studies, the reaction of ferric iron and citric acid and the affinity constants of various Fe-Cit complexes were successfully determined using spectrophotometric titration [17,23]. Inspired by these works, UV-vis spectrum was adopted in this study to investigate the reaction mechanism for the formation of Fe-Cit complexes. A series of solutions were prepared with various molar ratios of iron nitrate and citric acid (CA), i.e., CA:Fe, for the production of Fe-Cit complexes. Here, the using of nitrate precursor instead of iron chloride can avoid the formation of complex between ferric ion and chloride ions. Citric acid is considered to be a tetrabasic acid H_4Cit with pK_a values of 3.13, 4.76, 6.40 and 14.4, respectively, while $(Cit)^{4-}$ represents the completely ionized citrate ion with a molecular form of $C_6H_4O_7^{4-}$ upon neutralization [25]. As seen from the UV-vis spectra (Figure 1), the absorption peak is located at 350 nm after mixing with various amounts of citric acid and it is independent of the Fe:CA ratio. This means that the coordination's of dissociated citric acid and Fe(III) have the same structure. Lanford and co-worker have systematically studied the reaction of ferric ion and citric acid mixed in various ratios using spectrophotometric method, and a formula of $(Fe(H_2Cit)^+)$ was proposed for the complex under their experimental condition [17]. With the addition of 2M NaOH solution, the absorption peak at 350nm gradually disappears for all the solutions. The appearance of isosbestic points leads to the conclusion that chemical reaction(s) might have occurred and new Fe-Cit species have formed with certain amount of $(Cit)^{4-}$ and certain pH level. In early studies, iron(III) ions were reported to exist as the partially coordinated mononuclear hydrated species $(Fe(HCit)^0)$ at $pH \sim 1.5$ [26]. As seen from the UV-vis spectra, the transition from initial $Fe(H_2Cit)^+$ structure to $Fe(HCit)^0$ structure happens at $pH \sim 1.5$ in all the four Fe-Cit solutions. This discloses that the $Fe(HCit)^0$ complex is the predominant structure and it is independent of the nominal CA:Fe ratio under strong acidic condition. At the same time, the iron(III) ions tend to form oligomeric $Fe(Cit)^-$ species at $pH \sim 2.5$. For all the four solutions, the isosbestic points are observed at $pH \sim 3$, indicating the structure transition from $Fe(HCit)^0$ to $Fe(Cit)^-$ species happens at $pH \sim 2.5$. This observation within the pH range of 1-4 is consistent with that reported by Yokoi [26], and these Fe-Cit structures are controllable via adjusting the pH level under low pH range <4 . When the pH level is further increased from 4 to 7, there are

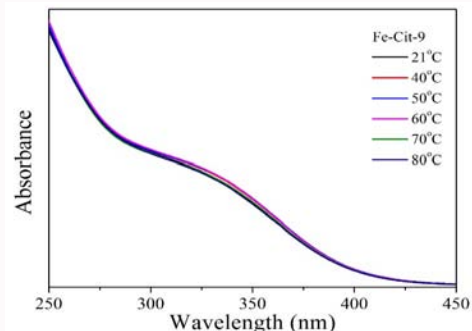


Figure 4: UV-vis spectra of Fe-Cit-9 after thermal treatment at various temperatures.

two possible competing reaction pathways depending not only on the pH value but also on the Fe:CA ratio [21]. One pathway might be that Iron(III) complexes $Fe(Cit)^-$ are apt to form di-nuclear complexes $Fe_2(Cit)(OH)_3$ by hydrolysis and polymerization at lower CA:Fe ratio at $pH \sim 5$. Further increase the pH to 7, the formed poly-nuclear structure is retained. Another pathway might be that the formed poly-nuclear complexes $Fe_2(Cit)(OH)_3$ at $pH \sim 5$ are attacked by excess citrate to form $Fe(Cit)_2^{5-}$ complex at $pH \sim 7$ or $Fe(Cit)^-$ species formed at $pH \sim 3$ directly convert to $Fe(Cit)_2^{5-}$ complex when pH value is around 7 with CA:Fe ratio larger than 20. For the Fe-Cit-2, Fe-Cit-5 and Fe-Cit-9 solutions, the transition from $Fe(Cit)^-$ species formed at $pH \sim 3$ to $Fe_2(Cit)(OH)_3$ happens at $pH \sim 5$ whilst $Fe(Cit)^-$ species maintains its structure for Fe-Cit-19 solution at $pH \sim 5$. The dinuclear $Fe_2(Cit)(OH)_3$ structures are still retained with further increasing the pH to 8 for Fe-Cit-2 and Fe-Cit-5 solutions. However, the absorption intensity decreases in the short wavelength range probably due to the degradation of the oligomeric $Fe_2(Cit)(OH)_3$ structure when the pH level reaches 7-8. For Fe-Cit-9 solution, the transition from dinuclear $Fe_2(Cit)(OH)_3$ structure to $[Fe(Cit)_2]^{5-}$ happens at $pH \sim 7$ due to the excess citrate. For Fe-Cit-19 solution with higher ratio of CA:Fe, the $Fe(Cit)^-$ species directly convert to $Fe(Cit)_2^{5-}$ complex at $pH \sim 7$. The UV-vis spectrum clearly shows that the transition of the Fe-Cit structure largely depends on the pH value (<4). At the same time, the structure conversion can be also controlled by the CA:Fe ratio at higher pH range (>4). For Fe-Cit-2 and Fe-Cit-5, the structure does not change from pH 5 to 8. For Fe-Cit-9 solution, the dinuclear complexes $Fe_2(Cit)(OH)_3$ forms at $pH \sim 5$, and are subsequently attacked by excess citrate to form $Fe(Cit)_2^{5-}$ complex at $pH \sim 7$. However, for Fe-Cit-19, the $Fe(Cit)^-$ species formed at $pH \sim 3$ directly convert to $[Fe(Cit)_2]^{5-}$ complex at $pH \sim 7$. Therefore, excess citrate is almost necessary for the formation of $[Fe(Cit)_2]^{5-}$ complex.

Structure of synthesized Fe-Cit complexes

It is well accepted that various Fe-Cit structures could form in the solution, such as $Fe_2(Cit)(OH)_3$ and $[Fe(Cit)_2]^{5-}$ complexes. For easy comparison, the UV-vis spectra of four types of Fe-Cit complexes are shown in Figure 2. Fe-Cit-2 and Fe-Cit-5 show similar adsorption curves, which correspond to the $Fe_2(Cit)(OH)_3$ complex. Fe-Cit-9 and Fe-Cit-19 show similar absorption characteristics which are very different from those of Fe-Cit-2 and Fe-Cit-5. These adsorption curves indicate the formation of mononuclear $[Fe(Cit)_2]^{5-}$ complexes. It could be concluded that excess citrate favors the formation of the mononuclear species $[Fe(Cit)_2]^{5-}$ in basic solution ($pH \sim 8$).

The coordination of citrate to the metal Fe^{3+} and the ligand structure were also affirmed by FT-IR spectra (Figure 3). Characteristic

Table 1: Osmotic pressure of various Fe-Cit solutions.

Concentration (M)	Osmotic pressure (bar)			
	Fe-Cit-2	Fe-Cit-5	Fe-Cit-9	Fe-Cit-19
0.25	18.64 ± 0.2	21.88 ± 0.3	23.22 ± 0.3	24.12 ± 0.5
0.5	36.58 ± 2.0	40.30 ± 3.0	47.62 ± 2.5	48.03 ± 4.0
1.0	69.51 ± 3.5	81.36 ± 4.0	90.79 ± 4.0	88.56 ± 4.0

Table 2: Relative viscosity of various Fe-Cit solutions.

Concentration (M)	Relative viscosity		
	Fe-Cit-2	Fe-Cit-5	Fe-Cit-9
0.5	2.80	2.50	2.35
1.0	10.93	8.64	8.46

Table 3: Lethal effect observed after dosing of Fe-Cit-9.

Test article	Dose of Fe-Cit-9 (mg/kg)	Dose of elemental iron (mg/kg)	Animal death* (%)
1	1953.5	200	0
2	3467.46	355	0
3	6173.06	632	0

*There were 3 animals in each test.

bands at ~ 3400 cm⁻¹ are induced by the vibrational stretch of O-H bond due to moisture. Two prominent peaks at ~ 1630 and ~ 1400 cm⁻¹ correspond to the vibrational stretches of $\nu_{\text{as}}(-\text{COO}^-)$ and $\nu_{\text{sy}}(-\text{COO}^-)$ groups, respectively [22]. The peaks at ~1305 and 1280cm⁻¹ represent the $-\text{COO}^-$ bending stretching, indicating the presence of carboxylic group [27]. No peaks appearing at ~ 1730cm⁻¹ suggests the fully deprotonated form of citric acid in all the Fe-CA complex structures and this is consistent with UV-vis characterization. The peaks at 1421cm⁻¹ are associated with CH₂ bending [28]. However, such peaks are only seen from the spectra of Fe-Cit-9 and Fe-Cit-19 samples with mononuclear [Fe(Cit)₂]⁵⁻ structures. In the meanwhile, the CH₂ bending model disappears in the poly-nuclear structure Fe₂(Cit)(OH)₃ for Fe-Cit-2 and Fe-Cit-5 due to their complicated oligomeric structure. This observation is consistent with the UV-vis spectrum and is another evidence of the structural difference of Fe-Cit-2 and Fe-Cit-5 from Fe-Cit-9 and Fe-Cit-19. The adsorption at ~ 587cm⁻¹ is characteristic for the metal-oxygen linkage (M-O bond), and it verifies the successful coordination of citrate to the metal centers.

Intrinsic properties of Fe-Cit complexes

The osmotic pressure of these synthesized Fe-Cit complexes is shown in Table 1. In the range of 0.25 to 1.0 M, the osmotic pressure is proportional to the Fe-Cit concentration. With increasing the CA:Fe ratio, the osmotic pressure increases due to the structural transition from di-nuclear Fe₂(Cit)(OH)₃ to mono-nuclear FeCit₂⁵⁻ structure while the latter gives more ionic species upon dissociation in water [26]. Further increasing the CA:Fe ratio to 19, the osmotic pressure of Fe-Cit-19 solution does not change much as compared to Fe-Cit-9 due to their similar structure, and this observation is consistent with the structural characterization (Figures 1 & 2). Early study and our experiment support the hypothesis that excess of citrate favors the formation of mononuclear [FeCit]₂⁵⁻ complex. Interestingly, the mononuclear [FeCit₂]⁵⁻ complex results in higher osmotic pressure compared with other Fe-Cit complexes. Therefore, Fe-Cit-9 is considered as the optimized receipt among the four candidates.

In the FO process, higher draw solution concentration leads to higher osmotic pressure and thus higher osmotic driving force. Correspondingly, increased draw solution concentration leads

to remarkable increase in the viscosity which would significantly affect the diffusion of draw solutes within the boundary layer at the membrane surface and amplify the adverse effect of concentration polarization. Thus, it is essential to know the relative viscosity of the aqueous solutions of the synthesized Fe-Cit. As shown in Table 2, Fe-Cit-2 solutions show higher relative viscosity than the other two due to the oligomeric di-nuclear structures. It should be noted that only solutions of 0.5 and 1.0 M are measured and discussed here for the relative viscosity because the Fe-CA solutions at higher concentrations are very viscous and are not suitable for FO applications. As well, Fe-Cit-19 is not included since it has similar structure as Fe-Cit-9. At each concentration, the relative viscosity decreases with increasing CA:Fe ratio where there is a transition from oligomeric di-nuclear structure to mononuclear structure. Obviously, mono-nuclear [FeCit₂]⁵⁻ based aqueous solution is less viscous than di-nuclear based solution at the same concentration. It is also noted that the relative viscosity increases by 3 to 4 times for all solutions when the concentration increases from 0.5 M to 1.0 M. Showing higher osmotic pressure and lower viscosity, Fe-Cit-9 is a better candidate than Fe-Cit-2 and Fe-Cit-5 as draw solutes for FO processes. Although the Fe-Cit solutions show higher viscosity than the solutions based on inorganic salts such as NaCl, the relative viscosity of Fe-Cit complexes is acceptable compared to polyacrylic acid sodium (PAA-Na) draw solutes at similar osmotic pressure [29].

In the FO process, recovery of the diluted draw solution is necessary in order to maintain the osmotic driving force and achieve sustainable separation. For example, FO can be integrated with membrane distillation (MD) method for continuous re-concentration of the draw solution and collection the clean water. Although the temperature for MD is not very high (e.g., 50-80°C), it still requires that the draw solutes possess thermal stability. The stability of Fe-Cit-9 solution at elevated temperatures is thus evaluated using UV-vis spectroscopy and is shown in Figure 4. Upon heating at 40, 50, 60, 70 and 80°C for 3hr, the light absorption curves of the Fe-Cit-9 solutions are identical with that of the control solution at room temperature. It can be safely concluded that Fe-Cit-9 maintains its original structure upon heating. This experiment provides solid evidence that Fe-Cit-9 is very stable and it could be regenerated or reconcentrated through MD or other thermal processes.

In addition to high osmotic pressure, low viscosity and good thermal stability, nontoxicity is also an important characteristic for draw solutions. Since the Fe-Cit complexes are to be used as FO draw solutes for liquid food and pharmaceutical enrichment, toxicity is even more critical than the other properties. Iron is the most abundant trace mineral in the body and is an essential element in most biological system. However, iron is toxic to cells in excessive amounts [30]. Acute iron poisoning is common and potentially lethal in many animals. Considering that FO membranes cannot be defect-free, one cannot completely avoid the leakage of draw solutes from the draw solution to the feed. Therefore, it is necessary to examine the toxicity of the Fe-Cit-9 complex since very minor leakage is almost unavoidable. The toxicology test is conducted in female ICR mice with 14 days post dosing recovery period observations (Table 3). At the end of the study, the Fe-Cit-9 compound does not show any lethal effect at the dosing amount of 1953.12mg·Kg⁻¹ (equivalent to 200mg·Kg⁻¹ dose of elementary iron) in female ICR mice. The amount of Median Lethal Dose (LD₅₀) for Fe-CA9 is higher than 6173.06mg·Kg⁻¹ (equivalent to 632 mg·Kg⁻¹ of elemental iron). The observed Maximum Tolerated Dose (MTD) is 6173.06mg·Kg⁻¹. Since it is already above the ethical

limitation of higher limit dose ($5000\text{mg}\cdot\text{Kg}^{-1}$), no further increase in the dosing amount is tried. The toxicology test proves that Fe-Cit-9 compound is nontoxic and can be safely used as draw solutes in FO processes for liquid food or pharmaceutical concentration.

Conclusions

A series of ferric citrate complexes have been successfully synthesized by changing the ratio of iron nitrate and citric acid. It is found that the di-nuclear Fe-Cit complexes can form with 2:1 and 5:1 ratios of citric acid and iron nitrate. Whilst, the mononuclear Fe-Cit complex is obtained with higher ratios of citric acid and iron nitrate, such as 9:1 and 19:1. The resulted Fe-Cit compounds are analyzed for their structures and intrinsic properties, including osmotic pressure, viscosity, thermal stability, and toxicity. Among the different Fe-Cit structures synthesized, the mononuclear structure Fe-Cit-9 based on 9:1 ratio of citric acid and iron nitrate displays outstanding intrinsic properties. At concentrations of 0.5 and 1.0 M, Fe-CA9 solutions show osmotic pressures of 47.62 and 90.79 bar, relative viscosities of 2.35 and 8.46, nil toxicity, and excellent thermal stability. These results show that the newly synthesized Fe-Cit-9 complex is a promising FO draw solute and has the potential to promote FO applications in the enrichment of pharmaceuticals or other high value products.

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