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DOI 10.1007/s10953-016-0452-3 Complex Formation Study of Binary and Ternary Complexes Including 2,3-Dihydroxybenzoic Acid,

**15N-acetylcysteine and Divalent Metal Ions Shella Permatasari**

Santoso<sup>1</sup> • Artik Elisa Angkawijaya<sup>1,2</sup> • Suryadi Ismadji<sup>3</sup> • Aning Ayucitra<sup>3</sup> • Felycia Edi Soetaredjo<sup>3</sup> • Tran Nguyen Phuong Lan<sup>4</sup> • Yi-Hsu Ju<sup>1</sup> Received: 22 October

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Springer Science+Business Media New York 2016 Abstract The**

binary and ternary complex stability constants between 2,3-dihydroxy- benzoic acid (DA) and N-acetylcysteine (Nac) with the divalent metal ions (M) Mn<sup>2+</sup>, Co<sup>2+</sup>, Ni<sup>2+</sup>, Cu<sup>2+</sup> and Zn<sup>2+</sup> were studied in aqueous solution at 310.15 K and an ionic medium of 0.15 mol/dm<sup>3</sup> NaCl. The complexes' stability constants (log<sub>10</sub> b), refined

**17from the potentiometric data using the** Hyperquad2008 **program,**

**10indicate that the ternary complexes are more stable than the binary complexes.**

The stability constants were supported by additional computation, refined from the spectrophotometric data using the Hypspec program. The values of the ternary complex stability relative to their binary complex (Dlog<sub>10</sub> K) and the disproportionation constant (log<sub>10</sub> X) indicate that formation of ternary complex species [M(DA)(Nac)]<sup>3-</sup> is more favorable than that of species formed by two identical ligands, [M(DA)<sub>2</sub>]<sup>4-</sup> or [M(Nac)<sub>2</sub>]<sup>2-</sup>. For the investigated M, the stability of complexes follows the trend Cu<sup>2+</sup> [ Zn<sup>2+</sup> [ Ni<sup>2+</sup> [ Co<sup>2+</sup> [ Mn<sup>2+</sup>. Keywords Stability constant ? Potentiometry ? N-acetylcysteine ? 2,3-dihydroxybenzoic acid ? Divalent metal 1 Introduction 2,3-Dihydroxybenzoic acid (DA) is a powerful iron chelator with a Fe<sup>3+</sup>-DA complex stability constant (log<sub>10</sub> K<sub>1</sub>) value of 20.5 [1]. The chelating ability of DA makes this compound useful in the excretion of excess iron [2]. DA naturally exists in plants such as &

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Vietnam *Salvinia molesta*, lobi–lobi fruit (*Flacourtia inermis*) and gooseberries (*Phyllanthus acidus*) [3, 4] and also in blood plasma and urine of human, as the product of aspirin metabolism [5, 6]. Biologically, DA provides health benefits due to its antioxidant, anti- inflammatory and antimicrobial actions. DA may act as a salicylate (COO–, ortho-O–) type ligand or catecholate (ortho-O–, meta-O–) type ligand [7–10]. Recently, researchers demonstrated that DA also can bind metal ions such as  $Al^{3+}$ ,  $VO^{2+}$ ,  $Mn^{2+}$ ,  $Cu^{2+}$  and  $Cd^{2+}$  as summarized in IUPAC equilibrium data report [11]. To the best of our knowledge, there are only a few reports on the stability constant of DA with divalent transition metal ions; excesses of these metal ions in human body may lead to metal toxicity. DA is often designated as a di-protic,  $H_2L$ , ligand (with 2 protonation constants, for the COO– and meta-O– groups) instead of tri-protic,  $H_3L$ , ligand [9–11]. Thus, in this work we attempted to treat DA as a tri-protic ligand by determining the protonation constant of the ortho-O– by means of spectrophotometry; this was then used for the stability constant determinations. Ternary complex study is interesting, because it is expected that the combination of two different ligands will give synergistic effect to strengthen stability of the complex, thus dissociation of the metal complex is less likely [12]. In this study, N-acetylcysteine (Nac), an antioxidant that is known as glutathione precursor, mucolytic agent and neuroprotective agent, was chosen to assist the complex formation of DA [13–17]. Nac is known as a drug for treating angina pectoris, acute respiratory distress syndrome, paracetamol overdoses, ischemia–reperfusion cardiac injury, schizophrenia and bipolar disorder [18–22]. Our previous study on Nac with some

### 2divalent metal ions ( $Cu^{2+}$ , $Zn^{2+}$ , $Ni^{2+}$ , $Co^{2+}$ and $Mn^{2+}$ )

indicates that the chelate complexes have stability constants in the range of 3.67 to 6.57 for  $\log_{10} K_1$  and 3.69 to 6.06 for  $\log_{10} K_2$ , which is sufficient for the chelate complex to disassociate [23]. Thus the combination of DA and Nac was expected to give a higher stability for the complexes formed. All the complexes formed were observed in conditions comparable to human blood (i.e. 310.15 K and

2ionic strength of  $0.15 \text{ mol} \cdot \text{dm}^{-3} \text{ NaCl}$ ). The equilibrium constants were refined using the

Hyperquad2008 and Hypspec computer programs. 2 Chemicals and Solutions Chemicals used in this study and their suppliers are as follows: analytical grade metal salts of

1nickel chloride hexahydrate ( $NiCl_2 \cdot 6H_2O$ , 98 %) was supplied by Alfa Aesar (Lancashire, UK);

copper chloride dehydrate ( $CuCl_2 \cdot 2H_2O$ , 99 %), cobalt nitrate hexahydrate Fig. 1 Structural formulae of a 2,3-dihydroxybenzoic acid and b N-acetylcysteine ( $Co(NO_3)_2 \cdot 6H_2O$ , 98 %), and zinc

**1** **nitrate hexahydrate** ( $\text{Zn}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ , 98 %) were purchased from Sigma Aldrich (St. Louis, USA); and manganese **chloride**

tetrahydrate ( $\text{MnCl}_2 \cdot 4\text{H}_2\text{O}$ , 99.8 %) was supplied from Fisher Scientific (New Jersey, USA). The 2,3-dihydroxybenzoic acid (DA,  $\text{C}_7\text{H}_6\text{O}_4$ , 99 %) was supplied by Alfa Aesar (Lancashire, UK) and N-acetylcysteine (Nac,  $\text{C}_5\text{H}_9\text{NO}_3\text{S}$ , 99 %) was purchased from Sigma Aldrich (St. Louis, USA); their structures are shown in Fig. 1. Sodium hydroxide (NaOH, 96 %) was provided by Yakuri Pure Chemical (Kyoto, Japan); potassium hydrogen phthalate (KHP, 99.95 %), and ethylenediaminetetraacetic acid (EDTA,  $\text{C}_{10}\text{H}_{16}\text{N}_2\text{O}_8$ , 98.5 %) were purchased from Sigma Aldrich (St. Louis, USA); sodium chloride (NaCl, 99.5 %) was obtained from Showa (Tokyo, Japan). Metal salt solutions were standardized by complexometry against EDTA. Carbonate free NaOH

**17** **(0.1 mol·dm<sup>-3</sup>)** used as titrant **was standardized against**

KHP. HCl (0.03 mol·dm<sup>-3</sup>) was prepared and used after standardization. All solutions were prepared freshly before use, using ultra pure water obtained from an ultrapure water system with a resistance of 18.3 MΩ·cm<sup>-1</sup>. 3 Experimental and Computational 3.1 Potentiometric Method

**6** **Potentiometric titrations were** performed in a **150** cm<sup>3</sup> commercial **double walled**

glass vessel under N<sub>2</sub> atmosphere. Reaction temperature was maintained at  $310.15 \pm 0.2$  K and the ionic strength of 0.15 mol·dm<sup>-3</sup> NaCl ( $\text{pK}_w = -13.384$ ). A Metrohm 888 Titrand potentiometer, with an 805 Dosimat, Ecotrode Plus pH glass electrode and 802 rod stirrer with 804 Ti stand, was used for the measurements. The electrode used for the measurements has a precision of  $\pm 0.001$  pH unit. The potentiometer, equipped with the titration software Tiamo2.3 and coupled to a personal computer, was used to control the titration and record the data. Calibration of the electrode was by means of strong acid–strong base titration, towards solution (a) defined right below, using the GLEE program [24]. For the equilibrium constant determination of binary and ternary systems, the following solutions each with a total volume of 50 cm<sup>3</sup> were prepared and titrated against equal increments of added 0.1 mol·dm<sup>-3</sup> carbonate-free NaOH: Table 1 Experimental condition of the investigated systems System Ratio Concentration (mol·dm<sup>-3</sup>) Metal salt DA Nac Potentiometric method Binary 1:1 1:2 1:2.5 1:3 1 9 10<sup>-3</sup> 5 9 10<sup>-4</sup> 4 9 10<sup>-4</sup> 4 9 10<sup>-4</sup> Ternary 1:1:1 1 9 10<sup>-3</sup> Spectrophotometric method Binary 1:2 1 9 10<sup>-4</sup> Ternary 1:1:1 2 9 10<sup>-4</sup> 1 9 10<sup>-3</sup> 1 9 10<sup>-3</sup> 1 9 10<sup>-3</sup> 1.2 9 10<sup>-3</sup> 1 9 10<sup>-3</sup> 2 9 10<sup>-4</sup> 2 9 10<sup>-4</sup> 1 9 10<sup>-3</sup> 2 9 10<sup>-4</sup> (a) 0.003

**9** **mol·dm<sup>-3</sup> HCl ? 0.15 mol·dm<sup>-3</sup> NaCl** (b) Solution (a) ? **0.001 mol·dm<sup>-3</sup>**

ligand DA (c) Solution (a) ? ligand DA ? metal salt (d) Solution (a) ? ligand DA ? ligand Nac ? metal salt The equilibrium constants include: the acid dissociation constant of ligand DA, which was determined by titrating solution (b); the metal complex stability constant, which was determined by titrating solution (c) at four different metal to DA molar ratios of 1:1, 1:2, 1:2.5 and 1:3; while ternary metal complex solution (d) was

determined at a metal to DA to Nac molar ratio of 1:1:1. The total concentration of each compound used in the experiment is shown in Table 1. Each solution was thermostatted at 310.15 K and

11left to stand for 15 min before titration. The titration was

carried out up to pH = 11.0.

11Each titration was repeated at least three times under controlled conditions,

with a reproducibility of  $\pm 0.04$  pH unit. Computations of complex equilibrium constants were performed

2by processing the potentiometric data using Hyperquad2008 program [25]. The

objective function was given as  $U = R \sum (W_i r_i^2)$ , where  $W_i$  is the weight at the  $i$ th data point and  $r_i$  is the square of the difference between the observed and the calculated pH values. The Gauss–Newton–Marquardt method was adopted to minimize the objective function. All constants are presented as overall formation constant in logarithm value ( $\log_{10} \text{bpqrs}$ )

6and expressed by the following equation:  $\text{pM} + \text{p}_{\text{qNac}} + \text{p}_{\text{rDA}} + \text{p}_{\text{SH}} + \text{p}_{\text{MNaqDArHs}} + \text{p}_{\text{MNaqDArHs}} + \text{bpqrs} + \frac{1}{2}\text{M} + \frac{1}{2}\text{Nac} + \frac{1}{2}\text{DA} + \frac{1}{2}\text{H} + \text{s}$

81P The selected model was the one that gave the best statistical fit, was chemically sensible and consistent with the titration data. The species distribution of each metal complex at the observed pH was produced by the HySS2009 simulation program, based on the refined stability constants [26]. 3.2 Spectrophotometric Method Spectrophotometric measurements were conducted using a JASCO V-550 spectrophotometer in a standard 1 cm path length quartz cell. The measurement was done by scanning the spectra of the solutions of binary and ternary systems (Table 1) from 200 to 400 nm. The spectra of each solution were measured at pHs between 2.5 and 11.0, where the pH was adjusted by using 0.1 mol $\cdot$ dm $^{-3}$  NaOH. The spectral data at various pHs were used to refine the formation constants using the Hypspec program [25, 27]. Spectral analyses were also carried out for the solution containing DA:Nac:metal (1:1:1) with a molar concentration of  $2.9 \times 10^{-4}$  mol $\cdot$ dm $^{-3}$  prior to the confirmation of the ternary species formation. 4 Results and Discussion 4.1 Ligand Acid–Base Behavior In aqueous solution, a ligand tends to deprotonate by releasing its hydrogen ion at certain pH; this deprotonation reaction property is expressed as pKa. A higher pKa value indicates that a more basic pH is needed to release a hydrogen ion. As a tri-protic ligand, DA possesses three functional groups, namely a carboxylic (COO $^{-}$ ) group and two hydroxyl (O $^{-}$ ) groups at ortho (ortho-O $^{-}$ ) and meta (meta-O $^{-}$ ) positions. As obtained from the potentiometry data, the deprotonation of COO $^{-}$  group has a pKa1 value of 2.63 and the second deprotonation occurs at the meta-O $^{-}$  group with a pKa2 value of 9.98. The second deprotonation is more likely to occur at meta-O $^{-}$  since this site is more reactive than the ortho-O $^{-}$ . This behavior is influenced by the electronic effect of the substituent groups and also the COO $^{-}$  functional group which makes the ortho-O $^{-}$  less nucleophilic than meta-O $^{-}$ . Since the ortho-

O<sup>-</sup> is less nucleophilic, a higher basic condition was needed for its deprotonation (third deprotonation). Thus, spectrophotometry was used to determine the deprotonation of the ortho-O<sup>-</sup> group instead of potentiometry; the pK<sub>a3</sub> obtained for ortho-O<sup>-</sup> 13.00. These pK<sub>a</sub> values and the deprotonation order of DA are in accord with the studies of Turkel et al. [10] and Kiss et al. [28]. In the case of Nac, the first deprotonation occurs at its COO<sup>-</sup> group with a pK<sub>a1</sub> value of 3.18, followed by the thiol S<sup>-</sup> group with a pK<sub>a2</sub> value of 9.48 [23]. The pK<sub>a</sub> values of the ligands are given in Table 2 and used for the calculation of the metal complex formation. Besides the pK<sub>a</sub>s of the ligands, the hydrolysis constants of the metal ions shown in Table 2 were also introduced into the calculation. Table 2 Dissociation constant of DA and Nac at

**4 310.15 K and I = 0.15 mol·dm<sup>-3</sup>**

NaCl Ligand pK<sub>a</sub>(SD) pK<sub>a1</sub> pK<sub>a2</sub> pK<sub>a3</sub> DA This work Ref. [10]b Ref. [28]b 2.63 (4) 2.68 2.66 9.98 (2) 10.11 9.80 13.00 (2)a 13.10 [14.00 Nac Hydrolysis constantd Cu(OH) Cu<sub>2</sub>(OH)<sub>2</sub> Cu<sub>3</sub>(OH)<sub>4</sub> Zn(OH) Zn(OH)<sub>2</sub> Zn(OH)<sub>3</sub> Ref. [23]c -7.71 -10.99 -21.62 -8.96 -16.90 -28.40 3.18 9.48 Co(OH) Co<sub>2</sub>(OH) Mn(OH) Mn(OH)<sub>2</sub> Mn<sub>2</sub>(OH) Mn<sub>2</sub>(OH)<sub>3</sub> -9.65 -11.23 -10.59 -22.20 -10.56 -23.30 Ni(OH) Ni(OH)<sub>2</sub> Ni<sub>2</sub>(OH) -9.86 -19.00 -10.70

**5 Standard uncertainties u are u(T) = 0.1 K, u(**

pK<sub>a</sub>) are represented by standard deviations SD in the parentheses for last place of decimal a Spectrophotometry, I = 0.15 mol·dm<sup>-3</sup> NaCl,

**4 T = 310.15 K b Potentiometry, I = 0.20 mol·dm<sup>-3</sup>**

KCl, T = 298.15 K c Potentiometry, I =

**15 0.15 mol·dm<sup>-3</sup> NaCl, T = 310.15 K**

d Hydrolysis constant of metal ions presented as log<sub>10</sub> b(SD) value, Ref. [29] 4.2 Complexation Study of Binary Systems The

**2 divalent metal ions Cu<sup>2+</sup>, Zn<sup>2+</sup>, Ni<sup>2+</sup>, Co<sup>2+</sup> and Mn<sup>2+</sup>**

were studied with DA and Nac. In our previous study on Nac–M chelate complexes, there were three species ([M(Nac)], [M(HNac)]<sup>+</sup> and [M(Nac)<sub>2</sub>]<sup>2-</sup> formed in the investigated pH range (2.5–11.0). The monoprotonated [M(HNac)]<sup>+</sup> species, which is formed by the attachment of M<sup>2+</sup> to the deprotonated COO<sup>-</sup> group, was observed in the Cu<sup>2+</sup>, Ni<sup>2+</sup>, Co<sup>2+</sup> and Mn<sup>2+</sup> systems. In this case, the proton is contributed by the H atom of the S<sup>-</sup> group. The formation of [M(Nac)] species occurs by the attachment of M<sup>2+</sup> to two deprotonated groups COO<sup>-</sup> and S<sup>-</sup>. The other species was [M(Nac)<sub>2</sub>]<sup>2-</sup> which is formed by the attachment of fully deprotonated Nac to the [M(Nac)] species [23]. In DA binary systems, the refinement results from Hyperquad showed that M(HDA), [M(DA)]<sup>-</sup>, [M(HDA)<sub>2</sub>]<sup>2-</sup>, [M(HDA)<sub>2</sub>]<sup>3-</sup> and [M(DA)<sub>2</sub>]<sup>4-</sup> were the species that



gave the best fit to the potentiometric data. As observed in the potentiometry titration curve in Fig. 2, the occurrence of inflection points along with pH jumps in  $M^{2+}$ -DA systems indicate the formation of metal complex species. In the case of the systems which contain ligand only, the inflection point in the titration curve indicates the deprotonation of an H atom of the ligand's donor group. An inflection point occurs when sufficient base is added to deprotonate a group (higher value of m indicates more base was added). In the case of Fig. 2 Titration curve for the  $M^{2+}$ -DA system

16 **at a metal to ligand ratio of 1:**

2.5 DA, the inflection points occur at  $m = 4.0$  and  $5.0$  indicating the deprotonation of  $COO^-$  and meta- $O^-$  groups, respectively. In the case of  $M^{2+}$ -DA, at the  $m \approx 5.0$  range the  $M(HDA)$  species was formed. The inflection points concomitantly with pH jump suggest that two functional groups are involved in the formed species, namely the  $COO^-$  and ortho- $O^-$  groups (salicylate type coordination), while the meta- $O^-$  group was still protonated. The deprotonation of ortho-  $O^-$  group was promoted by the presence of metal ions that were firstly bond to the  $COO^-$  group. A significant pH jump, observed from the inflection point at  $m = 6.0$ , suggests a stronger coordination of the metal complex compared to the salicylate type, specifically catecholate (ortho- $O^-$ , meta- $O^-$ ) type, where the corresponding species in this point is  $[M(DA)]^-$ . In the studies of Kiss et al. on  $Cu^{2+}$ -DA complexes [28], Turkel et al. on  $Al^{3+}$ -DA complexes [10], and Sahoo et al. on  $La^{3+}$ -DA complexes [30], they also proposed that salicylate type complex species of DA tend to form at lower pH and cate- cholate type at higher pH. At  $m = 5.0-6.0$  the presence of  $[M(HDA)_2]^{2-}$  and  $[M(HDA)_2]^{3-}$  around this point suggests the involvement of protonated functional groups in the species. In this case, the most thermodynamically sensible forms are: two salicylate ( $COO^-$ , ortho- $O^-$ ) coordination in the formation of  $[M(HDA)_2]^{2-}$ , and the combination of salicylate ( $COO^-$ , ortho- $O^-$ ) and catecholate (ortho- $O^-$ , meta- $O^-$ ) coordination in the formation of  $[M(HDA)_2]^{3-}$ , while the  $[M(DA)_2]^{4-}$  species, which are formed at higher pH, suggest the coordination of two catecholates. These proposed forms with specifically mixed combination of salicylate- catecholate type and two catecholate type (at higher pH) are also in good agreement with the literature [10, 28, 30]. In addition, as observed in the titration curve,  $Cu^{2+}$ -DA exhibits the strongest pH jump indicating that  $Cu^{2+}$  possesses the strongest coordination with DA. The overall stability constants ( $\log_{10} b$ ) of  $M^{2+}$ -DA complexes are given in Table 3. There is good agreement between  $\log_{10} b$  values from potentiometry and spectropho- tometry. As summarized in Table 3,

13 **the stability of the complexes shows a decrease in the order**

of  $Cu^{2+}$  [  $Zn^{2+}$  [  $Ni^{2+}$  [  $Co^{2+}$  [  $Mn^{2+}$  which

12 **is in accordance with the Irving- Williams order**

[31]. This Irving-Williams order is linear with the decrement of metal ions atomic number, where  $Zn^{2+}$  (30 pm) [  $Cu^{2+}$  (29 pm) [  $Ni^{2+}$  (28 pm) [  $Co^{2+}$  (27 pm) [  $Mn^{2+}$  (25 pm). The increase of the metal ion's electronegativity is proportional to the increase of its atomic number. In the case of  $Cu^{2+}$ , the atomic number of  $Cu^{2+}$  is smaller than  $Zn^{2+}$  but it has a more stable complex. This phenomenon is due to the smaller electronegativity of Zn (Zn (1.65) \ Cu (1.99)). The high  $\log_{10} b$  of  $Cu^{2+}$  is also due to Jahn-Teller distortion of an octahedral complex, which results in stabilization of the complex [32, 33]. The species distribution





ratio of 1:2.5 4.3 Complexation Study of Ternary Systems Formation of the ternary species  $[M(HDA)(HNAc)]^-$ ,  $[M(HDA)(Nac)]^{2-}$  and  $[M(DA)(Nac)]^{3-}$  is justified from the analysis of potentiometry data. In Fig. 4, the observed ternary titration curve exhibits greater pH jump than that of the corresponding binary system. At  $m = 5.0$ – $6.0$ , a pH jump is observed suggesting a stronger coordination compared to that of the salicylate type ( $COO^-$ , ortho- $O^-$ ) coordination in binary system. Thus it can be considered that Nac coordinates through the contribution of its  $COO^-$  group. Fig. 4 Titration curve on  $M^{2+}$ – $DA$ – $Nac$  system

16 **at a metal to ligand ratio of 1:1:**

1 A significant pH jump at  $m = 7.0$  suggests deprotonation, which is more likely to occur on the  $S^-$  group of Nac, participated in complex formation. Further deprotonation was observed from a big pH jump at  $m = 8.0$ , which occurs on the meta- $O^-$  group of DA, suggesting the catecholate type (ortho- $O^-$ , meta- $O^-$ ) coordination from DA and  $COO^-$ ,  $S^-$  coordination from Nac. Stability constants ( $\log_{10} b$ ) of ternary complexes are recorded in Table 4. The results from potentiometry and spectrophotometry measurements show good agreement. The species distribution of those ternary complex species are graphically represented by  $Cu^{2+}$  and  $Co^{2+}$  complexes. As shown in Fig. 5a, the first ternary species  $[Cu(HDA)(HNAc)]^-$  was formed in the pH region where  $[Cu(HNAc)]^+$  was observed. As the  $[Cu(HNAc)]^+$  concentration decreases the formation of  $[Cu(HDA)(HNAc)]^-$  increases, suggesting that one of the two protons in the ternary species was contributed by the protonated  $S^-$  group of Nac. Thus, the other proton was contributed by DA through its meta- $O^-$  group. Next, for  $[M(HDA)(Nac)]^{2-}$  species, since the  $S^-$  group of Nac is more likely to deprotonate earlier than the meta- $O^-$  group of DA, this suggests that the proton in the complex is contributed by the meta- $O^-$  group of DA. The final species  $[M(DA)(Nac)]^{3-}$  was formed at highly basic pH suggesting deprotonation on the meta- $O^-$  group and the species was formed from the binding through catecholate type coordination of ligand DA along with ( $COO^-$ ,  $S^-$ ) coordination of Nac. Table 4 Stability constant of ternary systems at

4 **310.15 K and  $I = 0.15 \text{ mol dm}^{-3}$**

NaCl Species p q r s  $\log_{10} b \pm SD$  a Hyperquad c Hypspeak d  $\log_{10} K$  b  $\log_{10} X$  b M =  $Cu^{2+}$   $[M(HDA)(HNAc)]^-$  1 1 1 2 34.77 (8)  $[M(HDA)(Nac)]^{2-}$  1 1 1 1 28.24 (5) 29.81 (2)  $[M(DA)(Nac)]^{3-}$  1 1 1 0 19.17 (8) 19.67 (5) -2.47 3.55 M =  $Zn^{2+}$   $[M(HDA)(Nac)]^{2-}$  1 1 1 1 25.15 (9) 26.28 (2)  $[M(DA)(Nac)]^{3-}$  1 1 1 0 16.38 (6) 16.66 (5) -0.33 4.27 M =  $Ni^{2+}$   $[M(HDA)(HNAc)]^-$  1 1 1 2 31.79 (9)  $[M(HDA)(Nac)]^{2-}$  1 1 1 1 23.66 (7) 24.69 (3)  $[M(DA)(Nac)]^{3-}$  1 1 1 0 14.40 (7) 14.79 (3) -0.13 -0.09 M =  $Co^{2+}$   $[M(HDA)(Nac)]^{2-}$  1 1 1 1 23.05 (2) 23.39 (4)  $[M(DA)(Nac)]^{3-}$  1 1 1 0 12.80 (5) 12.68 (7) -1.06 2.27 M =  $Mn^{2+}$   $[M(HDA)(HNAc)]^-$  1 1 1 2 30.45 (7)  $[M(HDA)(Nac)]^{2-}$  1 1 1 1 21.59 (9) 22.15 (7)  $[M(DA)(Nac)]^{3-}$  1 1 1 0 12.56 (4) 12.53 (3) 0.51 3.23

5 **Standard uncertainties u are  $u(T) = 0.1 \text{ K}$ ,  $u$ (**

pKa) are represented by standard deviations SD in the parentheses for the last place of the decimal a p, q, r and s represent the number of metal ion, Nac, DA, and hydrogen ion, respectively b  $\log_{10}$  value based on Hyperquad refinement K c Stability constants were refined by "Hyperquad" and "Hypspec" using potentiometric and spectrophotometric methods, respectively The parameters  $D\log_{10} K$  and  $\log_{10} X$  were noted as useful

10 to indicate the behavior of ternary complexes compared to binary

complexes [35–39].  $\log_{10} K$  expresses the stability of the ternary species  $[M(DA)(Nac)]^{3-}$  relative to the stability of the binary species,  $[M(DA)]^-$  and  $M(Nac)$ ; the value is calculated from equation:  $\log_{10} K = \log_{10} b_{MAB} - \log_{10} b_{MA} - \log_{10} b_{MB}$ . The parameter  $\log_{10} X$  expresses the disproportionation tendency of binary species  $[M(Nac)_2]^{2-}$  and  $[M(DA)_2]^{4-}$  to form the ternary species  $[M(DA)(Nac)]^{3-}$ , where  $\log_{10} X$  is calculated from equation:  $\log_{10} X = \log_{10} b_{MAB} - \log_{10} b_{MA} - \log_{10} b_{MB}$ . It was found that the complex with the highest  $\log_{10} b$  value for its binary complex tends to have the most negative  $\log_{10} K$  value, suggesting that more energy is needed to form a stable ternary complex from a stable binary complex. However, after the ternary complex is formed, it possesses a greater stability than the binary complex suggesting that the ternary complex is unlikely to disassociate back to the binary. This is supported by the Fig. 5 Speciation diagram of ternary a  $Cu^{2+}$ –DA–Nac and b  $Co^{2+}$ –DA–Nac at metal to ligand ratio of 1:1:1  $\log_{10} X$  parameter of the ternary species, which generally have positive values, indicating that the formation of the ternary complex  $[M(DA)(Nac)]^{3-}$  is more favorable than that of the binary species  $[M(DA)_2]^{4-}$  or  $[M(Nac)_2]^{2-}$  [40]. For instance, the  $[Cu(DA)(Nac)]^{3-}$  species has the most negative  $\log_{10} K$  value (-2.47) since  $Cu^{2+}$  possesses the most stable binary species  $\log_{10} b$ , indicating that less energy is gained in the formation of ternary species. However it has a positive  $\log_{10} X$  value of 3.55 indicating greater stability of its ternary species. In the case of  $[Mn(DA)(Nac)]^{3-}$ , the  $\log_{10} K$  value of 0.51 indicates that less energy is needed to form ternary species (compared to the  $Cu^{2+}$  system) and a  $\log_{10} X$  of 3.23 indicates that the ternary complex of Mn is more stable than its binary species. Fig. 6 Spectrum measurements of ternary a  $Cu^{2+}$  and b  $Co^{2+}$  system at  $M^{2+}:Nac:DA = 1:1:1$

#### 4.4 Spectrophotometric Measurements

The addition of metal ion into the ligand system yields a metal–ligand complex, which causes an alteration in the spectral behavior [37, 40]. In this work, the spectral measurements were done on ternary systems

9 as a function of pH; as shown in Fig. 6 the

wavelength range was 200–400 nm. The aromatic ring of DA gave strong absorbance at 220–250 nm for all systems. The bands observed at longer wavelength are related to the metal–ligand complex. The observed bands show similar shifts in all systems, so the  $Cu^{2+}$  and  $Co^{2+}$  systems were chosen as representative. For the  $Cu^{2+}$  ternary system, as observed in Fig. 5a, at pH = 2.5 a band occurred at 312 nm which then exhibited a blue shift to 309 nm as the pH increased to 5.0, which was affected by the formation of  $[Cu(HDA)(Nac)]^{2-}$  species. However with the pH increased to 11.0, the spectrum exhibited another red shift to 325 nm, which is more likely due to the formation of  $[Cu(DA)(Nac)]^{3-}$  species. Similarly, for  $Co^{2+}$  ternary system in Fig. 5b, at pH = 2.5 a band was firstly observed at 314 nm, which then exhibited a blue shift to 309 nm as the pH increased to 8.0 but, with increase of pH to 11.0, there was a red shift to 344 nm which was caused by the  $[Co(DA)(Nac)]^{3-}$  species.

#### 5 Conclusion

Binary species of DA ( $M(HDA)$ ,  $[M(DA)]^-$ ,  $[M(HDA)_2]^{2-}$ ,  $[M(HDA)_2]^{3-}$ ,  $[M(DA)_2]^{4-}$ ) and ternary species of DA–Nac ( $[M(HDA)(HNac)]^-$ ,  $[M(HDA)(Nac)]^{2-}$ ,  $[M(DA)(Nac)]^{3-}$ ) were found in the potentiometry analysis, supported by spectrophotometry analysis. It was found that the binding of  $M^{2+}$  to the  $COO^-$  group of DA was initiated the deprotonation of the meta- $O^-$  group, and then formed salicylate type coordination. However, at higher pH the coordination changed to catecholate type with respect to the deprotonation of the ortho- $O^-$  group. While for Nac, the  $COO^-$  group was also found to attach firstly to metal ions followed by the  $S^-$  group as pH was increased.

**13**The stability constants of the complexes in **binary and ternary** system showed **the same order**

with that of log<sub>10</sub> b values: i.e. Cu<sup>2+</sup> [

**2Zn<sup>2+</sup> [ Ni<sup>2+</sup> [ Co<sup>2+</sup> [ Mn<sup>2+</sup>. The analysis of Dlog<sub>10</sub> K and**

log<sub>10</sub> X indicated that formation of ternary species is favorable. Acknowledgments This work was supported by the

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