



ORIGINAL ARTICLE

Iron(III) and copper(II) complexes bearing 8-quinolinol with amino-acids mixed ligands: Synthesis, characterization and antibacterial investigation



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Abstract Four d-orbital metal complexes with mixed ligands derived from 8-hydroxyquinoline (HQ) and amino acids (AA): L-alanine and methionine have been synthesized through a mild reflux in alkaline solution and characterized by elemental analyses, infrared, electronic transition, and temperature dependant magnetic susceptibility. The IR spectroscopy revealed that iron and copper ions coordinated through carbonyl (C=O), hydroxyl group (O—H) of the amino acids, N-pyridine ring of hydroxyquinoline. The elemental analysis measurement with other obtained data suggested an octahedral geometry for the iron(III) complexes and tetrahedral geometry for the copper(II) complexes. From the molar magnetic susceptibility measurement, the iron(III) system ($S = 5/2$) d^5 (non-degenerate 6A_1) with $\chi_m T = 0.38 \text{ cm}^3 \text{ K mol}^{-1}$ showed an antiferromagnetic while Cu^{2+} ions system ($S = 1/2$) ($^2T_{2g}$) has $\chi_m T = 4.77 \text{ cm}^3 \text{ K mol}^{-1}$ described as paramagnetic behaviour. *In vitro* antimicrobial investigations of the metal complexes against standard bacteria species gave significant inhibition with, copper complex showing highest inhibitions against *Pseudomonas*

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aeruginosa (ATCC27853) of 43 mm at 10 µg/ml signalling its potential as pharmaceutical or chemotherapeutic agents.

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1. Introduction

The coordination compounds of mixed ligands such as benzo-heterocyclic rings and amino acids have been the focus of a considerable number of investigations for their good coordination ability with metal ions, (Kumar et al., 2013; Ndosiri et al., 2013; Solanki et al., 2009; Patil et al., 2012) and pharmacological values (Eddie et al., 2010; Khalil et al., 2010; Gaurav et al., 2011; Patel, 2011; Albert et al., 1953; Mashaly et al., 2004; Coyle et al., 2004). These properties could be attributed to the presence of nitrogen (N) atom and hydroxyl group in the ligand moieties (Moustafa, 2005) found to be of microbial inhibitory character similar to the benzimidazole (Khalafi-Neshad et al., 2005; Podunavac-Kuzmanovic and Cvetkovic, 2011) or phenanthroline class (Agwara et al., 2010). Since Barnett Rosenberg's initial discovery of cisplatin (Roserberg, 1978), many more transition metal complexes and in particular those with N- and O-donor atoms have been known to have antimicrobial properties. (Prafulla et al., 2012; Mwacham and Eno, 2013; Albert, 1979). It is evident that formation of chelates metal ions increases the lipophilicity of the bioactive compounds through diverse array of biological oxidation-reduction mechanism for the effective permeability of the compounds into the site of action (Zarranz et al., 2003; Irbaraj et al., 2003).

Interestingly, metal complexes of 8-hydroxyquinoline as a primary ligand can exhibit biological activity (Noorulla and Sreenivasulu, 2011; Singh et al., 2010; Freeman, 1973; Che and Siu, 2010; Podunavac-Kuzmanovic and Cvetkovic, 2007) and an amino acid as a secondary ligand were significant as potential model for enzyme metal ions substrate complexes (Patel et al., 2012). Literature survey to the best of our knowledge showed that our newly synthesized compounds inhibit the standard test microorganisms favourably (Patel et al., 2012; Eddie et al., 2010; Khalil et al., 2010; Gaurav et al., 2011). We believe based on chelating concept that the release of electron(s) from the transition metals decreases the polarizability of the metal which has been proven to enhance the cytotoxicity of the metal complex (Khalafi-Neshad et al., 2005). Bearing in mind the aforementioned and in continuation of our research on bioinorganic of bioactive compounds, we hereby report synthesis, characterization and antibacterial activities of synthesized iron(III) and copper(II) complexes of mixed ligands, 8-hydroxyquinoline and alanine or methionine amino acids: $[M(HQ)(AA)_n] \cdot nH_2O$, $n = 0-2$; $M = Fe(III)$ and $Cu(II)$.

2. Experimental

2.1. Materials and methods

All the reagents and solvents used for the syntheses were obtained commercially from Sigma-Aldrich Chemical Co. and were used without any further purification. The test microorganisms (*Staphylococcus aureus* – ATCC25923,

Pseudomonas aeruginosa – ATCC27853, *Escherichia coli* – ATCC36218, *Enterococcus faecalis* – ATCC29212) were obtained from Nigerian Institute of Medical Research (NIMR), Lagos State, Nigeria.

2.2. Physical measurements

Elemental analyses of carbon, hydrogen and nitrogen were carried out at the Service Center of Elemental Analyses of Pharmacy campus Kumamoto University, Japan. Metal analyses were done on a Shimadzu AA-625-11 Atomic Absorption/Flame Emission Spectrometer. Infrared spectra were measured using KBr pellets with FTIR-8700 SHIMADZU Fourier Transform infrared spectrophotometer in the 4000–400 cm^{-1} region. The magnetic susceptibilities measurements $\chi_m(T)$ for the transition metal complexes between 5 and 400 K were measured with a superconducting quantum interference device (SQUID) magnetometer (Quantum Design MPMS-5S) in an external field of 1.0 T. Samples were carefully weighed into gelatin capsules, with empty gelatin capsules above and below to eliminate background contributions from the gelatin, which were loaded into plastic straws, and attached to the sample transport rod. Diamagnetic corrections were made using Pascal's constants.

2.3. Synthesis of $Fe(III)$ – mixed ligand complexes (4a–b)

The iron complexes (4a–b) were synthesized with slight modification to the previously reported method (Patil et al., 2012). To a mixed solution of 0.81 g $FeCl_3$ (5 mmol) and (0.725 g, 5 mmol) 8-hydroxyquinoline in 20 mL methanol, the amino acid (0.445 g alanine (ALA) or 0.746 g methionine (MET) that is 5 mmol) was added with constant stirring at 60 °C mild reflux. Precipitates were formed at pH ca 8 of the reaction mixture with 4 mL of dilute 0.2 M sodium hydroxide solution which enhanced deprotonation of the oxine hydroxyl group for chelation. The reaction mixture was cooled, and the solid product was collected by filtration, washed with diethyl ether and dried in vacuo.

$([Fe(HQ)(ALA)]Cl \cdot 2H_2O)$ 4a: Yield. 770 mg, 42.8%, Anal. Calc. for $C_{12}H_{16}ClFeN_2O_5$, C, 40.08; H, 4.49; N, 7.79; Found: C, 40.10; H, 4.36; N, 7.81; IR (KBr, cm^{-1}): 3741, 1600, 1465, UV (nm) 338, 382.

$([Fe(HQ)(MET)]Cl \cdot 2H_2O)$ 4b: Yield. 410 mg, 19.5%, Anal. Calc. for $C_{14}H_{20}ClFeN_2O_5S$, C, 40.07; H, 4.80; N, 6.67; Found: C, 40.10; H, 4.65; N, 6.68; IR (KBr, cm^{-1}): 3741, 1610, 1500, UV (nm) 334, 378.

2.4. Synthesis of $Cu(II)$ – mixed ligand complexes (4c–d)

The copper(II) complexes (4c–d) were prepared by the same method as described for iron complexes.

([Cu(HQ)(ALA)]) **4c** Yield. 1250 mg, 84.5%, Anal. Calc. for $C_{12}H_{11}CuN_2O_3$, C, 48.73; H, 4.09; N, 9.47; Found: C, 48.196; H, 4.10; N, 9.49; IR (KBr, cm^{-1}): 3417, 3050, 1620, 1465, UV (nm); 340, 404.

([Cu(HQ)(MET)]) **4d** Yield. 1320 mg, 74.2%, Anal. Calc. for $C_{14}H_{16}CuN_2O_3S$, C, 47.25; H, 4.53; N, 7.87; Found: C, 47.36; H, 4.55; N, 7.83; IR (KBr, cm^{-1}): 3500, 2954, 1615, 1411, UV (nm) 338, 380 (see Scheme 1).

2.5. Antibacterial screening in vitro

The antibacterial activities of the metal complexes **4a–d** were screened against some pathogens using the agar well diffusion method (Anaconda and Rodriguez, 2004). The 3% acetic acid was prepared by measuring 3 mL acetic acid into 97% distilled water. Stock solutions of the complexes were prepared by dissolving 10 mg of the complex in 10 mL of 3% sterile acetic acid. Sterile nutrient agar inoculated with the test organisms (media) was poured into sterilized petri-dishes and allowed to stand for some minutes, then a cork-borer with a diameter of 12 mm was used to bore uniform holes on the surfaces of the dried agars and into each hole was added 0.1 mL, 0.2 mL and 0.4 mL diluted aliquots (equivalent of 10, 20 and 40 $\mu g/mL$) from the stock solution of 1000 $\mu g/mL$. The plates were covered and incubated for 24 h at 37 °C. The process was repeated with sterilized water as a control while all other reagents were also screened. The observed zones of inhibition were measured in mm and average zone inhibitions were determined. Triplicate data were taken for the calculation of mean inhibition.

3. Results and discussion

3.1. Analytical and spectroscopic studies

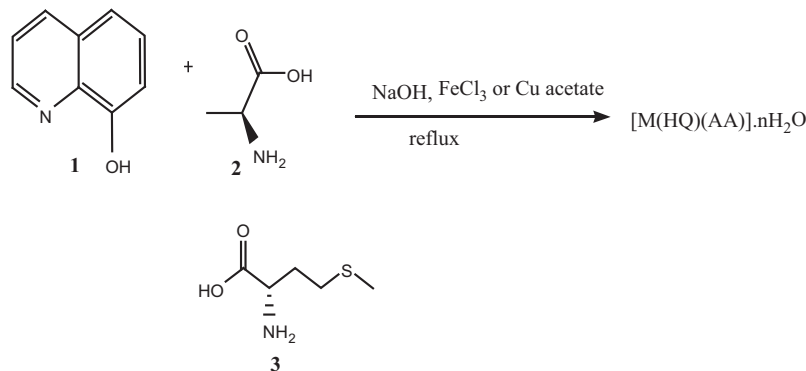
3.1.1. Molecular Structure Characterization of the compounds

All complexes are analytically pure. The iron(III) complexes **4a–b** obtained are black while copper(II) **4c–d** are greenish/grey colour powdery solids and air stable. The synthetic route yielded complexes of appreciable amount except complex **4b** with 19.5% yield. The complexes are partly soluble in less polar solvents but soluble in DMSO. The molar conductance values of the complexes in methanol are higher than their mixed ligands indicating relative ionic character, for instance **4a** is

15.3 $\mu S\ cm^{-1}$ and **4b** is 8.20 $\mu S\ cm^{-1}$ while **4c** and **4d** are 4.2 $\mu S\ cm^{-1}$, 3.2 $\mu S\ cm^{-1}$ respectively. All the complexes did not melt but decompose at temperature greater than their ligands; **4a–d** decompose from 164, 230, 220 and 199 °C respectively. Efforts to grow single crystals of complexes suitable for X-ray crystallography using variety of different techniques and solvent combinations have been unsuccessful. However, the elemental analysis results fit well with the proposed molecular formula; and on the basis of FT-IR and electronic transitions spectra we were able to predict the metal coordination upon the shift to lower energy level or disappearance in the vibrational frequencies of the donor atoms synonymous with previous reports (Labisbal et al., 2006; Anaconda and Rodriguez, 2004). For iron complexes **4a–b**, there is disappearance of hydroxyl (O–H) hydrogen bond attributed to coordination with the iron metal centre. The carbonyl group (C=O) vibrational frequency appeared red shifted with very weak intensity. The pyridine ring of the complexes showed strong absorption but with a bathochromic shift ca 25 cm^{-1} due to electron contribution to the coordination. No free O–H group was observed in the IR copper complexes **4c–d** spectra but the hydroxyl (O–H) appeared at 3417 cm^{-1} broad vibrational frequency while carbonyl bond (C=O) appeared around 1615–1620 cm^{-1} sharp and strong vibrational frequency. These bathochromic effects (ca 20 cm^{-1}) in the groups were attributed to coordination. See Fig. 1. The UV/visible spectra band assignment of the ligands and their complexes in dimethylsulphoxide gave electronic transitions in terms of bands due to their electron transfer within the ligands, charge transfer transition from ligand orbitals to the central atom or d–d electronic transition as case may be. No visible region was observed for iron complexes i.e. there is no d–d transition, non-degenerate 6A_1 however, complex **4c** contains a visible spectrum around 404 nm attributed to MLCT or d–d transition $^2E_g \rightarrow ^2T_{2g}$.

3.2. Magnetic properties

The magnetic behaviour for the complexes was followed by measurements of the molar magnetic susceptibility (χ_m) as a function of temperature (T). The temperature dependence of $\chi_m T$ for iron complexes is displayed in Fig. 2a. The $\chi_m T$ value for the complexes **4a–b** equals 4.77 $cm^3\ Kmol^{-1}$ at 400 K, which shows that Fe(III) site, is in the high spin (HS) state ($S = 5/2$), and $\chi_m T$ value steadily decrease until it reaches zero. This is antiferromagnetic behaviour, as no spin-cross



Scheme 1 Synthesis of the metal complexes (**4a–d**).

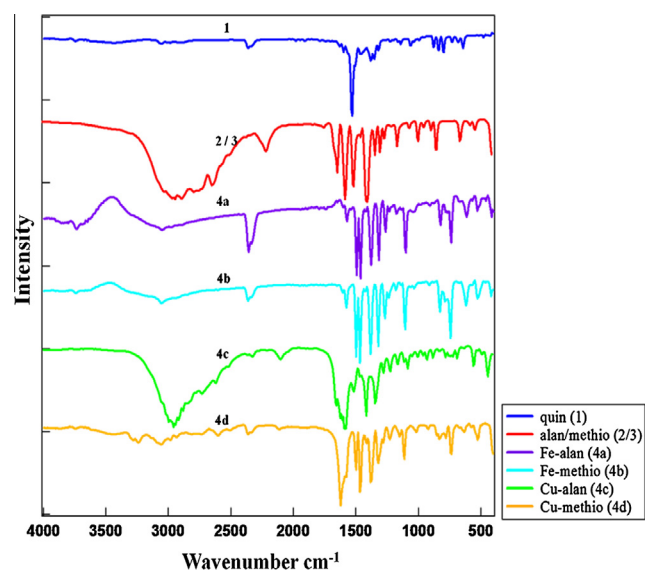


Figure 1 IR spectra of the ligands and complexes (4a–d).

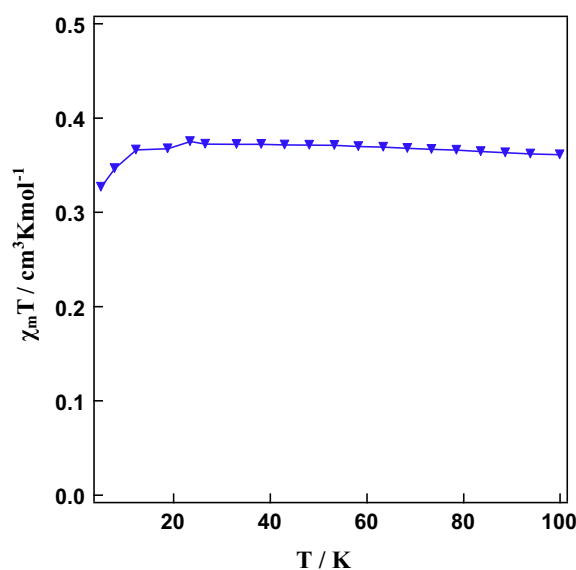


Figure 2b $\chi_m T$ versus T plots for complex (4c–d).

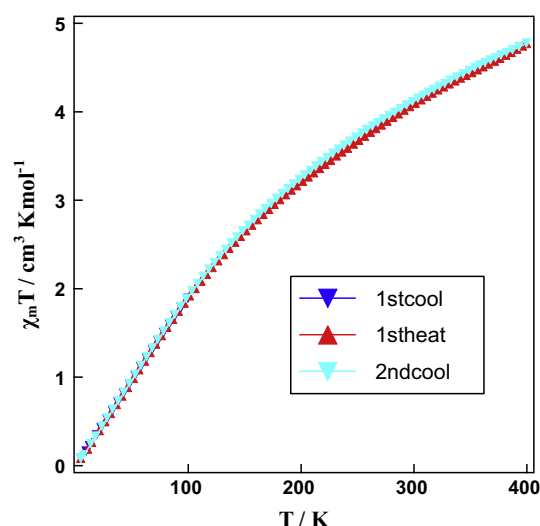


Figure 2a $\chi_m T$ versus T plots for complex (4a–b).

over (SCO) phenomenon (LS–HS) was observed between the iron d-orbitals suspected to be due to ligand field effect. The iron complexes were cooled from 400 to 5 K (2-cycles) and then warmed from 5 to 400 K (1-cycle) at a rate of 2 K min^{−1}. The temperature dependence of $\chi_m T$ for copper complexes is displayed in Fig. 2b. The magnetic behaviour of the copper complexes 4c–d was investigated between 100 and 5 K at a rate of 2 K min^{−1}. The $\chi_m T$ value for the complexes is equal to 0.38 cm³ Kmol^{−1} at 22 K, corresponds to copper(II) oxidation state with spin state ($S = 1/2$), and only one unpaired electron (paramagnetic). The Cu²⁺ is not a spin crossover d-orbital and therefore exhibits no molecular bistability (HS–LS) spin transition. It is thought that the decrease of $\chi_m T$ value below 15 K is due to zero field splitting (Singh et al., 2010; Kahn, 1993) (see Figs. 3a and 3b).

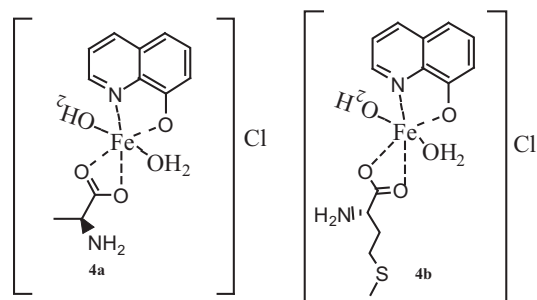


Figure 3a Iron octahedral geometry complexes.

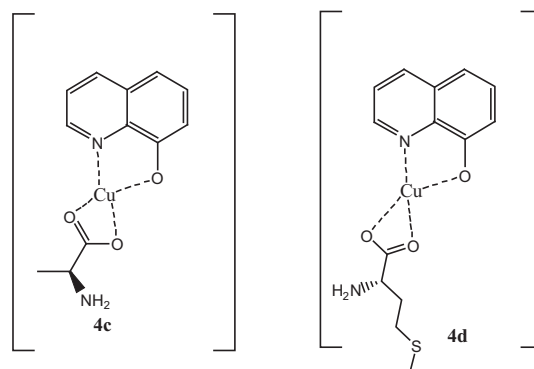


Figure 3b Copper tetrahedral geometry complexes.

3.3. Antibacterial activities

The antibacterial activities of all the compounds were screened against some standards bacterial agents (Table 1). Different concentrations for each compound were investigated against standard bacterial strains. The result showed that the metal

Table 1 Inhibition zone (mm) of complexes and other compounds against some standard. Microorganisms at different concentrations ($\mu\text{g/ml}$).^a

Ligands	Microorganisms											
	<i>S. aureus</i> ($\mu\text{g/ml}$)			<i>P. aeruginosa</i> ($\mu\text{g/ml}$)			<i>E. coli</i> ($\mu\text{g/ml}$)			<i>E. faecalis</i> ($\mu\text{g/ml}$)		
Complexes	1	2	4	1	2	4	1	2	4	1	2	4
Oxine (1)	31 mm	30 mm	27 mm	25 mm	23 mm	29 mm	20 mm	24 mm	32 mm	30 mm	30 mm	38 mm
Alanine (2)	30 mm	29 mm	30 mm	31 mm	29 mm	31 mm	30 mm	26 mm	26 mm	28 mm	26 mm	27 mm
Methionine (3)	31 mm	28 mm	–	30 mm	29 mm	–	29 mm	27 mm	–	23 mm	21 mm	–
FeCl_3	08 mm	10-	12-	30 mm	35 mm	36 mm	Nil	Nil	6 mm	Nil	Nil	Nil
$\text{Cu}(\text{ac})_2 \cdot \text{H}_2\text{O}$	04 mm	08 mm	10 mm	29 mm	29 mm	30 mm	Nil	Nil	12 mm	Nil	Nil	06 mm
3% Acetic acid	0 mm	Nil	Nil	Nil	Nil	8 mm	Nil	Nil	Nil	Nil	Nil	Nil
Sterile water	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
4a	34 mm	32 mm	31 mm	30 mm	28 mm	29 mm	28 mm	33 mm	31 mm	21 mm	25 mm	25 mm
4b	34 mm	30 mm	35 mm	34 mm	30 mm	30 mm	32 mm	28 mm	31 mm	25 mm	24 mm	21 mm
4c	41 mm	25 mm	28 mm	43 mm	21 mm	25 mm	35 mm	24 mm	34 mm	39 mm	28 mm	30 mm
4d	24 mm	28 mm	25 mm	32 mm	30 mm	32 mm	24 mm	26 mm	26 mm	20 mm	18 mm	18 mm

^a All experiments were done in triplicate.

complexes were found to be more active than the ligands and metal salts. At 10 ppm, Fe(III) – methionine-quinolinol mixed ligand complex **4b** was found to exert greater inhibitory activity against all the organisms than the alanine-quinolinol chelates **4a**. This may be due to the presence of sulphur in the methionine. The control (sterile water) did not show any inhibitory level as expected. Whereas, acetic acid showed the inhibitory level of 8 mm in *P. aeruginosa* but showed no inhibitory level in all other microbes. The metal salts showed only little or no inhibition. This further confirms that chelation tends to make the ligand to act as more powerful and potent bacterial agent (Crowder et al., 2006; Page and Badarau, 2008). The copper chelates system complex **4c** was found to demonstrate higher inhibition (43 mm) at 10 ppm against *P. aeruginosa* compared with all other chelates, this may be attributed to the mobilized electron in the copper orbital as indicated by its magnetic property (Mwadham, 2013; Podunavac-Kuzmanovic, 2007; Patel et al., 2012). Presence of free electron in the Cu^{2+} empowers its strong oxidative molecular activity for inhibitory ability on microorganisms as this re-emphasize the copper(II) ions as a key cofactor in a diverse array of biological oxidation–reduction reactions (Mwadham, 2013; Podunavac-Kuzmanovic, 2007; Jezowska, 2001; Jezowska et al., 1998; Solomon et al., 1996).

4. Conclusions

Hydroxyquinoline (HQ) and amino acids (AA) mixed ligands with Fe(III) and Cu(II) ions producing four bioactive metal complexes have been synthesized. The results of spectroscopy, elemental analyses and molar magnetic susceptibility parameters indicate that geometry of the two iron complexes: $[\text{Fe}(\text{HQ})(\text{AA})_2 \cdot 2\text{H}_2\text{O}]\text{Cl}$ (**4a–b**) are octahedral geometry while the two copper complexes: $[\text{Cu}(\text{HQ})(\text{AA})_2]$ (**4c–d**) are tetrahedral geometry. The spin transition of $\chi_m T = 0.38 \text{ cm}^3 \text{ K mol}^{-1}$ characteristic of Fe(III) complexes showed antiferromagnetic while Cu(II) of $\chi_m T = 4.77$ is a paramagnetic property. The synthesized metal complexes show excellent inhibition on the standard test microorganisms particularly the Cu^{2+} complex **4c** than their parent ligands which was attributed to the

enhanced kinetic lability of the alanine-amino acid ligand which, through Jahn–Teller distortion, may assist the ligand exchange and binding to the organisms. We would in nearest future based on our quest for metal based antiparasitic drugs research into construction of more highly active free electrons metal-chelates and/or with ferromagnetic property optimistic to be of interesting property for achieving robust antimicrobial therapy formulations.

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References

- Agwara, M.O., Ndifon, P.T., Ndosiri, N.B., Paboudam, A.G., Yufanyi, D.M., Mohamadou, A., 2010. Synthesis, characterization and antimicrobial activities of cobalt(II), copper(II) and zinc (II) mixed ligand complexes containing 1,10 phenanthroline and 2,2' bipyridine. *Bull. Chem. Soc. Ethiop.* 24 (3), 383–389.
- Albert, E., 1979. Selective Toxicity. The Physicochemical Basis of Therapy. Chapman and Hall, London, p. 346.
- Albert, A., Gibson, M.I., Rubbo, S.D., 1953. The influence of chemical constitution on antibacterial activity VI The bactericidal action of 8-hydroxyquinoline (oxine). *J. Exp. Pathol.* 34, 119–130.
- Anacona, J.R., Rodriguez, I., 2004. Synthesis and antibacterial activity of cephalixin metal complexes. *J. Coord. Chem.* 57, 1263–1269.
- Che, C.M., Siu, F.M., 2010. Metal complexes in medicine with a focus on enzyme inhibition. *Curr. Opin. Chem. Biol.* 14, 255–261.
- Coyle, B., McCann, M., Kavanagh, K., Devereux, M., McKee, V., Kayal, N., Egan, D., Deegan, C., Finn, G.J., 2004. Synthesis, X-ray crystal structure, anti-fungal and anti-cancer activity of $[\text{Ag}_2(\text{NH}_3)_2(\text{salH}_2)] \text{salH}_2 = \text{salicylic acid}$. *J. Inorg. Biochem.* 98, 1361–1366.
- Crowder, M.W., Spencer, J., Vila, A.J., 2006. Metallo-beta-lactamases: novel weaponry for antibiotic resistance in bacteria. *Acc. Chem. Res.* 39, 721–728.

- Eddie, L.C., Christa, S., Knight, D.A., 2010. Cobalt complexes as antiviral and antibacterial agents. *Pharmaceuticals* 3, 1711–1728.
- Freeman, H.C., 1973. Metal complexes of amino acids and peptides. *Inorganic Biochemistry Elsevier*, vol. 1. In: Eichhorn, G.L., (Ed.), Amsterdam, The Netherlands. p. 121.
- Gaurav, B., Neeraj, K., Rajesh, T., Neeraj, D., Sandeep, K., 2011. Antimicrobial Activity of Metal and Oxide Nanoparticles Interfaced With Ligand Complexes of 8-Hydroxyquinoline And Amino Acids AIP Conference Proceeding 1393. pp. 173–174.
- Irbaraj, J.J., Motten, A.G., Chignell, C.F., 2003. Photochemical and photobiological studies of tirapazamine (SR 4233) and related quinoxaline 1,4-di-N-oxide analogues. *Chem. Res. Toxicol.* 16 (2), 164–170.
- Jezowska, B.M., 2001. Copper(II)-lincomycin complexation pattern and oxidative activity. *J. Inorg. Biochem.* 84, 189–200.
- Jezowska, B.M., Karaczyn, A., Kozlowski, H., 1998. Copper(II) binding to tobramycin potentiometric and spectroscopy studies. *Carbohydr. Res.* 313, 265–269.
- Kahn, O., 1993. *Molecular Magnetism*. Wiley-VCH, New York.
- Khalafi-Neshad, A., Soltani Rad, M.N., Mohabatkari, H., Asrari, Z., Hemmateenejad, B., 2005. Design, synthesis, antibacterial and QSAR studies of benzimidazole and imidazole chloaryloxyalkyl derivatives. *Bioorg. Med. Chem.* 13, 1931–1938.
- Khalil, S.M.E., Shebl, M., Al-Gohani, F.S., 2010. Zn(II) thiosemicarbazone complex as a ligand towards some transition metal ions: synthesis, spectroscopic and antimicrobial studies. *Acta Chim. Slov.* 57, 716–725.
- Kumar, K.S., Chityala, V.K., Subhashini, N.J.P., Prashanthi, Y., Shivaraj, 2013. Synthesis, characterization, and biological and cytotoxic studies of copper (II) binary complexes of 3-amino-5-methyl isoxazole schiff base. *ISRN Inorg. Chem.* 10, 1–7.
- Labisbal, E., Rodriguez, L., Sousa-Pedrares, A., Alonso, M., Vizoso, A., Romero, J., Garcia-Vazquez, J.A., Sousa, A., 2006. Synthesis, characterisation and X-ray structures of diorganotin(IV) and iron(III) complexes of dianionic terdentate Schiff base ligands. *J. Organomet. Chem.* 691, 1321–1332.
- Mashaly, M.M., Ismail, T.M., El-Maraghy, S.B., Habib, H.A., 2004. Heteronuclear complexes of oxorhenium(V) with Fe(III), Co(II), Ni(II), Cu(II), Cd(II) and UO₂(VI) and their biological activities. *J. Coord. Chem.* 57 (13), 1099–1123.
- Moustafa, M.E., 2005. Synthesis and structural and biological activity studies on some lanthanides chelates with O- and N-containing ligands. *Spectrosc. Lett.* 38 (1), 23–24.
- Mwadham, M.K., Eno, E.E., 2013. Structure, stabilization energies, and binding energies of quinoxaline (H₂O)_n, quinoxaline dimer, and quinoxaline Cu complexes: a theoretical study. *J. Phys. Chem. A* 117, 1583–1595.
- Ndosiri, N.B., Agwara, M.O., Paboudam, A.G., Ndong, P.T., Yufanyi, D.M., Amah, C., 2013. Synthesis, characterization and antimicrobial evaluation of Mn(II), Co(II), Ni(II), Cu(II), and Zn(II) complexes of pyridine-2-carboxylic acid. *RJPBCS* 4 (2), 1370–1381.
- Noorulla, S., Sreenivasulu, N., 2011. Antibacterial activity of novel substituted quinoxaline heterocycles with isoniazide. *Int. J. Res. Pharm. Biomed. Sci.* 2 (3), 1100–1106.
- Page, M.I., Badarau, A., 2008. The mechanisms of catalysis by metallo beta-lactamases. *Bioinorg. Chem. Appl.* 23, 1–14.
- Patel, K.P., 2011. Synthesis and characterization of some ternary complexes of Zn(II) and Cd(II) and their antimicrobial activity. *Int. J. Chem. Sci.* 9 (1), 149–153.
- Patel, K.B., Kharadi, G.J., Nimavat, K.S., 2012. Synthesis and description of transition metal complexes and antimicrobial studies. *J. Chem. Pharm. Res.* 4 (5), 2422–2428.
- Patil, S.S., Thakur, G.A., Shaikh, M.M., 2012. Synthesis, spectral, thermal and antibacterial investigations of mixed ligand complexes of thorium(IV) derived from 8-hydroxyquinoline and some amino acids. *Acta Pol. Pharm. – Drug Res.* 69 (6), 1087–1093.
- Podunavac-Kuzmanovic, S.O., Cvetkovic, D.C., 2007. Anion effect on antimicrobial activity of metal complexes with benzimidazole derivative. *Chem. Indust. Chem. Eng. Q.* 13 (2), 68–71.
- Podunavac-Kuzmanovic, S.O., Cvetkovic, D.C., 2011. QSAR modeling of antibacterial activity of some benzimidazole derivatives. *Chem. Indust. Chem. Eng. Q.* 17 (1), 33–38.
- Prafulla, M.S., Jahanvi, P., Yogini, P., 2012. Metal complexes: current trends and future potential. *IJPCBS* 2 (3), 251–265.
- Roserberg, B., 1978. *Interdiscipl. Sci. Rev.* 3, 134.
- Singh, D.P., Deivedi, S.K., Hashim, S.R., Singhal, R.G., 2010. Synthesis and antimicrobial activity of some new quinoxaline derivatives. *Pharmaceuticals* 3 (8), 2416–2425.
- Solanki, M.R., Acharya, G.D., Hathi, M.V., 2009. Synthesis characterization and biological investigations on metal complexes of 2-[(8-Hydroxy-1-quinolin-5-yl) methyl]-1H-isoindole-1, 3 (2H) dione. *E-J. Chem.* 6 (4), 1023–1028.
- Solomon, E.I., Sundaram, U.M., Machonkin, T.E., 1996. Multicopper oxidases and oxygenases. *Chem. Rev.* 96, 2563–2605.
- Zarranz, B., Jaso, A., Aldana, I., Monge, A., 2003. Synthesis and antimycobacterial activity of new quinoxaline-2-carboxamide 1,4-di-N-oxide derivatives. *Bioorg. Med. Chem.* 11, 2149–2156.