

Schiff Base Complex of Cu (II) with Antibacterial and Electrochemical Study

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Abstract The complex *N, N'*-Disalicylideneethylenediaminecopper (2) has been prepared and the structure of the complex is confirmed from the IR, ¹H NMR, and Elemental analysis. In solid state the complex packs as a dimer with square pyramidal geometry. A reversible cyclic voltammogram (CV) is found from an electrochemical study that involves one electron redox process. The antibacterial activity of the complex is investigated against *E. Coli* and *Shigella Dysenteriae* gram negative bacteria where streptomycin antibiotic is used as a standard, and the complex has shown good inhibition towards the growth of these gram-negative bacteria.

Keywords Bacteria, Conductance, Complex, Ligand, Antibiotic

1. Introduction

The synthesis and study of Schiff base metal complexes [1] were started in the year 1984 since they have some potential applications as a catalyst [2-5], binding DNA [6], cleaving DNA [7-9], anticancer [10-11], antitumor [12-14] and antioxidants [15-20]. It was also noted that these class of compounds show some interesting magnetic [21] and optical [22-23] properties. Additionally, Schiff base metal complexes are being studied for oxygen reduction catalyst that is important in fuel cell [24-25] technology and in biological system [26]. Recently, a group has concentrated for using metal Schiff base complexes to track sub terranean fluid flow [27]. Considering the importance of their versatile applicability Schiff base metal complexes are still being studied by various research groups all over the world [28-33].

In this article, it is demonstrating the synthesis and characterization of Cu(salen) Schiff base [34] complex (2). This will be a possible application as a catalyst [35-38] in the future. This complex may also be possible to apply as an antimicrobial agent [39]. Previously, the complex was reported by a few research groups [40-42]. It exists as a dimeric form in solid state, and in solution it may exist as a smaller proportion of dimeric form or may be in the equilibrium [43-44] between dimer and monomer. However, it has been noted that from the birth of the Schiff base chemistry it has synthesized a large family of different

types of Schiff base metal complexes and some of them have been published without having any potential application. In this article, it is aimed to synthesize the Cu(salen) complex (2) again to investigate its antibacterial and electrochemical properties. It is believed that this research will be helpful for the future development of antibacterial drugs against various types of gram-negative bacteria. Additionally, electrochemical study will be helpful for the future development of electrocatalyst.

2. Experimental

2.1. Material and Measurements

All chemicals were purchased from commercially available sources and used without further purification. The conductance was measured by using Elico-conductometer. The IR spectrum was recorded by Perkin-Elmer spectrophotometer in KBr pellets. The UV-Visible spectrum was recorded in CHCl₃ on Beckman DU-64 spectrophotometer with quartz cells of 1 cm path length. ¹H NMR spectrum was recorded in CDCl₃ by Bruker Advance 400 MHz instrument. Melting point was determined from Fisher apparatus (up to 350°C).

2.2. Synthesis of the Schiff Base

30 ml of acidic (2 ml glacial acetic acid) ethanolic solution of salicylaldehyde (8.1412g, 66.66 mmol) was stirred for 10 min [26]. To the solution, ethylenediamine (2g, 33.28 mmol) was added drop wise, and finally, yellow color *N, N'*-bis(salicylidene)ethylenediamine was collected by filtering (Scheme 1). The whole solution was stirred for 4h at RT. The resulting crude product was recrystallized in CHCl₃ at room

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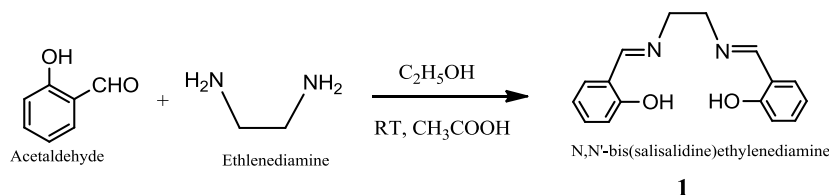
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temperature. Spectral data: Anal. Cal. For $C_{16}H_{16}N_2O_2$: C, 71.63; H, 6.01; N, 10.44. Found: C, 70.69; H, 6.19; N, 9.91. IR (ν CO, KBr): 3455 (OH, b), 3052 (ArC-H, w), 3014 (N=C-H, w), 2937 (CH_2 , w), 2860 (CH_2 , w), 1636 (C=N, vs),

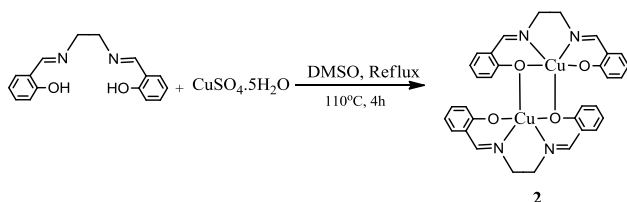
1578 (ArC=C, s), 1198 (C-C, s), 1283 (C-O, m), 1148 (C-N, vs). 1H NMR ($CDCl_3$): δ 13.2 (2H, s), δ 7.3-6.9 (8H, m), 8.4 (2H, s), 3.9 (4H, S).



Scheme 1. Synthesis of N, N'-bis(salicylidene)ethylene-diamine Schiff base

2.3. Synthesis of Metal Complex

0.4658 g (1.87 mmol) of $CuSO_4 \cdot 5H_2O$ was dissolved in 20 mL DMSO (dimethyl sulfoxide) and stirred for 30 min, and in another pot 0.500 g (1.87 mmol) of N, N'-Ethylenebis (salicylimine) (**1**) was also dissolved in 10 ml of DMSO. The Schiff base **1** was added to the metal salt solution and the resulting solution was refluxed for 4h. Finally, black crystalline material was separated and recrystallized in $CHCl_3$ (0.63g, 77.46%) (scheme 2). Spectral data: Anal. Cal. For $C_{32}H_{28}N_4O_4Cu_2$: C, 58.25; H, 4.28; N, 8.49. Found: C, 56.72; H, 4.44; N, 8.04. IR (ν CO, KBr): 3444 (H_2O -OH, b), 3052 (ArC-H, w), 3018 (N=CH, s) 2929 (CH_2 , w), 2853 (CH_2 , w), 1647 (C=N, vs), 1528 (ArC=C, s), 1191 (C-C, s), 1233 (C-O, m), 1137 (C-N, vs), 561 (Cu-N), 465 (Cu-O, m). 1H NMR ($CDCl_3$): δ 7.0-7.4 (8H, m), δ 8.1 (2H, s) δ 3.4 (4H, s), δ 1.6 (2H- H_2O , s). Melting Pont: $>300^\circ C$. Molecular conductance ($\mu S/cm$): 8.6 (DMSO), 9.6 (MeOH), 0 ($CHCl_3$). UV-Visible (λ_{max} , $CHCl_3$): 244, 275, 366, 570.



Scheme 2. Synthesis of N, N'-Disalicylideneethylene-diaminecopper

3. Result and Discussion

The synthesis of the Schiff base metal complex (**2**) are involved in two steps. The first step is the synthesis of the Schiff base ligand (**1**) (section 2.2, scheme 1). Next, this ligand is used for complexing with metal (section 2.3, scheme 2). The complexation reaction was done in solvent DMSO to achieve higher temperature. The IR and 1H NMR data of the ligand is shown in section 2.2.

The structure was investigated by infrared spectroscopy (IR) and the aromatic C-H gave stretching at 3052 cm^{-1} , imine C=N was found at 1647 cm^{-1} , aromatic C=C gave at 1528 cm^{-1} . The aliphatic ethylene group C-H symmetric and asymmetric stretching were found 2853 cm^{-1} and 2929 cm^{-1} , respectively. The details of other respective IR stretching values are given in the section 2.3.

The 1H NMR was recorded in $CDCl_3$, but due to poor solubility and the paramagnetic nature of the Cu (II) metal, the spectrum is not looking good. The aromatic protons gave multiplets at δ 7.0-7.4 (8H) and the two imine CH=N proton gave singlet at δ 8.1. The four ethylene protons gave singlet at δ 3.4 (4H, s). The melting point of the complex was determined and found above $300^\circ C$. The UV-Visible spectrum was recorded in $CHCl_3$ and two absorption peaks were detected at 275 and 366. The molecular conductivity was measured, and the conductivity was found very small (section 2.3). So, it is possible to conclude that the complex **2** acts as a poor electrolyte.

4. Electrochemical Study

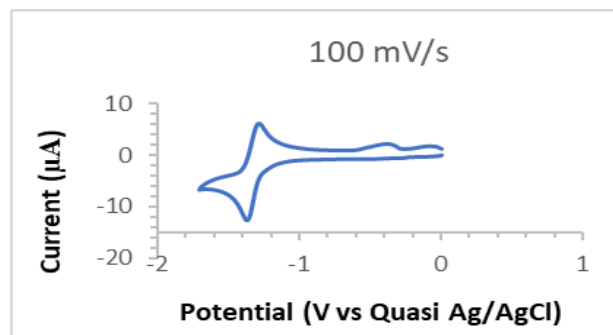


Figure 1. Cyclic voltammogram (CV) (Red to Ox) of the 0.1 mM Cu(salen) complex (**2**), the glassy carbon working electrode, Quasi Ag/AgCl reference electrode

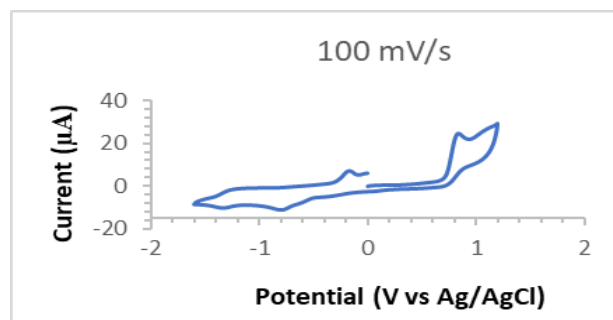


Figure 2. Cyclic voltammogram (CV) (Ox to Red) of the 0.1 mM Cu(salen) complex (**2**), the glassy carbon working electrode, Quasi Ag/AgCl reference electrode

The CV of the complex **2** was recorded from 0 to -2 V (Figure 1) with scan rate 100 mV/s under Ar atmosphere and

it went through a reversible redox process that involves one electron. This indicates that Cu^{II} goes to Cu^{I} after receiving an electron during negative scan, and later giving back that electron, it turns into the +2-oxidation state. The peak current (i_p) was found $11 \mu\text{A}$. But, when it is first oxidized, the process involves two electrons (Figure 2). May be this is due to the Cu^{II} to Cu^{III} state [35] and the residual ligand moiety may also oxidize. 10 mL of 0.1M $[\text{nBu}_4\text{N}]\text{BF}_4$ in dimethyl sulfoxide (DMSO) was used as electrolyte during studying electrochemistry. The glassy carbon was used as the working electrode and quasi Ag/AgCl was used as the reference electrode and counter electrode used Pt wire. The cyclic voltammogram indicates that the complex in the solution acts as monomer since the electrochemical process involves only one electron [35]. The CV of the complex **2** was also studied in MeCN and found similar result as in DMSO.

5. Antibacterial Study

5.1. Antibacterial Activity in Muller Hinton Agar Media

11.4 g of Muller Hinton agar was dissolved in 300 ml of distilled water, and after shaking was put into autoclave for $\frac{1}{2}$ h at 121°C . The resulting solution was poured into eight plates (disk) and the plates rested for 10 min. $10\mu\text{l}$ *E. coli* gram negative bacteria were applied to all disks uniformly and at the center of a plate standard antibiotic streptomycin was placed. In a test tube, 1mg of metal complex dissolved in 1ml CHCl_3 , and $10\mu\text{l}$ of the sample was dropped in the bacterial disks. It happens that CHCl_3 inhibits the bacterial growth, and in a separate disk, $10\mu\text{l}$ CHCl_3 was dropped to know the inhibition by CHCl_3 . All procedures were repeated for *Shigella Sonnei*, gram negative bacteria.



Figure 3. Antibacterial study of the Cu(salen): The bacteria is *Shigella Sonnei* and the media is Muller Hinton agar. 1A and 4A are Cu(salen) dimer complex, A is antibiotic streptomycin disk, C is CHCl_3

5.2. Antibacterial Study of the Cu(salen) (2)

The complex was tested against two-gram negative bacteria *E. Coli* and *Shigella Sonnei*. The complex inhibited the growth of *E. Coli* bacteria and found the length of inhibition around 40 mm. Alternately, the complex showed

negative result for *Shigella Sonnei*. The *E. Coli* and the *Shigella Sonnei* were grown in Muller Hinton Agar (MHA) media. The detail of the process is described in the supporting information (Figure 3 and Figure 4) and streptomycin was used as the standard.



Figure 4. Antibacterial study of the Cu(salen) complex: the bacteria is *E. Coli* in Muller Hinton Agar; 10 M, 12M is Cu(salen) complex, C is CHCl_3

6. Conclusions

The synthesis of the Cu(salen) complex (**2**) has been successful and has found good results from electrochemical and antibacterial studies. Antibacterial study suggests the complex is effective to inhibit the growth of *E. Coli*. The electrochemistry study suggests the complex will be good for one electron redox process. In the future, more research will be focused to give potential applications of some other Schiff base metal complexes.

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REFERENCES

- [1] Mandal, S. K., Nag, K., 1984, Synthesis of Phenoxo-bridged Dicopper (II) Complexes of N-(2-Aminoalkyl) salicyl aldimines and Their Use in the Formation of Monohalogeno-complexes and Non-symmetrical Quadridentate Schiff-base Complexes, J. Chem. Soc. Dalton trans, 2839-2841.
- [2] Ziegler, M. S., Lakshmi, K. V., Tilley, T. D., 2017, Dicopper Cu(I)Cu(I) and Cu(I) Cu(II) Complexes in Copper-Catalyzed Azide-Alkyne Cycloaddition, J. Am. Chem. Soc. 139, 5378-5386.

- [3] Warzeska, J. M., Pritzkow, S., Wadepohl, H., Imhof, P., Smith, J. C., Kreamer, R., 2005, Catalytic Transesterification of Dialkyl Phosphates by a Bioinspired Dicopper (II) Macrocyclic Complex, *J. Am. Chem. Soc.* 127 (43), 15061–15070.
- [4] Torelli, S., Belle, C., Gautier, L. I., Pierre, J. L., Saint, A. E., Latour, J. M., Le, P. L., Luneau, D., 2000, pH-Controlled Change of the Metal Coordination in a Dicopper (II) Complex of the Ligand H-BPMP: Crystal Structures, Magnetic Properties, and Catecholase Activity, *Inorg. Chem.* 39(16), 3526–3536.
- [5] Tai, A. F., Margerum, L. D., Valentine, J. S., 1986, Epoxidation of olefins by iodosylbenzene catalyzed by binuclear copper(II) complexes, *J. Am. Chem. Soc.* 108 (16), 5006–5008.
- [6] Amendola, V., Fabbri, L., Mangano, C., Pallavicini, P., Poggi, A., Taglietti, A., 2001, Anion recognition by dimetallic cryptates, *Coord. Chem. Rev.* 219–221, 821–837.
- [7] Anbu, S., Kandaswamy, M., Suthakaran, P., Murugan, V., Varghese, B., 2009, Structural, magnetic, electrochemical, catalytic, DNA binding and cleavage studies of new macrocyclic binuclear copper (II) complexes, *J. Inorg. Biochem.* 103 (3), 401–410.
- [8] Raman, N., Sakthivel, A., Rajasekaran, K., 2009, Design, structural elucidation, DNA interaction and antimicrobial activities of metal complexes containing tetraazamacrocyclic Schiff bases, *J. Coord. Chem.* 62 (10), 1661–1676.
- [9] Sreedaran, S., Shanmuga, B. K., Kalilur, R. A., Jagadish, L., Kaviyaranan, V., Narayanan, V., 2008, Novel unsymmetrical macrocyclic dicompartmental binuclear copper(II) complexes bearing 4- and 6-coordination sites: Electrochemical, magnetic, catalytic and antimicrobial studies, *Polyhedron*. 27 (13), 2931–2938.
- [10] Fandzloch, M., Dobrzańska, L., Jezierska, J., Psurska, B. F., Wiśniewska, J., Wietrzyk, J., Manuel, S. J., Lakomska, I., 2018, In search of new anticancer drug – Dimethylsulfoxide ruthenium(III) complex with bulky triazolopyrimidine derivative and preliminary studies towards understanding the mode of action, *Polyhedron*. 141, 239–246.
- [11] Wu, D., Guo, L., Li, S. J., 2020, Synthesis, structural characterization and anti-breast cancer activity, evaluation of three new Schiff base metal (II) complexes and their nanoparticles, *J. Mol. Struct.* 1199, 126938.
- [12] Zhang, H., Thomas, R., Oupicky, D., Peng, F., 2008, Synthesis and characterization of new copper thiosemicarbazone complexes with an ONNS quadridentate system: cell growth inhibition, S-phase cell cycle arrest and proapoptotic activities on cisplatin-resistant neuroblastoma cells, *J. Biol. Inorg. Chem.* 13, 47–55.
- [13] Yu, Y., Kalinowski, D. S., Kovacevic, Z., Siafakas, A. R., Jansson, P. J., Stefani, C., Lovejoy, D. B., Sharpe, P. C., Bernhardt, P. V., Richardson, D. R., 2009, Thiosemicarbazones from the Old to New: Iron Chelators That Are More Than Just Ribonucleotide Reductase Inhibitors, *J. Med. Chem.* 52, 5271–5294.
- [14] Arguelles, M. C. R., Vazquez, S. M., Matalobos, J. S., Deibe, A. M. G., Pelizzi, C., F. Zani, F., 2010, Evaluation of the antimicrobial activity of some chloro complexes of imidazole-2-carbaldehyde semicarbazone: X-ray crystal structure of *cis*-NiCl₂(H₂L)(H₂O), *Polyhedron*. 29, 864–870.
- [15] Tojal, J. G., Orad, A. G., Diaz, A. A., Serra, J. L., Urriaga, M. K., Arriortua, M. I., Rojo, T., 2001, Biological activity of complexes derived from pyridine-2-carbaldehyde thiosemicarbazone: Structure of [Co(C₇H₇N₄S)₂][NCS], *J. Inorg. Biochem.* 84, 271–278.
- [16] Ayaan, U. E., Youssef, M. M., Shihry, S. A., 2009, Mn(II), Co(II), Zn(II), Fe(III) and U (VI) complexes of 2-acetylpyridine 4N-(2-pyridyl) thiosemicarbazone (HAPT); structural, spectroscopic and biological studies, *J. Mol. Struct.* 936, 213–219.
- [17] Prabhakaran, R., Kalaivani, P., Poornima, P., Dallemer, F., Paramaguru, G., Padma, V. V., Renganathan, R., Huang, R., Natarajan, K., 2012, One pot synthesis of structurally different mono and dimeric Ni(II) thiosemicarbazone complexes and N-arylation on a coordinated ligand: a comparative biological study, *Dalton Trans.* 41, 9323–9336.
- [18] Lukmantara, A. Y., Kalinowski, D. S., Kumar, N., Richardson, D. R., 2013, Synthesis, and biological evaluation of substituted 2-benzoylpyridine thiosemicarbazones: Novel structure–activity relationships underpinning their anti-proliferative and chelation efficacy, *Bioorg. Med. Chem. Lett.* 23, 967–974.
- [19] Serda, M., Kalinowski, D. S., Wilczkiewicz, A. M., Musiol, R., Szurko, A., Ratuszna, A., Pantarat, N., Kovacevic, Z., Merlot, A. M., Richardson, D. R., Polanski, J., 2012, Synthesis and characterization of quinoline-based thiosemicarbazones and correlation of cellular iron-binding efficacy to anti-tumor efficacy, *Bioorg. Med. Chem. Lett.* 22, 5527–5531.
- [20] Walcourt, A., Loyevsky, M., Lovejoy, D. B., Gordeuk, V. R., D. R. Richardson, D. R., 2004, Novel aroylhydrazones and thiosemicarbazone iron chelators with anti-malarial activity against chloroquine-resistant and -sensitive parasites, *Int. J. Biochem. Cell Biol.* 36, 401–407.
- [21] (a) Miyasaka, H., Saitoh, A., Abe, S., 2007, Magnetic assemblies based on Mn(III) salen analogues, *Coord. Chem. Rev.* 251, 2622–2664. (b) Yazigi, D. V., Aravena, D., Spodine, E., Ruiz, E., Alvarez, S., 2010, Structural and electronic effects on the exchange interactions in dinuclear bis(phenoxo)-bridged copper (II) complexes, *Coord. Chem. Rev.* 254, 2086–2095. (c) Novoa, N., Justaud, F., Hamon, P., Roisnel, T., Cador, O., Guennic, B. L., Manzur, C., Carrillo, D., Hamon, J. R., 2015, Doubly phenoxide-bridged binuclear copper(II) complexes with one tridentate schiff base ligand: Synthesis, structural, magnetic and theoretical studies, *Polyhedron* 86, 81–88. (d) Costes, J. P., S. Padilla, S. T., Oyarzabal, I., Gupta, T., Duhayon, C., Rajaraman, G., Colacio, E., 2016, Effect of Ligand Substitution around the DyIII on the SMM Properties of Dual-Luminescent Zn–Dy and Zn–Dy–Zn Complexes with Large Anisotropy Energy Barriers: A Combined Theoretical and Experimental Magnetostructural Study, *Inorg. Chem.* 55, 4428–4440.
- [22] (a) Lacroix, P. G., Malfant, I., Lepetit, C., 2016, Second-order nonlinear optics in coordination chemistry: An open door towards multi-functional materials and molecular switches, *Coord. Chem. Rev.* 308, 381–394; (b) Nayar, C. R., Ravikumar, R., 2014, Review: Second order nonlinearities of Schiff bases derived from salicylaldehyde and their metal complexes *J. Coord. Chem.* 67, 1–16. (c) Lacroix, P. G.,

- 2001, *Eur. J. Inorg. Chem.*, 339. (d) Bella, S. D., 2001, Second-order nonlinear optical properties of transition metal complexes, *Chem. Soc. Rev.* 30, 355-366.
- [23] (a) Rigamonti, L., Demartin, F., Forni, A., Righetto, S., Pasini, A., 2006, Copper (II) Complexes of salen Analogues with Two Differently Substituted (Push–Pull) Salicylaldehyde Moieties. A Study on the Modulation of Electronic Asymmetry and Nonlinear Optical Properties, *Inorg. Chem.* 45, 10976-10989. (b) Gradinaru, J., Forni, A., Druta, V., Tessore, F., Zecchin, S., Quici, S., Garbalau, N., 2007, Structural, Spectral, Electric-Field-Induced Second Harmonic, and Theoretical Study of Ni(II), Cu(II), Zn(II), and VO(II) Complexes with [N₂O₂] Unsymmetrical Schiff Bases of S-Methylisothiosemicarbazide Derivatives, *Inorg. Chem.* 46, 884-895.
- [24] Anson, C. W., Stahl, S. S., 2017, Cooperative Electrocatalytic O₂ Reduction Involving Co(salophen) with p-Hydroquinone as an Electron–Proton Transfer Mediator, *J. Am. Chem. Soc.* 139, 18472–18475
- [25] (a) Nie, Y., Li, L., Wei, Z., 2015 Recent advancements in Pt and Pt-free catalysts for oxygen reduction reaction, *Chem. Soc. Rev.* 44, 2168-2201. (b) Shao, M., Chang, Q., Dodelet, J. P., Chenitz, R., 2016, Recent Advances in Electrocatalysts for Oxygen Reduction Reaction *Chem. Rev.* 116, 3594-3657.
- [26] Babcock, G. T., Wikström, M., 1992, Oxygen activation and the conservation of energy in cell respiration, *Nature.* 356, 301-309.
- [27] Boyle, T. J., Sears, J. M., Jeffery, A., Perales, G. D., Cramer, R., Staples, O., Rheingold, A. L., Coker, E. N., Roper, T. M., Kemp, R. A., 2018, Synthesis and Characterization of Structurally Diverse Alkaline-Earth Salen Compounds for Subterranean Fluid Flow Tracking, *Inorg. Chem.*, 57 (5), 2402–2415.
- [28] Bhowmick, A, Islam, M., Bhowmick, R., Sarkar, M., Shibly, A., Hossain, E., 2019, Synthesis and Structure Determination of Some Schiff Base Metal Complexes with Investigating Antibacterial Activity, *Am. J. Chem.*, 9(1): 21-25.
- [29] Bhowmick, A C., Nath, B. D., Moim, M. I., 2019, Coordination Complexes of Transition Metals and Schiff Base with Potent Medicinal Activity, *Am. J. Chem.*, 9(4): 109-114.
- [30] Cisterna, J., Artigas, V., Fuentealba, M., Hamon, P., Manzur, C., Dorcet, V., Hamon, J. R., Carrillo, D., 2017, Nickel(II) and copper(II) complexes of new unsymmetrically-substituted tetradentate Schiff base ligands: Spectral, structural, electrochemical and computational studies, *Inorg. Chim. Acta.*, 462, 266–280.
- [31] Iscen, A., Brue, C., Roberts, K. F., Kim, J., Schatz, G. C., Meade, T. J., 2019, Inhibition of Amyloid- β Aggregation by Cobalt(III) Schiff Base Complexes: A Computational and Experimental Approach, *J. Am. Chem. Soc.* 141, 42, 16685-16695.
- [32] Fabbrizzi, L., 2020, Beauty in chemistry: making artistic molecules with Schiff bases, *The Journal of Organic Chemistry*, DOI: 10.1021/acs.joc.0c01420.
- [33] Gusev, A. N., Kiskin, M. A., Braga, E. V., Chapran, M., Salyga, G. W., Baryshnikov, G. V., Minaeva, V. A., Minaev, B. F., Ivaniuk, K., Stakhira, P., Ågren, H., Linert, W., 2019, Novel Zinc Complex with an Ethylenediamine Schiff Base for High-Luminance Blue Fluorescent OLED Applications, *J. Phys. Chem. C.* 123, 18, 11850-11859.
- [34] Handa, S., Gnanadesikan, V., Matsunaga, S., Shibasaki, M., 2010, Heterobimetallic Transition Metal/Rare Earth Metal Bifunctional Catalysis: A Cu/Sm/Schiff Base Complex for Syn-Selective Catalytic Asymmetric Nitro-Mannich Reaction, *J. Am. Chem. Soc.*, 132, 4925–4934.
- [35] Nolte, C., Mayer, P., Straub, B. F., 2007, Isolation of a Copper(I) Triazolide: A “Click” Intermediate, *Angew. Chem., Int. Ed.* 46, 2101-2103.
- [36] Jin, L., Tolentino, D. R., Melaimi, M., Bertrand, G., 2015, Isolation of bis(copper) key intermediates in Cu-catalyzed azide-alkyne “click reaction”, *Sci. Adv.* 1, 1500304.
- [37] Worrell, B. T., Malik, J. A., Fokin, V. V., 2013, Direct Evidence of a Dinuclear Copper Intermediate in Cu(I)-Catalyzed Azide-Alkyne Cycloadditions, *Science.* 340, 457-460.
- [38] Parveena, H., Alatawia, R. A. S., Sayed, N. H. E., Hasan, S., Mukhtar, S., Khan, A. U., 2017, Synthesis, characterization and biological evaluation of some novel nitrogen and sulphurcontaining organometallic heterocycles, *Arab. J. Chem.* 10, 1098–1106.
- [39] Bhadbhade, M. M., Srinivas, D., 1993, Effects on Molecular Association, Chelate Conformation, and Reactivity toward Substitution in Cu(S-X-salen) Complexes, $\text{salen}^{2-} = \text{MN}'\text{-Ethylenebissalicylidenaminato}$, X = H, CH₃O, and Cl: Synthesis, X-ray Structures, and EPR Investigations, *Inorg. Chem.* 32, 6122-6130.
- [40] Hall, D., Waters, T. N., 1960, The colour isomerism and structure of some copper co-ordination compounds. Part IV. The structure of N,N'-disalicylidene-ethylenediaminecopper, *J. Chem. Soc.* 2644-2648.
- [41] Nathan, L. C., Koehne, J. E., Gilmore, J. M., Hannibal, K. A., Dewhirst, W. E., Mai, T. D., 2003, The X-ray structures of a series of copper(II) complexes with tetradentate Schiff base ligands derived from salicylaldehyde and polymethylenediamines of varying chain length, *Polyhedron* 22, 887 /894.
- [42] Consiglio, G., Failla, S., Finocchiaro, P., Oliveri, I. P., Bella, S. D., 2012, An Unprecedented Structural Interconversion in Solution of Aggregate Zinc(II) Salen Schiff-Base Complexes, *Inorg. Chem.* 51, 8409–8418.
- [43] See, R. F., Kruse, R. A., Strub, W.M., 1998, Metal-Ligand Bond Distances in First-Row Transition Metal Coordination Compounds: Coordination Number, Oxidation State, and Specific Ligand Effects, *Inorg. Chem.* 37, 5369-5375.
- [44] Cameron, S. A., Brooker, S., 2011, Metal-Free and Dicopper (II) Complexes of Schiff Base [2+2] Macrocycles Derived from 2,20-Iminobisbenzaldehyde: Syntheses, Structures, and Electrochemistry, *Inorg. Chem.* 50, 3697–3706.