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Synthesis and Characterization of a Novel Schiff Base and its Complexes with Cobalt(II), Nickel(II), Copper(II), and Zinc(II): Spectroscopic Study and Evaluation of Biological Activity

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تحضير وتشخيص قاعدة شف جديدة ومعقداتها مع الكوبلت(II)، النيكل(II)، النحاس(II)، والخارصين(II): دراسة طيفية وتقييم الفعالية البيولوجي

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Abstract

This study presents the synthesis and characterization of a novel Schiff base ligand, (Z)-4-((benzo[d]thiazol-2-ylimino)methyl)phenol (L1), derived from the condensation of 4-hydroxybenzaldehyde and 2-aminobenzothiazole. The ligand was used to prepare a series of transition metal complexes with Co(II), Ni(II), Cu(II), and Zn(II) in both Metal(M): Ligand (L1):1,10-Phenanthroline (phen) , and M: 2L1 stoichiometries. The ligand and complexes were characterized using various spectroscopic methods, including proton nuclear magnetic resonance spectroscopy (^{13}C, ^{1}H-NMR) as well as infrared (FTIR) and ultraviolet spectroscopy(UV), in addition to melting point, accurate elemental analysis (CHNS), and atomic absorption.

Magnetic measurements and molar conductivity revealed that all complexes adopt an octahedral shape, while thermogravimetric analysis (TGA) indicated that the formed complexes are free of water. Biological studies showed that the prepared ligands and complexes possess moderate antibacterial activity against both *Staphylococcus aureus* (Gram-positive) and *Pseudomonas aeruginosa* (Gram-negative). The major fragmentation patterns in the mass spectrometry of the $[Zn(L1)_2Cl_2]$ complex also supported its proposed structure.

Keywords: Biological Activity, Complexes of Transition Elements, Schiff Base as ligand, Staphylococcus aureus, Pseudomonas aeruginosa .

الملخص

يتناول هذا البحث تحضير وتشخيص ليكند قاعدة شف جديدة يُعرف باسم-(Z)-4-((benzo[d]thiazol-2-ylimino)methyl)phenol (L1)، الناتج من تكاثف 4-هيدروكسي بنزالدهايد مع 2-أمينو بنزوثايازول. وقد استُخدم الليكند لتحضير عدد من المعقدات مع عناصر انتقالية تشمل Co(II)، Ni(II)، Cu(II)، و Zn(II) بنسب مختلفة فلز(M):ليكند(L1) :1,10-فينانثرولين (phen) وفلز:2L1. تم تشخيص الليكند والمعقدات باستخدام طرائق طيفية مختلفة تتضمن طيف الرنين النووي المغناطيسي للبروتون والكربون (^{13}C,^{1}H-NMR) بالإضافة إلى طيف الأشعة تحت الحمراء (FTIR) وطيف الاشعة الفوق البنفسجية (UV)، بالإضافة الى درجة الانصهار، و التحليل الدقيق للعناصر (CHNS) والامتصاص الذري.

وأشارت القياسات المغناطيسية والتوصيلية المولارية إلى أن جميع المعقدات أتخذت شكل هندسة ثمانية السطوح كما أوضحت تحاليل التفكك الحراري (TGA) خلو هذه المعقدات من جزيئات الماء. أظهرت الدراسة البيولوجية أن الليكندات و المعقدات المحضّرة تمتلك فعالية متوسطة كمضادات بكتيرية ضد كل من *Staphylococcus aureus* (موجبة الغرام) و *Pseudomonas aeruginosa* (سالبة الغرام). كما دعمت أنماط التفتت الرئيسية في مطيافية الكتلة للمعقد $[Zn(L1)_2Cl_2]$ البنية المقترحة له.

الكلمات الدالة: الفعالية البيولوجي، معقدات العناصر الانتقالية، ليكند قواعدة شف، المكورات العنقودية الذهبية، الزائفة الزنجارية.

1-INTRODUCTION

The importance of cobalt lies in its biological effectiveness against cancer, as it is used as an antioxidant,(Genchi, Sinicropi, et al., 2020) Nickel has many uses, including its use in preserving pharmaceuticals and as a catalyst in industrial processes such as the hydrogenation of unsaturated organic compounds, fats, and oils, (Genchi, Carocci, et al., 2020) Copper also plays a role in brain functions such as development of the central nervous system, production of neurotransmitters, modification of amino acid receptors, purine receptors, etc, (Gromadzka et al., 2020) Zinc is important for good health, as it is a component of more than 300 types of enzymes that control various metabolic processes. It maintains the immune system and helps in the growth and repair of damaged cells and tissues (Cervantes et al., 2018), and Schiff bases are important in coordination chemistry due to their ability to form stable and diverse complexes with various shapes and properties, particularly with different transition metals. It has been found that most transition metal ions with Schiff base ligands form stable complexes, which can coordinate with metals through both nitrogen and oxygen atoms.(Derafa et al., 2024; Raj et al., 2023) Due to the biological importance of Schiff bases, they have become a significant player in the development of Schiff base complexes involving Pd(II). It is worth noting that many studies have investigated metal complexes of Schiff bases. Schiff base complexes of Co(II), Cu(II), and Zn(II) have played a major role in the development of coordination chemistry (Al-Janabi et al., 2019; Khalil & Abdullah, 2024) Palladium(II) complexes containing Schiff bases, phosphine, pyridine, ethylenediamine, and piperidine, 1,10-phenanthroline mixed glycans, have attracted much attention due to their various applications as antibacterial, antiviral, antifungal, and chemical sensing, catalytic applications, as well as insecticides (Gautam et al., 2021). In addition, Schiff's bases have been used in the field of analytical chemistry due to their ability to form colored complexes with many metals, which facilitates the estimation of these metals in selective and sensitive methods, i.e., they are used in quantitative and qualitative analysis (Abd El-Razek et al., 2020). In the field of industrial chemistry, they are used as polymer stabilizers, plasticizers, antioxidants, and polymerization initiators. They are also used in the manufacture of ink pigments and printing inks that contain complexes of transparent bases with copper, as well as pigments used in aircraft paints that are not detected by radar.(Wahba et al., 2017)

In 2023, researcher (Abdusalam) and his team used the prepared ligand (Z)-2-(1-(2-(2,4-dinitrophenyl)hydrazineylidene)ethyl)phenol to prepare five complexes containing some transition metal ions, such as Cr(III), Mn(II), Fe(III), Co(II), Ni(II). Then, A ligand and its complexes were diagnosed by characterized using analytical and spectroscopic methods, and based on the results obtained, the octahedral shape was proposed for all complexes. The biological activity was also studied, as the antibacterial activity was tested against two types of bacteria (Staphylococcus aureus and E. coli species). (Hamil et al., 2024).

In this study, a new Schiff base was prepared by condensation reaction between (2-aminobenzothiazole, and 4-hydroxybenzaldehyde) (Naglah et al., 2024), and its complexes with Cobalt(II), Nickel(II), Copper(II), and Zinc(II). A ligand and its complexes were diagnosed by different spectroscopic methods such as FTIR, ^{13}C,^{1}H-NMR, UV-Vis, accurate elemental analysis (CHNS), and atomic absorption, thermogravimetric analysis (TGA) (Abd El-Lateef et al., 2024), also using magnetic, and molar conductivity measurements, which proved that the complexes take an octahedral. The biological activity of the ligand and its complexes was measured and showed good activity against *Staphylococcus aureus* and *Pseudomonas aeruginosa*. (Sharma et al., 2020)

2- EXPERIMENTAL PART

2.1- Materials and Equipment

Fluka, Aldrich, and BDH, including (2-aminobenzothiazole, and 4-hydroxybenzaldehyde), prepared the materials. The solvents used were absolute ethanol, diethyl Ether, and petroleum Ether, and the mineral salts were ($CoCl_2.6H_2O$, $NiCl_2.6H_2O$, $CuCl_2$, and $ZnCl_2$).

The ligand and their complexes were detected by various measurements: Molar conductivity was measured using a device Conductivity Meter-Model (Eutech PC700), and device (Magnetic Susceptibility Balance.) to measure magnetic susceptibility, UV Spectrophotometer (PG INSTRUMENTS) to measure electronic spectra Both standards are available at the "College of Education for Pure Sciences_University of Mosul, Mass-Spectrum The measurement was performed using a (USA-Agilant device). In Iran - University of Tehran, the infrared spectra of the prepared complexes and ligand were determined using a (Shimadzu-type) device in the range (200 - 4000 cm^{-1}) in terms of wavenumber and using $CSIO_3$ disks at Tikrit University, College of Education for Pure Sciences. Thermal analysis measurements were performed at the University of Mosul, College of Basic Education. The analysis was conducted using a device (METTLER TOLEDO), thin-layer Chromatography (TLC) slide, the solvents used (hexane and ethyl acetate), and a device. (UVG-11 Compact UV Lamp, Varian Agilent USA) (400 MHZ). University of Mosul, College of Education for Pure Sciences ^{1}H-NMR, ^{13}C-NMR measurements of the prepared ligand were performed at University of Basra, College of Education for Pure Sciences using a (Varian Agilant USA) device (400 MHz) dissolving the sample in (DMSO-d^6) and using TMS as a standard reference at room temperature (298 K). Accurate element analysis of the proportions of carbon, hydrogen, nitrogen, and sulfur elements of the prepared compounds and complexes was estimated using an elemental analysis in Iran, University of Tehran. The amount of cobalt, nickel, copper, and zinc in the prepared complexes was determined using an atomic absorption spectrometer (Analytik Jena NovaA350) at the University of Mosul/College of Agriculture. Finally, the melting point of raw materials, prepared ligand, and their complexes were measured using the (Aparatues-Stuart-SMP) melting point device at the University of Mosul-College of Education for Pure Sciences. The values are shown in Table 1.

2.2- Synthesis of ligand (L1)

(0.01 mol, 1.2 g) 4-hydroxybenzaldehyde dissolved in (20 mL) of absolute ethanol. (0.01 mol, 1.5 g) of 2-aminobenzothiazole dissolved in (20 mL) of absolute ethanol was then added. The mixture was refluxed for (7 h) at (250 °C). During the reaction, three drops of glacial acetic acid were added. The reaction was tracked by TLC, then the mixture was heated to pre-drying and allowed to dry for (24 h). A yellow powder was formed, which was washed with petroleum ether. Its melting point was (200 °C). The same ligand was prepared in the same way, but using an alkaline medium, by adding drops of (0.1% NaOH) solution instead of glacial acetic acid. The result was the same, a yellow precipitate with a melting point of (200 °C) was obtained.

2.3-Preparation of complexes of the ligand with the formula [M(L1)(Phen)Cl_2]

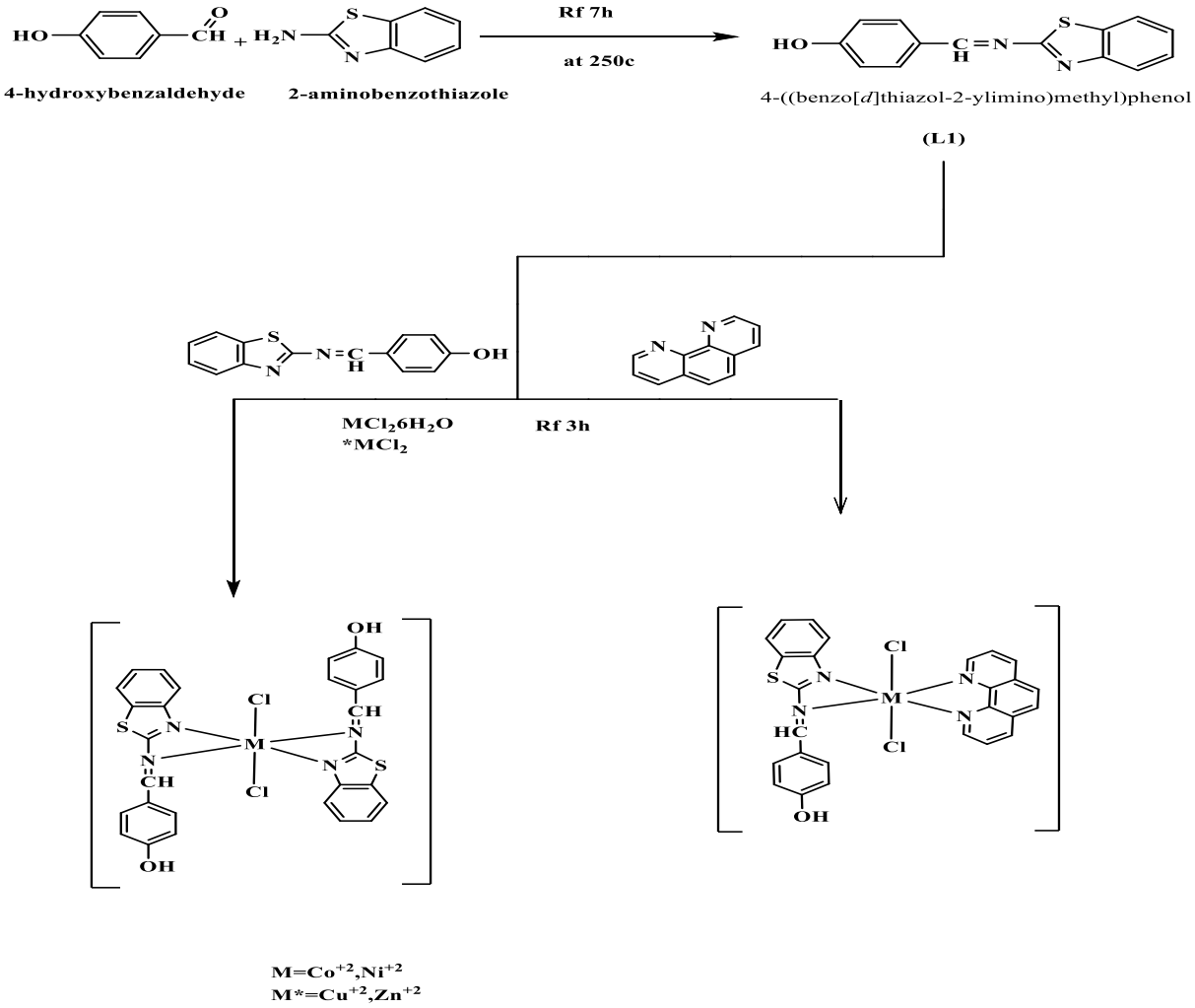
The complexes were prepared in a 1:1:1 ratio by reacting (0.001 mol, 0.237 g) of ($CoCl_2.6H_2O$) dissolved in (10 mL) distilled water with (0.001 mol, 0.25 g) of the ligand dissolved in (15 mL) absolute ethanol. The mixture was heated with stirring for half an hour at (250 °C), followed by the addition of (0.001 mol, 0.18 g) of 1,10-phenanthroline dissolved in (20 mL) absolute ethanol. Heating with a stirrer was completed for three hours, after which an olive-green precipitate was obtained and washed with diethyl ether.

The (2,3,4) complexes were prepared in the same way, using the same weights for both the (L1) and secondary ligand (Phen), along with the weights of the metal salts for each metal. (0.001 mol, 0.237g of $NiCl_2.6H_2O$) and (0.001 mol, 0.136g of $CuCl_2$, $ZnCl_2$).

3.3-Preparation of complexes of the ligand with the formula [M(L1)$_2$$Cl_2$]

The complexes were prepared in a ratio of 1:2 by reacting (0.001 mol, 0.50 g) of ($CoCl_2.6H_2O$) dissolved in (10 mL) distilled water with (0.002 mol, 0.50 g) of the ligand dissolved in (25 mL) absolute ethanol using reflux with a stirrer at (250 °C) for three hours.

The (6,7,8) complexes were prepared in the same way, using the same weights of the (L1) along with the weights of the metal salts for each metal.(0.001 mol, 0.237g of $NiCl_2.6H_2O$) and (0.001 mol, 0.136g of $CuCl_2$, $ZnCl_2$).



Scheme 1: for preparing the Schiff base and its complexes

3-RESULT AND DISCUSSION

1.3-Micro Elemental Analysi(C.H.N.S)

The elements (C.H.N.S) in the prepared ligand and complexes were analyzed, and the values are shown in Table 1. When comparing the theoretically calculated values with the practically measured values, a notable similarity was observed between them, confirming the validity of the proposed formulas.(Al-Badrane & Ahmed, 2023; Alemu, 2017; Ommenya et al., 2020)

2.3-Atomic absorption

The concentrations of cobalt, nickel, copper, and zinc in the prepared complexes were determined. The results were analyzed and compared with the calculated theoretical values. The concentrations of these complexes were found to fall within the standard range and conform to the linear range of the standard curve. The values are shown in Table1 (Abed et al., 2021)

3.3-Molar electrical conductivity

The measurements of the molar electrical conductivity showed that the formulas were in agreement with the proposed structural formulas for the prepared complexes of the type $[M(L1)_2Cl_2]$ and also of the type $[M(L1)(Phen)Cl_2]$. All the prepared complexes were found to have a neutral, non-electrolytic behavior. Table 1 shows the molar conductivity values for the prepared complexes(El-Zahed et al., 2024; Ismail & Lateef, 2022; Numan et al., 2018).

Table 1: shows the expected formulas, analytical results, and several physical properties of the ligand and the prepared complexes.

No.	Molecular Formula	Molar conductivity $\Omega^{-1}.cm^2.mol^{-2}$	M.p°C	Colour	Yelid%	Elemental analysis theoretical (Practical)				
						C%	H%	N%	S%	M%
L1	$C_{14}H_{10}N_2SO$	---	200	Light yellow	%88	66.06 (65.00)	3.93 (3.79)	11.01 (10.68)	12.58 (12.33)	---
1	$[CoL1(Phen)Cl_2]$	11	100	Bluish green	%77	55.32 (55.13)	3.19 (2.56)	9.93 (9.45)	5.67 (5.34)	10.44 (10. 23)
2	$[NiL1(Phen)Cl_2]$	15	123	Light brown	%73	55.35 (54.12)	3.19 (3.11)	9.93 (9.79)	5.67 (5.43)	10.39 (10.17)
3	$[CuL1(Phen)Cl_2]$	10	165	Light green	%87	54.88 (54.23)	3.16 (3.01)	9.85 (9.45)	5.62 (5.38)	11.16 (11.15)
4	$[ZnL1(Phen)Cl_2]$	18	88	Light yellow	%80	54.70 (54.62)	3.15 (3.05)	9.81 (9.79)	5.61 (5.45)	11.45 (11.22)
5	$[Co(L1)_2Cl_2]$	10	73	Blue green	%79	52.67 (52.12)	3.13 (3.01)	8.77 (8.42)	10.03 (9.53)	9.23 (9.15)
6	$[Ni(L1)_2Cl_2]$	10	89	Yellowish green	%79	52.69 (51.65)	3.13 (3.03)	8.78 (8.67)	10.03 (9.87)	9.19 (9.16)
7	$[Cu(L1)_2Cl_2]$	9	78	Dark brown	%83	52.29 (52.11)	3.11 (3.02)	8.715 (8.563)	9.961 (9.675)	9.883 (9.652)
8	$[Zn(L1)_2Cl_2]$	17	81	Light yellow	%74	52.14 (52.12)	3.10 (3.04)	8.691 (8.452)	9.933 (8.798)	10.135 (10.109)

Phen=1,10-phenanthrolen

Ll=(Z)-4-((benzo[d]thiazol-2-ylimino)methyl)phenol

4.3-Magnetic measurements

Magnetic susceptibility measurements revealed that the hexacoordinate Co(II), Ni(II), and Cu(II) complexes display paramagnetic behavior, consistent with an octahedral arrangement. The experimental magnetic moments in Table 2 align with theoretical predictions for high-spin d^7,d^8,d^9 systems in an Octahedral symmetry. Interestingly, while all complexes adopted octahedral coordination, the Zinc(II) complexes uniquely displayed diamagnetic behavior in contrast to the paramagnetic properties observed in other metal complexes.(Abousaty et al., 2024; Noor & Kareem, 2024)

5.3-Electronic spectra

The electronic spectra of Co(II), Ni(II), Cu(II), and Zn(II) complexes in DMF were analyzed. The results showed characteristic absorption bands for each complex as shown in Table 2,. Highly spin octahedral cobalt complexes showed three absorption bands, the first in the range (10986-11235cm^{-1}) belonging to the $^4T_1g(F) \rightarrow {}^4T_2g(F)$ transition, the second band was in the range (12345-15600 cm^{-1}) belonging to the $^4T_1g(F) \rightarrow {}^4A_2g(F)$ transition, and the third band in the range (18939-22573 cm^{-1}) belonging to the $^4T_1g(F) \rightarrow {}^4T_1g(p)$ transition, and charge transfer C.T. 31645-32573 cm^{-1}, The highly spin-coordinated hexagonal nickel(II) complexes showed three

absorption bands, the first ranging from (9675-10986 cm^{-1}) is due to the $^3A_2g(F)\rightarrow{}^3T_1g(F)$ transition, the second band ranging from (12984-13452 cm^{-1}) is due to the $^3A_2g(F)\rightarrow{}^3T_2g(F)$ transition, and the third band ranging from (21387-24317 cm^{-1}) is due to the $^3A_2g(F)\rightarrow{}^3T_1g(p)$ transition. In addition to the charge transfer spectrum C.T. 32156-33215 cm^{-1}, Hexa-coordinated Copper(II) complexes showed a single absorption band in the range (10989-12642 cm^{-1}) belonging to the $2Eg \rightarrow 2T_2g$ 2 transition as well as a charge transition band C.T. 33783-34246 cm^{-1}, As for Zinc(II) complexes, their outer shell is completely filled with electrons, and therefore no electronic transition bands (d–d) appear, but they give bands that belong to the electronic transitions of the ligand charge transition band C.T. 33321-35679 cm^{-1}, whose positions have changed from what they were in the ligand spectrum, which indicates the formation of complexes.(Mohamed et al., 2024; Sharma et al., 2020)

Table 2: Data on the electronic spectra and effective magnetic moment of the ligand and prepared complexes

NO	Formula of complexes	μeff B.M	UV-Vis. Bands (cm^{-1})	Charge transfer	Proposed Structure
L1	$C_{14}H_{10}N_2SO$	----	----	34693-41659	----
1	$[CoL1(Phen)Cl_2]$	4.6	11235-12345-18939	31645	Octahedral
2	$[NiL1(Phen)Cl_2]$	2.3	9675-13452-21387	33215	Octahedral
3	$[CuL1(Phen)Cl_2]$	1.6	12642	34246	Octahedral
4	$[ZnL1(Phen)Cl_2]$	Dia	----	35679	Octahedral
5	$[Co(L1)_2Cl_2]$	4.8	10952-15600-22573	32573	Octahedral
6	$[Ni(L1)_2Cl_2]$	2.8	10986-12984-24317	32156	Octahedral
7	$[Cu(L1)_2Cl_2]$	1.9	10989	33783	Octahedral
8	$[Zn(L1)_2Cl_2]$	Dia	----	33321	Octahedral

6.3-Infrared spectrum

The infrared spectra of the functional groups of the ligand and its complexes are in Table 3. The azomethine group (-CH=N-) appears at 1643 cm-1 in the ligand and shifts to lower values in the complexes, indicating the occurrence of coordination. The spectrum of the (-OH) group also appears at 3404 cm-1 in the ligand and remains in the same range, indicating dissymmetry with the metal. The appearance of new bands related to (M-N, M-Cl) indicates the occurrence of coordination and complex formation, as shown in Table 3. (Oladipo & Luckay, 2024; Rai et al., 2024; Sarto et al., 2020)

Table 3: IR bands (cm-1) data of ligand and prepared complexes

No.	Formula 0f complexes	ν(-OH)	ν(C=N) Phen	ν(C=N) L1	ν(M-Cl)	ν(M-N)	ν(C=N-S)
L1	$C_{14}H_{10}N_2SO$	3404	---	1648	---	---	2253
1	$[CoL1(Phen)Cl_2]$	3413	1555	1611	277	350	2252
2	$[NiL1(Phen)Cl_2]$	3412	1554	1623	238	342	2254
3	$[CuL1(Phen)Cl_2]$	3401	1553	1617	288	344	2251
4	$[ZnL1(Phen)Cl_2]$	3421	1556	1608	283	362	2250
5	$[Co(L1)_2Cl_2]$	3405	---	1633	290	341	2256
6	$[Ni(L1)_2Cl_2]$	3401	---	1621	271	329	2255
7	$[Cu(L1)_2Cl_2]$	3403	---	1621	298	390	2253
8	$[Zn(L1)_2Cl_2]$	3403	---	1611	267	391	2258

Phen=1,10-phenanthrolen

L1=(Z)-4-((benzo[d]thiazol-2-ylimino)methyl)phenol

7.3- $^{13}C,^{1}H$-NMR Spectroscopy

The NMR spectrum of the ligand (L1) was measured using DMSO-d^6 as the solvent, and the reference was tetramethylsilane (TMS). The ^{1}H-NMR spectrum of the ligand (L1) showed a single signal (S) at 10.63 ppm to the hydroxyl group (1H), a single signal (S) at a 9.03 ppm due to the protons of the azomethine group (1H) and multiple overlapping signals (m) due to the protons 8H of the aromatic rings of the benzathiazole group and 4-hydroxybenzaldehyde.(Kargar et al., 2021; Zarei & Naeimi, 2024)

The ^{13}C-NMR spectrum of the ligand (L1) was also measured, Show bands in the range (115.48-131.73 ppm) belonging to the carbon atoms of aromatic rings. A band at (171.60 ppm) was shown that belongs to the carbon atom in the Thiazole ring adjacent to the sulfur and nitrogen atoms, as well as a band at (161.60 ppm) that belongs to the carbon atom of the azomethine group, a band at (151.04 ppm) that belongs to the two carbon atoms connected to the Thiazole ring, and a band that belongs to the hydroxyl carbon atom group at a frequency of (162.48 ppm). (Derafa et al., 2024; Tahmasbi et al., 2023)

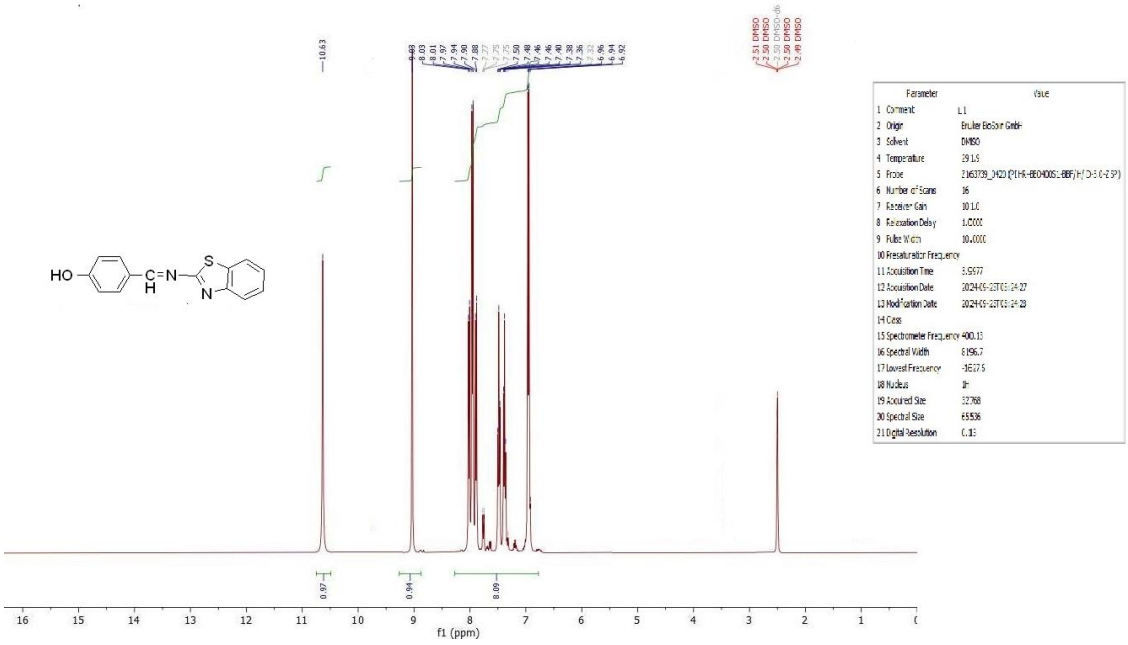


Figure 1: 1H-NMR spectrum of the ligand (L1)

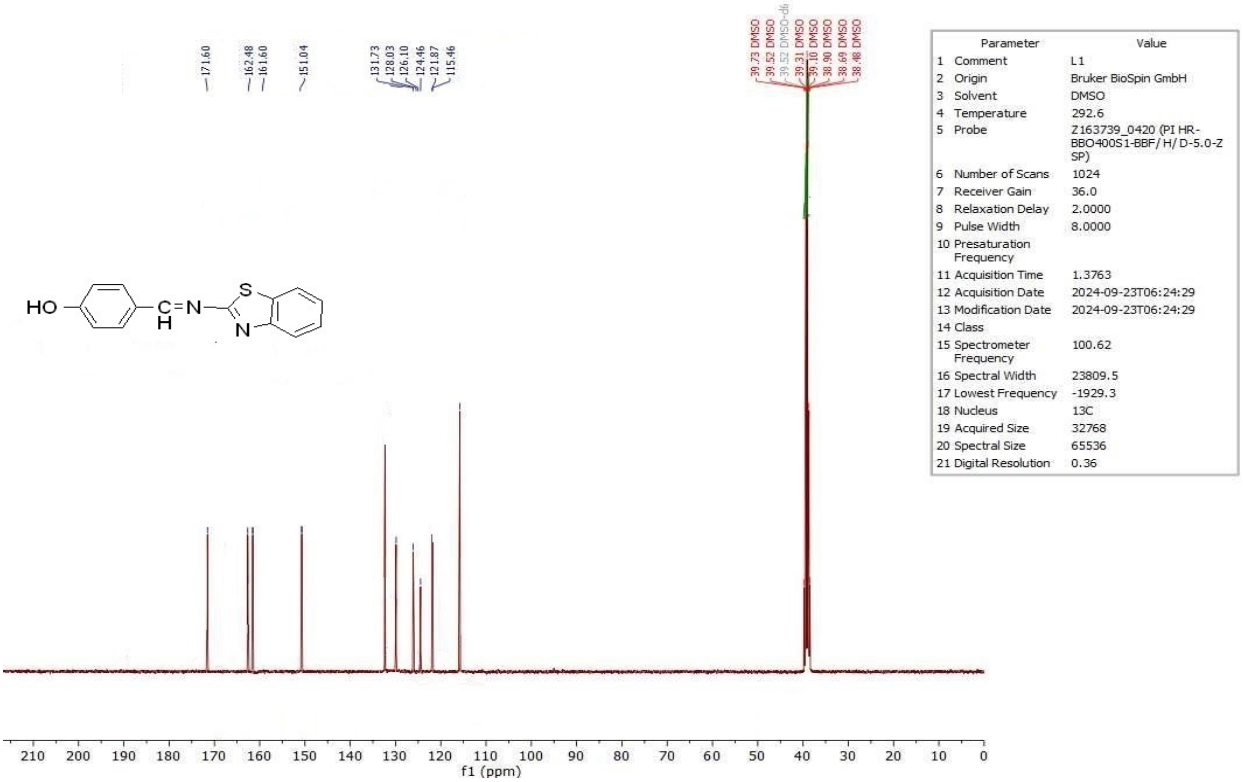


Figure 2: 13C-NMR spectrum of the ligand (L1)

8.3-Thermogravimetric analysis

Thermogravimetric analysis (TGA) revealed that $[Co(L1)_2Cl_2]$ maintained thermal stability with no significant mass loss, indicating an absence of coordinated water molecules. Complete decomposition occurred at high temperatures, forming the metal oxide.(Lupașcu et al., 2021; Mohamed et al., 2024)

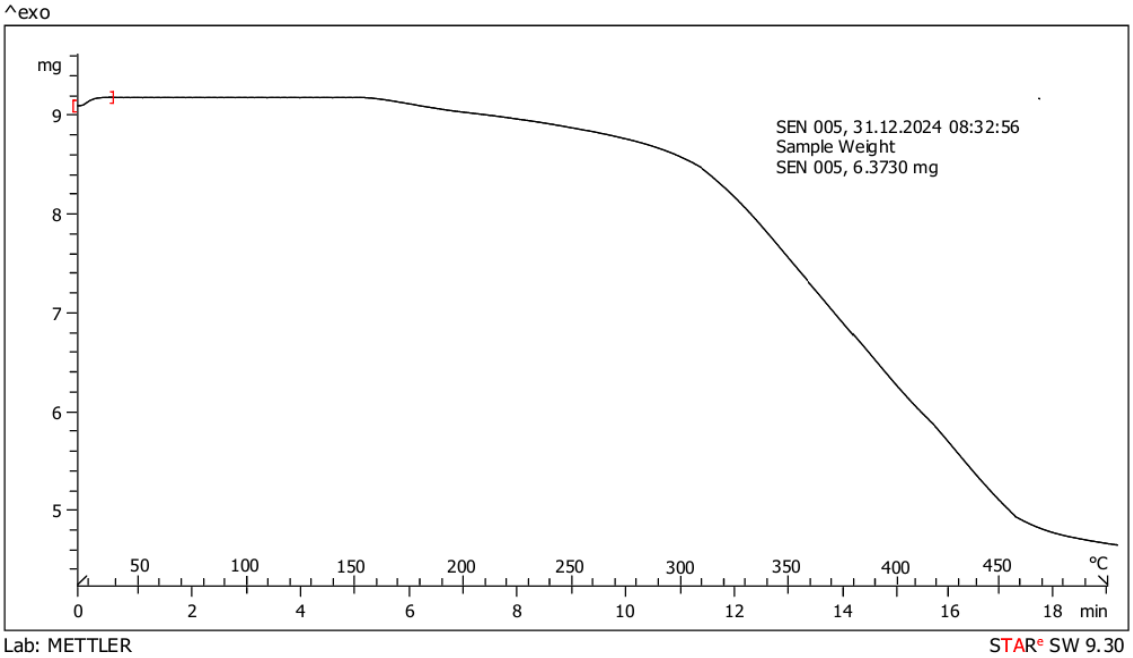


Figure 3: Thermogravimetric analysis (TGA) of complex (5)

9.3-Mass spectrum

The mass spectrum of the ligand and complex (3) was measured, where the backbone atom appears at (254,568 m/z), which corresponds to the molecular weight of the ligand and complex (254.31,568.5 g/mol), respectively In Table 4 we note the most important peaks of the two compounds' fractures.. (Ashraf et al., 2021)

Table 4: Mass spectra data of the Ligand and the metal(II) complexes

NO	Fragment	Mass/charge (m/z)
L1	$(C_{14}H_{10}N_2SO)$	
1	$C_{14}H_9N_2SO^+$	254
2	$C^{14}H_9N_2S^+$	238
3	$C_{14}H_9N_2^+$	190
4	$C_7H_7^+$	91
5	$C_6H_5^+$	77
Complex	$[Zn(L1)_2Cl_2]$	
1	$[Zn(L1)_2Cl_2]^+$	568
2	$[Zn(L1)_2Cl]^+$	507.5
3	$[Zn(L1)_2]^{2+}$	471
4	$[Zn(L1)Cl_2]^+$	392
5	$C_{14}H_9N_2SO^+$	254
6	$[ZnCl_2]^+$	139

9.3-Bioactivity Evaluation

The prepared ligand and its complexes were biologically tested on two types of bacteria: Staphylococcus aureus and Pseudomonas aeruginosa. This type of bacteria was chosen for its clinical importance, as it is characterized by its high resistance to antibiotics.. The compounds and ligand were dissolved in DMSO, and solutions were prepared at concentrations of (10^{-3}M) The bacteria were placed on agar medium. Holes were made, and the samples were placed into them. The plate was placed in an incubator at 37°C for 24 hours for bacteria (Al-barwari, 2025)

And the biological activity of the Schiff base complexes Co(II), Ni(II), Cu(II), Zn(II) stems from three synergistic mechanisms The biological activity of the Schiff base complexes Co(II), Ni(II), Cu(II), Zn(II) stems from three synergistic mechanisms:

1-Membrane Disruption: The benzothiazole moiety with S-N donors and aromatic rings enhances lipophilicity, facilitating penetration into bacterial membranes, especially Gram-negative. Metal ions Zn(II) disrupt ion gradients by forming non-specific channels.

2-Enzyme Inhibition: Metal coordination Cu(II) competitively inhibits metalloenzymes (DNA gyrase) by displacing essential ions (Mg^{+2}-Ca^{+2} or binding to thiol (-SH groups).

3-Oxidative Stress:Redox-active metals Cu(II)-Co(II) generate ROS, OH, and O_2^-, damaging DNA and lipids. Zn(II) complexes indirectly induce oxidative stress by depleting cellular antioxidants.(Abd El-Lateef et al., 2024; Aziz et al., 2023; Mansour et al., 2024)

Table 5: Biological activity of ligands and complexes against types of bacteria.

No.	*Stapyloccus Aurius*	*Pseudomonas aeruginosa*
L_1	22	17
1	25	16
2	16	15
3	16	16
4	24	17
5	22	15
6	14	17
7	25	17
8	22	20
TMSP	10	12
GTP	10	10

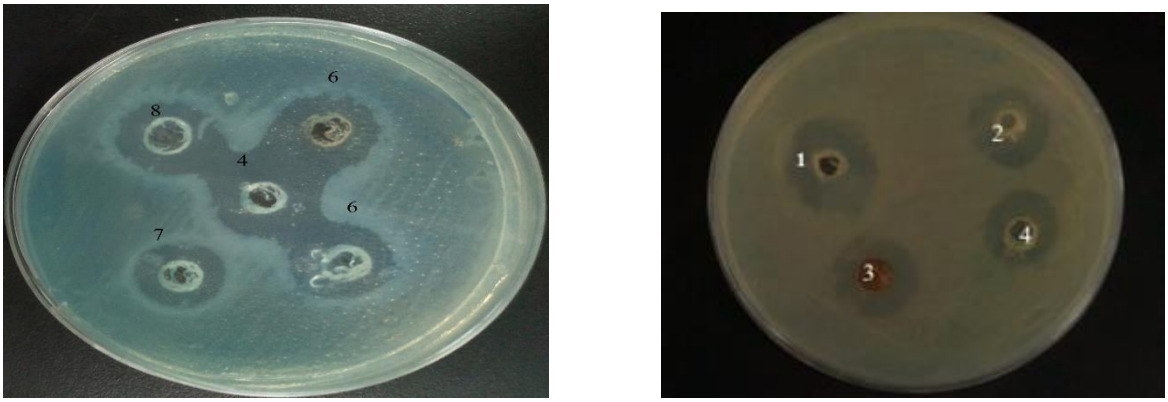


Figure 4: Inhibition zones of ligand L1 and metal complexes against Gram-positive (S. aureus) and Gram-negative (P. aeruginosa) strains

4-Conclusions

1-In this research, we were able to present new compounds with distinct physicochemical properties and promising biological activity, making them strong candidates for pharmaceutical and industrial applications.

2-The integrated results obtained by the research open the way for future studies to explore the precise mechanisms of action and develop practical applications for these compounds.

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6-Reference

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