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Int. J. Adv. Res. Sci. Technol. Volume 13, Issue 06, 2024, pp.1460-1467.

IJARST
International Journal of Advanced Research in
Science and Technology
https://doi.org/10.62226/ijarst202413190

ISSN 2319 – 1783 (Print)
ISSN 2320 – 1126 (Online)

Mixed Ligand Complexes: Room Temperature Synthesis, Structure Determination and Biological Utility

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ARTICLEINFO

Article history:

Received	25 May 2024
Accepted	01 Jun 2024
Available online	10 Jun 2024

Keywords:
2-Aminobenzothiazole,
5-Chloro-8-Hydroxyquinoline,
Antibacterial,
Antimalarial,
Antioxidant.

ABSTRACT

The synthesis of mixed ligand complexes at room temperature involving a Schiff base derived from a heterocyclic compound (S_5) and 5-chloro-8-hydroxyquinoline ligands, utilizing transition metals such as Fe(III), Co(II), Ni(II), and Cu(II), has been documented. The formation of the Schiff base (S_5) is achieved by reacting 2-hydroxy-3-methoxy-5-nitrobenzaldehyde with 2-aminobenzothiazole in ethanol, with glacial acetic acid serving as a catalyst. Various analysis techniques utilized to analyze the obtained compounds for their structure determination. Biological screening results revealed the obtained metal-ligand combinations are possible candidates for use as antibacterial, antimalarial and antioxidant agents owing to their potential activities.

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Introduction

The high coordinating ability of heterocyclic 2-aminobenzothiazole resultant of presence of sulphur, nitrogen and pi electron in its structure is well established [1-2]. This is reason behind numerous biological actions such as anticancer [3–4], antibacterial [5–10], antimalarial [11], and antioxidant [12] activities displayed by benzothiazole moiety. Hugo Schiff's discovery, which involved the reaction of primary amines with carbonyl compounds to form compounds with a carbon-nitrogen double bond, known as Schiff bases, marked a significant milestone in the field of coordination chemistry. The use of such molecules in complex formation added an advantage to coordination chemists around the world [13]. The imine group (-C=N-) in a structure is associated with various biological activities, including herbicidal, anticancer, and antibacterial properties [14].

A multitude of physiologically active compounds has been made available to researchers through the integration of heterocyclic molecules into Schiff base production. Another heterocyclic compound with strong coordinating power is 8-hydroxyquinoline. It has also been utilized in the paper, wood, and textile sectors as a fungicide [15–16]. The various quinoline derivatives are known be responsible for antimalarial activities.

Our goal is to create metal complexes with superior antimalarial properties based on heterocyclic moieties, and this study is a continuation of our journey in that direction [17–18]. In this study, we describe the room temperature synthesis of mixed ligand complexes using Schiff base (S_5) [(E)-2-((benzo[d]thiazol-2-ylimino)methyl)-6-methoxy-4-nitrophenol] and 5-chloro-8-hydroxyquinoline with Fe(III), Co(II), Ni(II), and Cu(II) ions. The Schiff base (S_5) was synthesized by reacting 2-hydroxy-3-methoxy-5-nitrobenzaldehyde with 2-aminobenzothiazole in an ethanolic solution. The structures of these complexes were elucidated through elemental analysis, melting point determination, molar conductance, magnetic susceptibility measurements, and spectral techniques including IR, UV-Vis, and 1H NMR (for the Schiff base only), as well as thermal analysis and powder XRD. For biological properties like antimalarial, antimicrobial and antioxidant properties, all of the compounds underwent screening using standard methods.

Experimental

Chemicals

Transition metal salts [Iron(III) chloride hexahydrate, Cobalt(II) chloride hexahydrate, nickel(II) chloride hexahydrate, copper(II) chloride dehydrate and zinc(II) chloride monodhydrate] were purchased from Qualigens Chemicals Private Limited. Sigma Aldrich Chemicals provided 2-hydroxy-3-methoxy-5-nitrobenzaldehyde, 2-aminobenzothiazole and 5-Chloro-8-hydroxyquinoline. All the chemicals used were of AR grade quality. The solvents utilized were double distilled prior to use.

Physical Methods

A simple capillary tube method was used to determine melting points or decomposition temperatures of all the synthesized compounds, which are further uncorrected. The synthesized compounds were dissolved in DMF to prepare 0.001 M solutions, and their room temperature molar conductance values were measured using an Equiptronics Conductivity Meter with a built-in magnetic stirrer (Model: Eq-664). Magnetic

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susceptibilities were determined at room temperature with a SES Instruments' Gouy's balance (Model: EMU-50), using copper(II) sulfate as the standard. IR spectra were recorded on a Perkin Elmer Spectrophotometer using KBr pellets in the range of 4000-400 cm^{-1}. The ^{1}H NMR spectral analysis of the S$_5$ ligand was performed using a Bruker instrument.

Thermal analysis (TGA/DTA) of the complexes was carried out using a Mettler instrument module [TGA 1 SF/1100/358, 04.02.2016 17:33:31] with a heating rate of 10.00 °C/min. Powder XRD patterns of the synthesized complexes were recorded using an Ultima IV instrument operating at 40 kV and 20 mA.

Schiff base (S$_5$) Preparation

Reacting equimolar quantities of 2-aminobenzothiazole and 2-hydroxy-3-methoxy-5-nitrobenzaldehyde led to Schiff base (S$_5$). For this, in a round bottom flask, 20 mL ethanolic solution of 2-aminobenzothiazole (1.50g,10 mmol) was taken and to it was added 20 mL ethanolic solution of 2-hydroxy-3-methoxy-5-nitrobenzaldehyde (1.97g, 10 mmol). The glacial acetic acid in catalytic amount was added to the resultant mixture and allowed to room temperature stirring for 30 min. The TLC record revealed completion of reaction. The yellow crystalline solid precipitatedat this point was separated, filtered and washed with cold water and ethanol. The recrystallization was carried out using ethanol (Yield: 83%).**(Fig. 1)**.

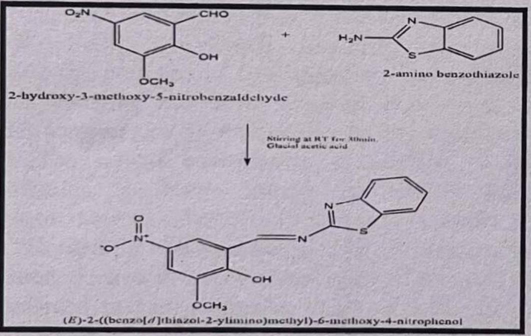

Fig. 1 Synthesis of Schiff base (S$_5$) ligand

Mixed ligand complexes preparation

The combination of transition metal salts, Schiff base (S$_5$) and 5-Chloro-8-hydroxyquinoline ligands in equimolar quantities (1:1:1 ratio) led to formation of mixed ligand complexes. In a round bottom flask, an ethanolic solution of metal chloride (10 mmol) was prepared with Fe(III) (0.326 g), Co(II) (0.286 g), Ni(II) (0.285 g), and Cu(II) (0.204 g). To this, a mixture of Schiff base ligand (S$_5$) [0.284 g, 10 mmol, 20 ml] and an ethanolic KOH solution of 5-chloro-8-hydroxyquinoline ligand (HQ) [0.175 g, 10 mmol, 20 ml] was added dropwise. The reaction progress was monitored using TLC at 30-minute intervals. After continuous stirring for 3-4 hours, the complexes formed as precipitates, which were washed with ethanol, filtered, recrystallized using ethanol, and then dried. This protocol's primary advantages included facile room temperature synthesis, easy isolation, and high yields.

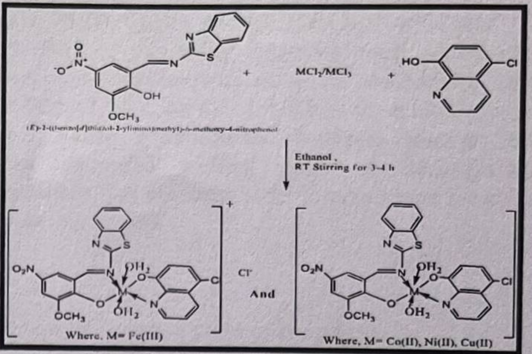

Fig. 2 Synthesis of mixed ligand complexes

Screening for biological properties

Antimalarial

Plasmodium sp. is responsible for malaria disease and is known to consume hemoglobin leaving toxic heme during its intra-erythrocytic stage. Parasite detoxifies free heme through β-hematin pigment formation. This principle is the base of screening compounds for their antimalarial activity [19].

Antimalarial properties of all the synthesized compounds were determined using β-hematin formation with the help of colorimetry by reading absorbance at 405 nm [20-21]. The hematin percentage inhibition was calculated using equation (2),

$$Percent inhibition(\%) = \frac{Acontrol - A\ treatedcells}{Acontrol} x\ 100 \qquad (2)$$

Antimicrobial

The antibacterial properties of the synthesized compounds were evaluated against E. coli and B. subtilis using the well plate method. The results were then compared with those of the standard antibiotic Streptomycin [22]. Similarly, antifungal property screening against *C. albicans* and *A. niger*was carried out using *Agar Well Diffusion Assay* [23].The results are represented in the form of diameter (mm) of growth inhibition zones [24].

Antioxidant

Free radicals are products of reactions when food breaks down in our body or when someone exposed to tobacco smoke or radiation and their production in living organisms is inevitable. Antioxidants protect your cells against such free radicals responsible for cancer, heart and other diseases. The free radical scavenging using DPPH [1,1-diphenyl-2-picrylhydrazyl] was the first approach to evaluate potential antioxidant nature of a compound, biological extract or other biological compounds. The reaction of DPPH with antioxidants resulting in its quenching can be measured at 525 nm, which is simplest approach.

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In this study, the antioxidant capacity of the synthesized compounds was assessed using the DPPH method, following a protocol with minor adjustments as described in previous references [25-26]. The outcomes were compared with those of the standard antioxidant ascorbic acid and expressed as the percentage of scavenging activity using a specific equation(3).

$$\text{Percentage inhibition \%} = \frac{A\,(Control) - A\,(Sample)}{A(Control)} \times 100 \quad (3)$$

Where A (Control) = Absorbance of DPPH and,
A(Sample) = Absorbance of reaction mixture (DPPH with Sample).

Results and Discussion

The synthesized metal complexes can be represented by the general formulas [C24H19ClN4O7SM] for M = Co(II), Ni(II), Cu(II), and [(C24H19ClN4O7SM)Cl] for M = Fe(III), accurately depicting their composition. These complexes showed complete solubility in DMF and DMSO, and partial solubility in chloroform and DCM. **Table 1** represents elemental analysis data, colour, recorded melting point or decomposition temperature and practical yield in percentage for all the complexes.

Table 1. Elemental analysis, color, melting point and percentage yield of complexes

Compound	Elemental Analysis (%)				Colour	Melting points/Decomposition Temp. (⁰C)	Percentage yield (%)
	C	H	N	M			
SB (S_5) $C_{15}H_{11}N_3O_4S$	54.70 (54.71)	3.37 (3.36)	12.74 (12.76)	--	Yellow	186	83%
$C_{24}H_{19}Cl_2$ N_4O_7SFe	45.40 (45.42)	3.03 (3.02)	8.84 (8.82)	8.80 (8.79)	Shiny Black	>250	75%
$C_{24}H_{19}Cl$ N_4O_7SCo	47.88 (47.83)	3.18 (3.19)	9.31 (9.33)	9.79 (9.78)	Light Green	>250	72%
$C_{24}H_{19}Cl$ N_4O_7SNi	50.96 (51.42)	2.67 (2.68)	9.91 (9.92)	10.38 (10.36)	Dark green	>250	70%
$C_{24}H_{19}Cl$ N_4O_7SCu	50.53 (50.55)	2.65 (2.64)	9.82 (9.80)	11.12 (11.14)	Brown grey	>250	74%

Magnetic susceptibility

The magnetic moments of 5.32 and 3.85 BM observed for the Fe(III) and Co(II) complexes, respectively, indicate the presence of five unpaired electrons in the Fe(III) complex and three unpaired electrons in the Co(II) complex, solely attributable to spin contribution [27]. The orbital contribution in addition to spin contribution is reason behind the slightly higher magnetic moment value of 3.13 BM than expected 2.87 BM recorded for Ni(II) complex[40-41].Presence of one unpaired electron in Cu(II) complex result revealed due to recorded magnetic moment value of 1.81 BM for Cu(II) complex. [27]

Molar Conductance

The molar conductance values for the divalent metal complexes (Co(II), Ni(II), and Cu(II)) were relatively low, ranging from 12.4 to 15.60 Ohm^{-1}cm^{2} mol^{-1}, whereas the Fe(III) complex exhibited a higher value of 83 Ohm^{-1}cm^{2} mol^{-1}. The data thus indicated towards non-electrolytic nature of divalent metal complexes [28] and 1:1 electrolytic nature of Fe(III) complex [29].

IR Spectra

Both ligands exhibit bidentate bonding with the metal ions, a conclusion supported by recording IR spectra within the range of 4000-400 cm-1 and comparing these spectra with those of the ligands alone.

The phenolic (-OH) and azomethine (C=N) groups in Schiff base ligand (S_5) yielded a broad band at 3542 cm^{-1} and a strong band at 1549 cm^{-1} respectively. Similarly, same functional groups yielded a broad peak at 3350-3450 cm^{-1} and a strong band at 1610 cm^{-1} in 5-Chloro-8-hydroxyquinoline [30]. The absence of broad peaks attributed to (-OH) groups in the complexes suggests that bonding between the metal and ligands occurs through the oxygen atoms of the phenolic (-OH) groups present in both ligands.

The observed shifting of bands to lower frequency values (1525, 1514, 1510, and 1502 cm^{-1}for Fe(III), Co(II), Ni(II), and Cu(II) complexes, respectively) compared to the original position at 1549 cm^{-1} in the Schiff base (S_5), as well as a similar shift in the range of 1581-1575 cm^{-1} from the original band at 1610 cm^{-1} in 5-chloro-8-hydroxyquinoline, indicates that both ligands are involved in bonding with the respective metals through the nitrogen of the (C=N) groups. The appearance of new peaks between 414-474 cm^{-1} and 507-590 cm^{-1} in the complexes indicates the presence of stretching vibrations associated with ν(M-N) and ν(M-O) bonding, respectively [31-32]. The presence of coordinated water molecules in complexes can be witnessed due to the presence of broad band at 3300-3400 cm^{-1}. Two peaks which were unchanged in the complexes were at 1627 and 750 cm^{-1} due to ν(C=N) and ν(C-S-C) in the thiazole ring of the Schiff base (S_5) which pointed towards non-involvement of nitrogen and sulphur atoms in thiazole ring in complex formation [33].The results are tabulated in **Table 2.**

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Table 2. presents the IR spectral data obtained for all synthesized compounds.

Compound	v(OH) H_2O	v(OH)	v(C=N) HQ	v(C=N)	v(C=N) Azo-methine	v(C-O)	v(C-S-C)	M-O	M-N
SB S_5 $C_{15}H_{11}N_3O_4S$	----	3542	----	1627	1549	1249	750	----	----
5CHQ ligand	----	3350-3450	1610	----	----	1281	----	----	----
$C_{24}H_{19}Cl_2$ N_4O_7SFe	3383-3302	----	1575	1625	1525	1292-1338	746	414-474	513-551
$C_{24}H_{19}Cl$ N_4O_7SCo	3360-3250	----	1579	1626	1514	1309-1340	750	421-457	507-590
$C_{24}H_{19}Cl$ N_4O_7SNi	3370-3243	----	1575	1628	1510	1321	750	416-424	543-586
$C_{24}H_{19}Cl$ N_4O_7SCu	3390	----	1579	1628	1502	1311	748	428-460	511-551

Electronic Spectra

The Schiff base exhibited two bands at 342 and 383 nm attributed to the ($\pi \rightarrow \pi^*$) transition of the aromatic benzene ring and the ($n \rightarrow \pi^*$) transition of the C=N group, respectively [34-35]. In the Fe(III) complex, three bands were observed at 302, 442, and 663 nm. The band at 302 nm was associated with ligand field transition, while the peaks at 442 and 663 nm corresponded to ${}^4T_{1g}$ (F) → ${}^4T_{1g}$ (P) and ${}^4T_{1g}$ (F) →${}^4A_{1g}$ (P) transitions, indicating octahedral geometry. Similarly, the Co(II) complex displayed two bands at 490 and 691 nm, with the latter appearing as a shoulder. These bands were attributed to ${}^4T_{1g}$ (F) → ${}^4T_{1g}$ (P) and ${}^4T_{1g}$ (F) →${}^4A_{1g}$ (P) d-d transitions, also suggestive of octahedral geometry [36].

Two bands at 410 and 515 nm due to d-d transitions ${}^3A_{2g}$ (F) → ${}^3T_1$ (P) and ${}^3A_{2g}$ (F) → ${}^3T_{1g}$ (F) respectively were observed in Ni(II) complex. A strong band at 405 nm due to ${}^2E_g \rightarrow {}^2T_{2g}$ transition with a tailing to higher wavelength at 732 and 774 nm was seen in Cu(II) complex. The evidence supports the conclusion that the Cu(II) complex adopts an octahedral geometry [37-38]. Results from molar conductance, magnetic susceptibility measurements, IR, and electronic spectra indicate that the Fe(III), Co(II), and Ni(II) complexes exhibit octahedral geometry, while the Cu(II) complex displays a distorted octahedral geometry.

^{1}H-NMR

The ^{1}H-NMR spectrum provides insights into the protonic arrangement of organic compounds and aids in structure determination. In this study, the ^{1}H-NMR spectrum of Schiff base (S_5) was recorded in $CDCl_3$ solvent with TMS as the internal standard, confirming its structure. The presence of proton at carbon adjacent to carbon bearing –OH group in aromatic ring of 2-hydroxy-3-methoxy-5-nitrobenzaldehyde is indicated by sharp singlet at δ 7.081 ppm. The aromatic proton of benzothiazole ring and that of 2-hydroxy-3-methoxy-5-nitrobenzaldehyde were indicated by multiplet at δ 7.526–7.667 ppm. The hydrogens in imine CH=N and phenolic –OH groups appeared as a singlet at δ 9.213 and a very sharp singlet at δ 11.263 in Schiff base (S_5).

Thermal (TGA/DTA) Analysis

Nitrogen atmosphere was used to analyze the synthesized complexes thermally (TGA/DTA) at the constant heating rate of 20°C/min. Two major weight loss steps were noted in the Thermogravimetric analysis curves recorded for all the complexes.

The first major step noted in the range 160-250°C indicated loss of coordinated water molecules while the second step noted in the range 450-750^0 C indicated loss of associated ligands simultaneously. At the end of analysis, metal oxides were found to be present beyond 750^0 C due to thermal effect on metal complexes. This is sufficient to prove the thermal stability of all mixed ligand complexes.

The broad exothermic peaks were noted in the range 450-750°C for all the mixed ligand complexes in their DTA curves.

Powder X-ray Diffraction analysis

Particle size determination and assessment of the nature (crystalline or amorphous) of all mixed ligand complexes were conducted using powder X-ray diffraction analysis. The particle size was calculated utilizing Scherer's formula, $D = 0.9\lambda/\beta \cos \theta$, where D represents particle size, λ denotes the wavelength of X-ray radiation, β indicates the Full Width Half Maximum, and θ stands for the diffraction angle. Additionally, Bragg's equation, $n\lambda = 2d \sin \theta$, was utilized to estimate the interplanar spacing (d), with λ representing the X-ray wavelength and θ denoting the diffraction angle.

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The powder x-ray diffraction patterns recorded in the range 20-80°C included the major reflexes recorded, calculated values of 2θ, inter planar spacing (d), mean particle size (D) (expressed in nm), miller indices (h,k,l) and full width half maximum (FWHM). The calculated average crystal sizes of synthesized mixed ligand complexes were in the range of 18.37–22.64 nm. Sharp crystalline peaks noted in the powder x-ray diffraction patterns of complexes were evidence in favor of micro-crystalline nature of the complexes. The data is tabulated in **Table 3.**

Table 3. Powder XRD data recorded for all the synthesized complexes

Complex	Reflexes	2-θ	Miller Indices	Inter planar spacing (d) (A°)	Crystal Size (D)	Average Crystal Size	FWHM
$C_{24}H_{19}Cl_2\ N_4O_7SFe$	Peak 1	14.54	1.11	6.087	22.68	22.64 nm	0.353
	Peak 2	15.00	111	5.901	24.73		0.329
	Peak 3	18.62	210	4.761	22.80		0.353
	Peak 4	25.02	300	3.556	20.34		0.400
$C_{24}H_{19}Cl\ N_4O_7SCo$	Peak 1	26.34	111	3.380	23.11	21.77 nm	0.353
	Peak 2	27.29	111	3.271	20.43		0.400
$C_{24}H_{19}Cl\ N_4O_7SNi$	Peak 1	16.36	111	5.413	17.95	18.37 nm	0.447
	Peak 2	18.32	200	4.839	18.97		0.424
	Peak 3	23.22	211	3.827	19.12		0.424
	Peak 4	29.54	310	3.021	17.44		0.471
$C_{24}H_{19}Cl\ N_4O_7SCu$	Peak 1	6.68	111	13.221	14.70	18.77 nm	0.541
	Peak 2	12.66	311	6.986	19.98		0.400
	Peak 3	16.08	410	5.507	21.33		0.376
	Peak 4	26.84	632	3.319	16.53		0.494
	Peak 5	27.82	711	3.204	18.30		0.447

Biological properties Antimalarial

Table. 4 depicts the record of antimalarial property results for all the synthesized compounds. Excellent antimalarial potential was noted for Co complex with percentage inhibition value of 67.81% which is almost equal to standard (68.90%). Out of other complexes, Fe(III), Ni (II) complexes with percentage inhibition values of 63.80%, 6452% were also having excellent antimalarial potential. The Cu(II) complex with least percentage inhibition value of 56.34 % was also better than Schiff base (S_5) (52.02%). Overall, all the complexes were having good to excellent antimalarial properties.

Table. 3 Antimalarial property record of all the synthesized compounds

Compound	Concentration	Absorbance	% Inhibition
Control		1.19	--
Standard	100 µg/ml	0.375	68.90
SB S_5 $C_{15}H_{11}N_3O_4S$	1000 µg/ml	0.629	52.02
$C_{24}H_{19}Cl_2\ N_4O_7SFe$	1000 µg/ml	0.425	63.80
$C_{24}H_{19}Cl\ N_4O_7SCo$	1000 µg/ml	0.375	67.81
$C_{24}H_{19}Cl\ N_4O_7SNi$	1000 µg/ml	0.426	64.52
$C_{24}H_{19}Cl\ N_4O_7SCu$	1000 µg/ml	0.529	56.34

Antimicrobial

All the synthesized compounds was tested for their potential to act as antibacterial agent against *E. coli* and *B. subtilis* and for their potential to act as antifungal agent against *C. albicans* and *A. niger*.The outcome of these tests were compared with standard antibacterial agent Streptomycin and standard antifungal agent Clotrimazole to decide potential in synthesized compounds. All the compounds were found to have poor potential as antibacterial against *E. coli* and moderate potential against *B. subtilis* which are depicted in **Fig. 3.**

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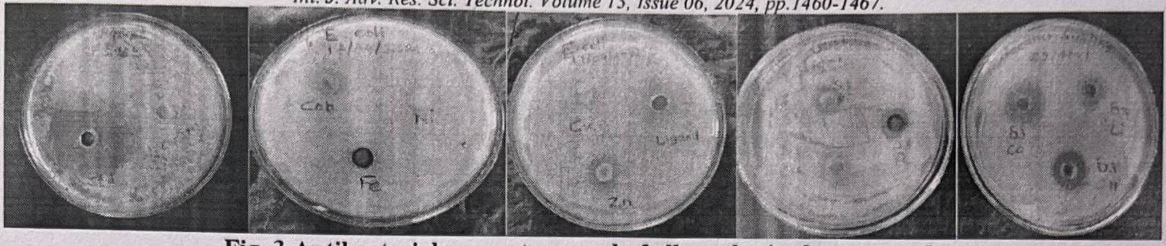

Fig. 3 Antibacterial property record of all synthesized compounds

All synthesized complexes were found to have moderate to good potential as antifungal agent *C. albicans*. In case of *A. niger* varied behaviour was observed, where, the Fe(III) and Cu(II) complexes were moderate but other complexes were inactive. The metal complexes were note to be better antifungal agents compared to Schiff base (S_5). The results had depicted in **Fig. 4**

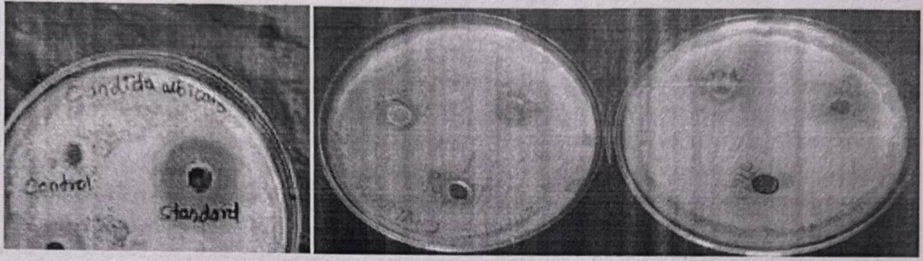

Fig. 4. Antifungal property record of all the synthesized compounds

The enhanced potential of metal complexes, as compared to the individual ligands used in their formation, is attributed to chelation, which can be elucidated through Overtone's Concept and Chelation Theory. Chelation leads to a reduction in the polarity of the metal ion and enhances the lipophilic and hydrophobic properties of the complex [39-40]. Consequently, this alteration facilitates the favorable permeation of these molecules through the lipid layer of cell membranes. Extensive literature supports the notion that nitrogen and oxygen donor systems possess the ability to inhibit enzyme production [41-45]. The coordination of ligands' nitrogen and oxygen to metal ions in our study is undoubtedly a contributing factor to the enhanced biological properties of metal complexes when compared to the free Schiff base (S_5).

The involvement of bulky substituents or ligands in metal chelates is reported to be the reason behind improved biological properties in mixed ligand complexes [46-47].

Antioxidant activity

The antioxidant activities of all synthesized compounds were assessed and compared with standard ascorbic acid (Vitamin C) based on their ability to scavenge stable DPPH free radicals. The results were analyzed in terms of the percentage inhibition observed at a concentration of 1000 μg/mL.

The mixed ligand complexes showed significantly improved DPPH radical scavenging activity compared to the free Schiff base ligand (S_5). The Co(II) complex demonstrated the highest inhibition value (94.51%), nearly comparable to that of standard ascorbic acid (97.79%), suggesting excellent antioxidant activity. Both the Fe(III) (85.21%) and Ni(II) (69.52%) complexes exhibited good antioxidant activities, while the Cu(II) complex showed no activity in terms of antioxidant activity. These findings indicate that the complexes are superior free radical scavengers compared to the free Schiff base ligand (S_5) molecule [48]. The detailed results are presented in the accompanying table.

Table. 5. Graphical depiction of the antioxidant activity observed for all synthesized compounds.

Compound	Concentration	Absorbance	% Inhibition
Control		0.454	--
Standard Ascorbic Acid	100 μg/ml	0.010	97.79
SB S_5 $C_{15}H_{11}N_3O_4S$	1000 μg/ml	0.0.352	23.28
$C_{24}H_{19}Cl_2$ N_4O_7SFe	1000 μg/ml	0.041	85.21
$C_{24}H_{19}Cl$ N_4O_7SCo	1000 μg/ml	0.104	94.51
$C_{24}H_{19}Cl$ N_4O_7SNi	1000 μg/ml	0.124	69.52
$C_{24}H_{19}Cl$ N_4O_7SCu	1000 μg/ml	0.529	5.34

It is already established that, compounds with phenolic OH groups exhibit better antioxidant activities [49-51].

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Conclusion

Mixed ligand complexes of Fe(III), Co(II), Ni(II), and Cu(II) ions were synthesized using a novel Schiff base ligand (S_5) and 5-Chloro-8-hydroxyquinoline. Various spectral techniques were employed to characterize all synthesized compounds. Based on the results, Fe(III) and Co(II) complexes were suggested to adopt octahedral geometry, while Ni(II) and Cu(II) complexes were proposed to have a distorted octahedral geometry. Molar conductance values indicated that all complexes except Fe(III) were non-electrolytic, with Fe(III) exhibiting electrolytic behavior in a 1:1 ratio. Biological screening revealed that the complexes exhibit potential as antimalarial and antioxidant agents.

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