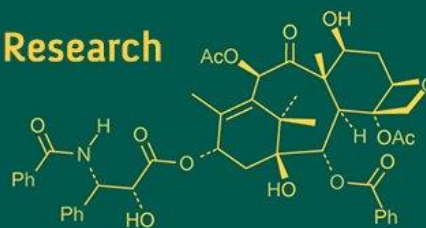


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Antimicrobial potential of iron complexes of benzothiazole-based Schiff bases against bacterial and phytopathogenic fungal species

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Abstract

A series of Schiff base ligands (L₁-L₃) were synthesized by the condensation of 2-hydroxynaphthaldehyde with 4-methoxy-2-aminobenzothiazole, 4-chloro-2-aminobenzothiazole, and 2-aminobenzothiazole. Their corresponding iron(II) and iron(III) complexes were prepared using conventional reflux method. The synthesized compounds were characterized by various physicochemical and spectroscopic techniques including molar conductance measurements, melting point determination, Fourier Transform Infrared (FTIR), UV-Visible, and Proton Nuclear Magnetic Resonance (¹H NMR) spectroscopy. Spectroscopic characterization confirmed Schiff base formation and indicated coordination of the ligands to the metal center through azomethine nitrogen and phenolic oxygen atoms. Antibacterial activity was evaluated against Gram-positive strains *i.e.* *Staphylococcus aureus* VTCCBAA20, *Bacillus cereus* VTCCBAA443, and Gram-negative strains *i.e.* *Pseudomonas aeruginosa* VTCCBAA2 and *Xanthomonas spp.* using agar well diffusion method, while antifungal activity against *Fusarium oxysporum*, *Rhizopus spp.*, and *Alternaria spp.* was evaluated using the poison plate technique. Biological evaluation revealed that ligand L₁ possessed the highest antibacterial activity against all tested bacterial strains except *P. aeruginosa*, for which ligand L₂ exhibited superior activity. Additionally, ligand L₂ and its Fe(II) and Fe(III) complexes (L₂₁ and L₂₂) demonstrated the highest antifungal efficacy against all tested fungal pathogens.

Keywords: Schiff base, azomethine, chelation, metal complex, antimicrobial activity

Introduction

In present, one of the major problem in the context of infectious diseases is the persistent rise and spread of Antimicrobial Resistance (AMR) to currently available antimicrobial agents. As existing antimicrobial drugs are becoming less effective in controlling the bacterial/fungal infections due to emergence of resistant microorganisms, this highlights the urgent and continuous need for new, safe and effective antimicrobial drugs (Singh *et al.*, 2025) [18]. In 1864, a German chemist named Hugo Schiff first synthesized the compound known as Schiff base by condensation reaction of primary amine with the carbonyl compounds aldehydes or ketones (Dinku *et al.*, 2024; Ashraf *et al.*, 2011; Al-Saadawy *et al.*, 2016) [6, 2, 3]. These can be classified as aldimine or ketimine based on their structure (Sanjurani *et al.*, 2024) [17]. Imine or azomethine functional group is the characteristic feature of these compound. The sp² hybridized nitrogen atom of azomethine group having a lone pair of electrons is of considerable biological and chemical importance (Isiyaku *et al.*, 2021; Uddin *et al.*, 2020) [11, 20]. Various studies have reported that these compounds exhibit diverse biological properties such as antidepressant, antidiabetic, anti-inflammatory, antiviral, antifungal, cytotoxic, anticancer, antioxidant, and antibacterial activities (Sahib *et al.*, 2021; Etaiw *et al.*, 2011; Ceramella *et al.*, 2022) [16, 7, 5]. Schiff bases have been known to form complexes with nearly all the transition metals (Hameed *et al.*, 2017; Tawfiq *et al.*, 2025) [9, 19]. Due to their property of being easy to synthesize, synthetic flexibility, and presence of the C=N group, these serve as an important class of ligands in coordination chemistry and can coordinate with a wide range of metal ions in different coordination geometries and oxidation states. Heterocyclic Schiff base compounds are the most bioactive class of organic compounds (Kumar *et al.*, 2023; Mesbah *et al.*, 2018; Ismail & Lateef, 2022) [12, 13, 10]. Metal complexes of Schiff bases derived from heterocyclic compounds having nitrogen, sulfur, and oxygen as ligand atoms

have been reported for their enhanced biological activities. Because of their wide range of pharmacological actions and structural resemblance to naturally occurring biological molecules, Schiff bases synthesized from 2-aminobenzothiazole have garnered significant interest in medicinal chemistry. These have been shown to have antidepressant, antidiabetic, anti-inflammatory, antiviral, antifungal, cytotoxic, anticancer, antioxidant, and antibacterial properties (Akyol *et al.*, 2025; Farhan *et al.*, 2025; Abrol *et al.*, 2019) [4, 8, 1].

Materials and Methods

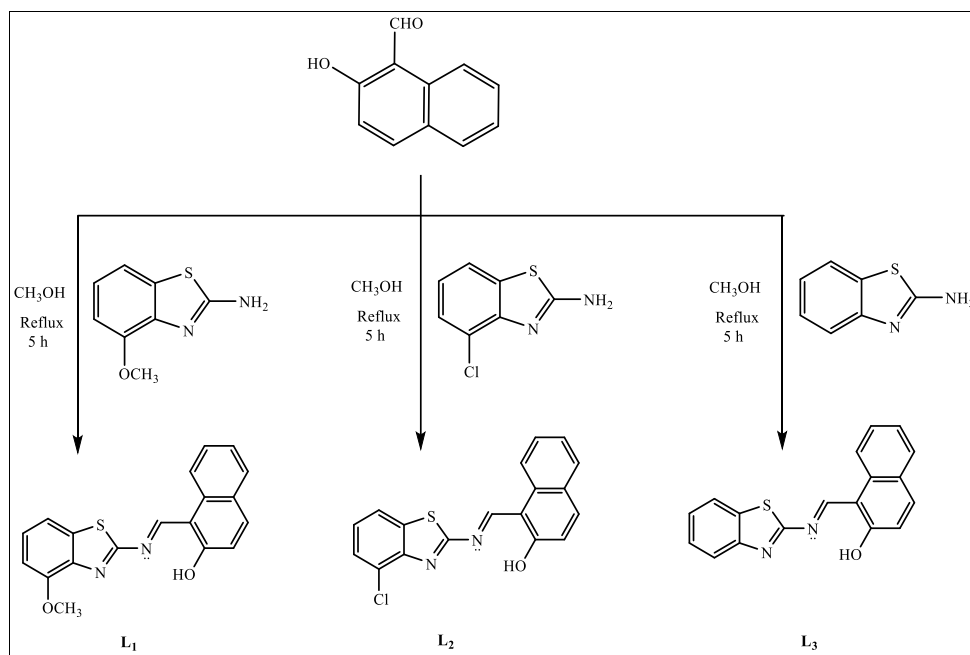
All chemicals were of analytical reagent grade and used without further purification. 2-amino- benzothiazole, 4-methoxy-2-aminobenzothiazole and 4-chloro-2-aminobenzothiazole were purchased from Sigma Aldrich chemical company. 2-Hydroxy-1-Naphthaldehyde, Ferric chloride (FeCl_3), Ferrous chloride (FeCl_2), and Methanol (CH_3OH) were purchased from CDH. The melting point of the synthesized compounds was determined using a digital melting point apparatus (LT-108) from the Department of Chemistry, COBS&H, CCS HAU Hisar. Infrared spectra of the Schiff base ligands and their metal complexes synthesized during research were recorded in KBr pellets in the region $4000\text{--}400\text{ cm}^{-1}$ on a PerkinElmer FTIR spectrometer from the Department of Physics, COBS&H, CCS HAU Hisar. UV-Visible spectra of the synthesized

compounds were recorded in range of 200-800 nm on Model SHIMADZU (UV 3600 PLUS) UV-Visible spectrophotometer from Department of Chemistry, COBS&H, CCS HAU Hisar. Proton NMR spectra of the synthesized compounds were recorded in DMSO-d_6 using TMS as an internal reference on an NMR cryo-magnet Spectrometer 400 MHz (Bruker) NMR spectrometer at GJUS&T, Hisar.

Synthesis of Schiff base ligands and metal complexes

The Schiff base ligands ($\text{L}_1\text{--L}_3$) were prepared by refluxing in equimolar quantities (5 mmol each) of 4-methoxy-2-aminobenzothiazole, 4-chloro-2-aminobenzothiazole and 2-aminobenzothiazole with 2-hydroxy-1-naphthaldehyde in methanol for 5 hours. The reaction mixtures were cooled to room temperature, and the precipitated products were filtered, washed with methanol, and dried over anhydrous CaCl_2 .

The iron(II) and iron(III) complexes of the synthesized Schiff base ligands were prepared by reacting equimolar amounts (5 mmol) of the respective ligand ($\text{L}_1\text{--L}_3$) and iron salts (FeCl_2 or FeCl_3) in methanol. The reaction mixtures were refluxed for 5 hours (Ndolene *et al.*, 2025) [14]. After completion of the reaction, the mixtures were cooled to room temperature, and the resulting precipitates were collected by filtration, washed thoroughly with methanol, and dried over anhydrous CaCl_2 in a desiccator (Scheme 1).



Scheme 1: Synthesis of Schiff base ligands ($\text{L}_1\text{--L}_3$)

Results

Physicochemical properties

The physicochemical properties of the synthesized Schiff base ligands ($\text{L}_1\text{--L}_3$) and their corresponding iron(II) and iron(III) complexes are summarized in Table 1. All the synthesized compounds were obtained as colored, crystalline solids that were stable at room temperature and non-hygroscopic in nature. The compounds were readily

soluble in polar organic solvents such as dimethyl sulfoxide (DMSO), methanol, ethanol, acetone, and chloroform. The synthesized compounds were obtained in good to excellent yields ranging from 52 to 91% and molar conductance measurements were carried out in methanol at room temperature. The observed molar conductance values ranged from 13.92 to $42.00\text{ S cm}^2\text{ mol}^{-1}$, indicating the non-electrolytic behavior of ligands and complexes in solution.

Table 1: Physicochemical properties of the synthesized compounds

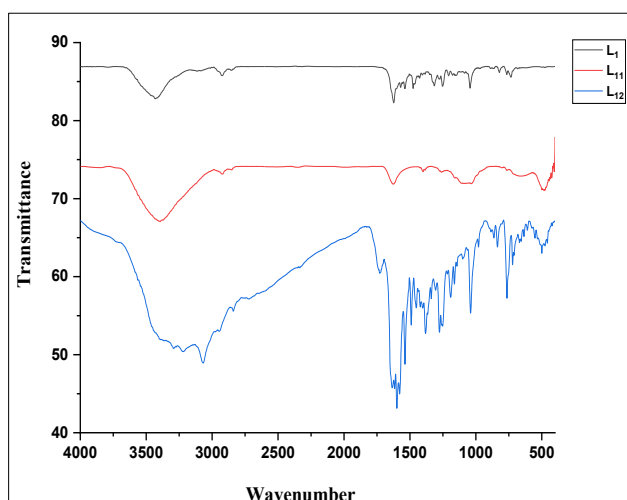
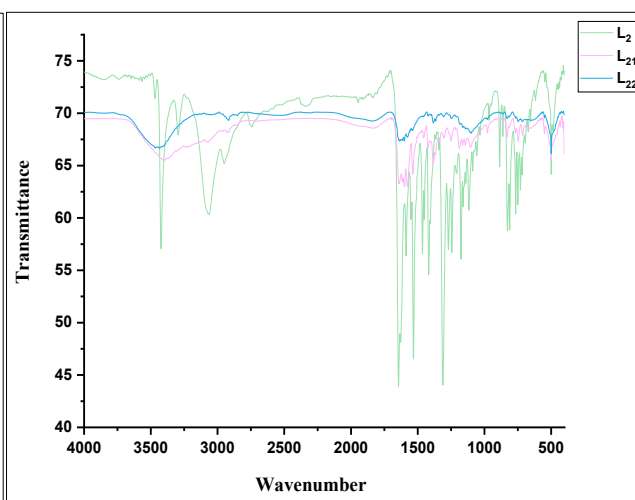
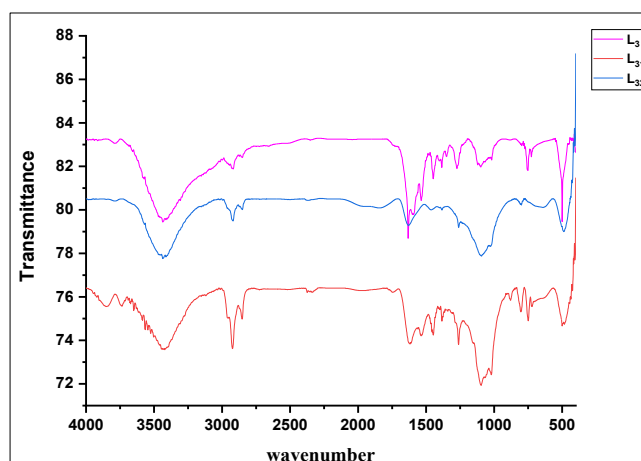
Sr. No.	Compound	Empirical formula	Color	Yield (%)	M.pt. (°C)	Molar conductance (Λ_m) S cm ² mol ⁻¹
1.	L ₁	C ₁₉ H ₁₄ N ₂ O ₂ S	Dark Brown	72	130-132	14.78
2.	L ₁₁	C ₁₉ H ₁₇ Cl ₂ FeN ₂ O ₄ S	Brown	87	100-102	16.03
3.	L ₁₂	C ₁₉ H ₁₅ Cl ₃ FeN ₂ O ₃ S	Black	52	72-73	25.34
4.	L ₂	C ₁₈ H ₁₁ ClN ₂ OS	Yellow	90	128-130	13.92
5.	L ₂₁	C ₁₈ H ₁₄ Cl ₃ FeN ₂ O ₃ S	Black	86	106-108	42.00
6.	L ₂₂	C ₁₈ H ₁₂ Cl ₄ FeN ₂ O ₂ S	Green	79	195-196	36.32
7.	L ₃	C ₁₈ H ₁₂ N ₂ OS	Black	91	101-103	15.21
8.	L ₃₁	C ₁₈ H ₁₅ Cl ₂ FeN ₂ O ₃ S	Brown	85	78-80	18.33
9.	L ₃₂	C ₁₈ H ₁₃ Cl ₃ FeN ₂ O ₂ S	Black	80	82-83	32.25

Spectral studies**FTIR analysis**

The spectra of free ligands L₁, L₂, and L₃ displayed bands at 1621, 1642, and 1631 cm⁻¹, which are due to the stretching frequency of $\nu(\text{C}=\text{N})$, and bands at 1252, 1311, and 1273 cm⁻¹ are due to $\nu(\text{C}-\text{O})$. In the spectra of their metal complexes, a slight shift in bands was observed for $\nu(\text{C}=\text{N})$ and $\nu(\text{C}-\text{O})$, confirming the coordination of azomethine nitrogen and oxygen atom (Table 2). The shift in these bands and the presence of bands in the regions 481-499 cm⁻¹ and 740-799 cm⁻¹ are due to $\nu(\text{M}-\text{O})$ and $\nu(\text{M}-\text{N})$ also indicate complex formation. Based on IR results, it was confirmed that the ligands L₁, L₂, and L₃ act as neutral bidentate (N, O) ligands bonded with the metal ion through the azomethine-nitrogen and oxygen atoms (Figure 1-3).

Table 2: Infrared spectral data (cm⁻¹) of ligands and their metal complexes

Sr. No.	Compound	$\nu_{\text{C}=\text{N}}$	$\nu_{\text{C}-\text{O}}$	$\nu_{\text{M}-\text{O}}$	$\nu_{\text{M}-\text{N}}$
1.	L ₁	1621	1252	-	-
2.	L ₁₁	1632	1264	481	750
3.	L ₁₂	1606	1268	495	760
4.	L ₂	1642	1311	-	-
5.	L ₂₁	1635	1380	497	740
6.	L ₂₂	1632	1382	499	713
7.	L ₃	1631	1273	-	-
8.	L ₃₁	1621	1262	499	749
9.	L ₃₂	1625	1260	490	799

**Fig 1:** FTIR spectra of ligand L₁ and its complexes**Fig 2:** FTIR spectra of ligand L₂ and its complexes**Fig 3:** FTIR spectra of ligand L₃ and its complexes

UV-visible analysis

The UV-Visible spectra of Schiff base ligands and their corresponding complexes are presented in Figures 4-6. The intense bands observed at 235-273 nm were assigned to $\pi \rightarrow \pi^*$ transitions of the aromatic system, while the bands appearing at 297-302 nm were attributed to $n \rightarrow \pi^*$ transitions associated with the azomethine (C=N) group. In the spectra of the corresponding metal complexes, the

ligand-centered $\pi \rightarrow \pi^*$ and $n \rightarrow \pi^*$ bands show slight bathochromic shifts, indicating coordination of the ligand through the azomethine nitrogen atom. Furthermore, broad absorption bands at 328 nm and 357 nm in Fe^{2+} and Fe^{3+} complexes of ligand L_2 are attributed to Ligand-to-Metal Charge Transfer (LMCT) transitions, confirming interaction between ligand and metal ions (Table 3).

Table 3: UV-Visible spectral data (nm) of ligands and their metal complexes

Sr. No.	Compound	λ_{max}	Transition
1.	L_1	257, 273 and 301	$\pi \rightarrow \pi^*$, $\pi \rightarrow \pi^*$ and $n \rightarrow \pi^*$
2.	L_{11}	267 and 294	$\pi \rightarrow \pi^*$ and $n \rightarrow \pi^*$
3.	L_{12}	265 and 320	$\pi \rightarrow \pi^*$ and $n \rightarrow \pi^*$
4.	L_2	235, 256, 265, 302 and 360	$\pi \rightarrow \pi^*$ and $n \rightarrow \pi^*$
5.	L_{21}	238, 262, 289 and 328	$\pi \rightarrow \pi^*$, $n \rightarrow \pi^*$ and LMCT
6.	L_{22}	263, 317 and 357	$\pi \rightarrow \pi^*$, $n \rightarrow \pi^*$ and LMCT
7.	L_3	262 and 297	$\pi \rightarrow \pi^*$ and $n \rightarrow \pi^*$
8.	L_{31}	265, and 295	$\pi \rightarrow \pi^*$ and $n \rightarrow \pi^*$
9.	L_{32}	279 and 290	$\pi \rightarrow \pi^*$ and $n \rightarrow \pi^*$

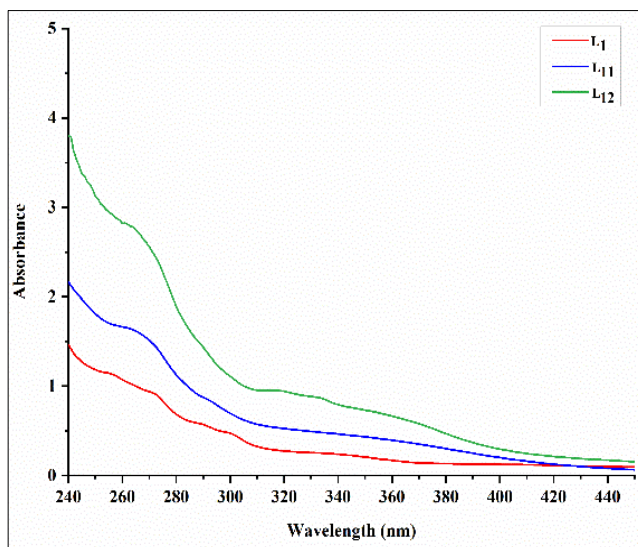


Fig 4: UV-visible spectra of ligand (L_1) and its complexes

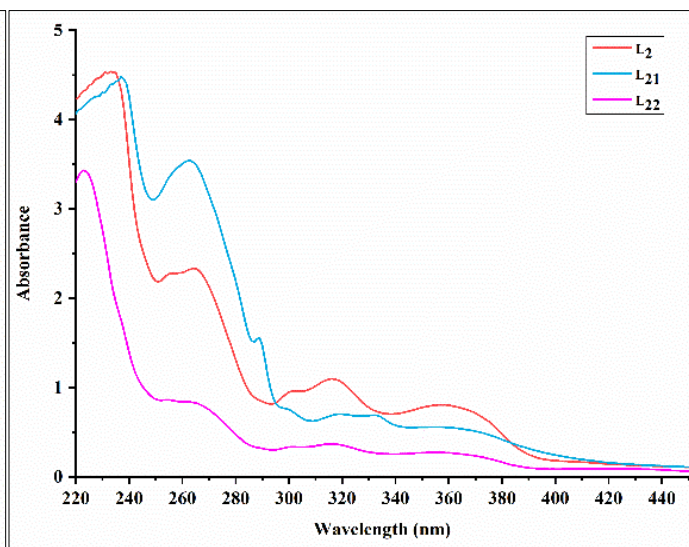


Fig 5: UV-visible spectra of ligand (L_2) and its complexes

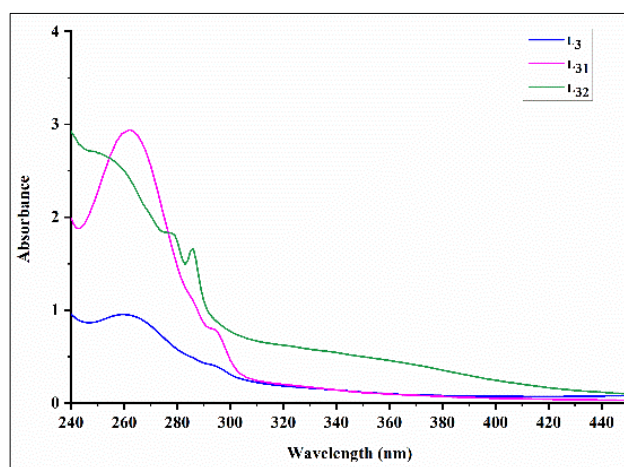


Fig 6: UV-visible spectra of ligand (L_3) and its complexes

^1H NMR analysis

The ^1H NMR spectral data of the synthesized ligands and their corresponding metal complexes are summarized in Table 4. The spectra of the Schiff base ligands (L_1 , L_2 , and

L_3) exhibited characteristic singlet signals in the downfield region $\delta \sim 10.00$ - 10.82 ppm corresponding to the azomethine ($-\text{CH}=\text{N}$) proton, confirming the formation of the Schiff base framework. Singlets observed around $\delta \sim 11.60$ - 12.05

ppm were assigned to the phenolic -OH proton. The aromatic protons of the ligands appeared as multiplet signals in the region $\delta \sim 6.60$ -8.60 ppm, which is consistent with the presence of aromatic and heteroaromatic rings in the ligand structure. In the spectra of some metal complexes, a slight shifting of the azomethine proton signal was observed,

indicating coordination of the ligand to the metal ion through the azomethine nitrogen atom. However, the detailed interpretation of certain complex spectra was limited by poor solubility and insufficient spectral resolution.

Table 4: ^1H NMR spectral data (δ ppm) of ligands and their metal complexes

Sr. No.	Compound	Phenolic -OH	-CH=N	Aromatic protons
1.	L ₁	12.05	10.82	6.80-8.00
2.	L ₁₁ *	-	-	-
3.	L ₁₂	-	11.80	6.60
4.	L ₂	12.00	10.70	7.00-8.00
5.	L ₂₁ *	-	-	-
6.	L ₂₂	-	10.68	7.00-8.60
7.	L ₃	11.60	10.00	7.00-8.00
8.	L ₃₁	-	9.00	7.00-7.60
9.	L ₃₂	-	9.08	7.00-8.20

*Spectra not resolved due to poor solubility of compounds

The combined spectroscopic results provide evidence for the successful synthesis of the Schiff base ligands and their corresponding iron complexes. The presence of the azomethine $\nu(\text{C}=\text{N})$ stretching bands and the characteristic azomethine proton signals confirmed the formation of the Schiff base ligands. The shift of the azomethine $\nu(\text{C}=\text{N})$ band to lower wavenumbers in the FTIR spectra and

bathochromic shift of ligand-centered transitions indicate the coordination of the ligand to the metal. Thus, from the above spectral studies, it was concluded that all the Schiff bases (L₁, L₂, and L₃) act as neutral bidentate (N, O) donor ligands and spectral data support the proposed structures of the synthesized complexes.

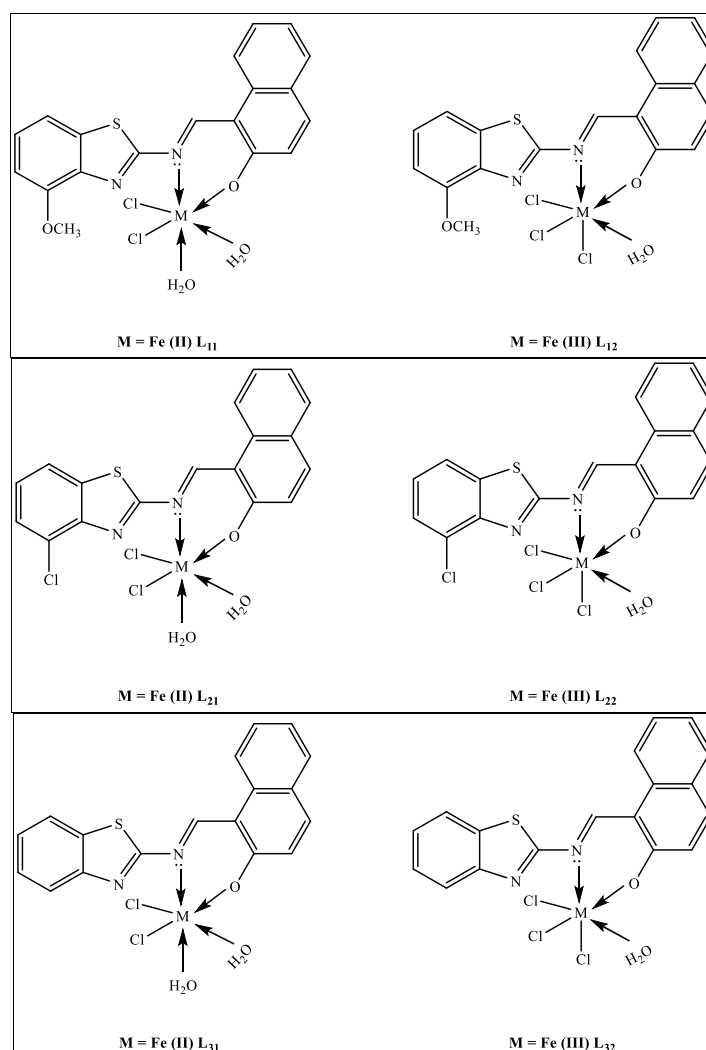


Fig 7: Proposed structures for metal complexes of ligand L₁, L₂, and L₃

Antibacterial activity

The antibacterial activity of the synthesized compounds was evaluated against Gram-positive strains, *i.e.* *Staphylococcus aureus* VTCCBAA20 and *Bacillus cereus* VTCCBAA443 and Gram-negative strains, *i.e.* *Xanthomonas spp.* and *Pseudomonas aeruginosa* VTCCBAA2 using the agar well diffusion method. Muller Hinton agar medium was used to culture the bacteria. The standard antibiotic chloramphenicol was used as a positive control for the study. The experimental details and Zone of Inhibition (ZOI) in respect antibacterial activity of synthesized compounds against pathogenic bacterial strains which are given in Table 5-6. Among the synthesized compounds, ligand L₁ exhibited the highest antibacterial activity,

producing inhibition zones of 17 mm against *S. aureus*, 13 mm against *B. cereus*, and 15 mm against *Xanthomonas spp.* at 1500 µg mL⁻¹. Ligand L₂ and its complexes demonstrated moderate antibacterial activity, with L₂₂ showing slightly improved inhibition against *B. cereus* compared with the parent ligand. Similarly, the unsubstituted ligand L₃ exhibited moderate activity, whereas its iron complexes (L₃₁ and L₃₂) generally showed comparable or slightly reduced antibacterial effects. Overall, the synthesized compounds were more effective against Gram-positive bacteria than Gram-negative bacteria, which may be attributed to the simpler cell wall structure of Gram-positive organisms, allowing easier penetration of antimicrobial agents.

Table 5: Zone of Inhibition (mm) of Synthesized compounds against Gram-positive bacteria at different concentrations

Sr. No.	Compound	Zone of inhibition (mm)					
		<i>Staphylococcus aureus</i>			<i>Bacillus cereus</i>		
		Conc. (µg/mL)			Conc. (µg/mL)		
		1500	1000	700	1500	1000	700
1.	Chloramphenicol	48.00±0.67	45.00±0.35	42.00±1.00	37.00±0.80	33.00±0.01	29.00±0.42
2.	L ₁	17.00±0.42	15.00±0.30	7.02±0.15	13.00±0.11	9.00±0.09	8.02±0.01
3.	L ₁₁	9.00±0.05	7.00±0.13	5.00±0.10	6.00±0.13	5.00±0.09	4.00±0.08
4.	L ₁₂	11.00±0.26	10.00±0.03	6.00±0.04	8.00±0.10	7.00±0.02	6.00±0.06
5.	L ₂	8.00±0.12	7.00±0.12	6.00±0.06	11.00±0.07	10.00±0.10	9.00±0.09
6.	L ₂₁	8.00±0.12	7.00±0.16	6.00±0.06	10.00±0.14	6.00±0.11	5.00±0.05
7.	L ₂₂	11.00±0.01	10.00±0.02	8.00±0.16	12.00±0.24	10.00±0.14	8.00±0.02
8.	L ₃	13.00±0.09	11.00±0.01	10.00±0.01	11.00±0.05	10.00±0.07	8.00±0.04
9.	L ₃₁	9.00±0.12	8.00±0.08	6.00±0.12	9.00±0.15	8.00±0.15	7.00±0.12
10.	L ₃₂	9.00±0.16	7.00±0.16	5.00±0.06	7.00±0.01	6.00±0.14	5.00±0.05

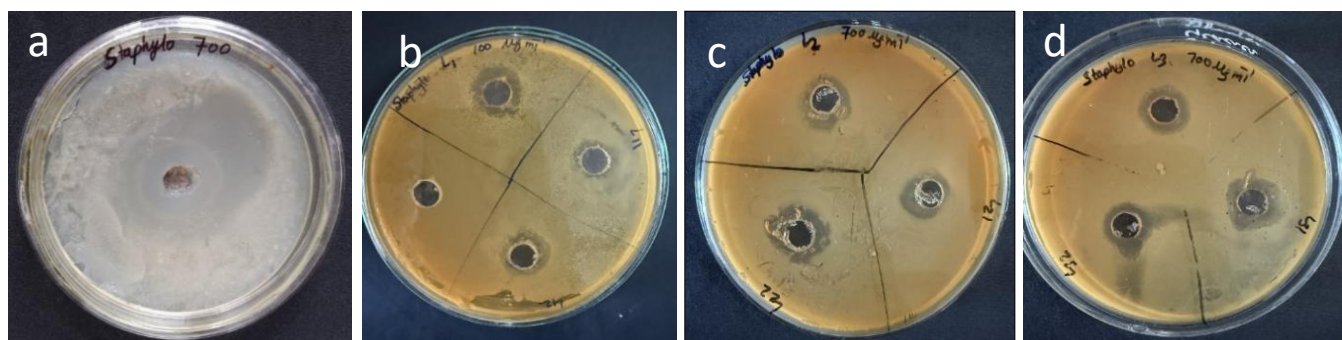


Fig 8: Agar well diffusion assay showing antibacterial activity of synthesized compounds against *S. aureus* at 700 µg mL⁻¹: (a) chloramphenicol (b) L₁, L₁₁ and L₁₂ (c) L₂, L₂₁ and L₂₂ (d) L₃, L₃₁ and L₃₂

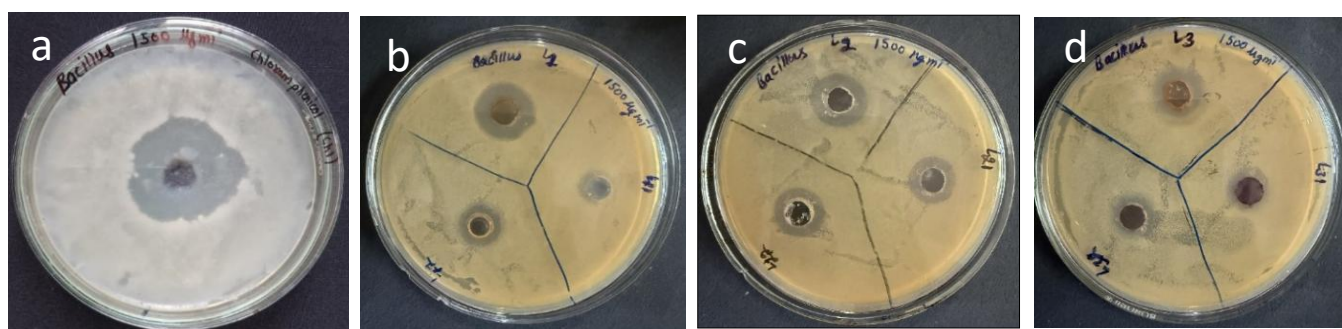
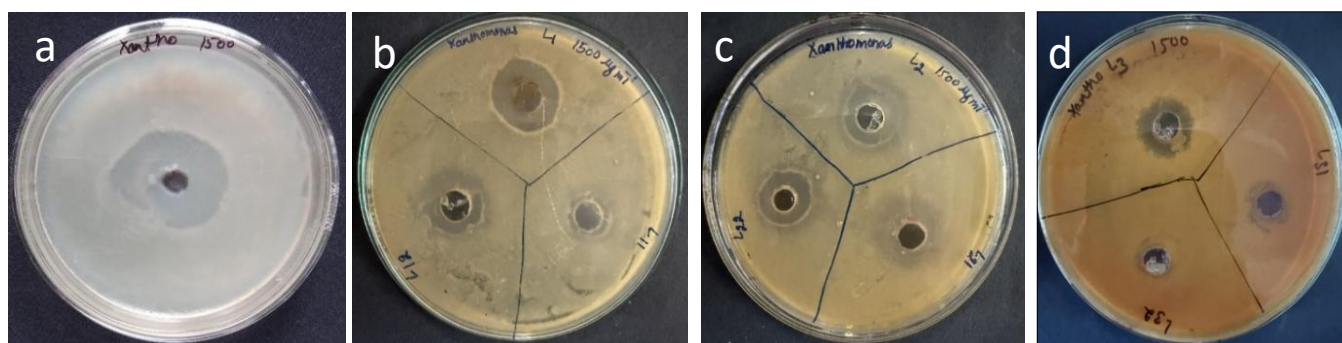
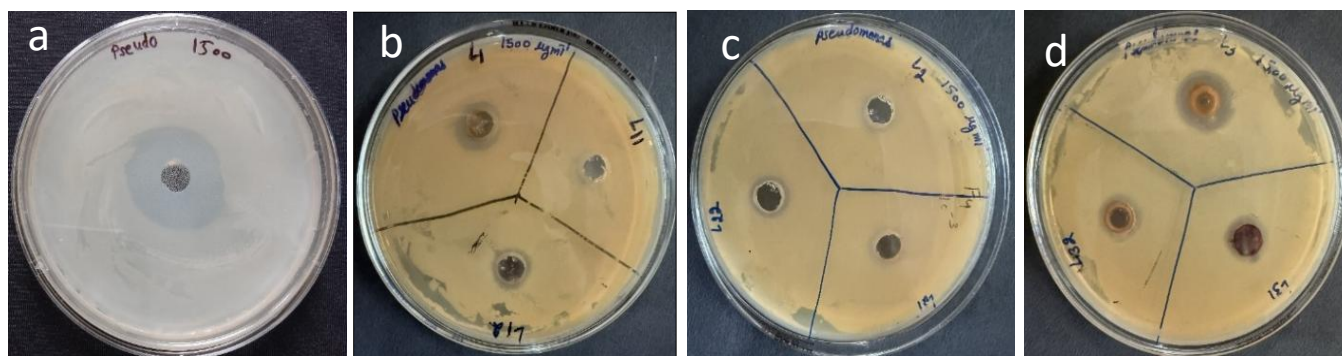


Fig 9: Agar well diffusion assay showing antibacterial activity of synthesized compounds against *B. cereus* at 1500 µg mL⁻¹: (a) chloramphenicol (b) L₁, L₁₁ and L₁₂ (c) L₂, L₂₁ and L₂₂ (d) L₃, L₃₁ and L₃₂

Table 6: Zone of Inhibition (mm) of Synthesized compounds against Gram-negative bacteria at different concentrations

Sr. No.	Compound	Zone of inhibition (mm)					
		<i>Pseudomonas aeruginosa</i>			<i>Xanthomonas</i> spp.		
		Conc. ($\mu\text{g/mL}$)			Conc. ($\mu\text{g/mL}$)		
		1500	1000	700	1500	1000	700
1.	Chloramphenicol	30.00 $\pm$ 0.18	26.00 $\pm$ 0.18	24.00 $\pm$ 0.18	34.00 $\pm$ 0.12	30.00 $\pm$ 0.48	27.00 $\pm$ 0.44
2.	L ₁	8.00 $\pm$ 0.11	7.00 $\pm$ 0.10	6.00 $\pm$ 0.01	15.00 $\pm$ 0.12	12.00 $\pm$ 0.23	10.00 $\pm$ 0.02
3.	L ₁₁	0.00 $\pm$ 0.00	0.00 $\pm$ 0.00	0.00 $\pm$ 0.00	11.00 $\pm$ 0.01	7.00 $\pm$ 0.15	5.00 $\pm$ 0.12
4.	L ₁₂	7.00 $\pm$ 0.13	6.00 $\pm$ 0.06	5.00 $\pm$ 0.12	10.00 $\pm$ 0.21	6.00 $\pm$ 0.05	5.00 $\pm$ 0.01
5.	L ₂	12.00 $\pm$ 0.08	7.00 $\pm$ 0.10	5.00 $\pm$ 0.02	11.00 $\pm$ 0.00	9.00 $\pm$ 0.04	8.00 $\pm$ 0.12
6.	L ₂₁	8.00 $\pm$ 0.05	7.00 $\pm$ 0.13	6.00 $\pm$ 0.04	10.00 $\pm$ 0.06	9.00 $\pm$ 0.11	6.00 $\pm$ 0.08
7.	L ₂₂	8.00 $\pm$ 0.18	6.00 $\pm$ 0.04	5.00 $\pm$ 0.05	10.00 $\pm$ 0.03	9.00 $\pm$ 0.14	7.00 $\pm$ 0.14
8.	L ₃	9.00 $\pm$ 0.07	7.00 $\pm$ 0.14	6.00 $\pm$ 0.09	13.00 $\pm$ 0.02	11.00 $\pm$ 0.24	6.00 $\pm$ 0.08
9.	L ₃₁	10.00 $\pm$ 0.21	7.00 $\pm$ 0.12	6.00 $\pm$ 0.13	11.00 $\pm$ 0.20	6.00 $\pm$ 0.03	5.00 $\pm$ 0.10
10.	L ₃₂	6.00 $\pm$ 0.10	4.00 $\pm$ 0.05	0.00 $\pm$ 0.00	6.00 $\pm$ 0.03	5.00 $\pm$ 0.01	0.00 $\pm$ 0.00

**Fig 10:** Agar well diffusion assay showing antibacterial activity of synthesized compounds against *P. aeruginosa* at 1500 $\mu\text{g mL}^{-1}$: (a) chloramphenicol (b) L₁, L₁₁ and L₁₂ (c) L₂, L₂₁ and L₂₂ (d) L₃, L₃₁ and L₃₂**Fig 11:** Agar well diffusion assay showing antibacterial activity of synthesized compounds against *Xanthomonas* spp. at 1500 $\mu\text{g mL}^{-1}$: (a) chloramphenicol (b) L₁, L₁₁ and L₁₂ (c) L₂, L₂₁ and L₂₂ (d) L₃, L₃₁ and L₃₂

Antifungal activity

The antifungal activity of the synthesized compounds was evaluated against fungal strains *Fusarium oxysporum*, *Alternaria* spp., and *Rhizopus* spp. using the poison plate technique at different concentrations (10-1500 $\mu\text{g mL}^{-1}$) and the percentage growth inhibition was calculated. The standard antibiotic cycloheximide was used as a positive control for the study. All synthesized compounds exhibited concentration-dependent antifungal activity, with inhibitory effects generally increasing as the concentration increased.

Among the tested compounds, the chloro-substituted ligand L₂ consistently demonstrated the highest antifungal activity against all three fungal pathogens, showing complete inhibition against *Fusarium oxysporum* at all tested concentrations and showed nearly complete inhibition of *Alternaria* spp. and *Rhizopus* spp. over a broad concentration range. The corresponding Fe(II) complex (L₂₁ and L₂₂) also exhibited excellent antifungal activity, maintaining complete or near-complete inhibition at moderate to high concentrations.

Table 7: Percentage growth inhibition of *Fusarium oxysporum* against the tested compounds at different concentrations ($\mu\text{g mL}^{-1}$)

Sr. No.	Compound	Concentration ($\mu\text{g mL}^{-1}$)									
		1500	1000	700	500	300	200	100	50	25	10
1.	Cycloheximide	100.00 $\pm$ 0.00	68.29 $\pm$ 0.27	56.09 $\pm$ 0.88	51.21 $\pm$ 0.41	36.58 $\pm$ 0.64	31.70 $\pm$ 0.11	26.82 $\pm$ 1.49	19.51 $\pm$ 0.30	12.20 $\pm$ 0.07	0.00 $\pm$ 0.00
2.	L ₁	100.00 $\pm$ 0.00	100.00 $\pm$ 0.00	100.00 $\pm$ 0.00	100.00 $\pm$ 0.00	87.80 $\pm$ 0.19	60.97 $\pm$ 0.34	51.21 $\pm$ 0.18	36.59 $\pm$ 1.05	24.39 $\pm$ 0.58	0.00 $\pm$ 0.00
3.	L ₁₁	87.80 $\pm$ 0.12	85.36 $\pm$ 0.11	82.92 $\pm$ 0.27	78.04 $\pm$ 0.43	63.41 $\pm$ 0.76	53.65 $\pm$ 0.49	24.39 $\pm$ 0.54	12.20 $\pm$ 1.04	0.00 $\pm$ 0.00	0.00 $\pm$ 0.00

4.	L ₁₂	100.00±0.00	100.00±0.00	100.00±0.00	100.00±0.00	100.00±0.00	60.97±0.18	46.34±0.48	39.02±0.18	29.27±0.90	0.00±0.00
5.	L ₂	100.00±0.00	100.00±0.00	100.00±0.00	100.00±0.00	100.00±0.00	100.00±0.00	100.00±0.00	100.00±0.00	100.00±0.00	100.00±0.00
6.	L ₂₁	100.00±0.00	100.00±0.00	100.00±0.00	100.00±0.00	100.00±0.00	100.00±0.00	100.00±0.00	100.00±0.00	100.00±0.00	80.49±0.17
7.	L ₂₂	100.00±0.00	100.00±0.00	100.00±0.00	100.00±0.00	100.00±0.00	75.60±0.21	70.73±0.12	56.10±0.09	29.27±0.30	0.00±0.00
8.	L ₃	100.00±0.00	100.00±0.00	100.00±0.00	100.00±0.00	75.60±0.22	43.90±0.81	24.39±1.12	0.00±0.00	0.00±0.00	0.00±0.00
9.	L ₃₁	80.48±0.19	78.04±0.18	75.60±0.17	60.97±0.13	48.78±0.53	39.02±0.36	7.30±0.23	0.00±0.00	0.00±0.00	0.00±0.00
10.	L ₃₂	80.48±0.04	73.17±0.21	68.29±0.20	60.97±0.58	43.90±0.88	14.63±1.67	0.00±0.00	0.00±0.00	0.00±0.00	0.00±0.00

Table 8: Percentage growth inhibition of *Rhizopus* spp. against the tested compounds at different concentrations (µg mL⁻¹)

Sr. No.	Compound	Concentration (µg mL ⁻¹)									
		1500	1000	700	500	300	200	100	50	25	10
1.	Cycloheximide	100.00±0.00	78.04±0.32	68.29±0.20	46.34±0.87	34.14±0.05	29.26±0.63	24.39±1.09	0.00±0.00	0.00±0.00	0.00±0.00
2.	L ₁	100.00±0.00	100.00±0.00	75.60±0.43	65.85±0.33	56.09±0.58	46.34±0.93	29.26±0.96	0.00±0.00	0.00±0.00	0.00±0.00
3.	L ₁₁	73.17±0.18	63.41±0.47	63.41±0.29	60.97±0.34	46.34±0.29	41.46±0.62	14.63±0.65	0.00±0.00	0.00±0.00	0.00±0.00
4.	L ₁₂	100.00±0.00	70.73±0.58	68.29±0.52	48.78±0.83	46.34±0.84	43.90±0.14	19.51±1.03	0.00±0.00	0.00±0.00	0.00±0.00
5.	L ₂	100.00±0.00	100.00±0.00	100.00±0.00	100.00±0.00	100.00±0.00	100.00±0.00	100.00±0.00	100.00±0.00	100.00±0.00	80.48±0.37
6.	L ₂₁	100.00±0.00	100.00±0.00	100.00±0.00	100.00±0.00	100.00±0.00	100.00±0.00	100.00±0.00	100.00±0.00	56.59±0.67	41.46±0.97
7.	L ₂₂	100.00±0.00	100.00±0.00	100.00±0.00	100.00±0.00	80.48±0.12	75.60±0.01	70.73±0.47	56.09±0.61	48.78±0.85	0.00±0.00
8.	L ₃	85.36±0.28	80.48±0.08	68.29±0.27	65.85±0.51	63.41±0.45	60.97±0.79	58.53±0.77	34.14±0.47	0.00±0.00	0.00±0.00
9.	L ₃₁	65.85±0.33	60.97±0.74	58.53±0.49	51.21±0.52	34.14±1.38	29.26±0.87	12.19±1.84	0.00±0.00	0.00±0.00	0.00±0.00
10.	L ₃₂	75.61±0.87	73.17±0.30	70.73±1.04	68.29±0.23	43.90±0.84	39.02±1.24	24.39±1.22	0.00±0.00	0.00±0.00	0.00±0.00

Table 9: Percentage growth inhibition of *Alternaria* spp. against the tested compounds at different concentrations (µg mL⁻¹)

Sr. No.	Compound	Concentration (µg mL ⁻¹)									
		1500	1000	700	500	300	200	100	50	25	10
1.	Cycloheximide	83.33±0.27	76.19±0.44	66.67±0.64	61.90±0.23	54.76±0.92	45.24±0.98	30.95±1.02	16.67±1.75	0.00±0.00	0.00±0.00
2.	L ₁	100.00±0.00	100.00±0.00	73.81±0.41	69.05±0.56	61.90±0.36	57.14±0.22	45.24±0.11	0.00±0.00	0.00±0.00	0.00±0.00
3.	L ₁₁	76.19±0.08	73.81±0.46	66.67±0.55	64.29±0.54	45.24±1.12	35.71±0.81	30.95±0.57	0.00±0.00	0.00±0.00	0.00±0.00
4.	L ₁₂	83.33±0.17	76.19±0.12	73.81±0.14	73.81±0.38	54.76±0.23	45.24±0.26	40.48±0.62	0.00±0.00	0.00±0.00	0.00±0.00
5.	L ₂	100.00±0.00	100.00±0.00	100.00±0.00	100.00±0.00	100.00±0.00	100.00±0.00	100.00±0.00	100.00±0.00	80.95±0.11	69.05±0.40
6.	L ₂₁	100.00±0.00	100.00±0.00	100.00±0.00	100.00±0.00	88.10±0.22	83.33±0.15	76.19±0.48	69.05±0.21	52.38±0.72	0.00±0.00
7.	L ₂₂	100.00±0.00	100.00±0.00	100.00±0.00	100.00±0.00	83.33±0.25	57.14±0.24	35.71±1.06	0.00±0.00	0.00±0.00	0.00±0.00
8.	L ₃	80.95±0.04	76.19±0.01	69.05±0.24	66.67±0.32	61.90±0.21	45.24±0.90	9.52±1.18	0.00±0.00	0.00±0.00	0.00±0.00
9.	L ₃₁	73.81±0.40	71.43±0.13	64.29±0.65	59.52±0.79	54.76±0.78	33.33±1.36	26.19±0.48	0.00±0.00	0.00±0.00	0.00±0.00
10.	L ₃₂	78.57±0.43	71.43±0.16	63.10±0.45	64.29±0.21	45.24±0.71	40.48±0.12	33.33±1.07	0.00±0.00	0.00±0.00	0.00±0.00

Discussion

Among all tested compounds Ligand L₁ with an electron-donating group showed the highest antibacterial activity among the series, followed by unsubstituted Ligand L₃ and then Ligand L₂ with an electron-withdrawing group. As biological activity of complex depends on many factor like chelate effect of the ligand, type of donor atoms involved, type of metal ions, overall charge of the complex, the nature of counter ion, and geometry of the complex (Ramadan *et al.*, 2025) [15]. Ligand L₂ with chloro group and its complexes exhibited the highest antifungal activity among tested compounds against all the tested fungal strains, which may be attributed to the presence of an electron-withdrawing group. Ligand L₁ with an methoxy group also exhibited good antifungal activity, achieving 100% inhibition at higher concentrations, its activity decreased progressively at lower concentrations. As Schiff bases containing sulfur-bearing heterocyclic moieties such as thiazole and benzothiazole derivatives, have been widely reported to exhibit significant antifungal properties, and presence of halogen, methoxy and naphthyl like group on these ligands further enhances their antifungal potential (Uddin *et al.* 2020) [20]. The unsubstituted ligand L₃ showed moderate antifungal activity, with inhibition values around 85% at higher concentrations, decreasing significantly at lower concentrations. Its complexes (L₃₁ and L₃₂) exhibited moderate to low activity, particularly at lower concentrations where inhibition was minimal or absent.

Conclusion

Three Schiff base ligands (L₁-L₃) derived from substituted 2-aminobenzothiazole with 2-Hydroxynaphthaldehyde and their corresponding iron (II) and iron (III) complexes were successfully synthesized and characterized by various spectroscopic technique. Synthesized compounds were evaluated for antibacterial and antifungal activities. Among the ligand series, the methoxy-substituted ligand (L₁) exhibited superior antibacterial activity, whereas the chloro-substituted ligand (L₂) showed comparatively lower activity and the unsubstituted ligand (L₃) displayed intermediate behavior. The enhanced activity of L₁ may be associated with the electron-donating methoxy group, which can increase electron density within the conjugated system and favor interactions with bacterial targets. Synthesized compounds, particularly ligand L₂ and its complexes L₂₁ and L₂₂) matched or exceeded the activity of the standard across a wider concentration range, highlighting their potential as effective antifungal agents. These findings demonstrate that the nature of the substituent on the benzothiazole ring significantly influences antibacterial and antifungal activity. Thus, overall results suggest that benzothiazole-derived Schiff bases represent a promising class of compounds for future antimicrobial research. The significant antifungal activity against crop pathogens such as *Fusarium oxysporum* and *Alternaria* spp. highlights the potential of these compounds for the development of novel agrochemical fungicides. However, further greenhouse and

field studies are required to evaluate their practical applicability.

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