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Research Article

Design, Synthesis, and Spectroscopic Investigation of Cobalt(II) and Ni(II) Complexes of Schiff Bases Incorporating Bicyclic Heterocycles and Pyridine-Linked Aminothiol Moieties

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ABSTRACT

A series of new Schiff base ligands incorporating bicyclic heterocycles and a pyridine-linked aminothiol framework were designed and synthesized, followed by preparation of their cobalt(II) and nickel(II) complexes. The ligands were obtained through condensation of 2-(pyridin-2-ylthio)aniline with indole-3-, benzothiophene-3-, and benzofuran-based aldehydes, providing N,S-donor systems capable of effective metal coordination. Complexation reactions with cobalt(II) and nickel(II) salts afforded stable, colored compounds in moderate yields. The synthesized ligands and complexes were characterized by elemental analysis, Fourier transform infrared, NMR spectroscopy, and magnetic susceptibility measurements. Spectral data indicated coordination through the azomethine nitrogen and thioether sulfur atoms, forming chelate structures around the metal centers. Magnetic studies suggested octahedral geometry for both cobalt(II) and nickel(II) complexes. The study demonstrates how incorporation of bicyclic heteroaromatic units and mixed donor sites can influence coordination behavior and stability, providing structurally diverse metal complexes with potential relevance for catalytic and biological applications.

Key words: Cobalt, Metal complexes, Pyridine heterocycle, Schiff's base.

1. INTRODUCTION

The synthesis and structural investigation of transition metal complexes derived from Schiff base ligands continue to attract considerable interest in coordination chemistry [1-2]. This interest arises primarily from the structural versatility of Schiff bases and their strong affinity toward metal ions. The azomethine (–C=N–) linkage, which defines these ligands, serves as an effective coordination site and plays a decisive role in modulating the electronic environment of the metal center. Due to these features, Schiff base metal complexes have been widely studied for their catalytic, physicochemical, and biological properties [3-6]. Schiff bases are typically formed through the condensation of primary amines with aldehydes or ketones, providing a convenient and adaptable synthetic pathway. The ease of synthesis allows systematic structural modification by selecting appropriate amine and carbonyl pre-cursors. When additional donor atoms, such as nitrogen or sulfur are incorporated into the ligand backbone, multidentate coordination becomes possible, often resulting in stable chelate complexes. The denticity and donor set significantly influence the geometry, stability, and electronic characteristics of the resulting metal complexes [7-9]. Among transition metals, Co(II) and Ni(II) occupy a prominent position due to their distinct coordination behavior and relevance in chemical and biological systems. Co(II) complexes commonly adopt octahedral or tetrahedral geometries and exhibit characteristic magnetic properties that provide valuable information regarding the ligand field environment and structural arrangement. Comparative studies of Co and Ni complexes derived from identical ligand systems allow meaningful evaluation of structure–property relationships, particularly in terms of geometry, electronic distribution, and coordination mode [10-12]. Recent developments in ligand design have focused on incorporating heterocyclic frameworks into Schiff base systems to enhance electronic delocalization and structural rigidity. Bicyclic heterocycles, such as indole, benzothiophene, and benzofuran are especially attractive because of their extended π-conjugation and occurrence in biologically significant molecules. These heteroaromatic units can influence both coordination behavior and spectroscopic properties when integrated into Schiff base architectures. Furthermore, the introduction of a pyridine ring provides an additional nitrogen donor site capable of strengthening metal coordination [13-15]. The presence of sulfur donors within a ligand framework further enriches its coordination chemistry. Aminothiol- or thioether-linked pyridine systems introduce an N,S-donor environment, which can stabilize metal ions through mixed hard–soft donor interactions. Such N,S-containing ligands often display distinctive bonding characteristics compared to purely nitrogen-based systems [16-18]. Therefore, combining bicyclic heteroaromatic aldehydes with aminothiol-tethered pyridine amines offers a rational strategy for constructing multifunctional Schiff base ligands capable of forming stable and structurally diverse metal complexes. In the present work, Schiff base ligands were synthesized by condensation of 2-(pyridin-2-ylthio)aniline with selected bicyclic heterocyclic aldehydes, namely, indole-3-carboxaldehyde, benzothiophene-3-carboxaldehyde, and

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benzofuran-2-carboxaldehyde. The pre-cursor amine was prepared through nucleophilic substitution involving aminothiol derivatives and 2-chloropyridine, thereby introducing a pyridine unit tethered through a sulfur linkage. Subsequent condensation reactions afforded structurally distinct imine ligands containing combined N and S donor sites. These ligands were further reacted with cobalt(II) and Ni(II) salts to obtain the corresponding metal complexes. The synthesized compounds were evaluated in terms of their physical properties, elemental composition, and spectroscopic characteristics. Elemental analysis was employed to confirm stoichiometry and purity, while physical observations, such as color, melting point, and solubility provided preliminary insight into complex formation. Infrared spectroscopy was utilized to monitor the coordination behavior of the azomethine group and other donor functionalities by examining characteristic shifts in stretching frequencies upon complexation. Particular emphasis was placed on changes in the C=N stretching band and the appearance of new metal–ligand vibrations, which provide evidence of coordination through nitrogen and sulfur donor atoms. ^{1}H NMR spectroscopy was performed for free ligands to confirm ligand formation. Magnetic susceptibility measurements were carried out for cobalt(II) complexes to determine their magnetic moments and to gain insight into their probable geometrical arrangements. The magnetic data, combined with spectroscopic findings, allowed the proposal of plausible coordination geometries for the synthesized complexes. By integrating bicyclic heterocyclic frameworks with aminothiol-tethered pyridine systems, this study aims to expand the structural diversity of N,S-donor Schiff base complexes of cobalt and Ni (Figure 1). The systematic synthesis, elemental analysis, spectroscopic characterization, and magnetic evaluation presented herein provide a comprehensive approach to understanding their coordination behavior.

Despite the extensive literature on Schiff base complexes, systems incorporating indole, benzothiophene, or benzofuran units linked to a pyridine-thioether fragment remain relatively less explored. The novelty of this work lies in the deliberate construction of such multifunctional ligand architectures and the comparative analysis of their cobalt(II) and Ni(II) complexes through detailed physicochemical characterization. The results are expected to contribute to a clearer understanding of structure–property relationships in mixed N,S-donor coordination systems and to provide a basis for future investigations into their functional applications.

2. RESULTS AND DISCUSSION

2.1. Synthesis of Schiff Base Ligands

The synthesis of the Schiff base ligands was achieved through a two-step procedure involving the preparation of a key pre-cursor amine followed by condensation with selected heterocyclic aldehydes. In the first step, the pre-cursor amine, 2-(pyridin-2-ylthio)aniline, was synthesized through nucleophilic aromatic substitution between an aminothiol derivative and 2-chloropyridine (Scheme 1). This reaction introduced a pyridine ring tethered to the aniline moiety through a thioether (–S–) linkage, thereby generating a ligand framework containing both nitrogen and sulfur donor atoms. The substitution proceeded through an addition–elimination mechanism facilitated by the electron-deficient pyridine ring. The reaction was carried out in dimethylformamide (DMF) as a polar aprotic solvent in the presence of potassium carbonate (K_2CO_3), which acted as a base to deprotonate the thiol group and promote nucleophilic attack. The reaction mixture was heated and stirred for 10 h to ensure complete conversion, after which the product was isolated and purified by conventional methods.

In the second step, the obtained pre-cursor amine was subjected to condensation reactions with various bicyclic heterocyclic aldehydes, namely, indole-3-carboxaldehyde, benzothiophene-3-carboxaldehyde, and benzofuran-2-carboxaldehyde (Scheme 2). These aldehydes were selected to introduce distinct heteroaromatic frameworks capable of influencing the electronic and coordination properties of the resulting

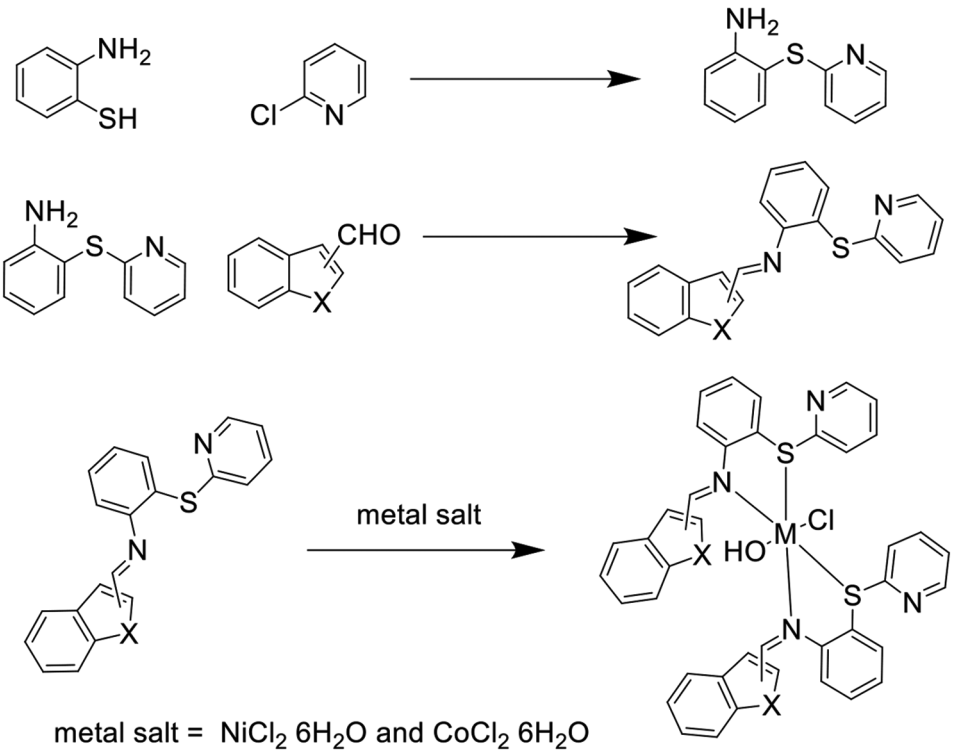


Figure 1: Design of new metal complexes of Schiff bases incorporating bicyclic heterocycles and pyridine-linked aminothiol moieties.

ligands. The condensation reactions were performed in ethanol under reflux conditions for 12 h, leading to the formation of the corresponding Schiff bases (Indole-Linked Aminothiophene Pyridine [IAP], Benzothiophene-Linked Aminothiophene Pyridine [TAP] and Benzofuran-Linked Aminothiophene Pyridine [FAP]) through elimination of water and generation of the azomethine (–CH=N–) linkage. The resulting ligands incorporate multiple donor sites, including the imine nitrogen and thioether sulfur atoms, providing a potentially didentate N and S coordination environment.

The formation of the Schiff bases was indicated by the appearance of characteristic coloration and confirmed by spectroscopic analysis. These reactions afforded structurally diverse imine ligands possessing extended π-conjugation and heteroatom donor sets suitable for coordination with transition metal ions. The overall synthetic pathway for the preparation of the ligands is summarized in Scheme 1.

2.2. Synthesis of Cobalt(II) and Ni(II) Complexes using Schiff Bases (IAS, TAP and FAP)

The Co(II) and Ni(II) complexes were synthesized by reacting the corresponding metal salts with the Schiff base ligands IAS, TAP, and FAP under appropriate conditions (Scheme 3). The reactions proceeded smoothly in an alcoholic medium, leading to the formation of stable, colored complexes. The products were isolated as solid compounds after filtration, washed thoroughly to remove unreacted starting materials, and dried under reduced pressure. The formation of the complexes was indicated by noticeable color changes compared to the free ligands, suggesting successful coordination of the metal ions with the azomethine nitrogen and other donor atoms present in the Schiff bases. The complexes were found to be air-stable and soluble in common organic solvents, such as dimethyl sulfoxide (DMSO) and DMF but sparingly soluble in water.

2.3. Physical Properties and Elemental Analysis

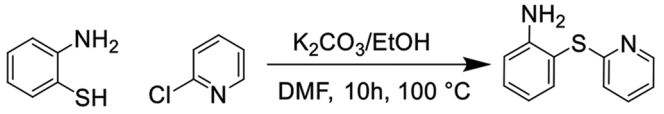
The cobalt(II) and nickel(II) complexes obtained from the Schiff base ligands (IAP, TAP, and FAP) were isolated as stable, colored solid compounds in moderate to good yields. The cobalt complexes appeared mainly blue, while the nickel complexes showed green shades, which are typical for such transition metal complexes. All complexes exhibited relatively high melting or decomposition temperatures (above ~225°C), suggesting good thermal stability and strong coordination between the metal ions and ligands.

These complexes were insoluble in water and most common organic solvents but dissolved in coordinating solvents, such as DMSO and DMF. This solubility pattern indicates the polar nature of the complexes and supports the formation of metal–ligand coordination structures. The physical characteristics of the complexes were clearly different from those of the free ligands, confirming that complexation had taken place.

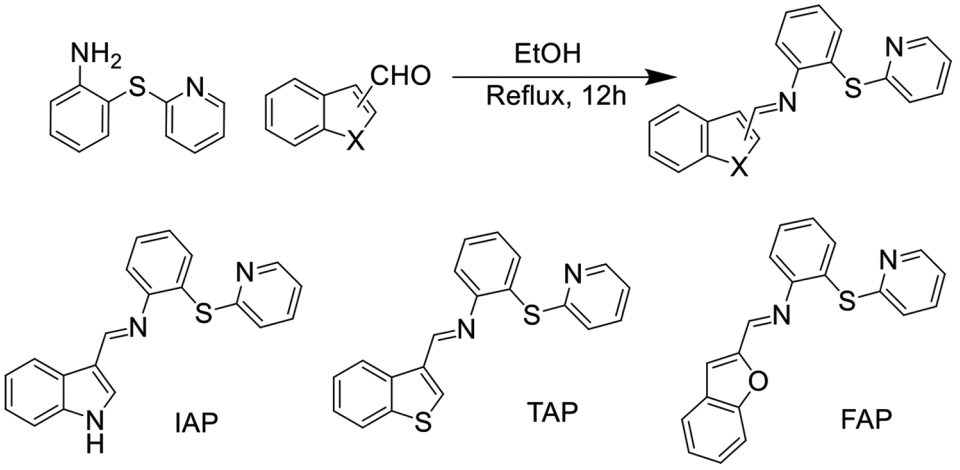
Elemental analysis for C, H, N, S, O, Cl, and the respective metal ions was consistent with the calculated values for the proposed compositions (Section 3.3). The small differences between calculated and found values are within acceptable experimental limits. These results support the proposed stoichiometry and suggest the formation of mononuclear complexes in which the Schiff base ligands coordinate to the metal center through nitrogen and sulfur donor atoms.

2.4. Magnetic Susceptibility Measurements

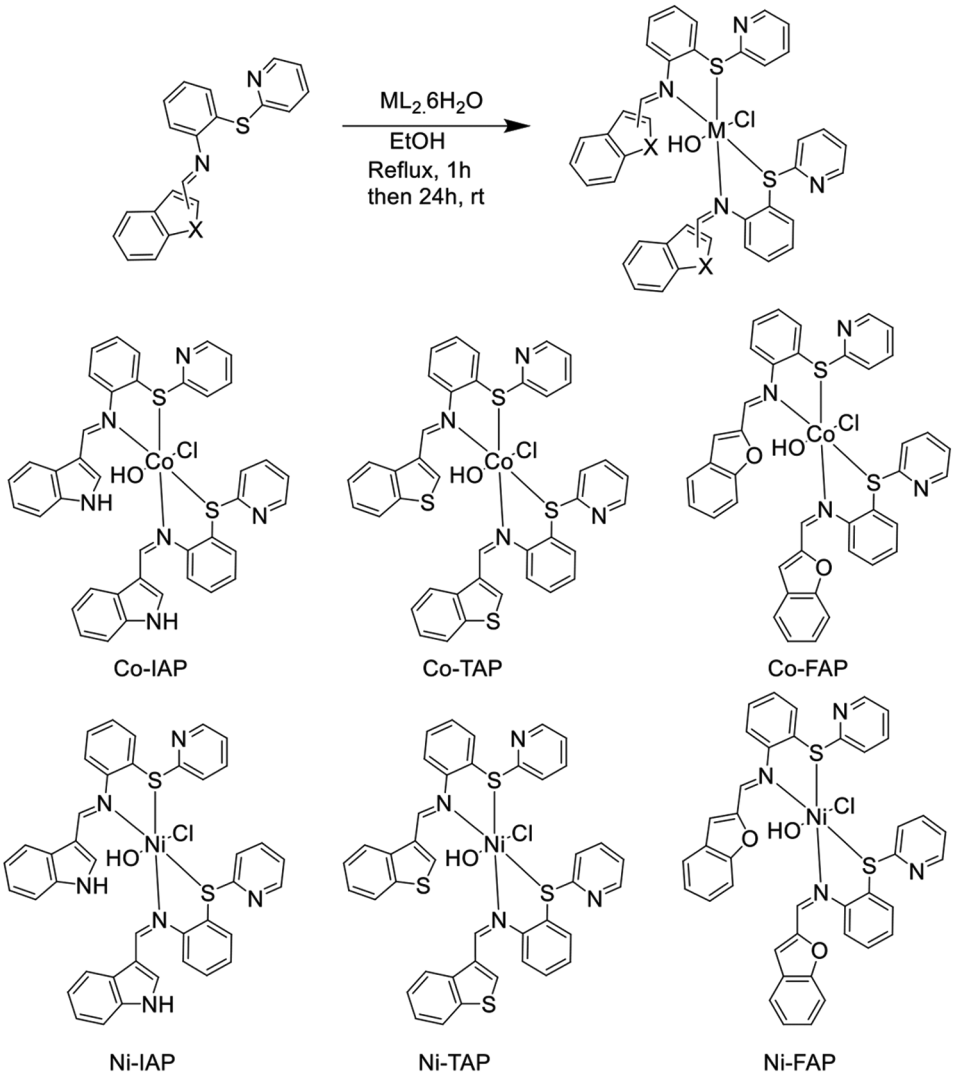
The effective magnetic moments (μ_eff, B.M.) of the synthesized complexes were measured at room temperature, and the values are summarized in Table 1. These experimental values were evaluated in relation to the spin-only magnetic moments calculated from the number of unpaired electrons, which provide useful insight into the electronic configuration and probable geometry around the metal center. The Ni(II) complexes derived from IAP, TAP, and FAP exhibited magnetic moment values in the range of about 2.95–3.30 B.M. Such values are typical for high-spin octahedral Ni(II) (d^8) systems containing two unpaired electrons and are close to the expected spin-only value (≈2.83 B.M.). The results therefore support an octahedral arrangement around the Ni(II) ions. Significantly higher values expected for tetrahedral Ni(II) species were not observed, while square-planar Ni(II) complexes, which are usually diamagnetic, can also be ruled out. The Co(II) complexes showed magnetic moments in the range of approximately 4.70–5.60 B.M., indicating the presence of three unpaired electrons characteristic of high-spin Co(II) (d^7) ions. These values are higher than the spin-only moment (≈3.87 B.M.), suggesting an additional orbital contribution, which is commonly observed for octahedral Co(II) complexes. The measured values are inconsistent with tetrahedral or square-planar geometries and therefore point toward a high-spin octahedral environment around the cobalt centers.



Scheme 1: Synthesis of 2-(pyridin-2-ylthio)aniline.



Scheme 2: Synthesis of Schiff base ligands.



Scheme 3: Synthesis of Cobalt(II) and Ni(II) complexes of schiff bases incorporating bicyclic heterocycles and pyridine-linked aminothiol moieties.

Table 1: Effective magnetic moment (μ_eff) values of the cobalt (II) and nickel (II) complexes measured at room temperature, together with the suggested coordination geometries based on magnetic data.

Complex	μ_eff (B.M.)	Suggested geometry
Ni–IAP	3.12	Octahedral
Ni–TAP	2.98	Octahedral
Ni–FAP	3.25	Octahedral
Co–IAP	4.82	Octahedral
Co–TAP	5.11	Octahedral
Co–FAP	5.48	Octahedral

2.5. Fourier Transform Infrared (FT-IR) Spectral Analysis

The main FT-IR absorption bands of the Schiff base ligands and their metal complexes are listed in Table 2. The spectra of the free ligands (IAP, TAP, and FAP) show a prominent band in the 1520–1535 cm^{-1} region, which can be assigned to the azomethine ν(–HC=N–) stretching vibration. Because this region also contains aromatic ν(C=C) absorptions, some overlap is possible, making exact assignment less straightforward. After coordination with Co(II) and Ni(II) ions, this band shifts to slightly higher frequencies (about

Table 2: Selected FT-IR spectral bands (cm^{-1}) of the Schiff base ligands (IAP, TAP, FAP) and their cobalt (II) and nickel (II) complexes, showing azomethine ν(C=N), thioether ν(C–S), and newly appeared ν(M–N) and ν(M–S) vibrations.

Code	-HC=N-, Azomethine	C-S	M-N	M-S
IAP	1525	718	-	-
Co-IAP	1542	710	520	358
Ni-IAP	1538	712	517	352
TAP	1528	724	-	-
Co-TAP	1546	716	522	360
Ni-TAP	1541	718	519	355
FAP	1530	720		
Co-FAP	1550	714	524	362
Ni-FAP	1544	716	521	357

FT-IR: Fourier transform infrared

1535–1555 cm^{-1}), indicating that the imine nitrogen is involved in bonding to the metal center. The ν(C–S) band of the thioether group appears around 710–730 cm^{-1} in the free ligands and shows a small shift in the complexes, suggesting that the sulfur atom also participates in coordination. In addition, new weak bands appear in the far-IR region of the complexes at approximately 510–525 cm^{-1} and 340–360 cm^{-1}. These bands are attributed to ν(M–N) and ν(M–S) vibrations, respectively, and are not present in the spectra of the uncoordinated ligands. Their appearance provides further evidence that coordination occurs through both the azomethine nitrogen and the thioether sulfur atoms. Taken together, the shift of the ν(C=N) band along with the emergence of ν(M–N) and ν(M–S) vibrations supports the formation of chelate complexes in which the Schiff bases act as bidentate N,S-donor ligands bound to the Co(II) and Ni(II) ions.

3. MATERIALS AND METHODS

3.1. Chemicals and Instrumentation

All chemicals and solvents used in the present study were of analytical reagent grade and employed without further purification. The metal salts $MCl_2 \cdot nH_2O$ [M = Co(II), Ni(II) (n = 6)] were obtained from E. Merck as commercially pure samples and used as received. The aldehydes and other organic reagents required for ligand synthesis were also procured from standard commercial sources and used without additional treatment. Elemental analyses were carried out using a PerkinElmer 2400 CHN elemental analyzer. Infrared spectra were recorded in the range 4000–400 cm^{-1} using the KBr pellet technique on a Bruker Vertex 70 FT-IR spectrometer. Proton nuclear magnetic resonance (^{1}H NMR) and carbon-13 nuclear magnetic resonance (^{13}C NMR) spectra were recorded at room temperature on a Bruker Avance II 400 MHz NMR spectrometer using DMSO-d_6 as solvent and tetramethylsilane as an internal reference. Melting points of the synthesized compounds were determined on a Stuart Scientific melting point apparatus and are uncorrected. Magnetic susceptibility measurements of the metal complexes were performed at room temperature (25 ± 2°C) using a Johnson–Matthey magnetic susceptibility balance. The effective magnetic moment (μeff) values were calculated from the molar magnetic susceptibility (χ_m) using the standard relation: μeff = 2.84 $\sqrt{(\chi_m T)}$, where χ_m is the molar magnetic susceptibility, and T is the absolute temperature.

3.2. Synthesis of Schiff Base Ligands

The Schiff base ligands were prepared in two steps. The purified ligands were characterized by ^{1}H NMR and ^{13}C NMR spectroscopy, which confirmed the formation of the Schiff base and the expected structures.

3.2.1. Synthesis of 2-(pyridin-2-ylthio)aniline precursor

In the first step, the pre-cursor 2-(pyridin-2-ylthio)aniline was synthesized by reacting an aminothiol compound with 2-chloropyridine in a 1:1 molar ratio. The reaction was carried out in DMF using K_2CO_3 (approximately two equivalents) as a base. The reaction mixture was heated at 100°C under continuous stirring to facilitate the nucleophilic substitution process. After completion of the reaction, the mixture was cooled to room temperature and poured into ice-cold water, resulting in the precipitation of the product. The obtained solid was filtered, washed thoroughly with water, and recrystallized from ethanol to afford the pure pre-cursor amine as a colorless solid in 74% yield. Rf = 0.42 (EtOH/hexane); mp = 183–185°C. ^{1}H NMR (400 MHz, DMSO-d_6) δ (ppm): 7.20–7.12 (m, 3H), 7.01–6.92 (m, 2H), 6.85–6.74 (m, 3H), 6.52 (s, 2H). ^{13}C NMR (100 MHz, DMSO-d_6) δ (ppm): 157.8, 155.3, 152.1, 151.4, 150.3, 144.2, 143.3, 140.6, 139.9, 139.0, 135.7.

3.2.2. Synthesis final schiff base ligands

In the second step, the above amine was condensed with the corresponding bicyclic heterocyclic aldehydes (indole-3-carboxaldehyde, benzothiophene-3-carboxaldehyde, or benzofuran-2-carboxaldehyde) in a 1:1 molar ratio. The reactions were carried out in ethanol under reflux for 12 h. On cooling, the Schiff base ligands (IAP, TAP and FAP) separated as solid products. These were filtered, washed with cold ethanol, and purified by recrystallization from ethanol.

3.2.2.1. 1-(1H-indol-3-yl)-N-(2-(pyridin-2-ylthio)phenyl)methanimine (IAP)

Rf = 0.21 (MeOH/DCM); pale yellow solid; mp 165–167°C; yield 72%. ^{1}H NMR (400 MHz, DMSO-d_6) δ 9.15 (s, 1H), 7.31–7.15 (m, 4H), 7.01–6.92 (m, 4H), 6.82–6.69 (m, 4H), 6.15 (s, 1H). ^{13}C NMR (100 MHz, DMSO-d_6) δ 163.2, 156.9, 156.6, 154.1, 153.9, 153.6, 153.7, 152.1, 150.8, 150.5, 149.2, 148.5, 147.3, 145.9, 143.5, 142.4, 139.6, 137.1, 136.0, 133.8.

3.2.2.2. 1-(benzo[b]thiophen-3-yl)-N-(2-(pyridin-2-ylthio)phenyl) methanimine (TAP)

Rf = 0.27 (MeOH/DCM); orange solid; mp 170–172°C; yield 80%. ^{1}H NMR (400 MHz, DMSO-d_6) δ 9.32 (s, 1H), 8.12–8.05 (m, 2H), 7.98–7.90 (m, 2H), 7.76–7.62 (m, 4H), 7.45–7.28 (m, 4H), 6.18 (s, 1H). ^{13}C NMR (100 MHz, DMSO-d_6) δ 164.5, 158.2, 156.1, 154.8, 152.9, 151.7, 149.6, 147.8, 146.2, 144.9, 142.7, 141.3, 139.8, 138.6, 137.4, 135.9, 134.2, 132.8, 131.6, 129.7.

3.2.2.3. 1-(benzofuran-2-yl)-N-(2-(pyridin-2-ylthio)phenyl)methanimine (FAP)

Rf = 0.24 (MeOH/DCM); yellow solid; mp 177–178°C; yield 60%. ^{1}H NMR (400 MHz, DMSO-d_6) δ 9.21 (s, 1H), 8.05–7.98 (m, 2H), 7.82–7.70 (m, 3H), 7.58–7.46 (m, 4H), 7.32–7.20 (m, 3H), 6.04 (s, 1H). ^{13}C NMR (100 MHz, DMSO-d_6) δ 162.8, 159.6, 156.4, 154.2, 153.1, 151.9, 149.8, 147.1, 145.6, 143.8, 142.5, 140.9, 139.2, 137.6, 135.8, 133.9, 132.4, 130.7, 128.9, 127.5.

3.3. Synthesis of Metal Complexes

A solution of the metal chloride (1 mmol) [$CoCl_2 \cdot 6H_2O$ or $NiCl_2 \cdot 6H_2O$] in ethanol (10 mL) was added slowly to a solution of the corresponding Schiff base ligand (2 mmol) dissolved in ethanol (25 mL). The reaction mixture was refluxed for 1 h and then stirred at room temperature for 24 h. During this period, the solid metal complex gradually separated out. The precipitated product was filtered, washed several times with ethanol to remove unreacted ligand and impurities, and dried under vacuum over anhydrous calcium chloride. The yield, color, and elemental analysis data for the complexes are summarized below.

3.3.1. Co-IAP

Yield 54%; blue solid; mp 230–232°C. Elemental analysis (%) for $C_{40}H_{31}ClCoN_6OS_2$: calcd C 62.38, H 4.06, Cl 4.60, N 10.91, O 2.08, S 8.32; found C 62.21, H 4.11, Cl 4.55, N 10.84, O 2.12, S 8.27.

3.3.2. Co-TAP

Yield 58%; dark green solid; mp 238–240°C. Elemental analysis (%) for $C_{40}H_{29}ClCoN_4OS_4$: calcd C 59.73, H 3.63, Cl 4.41, N 6.97, O 1.99, S 15.94; found C 59.58, H 3.69, Cl 4.37, N 6.90, O 2.03, S 15.88.

3.3.3. Co-FAP

Yield 52%; brown solid; mp 242–244°C. Elemental analysis (%) for $C_{40}H_{29}ClCoN_4O_3S_2$: calcd C 62.22, H 3.79, Cl 4.59, N 7.26, O 6.22, S 8.30; found C 62.05, H 3.84, Cl 4.54, N 7.19, O 6.27, S 8.24.

3.3.4. Ni-IAP

Yield 56%; light green solid; mp 228–230°C. Elemental analysis (%) for $C_{40}H_{31}ClN_6NiOS_2$: calcd C 62.40, H 4.06, Cl 4.60, N 10.91, O 2.08, S 8.33; found C 62.26, H 4.12, Cl 4.56, N 10.85, O 2.11, S 8.29.

3.3.5. Ni-TAP

Yield 60%; dark green solid; mp 235–237°C. Elemental analysis (%) for $C_{40}H_{29}ClN_4NiOS_4$: calcd C 59.75, H 3.64, Cl 4.41, N 6.97, O 1.99, S 15.95; found C 59.61, H 3.68, Cl 4.36, N 6.90, O 2.02, S 15.90.

3.3.6. Ni-FAP

Yield 55%; olive green solid; mp 240–242°C. Elemental analysis (%) for $C_{40}H_{29}ClN_4NiO_3S_2$: calcd C 62.24, H 3.79, Cl 4.59, N 7.26, Ni 7.60, O 6.22, S 8.31; found C 62.09, H 3.83, Cl 4.55, N 7.19, Ni 7.54, O 6.27, S 8.26.

4. CONCLUSION

In this work, a new set of Schiff base ligands containing bicyclic heteroaromatic units and a pyridine-linked aminothiol moiety was successfully synthesized and used to prepare cobalt(II) and nickel(II) complexes. The synthetic strategy combined structural rigidity from the heterocyclic aldehydes with mixed nitrogen and sulfur donor sites, resulting in ligands well suited for coordination with transition metal ions. The preparation of the pre-cursor amine and its subsequent condensation with indole, benzothiophene, and benzofuran derivatives provided an efficient route to structurally diverse Schiff bases. The formation of the metal complexes was confirmed by noticeable changes in color, melting behavior, and solubility compared to the free ligands. Elemental analysis data closely matched the calculated values, supporting the proposed stoichiometry and purity of the synthesized compounds. Infrared spectral studies revealed shifts in the azomethine stretching frequency and the appearance of new metal–nitrogen and metal–sulfur bands, indicating coordination through both donor atoms. NMR spectra of the ligands supported ligand formation, while the paramagnetic nature of cobalt(II) and nickel(II) complexes limited detailed NMR interpretation after complexation. Magnetic susceptibility measurements indicated high-spin octahedral geometries for both cobalt(II) and nickel(II) complexes, consistent with the observed spectral features. Overall, the combined analytical and spectroscopic results suggest the formation of mononuclear chelate complexes in which the Schiff bases act as bidentate N,S-donor ligands. This study highlights the importance of ligand design in controlling coordination behavior and structural properties of metal complexes. Incorporating bicyclic heterocycles and pyridine-thioether fragments provides a versatile platform for developing new mixed-donor systems. The findings expand the understanding of cobalt and nickel coordination chemistry with multifunctional Schiff bases and may serve as a basis for future investigations into their catalytic, electronic, or biological applications.

5. ETHICS APPROVAL

Not applicable.

6. DECLARATION OF COMPETING INTEREST

The authors declare no conflict of interest.

7. ACKNOWLEDGMENTS

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