Research Article

Ni(II), Cu(II), Mn(II), and Fe(II) Metal Complexes Containing 1,3-Bis(diphenylphosphino)propane and Pyridine Derivative: Synthesis, Characterization, and Antimicrobial Activity

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1. Introduction

Coordination compounds have been known since the beginning of modern chemistry; also, coordination compounds are so common that their structures and reactions are described as in many ways. The atom within a ligand is bonded to the central metal atom. Especially in hydrometallurgy, the coordination chemistry of the metals participate plays a large role in their solubility and reactivity, as the ore is refined into a precious transition elements. Diphosphine ligands, such as 1,3-bis(diphenylphosphino)propane, are organophosphorus compounds, and these compounds are white solids that are soluble in organic solvents. It is also degraded in air to phosphate oxide and slightly air-sensitive. It is classified as a diphosphine ligand in coordination chemistry and homogeneous catalysis [1–3]. The mixed use of metal complexes containing diphosphines and other ligands, which consist of N or S atoms have been intensively inspected during the past years because of their possibility applications in the fields of light emitting devices, biological activity, and catalysis [4–8]. Additionally, a pronounced attention has been induced by the investigation of the new bioactivity of metal-organic framework materials (BIOMOFs) contained in construction materials as potential antifungal and antibacterial materials (e.g., antifungal glass, antibacterial coating, or antibacterial) [9–14]. Diphosphines are essential ligand backbones, which are coordinated to the metal via monodentate or bidentate manner, and these ligands were used in the development of biologically active metal coordination complexes [15–18]. Pyridine derivatives avail as useful chelating ligands in a large form of inorganic and organometallic applications, and additions act as monodentate ligands that coordinate transition metal ions (N–Ni, N–Cu, Mn–N, and Fe–N) occupy an important position in organometallic chemistry. In addition, there are several reports on pyridine derivative compounds in which the amino group (NH2) also participates in coordination [19–23]. In view of the above importance of these ligands...
and its complexes, we report in this work on the synthesis and characterization of Ni(II), Cu(II), Mn(II), and Fe(II) coordination compounds with DPPP and APY. The structures of the ligands are presented in Figure 1.

2. Experimental

2.1. Materials. High purity 1,3-bis(diphenylphosphino) propane and 2-aminopyridine were supplied from Sigma Aldrich grade. They were purchased and used without purification.

2.2. Physical Measurements. The chemical analyses, CHN, were performed using, Analyischer Functions test Var. El Fab Nr. (11982027) elemental analyzer. FT-IR were recorded as potassium bromide disks (400 to 4000 cm⁻¹) with a FT-IR spectrophotometer and the UV-Vis spectra were obtained using a Shimadzu (UV-2101) PC spectrophotometer. Magnetic susceptibility measurements were done on a magnetic susceptibility balance of the type (MSB-Auto). The conductance of the complexes was measured using a conductivity meter model (4310, JENWAY). Thermal analysis of the compounds was carried out in dynamic air on a Shimadzu (DTG-60-H) thermal analyzer at a heating rate (10°C min⁻¹).

2.3. Antimicrobial Activity of the Complexes

2.3.1. Bacterial and Fungal Strains. The antimicrobial activity of different four complexes extracts was evaluated using five bacterial strains and three fungal strains. Three strains of gram-positive cocci (Staphylococcus epidermidis, Enterococcus faecalis, and Staphylococcus aureus), two strains of gram-negative bacilli (Escherichia coli, and Pseudomonas aeruginosa), one stain of yeast-like fungi (Candida albicans), and 2 molds (Aspergillus fumigatus and Aspergillus flavus) were used in this study.

2.3.2. Inoculum Preparation. Bacterial and yeast-like fungal inoculum were prepared from fresh pure cultures in Muller Hinton broth. Each bacterial and yeast-like fungal suspension were compared with 0.5 McFarland standard. Mold samples were inoculated directly into Sabouraud dextrose agar.

2.3.3. Agar Diffusion Assay. The antimicrobial activity of different chemical complex extracts against the selected microorganisms was evaluated using the agar diffusion assay. Each bacterial inoculum was spread on to two Mueller–Hinton agar plates using a sterile cotton swab by lawn culture technique, and the mold samples were inoculated directly onto Sabouraud dextrose agar. After inoculation, wells were made with the help of a sterile cork borer; three wells were made in one of the agar plates for extract numbers 1–3, and four wells were made in the second plate for extract numbers 4–7. Then, each extract (100 μl) was added to already marked well. The plates were then incubated for 18–24 hrs at 37°C. After incubation, we observed the zone of inhibition around the wells and measured the zone diameter in millimeters (mm) by a ruler.

2.4. Preparation of the Four Complexes

2.4.1. Preparation of [Ni(DPPP)(APY)(H₂O)Cl₂]H₂O Complex (1). An aqueous solution (10 mL) of NiCl₂.6H₂O (0.46 g, 1.9 mmol) was added to 1,3-bis(diphenylphosphino) propane (DPPP) (0.8 g, 1.9 mmol) in 10 mL in the presence of NaOH (0.1 M). To the whole solution, an ethanolic solution (10 mL) of 2-aminopyridine (APY) (0.18 g, 1.9 mmol) was added. Pale brown precipitate was separated after refluxing for 3 h. The precipitate was filtered out after being cooled, washed with distilled water and ethanol, and then dried over P₂O₅ in a desiccator.

2.4.2. Preparation of [Cu(DPPP)(APY)(H₂O)Cl₂] Complex (2). The complex was synthesized by adding the CuCl₂.2H₂O solution (0.82 g, 4.4 mmol) in 20 mL distilled water to 2 g (4.8 mmol) of 1,3-bis(diphenylphosphino)propane in 10 mL of CH₂Cl₂ in the presence of NaOH (0.1 M). Then, to the mixture solution, a 15 mL ethanolic solution of APY (0.45 g, 4.8 mmol) was added immediately. The mixture was refluxed for 3 h and then left aside at room temperature. A light green color was produced and the latter was separated and washed with H₂O and ethanol.

2.4.3. Preparation of [Mn(DPPP)(APY)(H₂O)Cl₂] Complex (3). The Mn(II) complex was prepared by adding the metal salt MnCl₂.4H₂O (0.87 g, 4.4 mmol) dissolved in 20 mL of distilled water with DPPP ligand (1.8 g, 4.4 mmol) dissolved in about 15 mL of a solution (1:2 MeOH/CH₂Cl₂) in the presence of NaOH. The subsequent process was the addition of a 10 mL ethanolic solution of APY ligand (0.41 g, 4.4 mmol). The mixture was refluxed for about 4 h and then cooled. The dark-brown color formed separated, which was filtered and washed with EtOH and dried over P₂O₅.

2.4.4. Preparation of [Fe(DPPP)(APY)(H₂O)Cl₂]₂H₂O Complex (4). A 1,3-bis(diphenylphosphino)propane (2 g, 4.8 mmol) was dissolved in 15 mL of a solution (1:2 MeOH/CH₂Cl₂) in the presence of sodium hydroxide and then the metal salt FeCl₃ (0.61 g, 4.8 mmol) was added in 15 mL of distilled water followed by addition 15 mL ethanolic solution of 2-aminopyridine (0.45 g, 4.8 mmol), and the resultant product was refluxed for 4 h and then cooled and filtered. Light-yellow precipitate formed and was collected.

3. Results and Discussion

The nickel(II), copper(II), manganese(II), and iron(II) coordination compounds were prepared by the reaction of 1,3-bis(diphenylphosphino)propane with metal salts and 2-aminopyridine. The prepared four compounds were found to react in the molar ratio 1:1: 1 metal: DPPP: APY. In addition, these compounds are air stable and insoluble in
common organic solvents but sparingly soluble in dimethylsulphoxide. The conductivities of the compounds were measured in DMSO using $10^{-3}$ M solutions of the complexes. The molar conductivity values of the transition metal compounds were 59, 40, 32, and 52 Å·m$^2$·mol$^{-1}$·cm$^{-1}$, respectively. The compositions of the complexes supported by the elemental analysis are recorded together with color in Table 1.

### 3.1. FT-IR Spectra

The main infrared spectra of these compounds are listed in Table 2. A comparison of the FT-IR spectra of the complexes 1, 2, 3, and 4 with those of the free DPPP and APY ligands reveals interesting features relating to the metal-ligand (M-L) interactions. From the FT-IR spectra, it is found that the P-PH band, which shows at 1440 cm$^{-1}$ in the spectrum of DPPP, is shifted to a lower wave number (1430–1434 cm$^{-1}$), indicating a sharing of this group in the bonding with the metal ions [24]. The stretching frequencies of $\nu$(NH$_2$) are observed at 3440 cm$^{-1}$ in all complexes; the spectrum almost undergoes no shift, indicating the nonparticipation of this group in the coordination [25].

On the other hand, the stretching vibration of pyridine group located at 1617 ($\nu$) C = C and 1473 ($\nu$) C = N cm$^{-1}$ in the APY ligand exhibits a notable shift to a wave number (1438–1482 cm$^{-1}$), [25]. On the other hand, the stretching vibration of pyridine group shows at 1617 (C = C) and 1473 (C = N) cm$^{-1}$ in the APY ligand exhibits a notable shift to a wave number (1438–1482 cm$^{-1}$), indicating a sharing of this group in the bonding with the metal ions [24]. The stretching frequencies of $\nu$(NH$_2$) are observed at 3440 cm$^{-1}$ in all complexes; the spectrum almost undergoes no shift, indicating the nonparticipation of this group in the coordination [25].

#### 3.2. Electronic Spectra

The UV-Visible spectra of the complexes were measured. The Ni(II) complex has a magnetic moment located in the range 3.20 BM. As foretold for a high spin d$^8$ system with two unpaired electrons which falls in the range expected for octahedral Ni(II) compounds [34]. Copper(II) complex gave a value of magnetic moment 1.74 BM [34]. The magnetic moment of the iron complex (5.46 BM) measured at room temperature suggests a high spin d$^6$ configuration of octahedrally coordinated Fe$^{3+}$ ions [35].

Regarding [Ni(DPPP)(APY)H$_2$O]Cl$_2$·H$_2$O complex, its decomposition proceeds in five steps (Figure 5). The first and second correspond to the loss of one crystalline H$_2$O and one coordinated H$_2$O molecule (calc. 5.36%, found 4.92%) (DTG peak at 72, 122°C), for which a broad, endothermic peak appears in the DTA curve at 74 and 124°C. The third and fourth mass loss is

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**Figure 1**: Structure of the ligands. (a) 1,3-Bis(diphenylphosphino)propane. (b) 2-Aminopyridine.

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3.3. Magnetic Moments. The magnetic moments of the complexes were measured. The Ni(II) complex has a magnetic moment located in the range 3.20 BM. As foretold for a high spin d$^8$ system with two unpaired electrons which falls in the range expected for octahedral Ni(II) compounds [34]. Copper(II) complex gave a value of magnetic moment 1.74 BM [34]. The magnetic moment of the iron complex (5.46 BM) measured at room temperature suggests a high spin d$^6$ configuration of octahedrally coordinated Fe$^{3+}$ ions [35]. In the case of Mn(II) a compound the value of the magnetic moment 5.30 BM typical for high spin d$^5$ system with five unpaired electrons with octahedral arrangement around Mn(II) [34, 36]. From the foregoing data, the structure of the compounds can be postulated as follows (Figures 3 and 4).

3.4. Thermal Analysis Studies. Regarding [Ni(DPPP)(APY)H$_2$O]Cl$_2$·H$_2$O complex, its decomposition proceeds in five steps (Figure 5). The first and second correspond to the loss of one crystalline H$_2$O and one coordinated H$_2$O molecule (calc. 5.36%, found 4.92%) (DTG peak at 72, 122°C), for which a broad, endothermic peak appears in the DTA curve at 74 and 124°C. The third and fourth mass loss is
concerned to the expulsion of the 2-aminopyridine ligand and chlorine (calc. 24.54%, found 23.69%) (DTG peak at 312, 373°C). This step is marked on the DTA curve by an exothermic effect at 314 and 375°C. The subsequent steps are the decomposition products of the remainder and the rest of the organic ligand. The residue is assigned to be NiO as indicated by the mass loss (calc. 11.10%, found 10.24%) (Scheme 1).

Regarding [Cu(DPPP)(APY)(H2O)Cl2] complex, the TG, DTG, and DTA curves of this compound show that the thermal decomposition processes involve four stages. The first stage occurs in the temperature range 58–145°C due to the release of the H2O molecules (calc. 2.73%, found 2.52%). At this step, a DTG peak appears at 70°C and a broad endothermic effect is recorded in the DTA trace at 73°C. The second step represents a detachment of APY ligand as indicated by mass loss consideration (calc. 14.27%, found 14.05%). This step is manifested in the DTG curve as a peak at 258°C and the DTA trace furnishes an exothermic effect at 260°C. The decomposition of the rest complex proceeds in...
the next step leaving a stable residue of CuO (calc. 12.06%, found 11.56%).

Regarding [Mn(DPPP)(APY)(H2O)Cl2] complex, the compound undergoes a stepwise decomposition in three distinct steps of mass loss, namely, at 54–106, 107–320, and 322–600°C. The first step is consistent with the release of H2O molecules (calc. 2.77%, found 2.45%). It has a DTG peak at 80°C corresponding to an endothermic peak at 82°C in the DTA trace. In the 2nd step, elimination of the (APY) ligand occurs (calc. 14.46%, found 13.98%). A DTG peak at 296°C with a corresponding broad exothermic peak at 298°C in the DTA trace is observed. The third step represents the thermal decomposition of the rest of the complex. The final product of the compound is compatible with MnO (calc. 10.90%, found 9.97%).

Regarding [Fe(DPPP)(APY)(H2O)Cl2].2H2O complex, the thermogram of [Fe(DPPP)(APY)(H2O)Cl2].2H2O consists of four decomposition stages, namely, at 57–165, 167–278, 280–402, and 404–600°C. The 1st mass loss correlates well with the corresponding of three water molecules, namely, two crystalline and one coordinated, and this may be attributed to an ion-dipole interaction between iron and water (calc. 7.86%, found 7.27%). This step (DTG peak at 81°C) is characterized by an endothermic peak in the DTA curve at 83°C. The second, third, and fourth steps correspond to the decomposition products of the remaining ligands. The final product is assigned to be FeO as indicated by the mass loss in the TG curve (calc. 10.44%, found 10.32%).

3.5. Kinetic Studies. Nonisothermal kinetic study of the four coordination compounds was carried out applying the Coats–Redfern and Horowitz–Metzger methods (Figures 6–8). The kinetic parameters for all complexes are calculated for the first, second, and third steps according to the Coats–Redfern method and are cited in Tables 4 and 5.

3.6. Decomposition Rate and Stability of the Complexes. The decomposition rates of the four complexes have concluded the plotting of the fraction decomposition ($\alpha$) against the temperature ($T$) of the decomposition for the first stage as shown in (Figure 8).

The stabilities of the Ni(II), Cu(II), Mn(II), and Fe(II) coordination complexes could be correlated. In addition to that, the following are the stability orders of the four complexes and the decomposition rates are based on the following:

(i) The stability order at the initial temperature of the 1st stage of the anhydrous complexes

(ii) The temperature of the inflection point

(iii) DTG maximum temperatures (decomposition rate) and initial temperatures (sequence of stability) that are in parentheses

(iv) The regression of the curves ($\alpha$ against $T$) indicates that the complexes decompose by various decomposition rates based on the respective metal ions
(−Ve) $\Delta S^*$ values for the different steps of decomposition of nickel(II), copper(II), manganese(II), and iron(II) compounds propose that the activated complexes are in higher order than the reactants and also that the reactions are slower than the normal level. The different numbers of enthalpies ($\Delta H^*$) and free energy ($\Delta G^*$) of the four

\[
\begin{align*}
[Ni(DPPP)(APY)(H_2O)Cl_2] \cdot H_2O & \rightarrow [Ni(DPPP)(APY)Cl_2] + 2H_2O \\
[Ni(DPPP)(APY)(H_2O)Cl_2] & \rightarrow [Ni(DPPP)(APY)(H_2O)Cl_2] . H_2O \\
[Ni(DPPP)(APY)(H_2O)Cl_2] & \rightarrow [Ni(DPPP)(APY)(H_2O)Cl_2] . H_2O \\
 NiO + Decomposition products & \rightarrow 52-148°C -2H_2O 150-333°C 335-600°C
\end{align*}
\]

\[\text{Scheme 1: The decomposition stages for nickel(II) complex in dynamic air.}\]

\[\text{Figure 6: Coats–Redfern plot for the complex 2}^{\text{nd}}\text{ step in dynamic air.}\]

\[\text{Figure 7: Horowitz–Metzger plot for complex 2}^{\text{nd}}\text{ step in dynamic air.}\]
Figure 8: Fraction decomposed ($\alpha$) and temperature plots ($T$) of the complexes.

Table 4: Kinetic parameters for the thermal decomposition of Ni(II) and Cu(II) complexes using nonmechanistic equations in dynamic air by Coats–Redfern equation.

| Step | $n$  | $r$   | $E$ (kJ mol$^{-1}$) | $Z$ (s$^{-1}$) | $n$  | $r$   | $E$ (kJ mol$^{-1}$) | $Z$ (s$^{-1}$) |
|------|------|-------|---------------------|---------------|------|-------|---------------------|---------------|
| 1st  | 0.00 | 0.9968 | 36.70       | 7.24 × 10$^3$ | 0.00 | 0.9992 | 39.15       | 7.76 × 10$^2$ |
|      | 0.33 | 0.9946 | 49.63       | 1.00 × 10$^2$ | 0.33 | 0.9999 | 46.71       | 9.33 × 10$^2$ |
|      | 0.50 | 1.0000 | 57.62       | 1.14 × 10$^2$ | 0.50 | 1.0000 | 51.17       | 1.02 × 10$^2$ |
|      | 0.66 | 0.9988 | 65.80       | 1.31 × 10$^2$ | 0.66 | 0.9999 | 55.46       | 1.12 × 10$^2$ |
|      | 1.00 | 0.9981 | 86.53       | 1.73 × 10$^2$ | 1.00 | 0.9993 | 65.57       | 1.31 × 10$^2$ |
|      | 2.00 | 0.9893 | 169.64      | 3.54 × 10$^2$ | 2.00 | 0.9958 | 102.21      | 2.08 × 10$^2$ |
| 2nd  | 0.00 | 0.9961 | 74.17       | 1.47 × 10$^2$ | 0.00 | 0.9574 | 17.07       | 3.46 × 10$^2$ |
|      | 0.33 | 0.9972 | 83.68       | 1.65 × 10$^2$ | 0.33 | 0.9647 | 19.99       | 3.98 × 10$^2$ |
|      | 0.50 | 0.9980 | 89.07       | 1.78 × 10$^2$ | 0.50 | 0.9673 | 21.54       | 4.26 × 10$^2$ |
|      | 0.66 | 0.9984 | 94.14       | 1.90 × 10$^2$ | 0.66 | 0.9703 | 23.22       | 4.57 × 10$^2$ |
|      | 1.00 | 0.9989 | 105.55      | 2.13 × 10$^2$ | 1.00 | 0.9753 | 26.91       | 5.42 × 10$^2$ |
|      | 2.00 | 1.0000 | 144.22      | 2.95 × 10$^2$ | 2.00 | 0.9859 | 40.09       | 7.94 × 10$^2$ |
| 3rd  | 0.00 | 0.9994 | 29.22       | 5.75 × 10$^2$ | 0.00 | 0.9978 | 17.40       | 3.46 × 10$^2$ |
|      | 0.33 | 0.9969 | 34.03       | 6.76 × 10$^2$ | 0.33 | 0.9992 | 21.49       | 4.26 × 10$^2$ |
|      | 0.50 | 0.9951 | 36.76       | 7.24 × 10$^2$ | 0.50 | 0.9997 | 23.86       | 4.78 × 10$^2$ |
|      | 0.66 | 0.9929 | 39.59       | 7.94 × 10$^2$ | 0.66 | 0.9999 | 26.15       | 5.24 × 10$^2$ |
|      | 1.00 | 0.9873 | 46.12       | 9.12 × 10$^2$ | 1.00 | 1.0000 | 31.76       | 6.30 × 10$^2$ |
|      | 2.00 | 0.9678 | 70.27       | 1.42 × 10$^3$ | 2.00 | 0.9983 | 52.30       | 10.47 × 10$^2$ |

Bold values of $r$ represent the best fit values of $n$, $E$, and $Z$.

Table 5: Kinetic parameters for the thermal decomposition of Mn(II) and Fe(II) complexes using nonmechanistic equations in dynamic air by Coats–Redfern equation.

| Step | $n$  | $r$   | $E$ (kJ mol$^{-1}$) | $Z$ (s$^{-1}$) | $n$  | $r$   | $E$ (kJ mol$^{-1}$) | $Z$ (s$^{-1}$) |
|------|------|-------|---------------------|---------------|------|-------|---------------------|---------------|
| 1st  | 0.00 | 0.9951 | 14.92       | 3.01 × 10$^2$ | 0.00 | 0.9926 | 25.16       | 5.01 × 10$^2$ |
|      | 0.33 | 0.9909 | 18.16       | 3.71 × 10$^2$ | 0.33 | 0.9947 | 31.48       | 6.30 × 10$^2$ |
|      | 0.50 | 0.9886 | 20.07       | 3.98 × 10$^2$ | 0.50 | 0.9961 | 35.09       | 6.91 × 10$^2$ |
|      | 0.66 | 0.9860 | 21.98       | 4.36 × 10$^2$ | 0.66 | 0.9968 | 38.89       | 7.76 × 10$^2$ |
|      | 1.00 | 0.9812 | 26.57       | 5.24 × 10$^2$ | 1.00 | 0.9978 | 47.34       | 9.33 × 10$^2$ |
|      | 2.00 | 0.9664 | 43.24       | 8.70 × 10$^2$ | 2.00 | 0.9996 | 78.89       | 15.8 × 10$^2$ |
| 2nd  | 0.00 | 0.9926 | 33.75       | 6.76 × 10$^2$ | 0.00 | 0.9934 | 128.37      | 25.70 × 10$^2$ |
|      | 0.33 | 0.9970 | 41.08       | 8.12 × 10$^2$ | 0.33 | 0.9920 | 140.46      | 28.18 × 10$^2$ |
|      | 0.50 | 0.9984 | 45.26       | 8.91 × 10$^2$ | 0.50 | 0.9917 | 146.58      | 29.51 × 10$^2$ |
|      | 0.66 | 0.9994 | 49.73       | 1.0 × 10$^2$  | 0.66 | 0.9913 | 152.69      | 30.09 × 10$^2$ |
|      | 1.00 | 1.0000 | 60.19       | 1.20 × 10$^2$ | 1.00 | 0.9904 | 166.68      | 33.88 × 10$^2$ |
|      | 2.00 | 0.9952 | 100.23      | 19.95 × 10$^2$ | 2.00 | 0.9870 | 210.84      | 41.68 × 10$^2$ |

Bold values of $r$ represent the best fit values of $n$, $E$, and $Z$. 
compounds turn on the effect of the structure, each of the metal ions on the thermal stability of the coordination compounds. The \( (\Delta H^* + Ve) \) values of \( \Delta G^* \) indicated that during the decomposition, reaction is not spontaneous (Table 6).

### Table 6: Thermodynamic parameters for the thermal decomposition of the compounds.

| Complex    | Step | \( \Delta S^* \) kJ mol\(^{-1}\)K\(^{-1}\) | \( \Delta H^* \) kJ mol\(^{-1}\) | \( \Delta G^* \) kJ mol\(^{-1}\) |
|------------|------|---------------------------------|-------------------------------|-------------------------------|
| Ni(II) complex | 1\(^{st}\) | -190.92 | 33.98 | 96.41 |
|            |      | -188.23 | 46.91 | 108.46 |
|            |      | -187.09 | 54.90 | 116.07 |
|            |      | -185.94 | 63.08 | 123.88 |
|            |      | -183.64 | 83.81 | 143.86 |
|            |      | -177.70 | 166.92 | 225.02 |
| Cu(II) complex | 1\(^{st}\) | -190.10 | 36.50 | 96.91 |
|            |      | -188.57 | 44.06 | 103.98 |
|            |      | -187.81 | 48.52 | 108.20 |
|            |      | -187.04 | 52.81 | 112.25 |
|            |      | -185.70 | 62.92 | 121.93 |
|            |      | -181.87 | 99.56 | 157.35 |
| Mn(II) complex | 1\(^{st}\) | -203.52 | 9.77  | 135.66 |
|            |      | -201.78 | 13.01 | 137.83 |
|            |      | -201.19 | 14.92 | 139.37 |
|            |      | -200.43 | 16.83 | 140.81 |
|            |      | -198.91 | 21.42 | 144.46 |
|            |      | -194.69 | 38.09 | 158.52 |
| Fe(II) complex | 1\(^{st}\) | -194.13 | 22.39 | 87.03 |
|            |      | -192.23 | 28.71 | 92.72 |
|            |      | -191.46 | 32.32 | 96.07 |
|            |      | -190.49 | 36.12 | 99.55 |
|            |      | -188.96 | 44.57 | 107.49 |
|            |      | -184.56 | 76.12 | 137.57 |

3.7. X-Ray Powder Diffraction of the Four Complexes. The X-ray powder diffraction types were recorded for the complexes 1–4. The diffraction shapes indicate that the four compounds are crystalline (Figures 9–12). The crystal data for nickel(II), copper(II), Mn(II), and Fe(II) mixed-ligand coordination complexes belong to the monoclinic, triclinic, and monoclinic crystal system, analyzed by Scherrer’s equation. The crystal data for all compounds are listed in Table 7.

3.8. Biological Activity of the Coordination Compounds. Prepared compounds of nickel(II), copper(II), manganese(II), and iron(II) were tested for \textit{in vitro} antimicrobial activity and evaluated against selected bacterial and fungal strains (Figures 13–18). Three strains of gram-positive cocci (\textit{Staphylococcus epidermidis}, \textit{Enterococcus faecalis},...
and *Staphylococcus aureus*, two strains of gram-negative Bacilli (*Pseudomonas aeruginosa* and *Escherichia coli*), one stain of yeast like fungi (*Candida albicans*), and 2 molds (*Aspergillus fumigatus* and *Aspergillus flavus*) were used. The data showed that all complexes have good activity against bacterial strains. Yeast-like fungal stain and mold strains showed good activity mainly toward Ni(II), Cd(II), and Co(II) complexes. Gram-positive bacteria were found to be more sensitive to all tested extracts with significantly higher zones of inhibition than those of gram-negative bacteria and fungal strains. Nickel(II), cadmium(II), and cobalt(II) complexes show higher inhibition zone than the

| Parameters                  | Ni(II) complex | Cu(II) complex | Mn(II) complex | Fe(II) complex |
|-----------------------------|----------------|----------------|----------------|---------------|
| Empirical formula           | C$_{32}$H$_{36}$NiP$_2$O$_2$Cl$_2$ | C$_{32}$H$_{34}$CuP$_2$OCl$_2$ | C$_{32}$H$_{34}$MnP$_2$OCl$_2$ | C$_{32}$H$_{38}$FeP$_2$O$_3$Cl$_2$ |
| Formula weight              | 672.2          | 659.02         | 650.41         | 687.38        |
| Crystal system              | Triclinic      | Monoclinic     | Triclinic      | Monoclinic    |
| a (Å)                       | 15.509         | 13.140         | 15.503         | 11.491        |
| b (Å)                       | 16.785         | 9.857          | 16.788         | 7.393         |
| c (Å)                       | 10.223         | 6.018          | 10.224         | 9.781         |
| Alfa (°)                    | 103.303        | 90.00          | 103.295        | 90.00         |
| Beta (°)                    | 96.349         | 103.20         | 96.342         | 117.25        |
| gamma (°)                   | 105.685        | 90.00          | 105.656        | 90.00         |
| Volume of unit cell (Å³)    | 2450.6         | 758.99         | 2450.9         | 738.7         |

Figure 11: XRD of manganese(II) complex.

Figure 12: XRD of iron(II) complex.
Figure 13: Microbiological screening of Ni(II), Cu(II) and Mn(II) complexes against *E. coli*.

Figure 14: Microbiological screening of Ni(II), Cu(II) and Mn(II) complexes with *S. aureus*.

Figure 15: Microbiological screening of Ni(II), Cu(II) and Mn(II) complexes with *S. epidermidis*.

Figure 16: Microbiological screening of Ni(II), Cu(II) and Mn(II) complexes against *Aspergillus flavus*.

Figure 17: Microbiological screening of Ni(II), Cu(II) and Mn(II) complexes against *Aspergillus fumigatus*.

Figure 18: Microbiological screening of Ni(II), Cu(II) and Mn(II) complexes against *Candida albicans*. 

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other tested extract complexes as stated in Table 8. The zone of inhibition around the wells is measured in millimeters (mm) by a ruler.

4. Conclusion

A number of new one-dimensional nickel(II), copper(II), manganese(II), and iron(II) metal supramolecular coordination compounds of 1,3-bis(diphenylphosphino)propane and 2-aminopyridine have been prepared and characterized by various spectral and physical techniques. From the X-ray analysis, different crystal systems, monoclinic, triclinic, and orthorhombic system for the complexes, were found. The results of antimicrobial activity observed good biological activity for the four compounds, but the nickel(II) complex was over the other three complexes.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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