Two Cu(II) and Co(II) Coordination Polymers: Important Values on Colon Cancer Patients by Reducing Insulin Resistance

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Abstract: In the current study, via utilizing H₂L (H₂L = 2,4-di(3,5′-dicarboxylphenyl)benzoic acid), the symmetrical rigid polycarboxylic acid ligand with V-shape geometry, two new coordination polymers containing Cu(II) and Co(II) have been produced, and their chemical formulae respectively are [Co₂(L)₂(H₂O)₆]·6H₂O (1) and [H₂N(Me)][Co₂(L)(H₂O)]·DMF·H₂O)₆ (2), leading to a variety kinds of coordination patterns of H₂L and multifunctional skeletons. Their inhibitory activity on the insulin resistance of colon cancer patients was assessed. In addition, the detailed mechanism of the compound was also investigated. Firstly, the detection of enzyme-linked immunosorbent assay was carried out and the Tumor Necrosis Factor-α (TNF-α) level and the Interleukin-1β (IL-1β) level was detected. Then, the glucose concentration was determined with blood glucose meter. Next, the insulin receptor expression levels of β cells were determined with the real time reverse transcription-polymerase chain reaction assay. Ultimately, the cytotoxicity of compounds 1 and 2 was determined with Cell Counting Kit-8 assay.

Key words: coordination polymer, colon cancer, ELISA, RT-PCR, interleukin-1β

1 Introduction

In emergency situations such as severe trauma and infection, the body will have abnormal energy and material metabolism, which is mainly manifested as insulin resistance characterized by stress hyperglycemia¹. Strengthening the treatment of postoperative insulin resistance and reducing the incidence of insulin resistance has received more and more attention from surgeons². The incidence of malnutrition is higher in hospitalized patients, especially patients with colon tumors. Therefore, for patients with malnutrition, seeking methods for insulin resistance has become an effective measure to reduce trauma and mortality in critically ill patients and improve prognosis³.

In the last decade, the coordination polymers (CPs) have become one of the most promising microporous materials, especially considering their latent applications. A lot of one-, two- and three-dimensional architectures have been generated through the reasonable design of metal oriented self-assembly methods. In the past several years, owing to the diversity of their structures, for example, nanotubes, bowls and cages, molecular polygon, etc., it has received extensive attention. At the same time, because of the abundant physical performances of the system of metal assembly in luminescence and magnetism, as well as in some fascinating applications in molecular recognition, drug delivery, selective guest inclusion, biological simulation and catalysis⁴−¹⁰. The establishment of CPs generally depends on the combination of central metal ions and organic ligands, as well as a series of external factors involving reactant molar ratio, solvent, pH and temperature, etc¹¹−¹⁵. On the other hand, Cobalt as a human essential element in the active site of vitamin B12, which indirectly regulates the synthesis of DNA, has attracted many biological and organometallic chemists who have investigated cobalt complexes with the aim of medical applications, due to their significant bioactivity¹⁶. In experimental investigation of malignant tumor therapy, the interest in cobalt complexes results from their role as systemic anticancer agents as well as their ability to redox-dependent target the malignant tissue of solid tumors¹⁷. For example, Raja et al. synthesized a cobalt(II) coordination polymer ofisonicotinic hydrazide with substantial anticancer activity¹⁸. Copper

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(II) ion complexes were found to show antiproliferative, cytotoxic, antitumour and genotoxic activities\(^\text{1}^\text{1}\). Another drive for targeting copper (II) was due to its less toxic nature, which can be further decreased on complexion with ligands and thus proved promising in the development of copper complexes as anticancer agents. For instance, Wang and co-workers report the Cu-based polymer particles show in vitro anticancer activities against three chosen cancer lines MCF-7, HeLa, and NCI-H446\(^\text{2}^\text{0}\). In this experiment, via utilizing H\(_2\)L (H\(_2\)L = C\(_2\)H\(_4\)O\(_2\)N\(_4\)) 2 equiv. (3', 5'-dicarboxylphenyl) benzoic acid), the symmetrical rigid polycarboxylic acid ligand with V-shape, two new coordination polymers containing Cu(II) and Co(II) have been produced, and their chemical formulae respectively are [[Co\(_2\)(L)\(_2\)](H\(_2\)O)\(_{12}\)] \(\cdot\) 6H\(_2\)O\(_n\) (1) and [[H\(_2\)N(Me)\(_2\)] [Cu\(_2\)(L) (H\(_2\)O) \cdot DMF \cdot H\(_2\)O] \(\cdot\) 2, leading to a variety of coordination patterns of H\(_2\)L and multifunctional skeletons. The two complexes acquired are completely investigated with the PXRD, thermogravimetric analyses, the IR spectra as well as the diffraction of single crystal X-ray. Furthermore, the compounds’ important application values on gastric cancer patients were evaluated, and their detailed mechanism was also investigated. The enzyme-linked immunosorbent assay detection outcomes reflected that 1 could evidently decrease the inflammatory cytokines TNF-\(\alpha\) level and the IL-1\(\beta\) level, but not compound 2. Besides, the glucose concentration was reduced in the presence of compound 1, which is also stronger than 2. Subsequently, we also revealed that 1 possessed much more superb promotion activity on increasing the insulin receptor expression on the \(\beta\) cells. In the end, the results of the CCK-8 showed that both compounds 1 and 2 exhibited no cytotoxicity. Above all, compound 1 was more excellent than compound 2 on the insulin resistance of colon cancer patients by reducing the inflammatory cytokines TNF-\(\alpha\) level and the IL-1\(\beta\) level.

2 Experimental

2.1 Chemicals and measurements

All the solvents and reagents involved in our present experiment could be acquired from market, which could be applied with no in-depth purification. For the compounds’ infrared spectra utilizing KBr pellets (with 5 mg sample in the 500 mg KBr), it was implemented with the FT-IR spectrometer of Nicolet (Impact 410), with 400 cm\(^{-1}\) to 4000 cm\(^{-1}\) infrared spectra range. With the Elemental analyzer of Perkin–Elmer 240C, we analyzed the elements of Hydrogen, Nitrogen and Carbon. For the data of PXRD, it can be recorded through utilizing the X-ray powder diffractometer of Bruker D8ADVANCE (with CuK of 1.5418 Å). The measurements of TGA can be conducted from ambient temperature to 800°C in the atmosphere of \(\mathrm{N}_2\) at 10°C min\(^{-1}\) heating rate on the thermal analyzer of NETZSCH TG 209.

2.2 Preparation and characterization for \(\left\{\left[\mathrm{Co}_2(L)_2(H_2O)_{12}\right]\cdot 6H_2O\right\}_{n}(1)\) and \(\left\{\left[H_2N(\text{Me})_2\right][\text{Cu}_2(L) (H_2O) \cdot \text{DMF} \cdot H_2O]\right\}_{n}(2)\)

The mixture synthesized from 0.03 mmol and 0.0072 g Co(NO\(_3\))\(_2\)-\(3H_2O\), 0.05 mmol and 0.022 g H\(_2\)L and 10 mL of H\(_2\)O and DMA mixed solution (with the volume ratio of 6:4) was kept into the autoclave (25 mL), and this mixture acquired was heated for seventy-two hours at 120°C, afterwards, this mixture was cooled gradually to ambient temperature. Ultimately, the compound 1’s pink massive crystals could be generated (with approximately 61.0% yield according to Co). Anal. calcld for C\(_{64}\)H\(_{59}\)ON\(_{2}\)Co\(_6\): H, 3.61% and C, 36.60%. Found: H, 3.65% and C, 36.13%. \(\text{IR}(\text{cm}^{-1}):\) 737w, 776w, 1393s, 1446s, 1523m, 1576s, 1622s, 3435m.

The mixture synthesized from 0.1 mmol and 0.024 g Cu(NO\(_3\))\(_2\)-\(3H_2O\), 0.05 mmol and 0.022 g H\(_2\)L and 9.0 mL of H\(_2\)O and DMF mixed solution (with the volume ratio of 2:7) was kept into the autoclave (25 mL), and this mixture acquired was heated for seventy-two hours at 105°C, afterwards, this mixture was cooled gradually to ambient temperature. Ultimately, the compound 2’s blue massive crystals could be generated (with approximately 63.0% yield according to Cu). Anal. calcld for Cu\(_2\)H\(_{6}\)O\(_6\)Cu: N, 3.85%; C, 46.22% and H, 3.88%. Found: N, 3.05%; C, 46.16% and H, 4.38%. \(\text{IR}(\text{cm}^{-1}):\) 599m, 669w, 819w, 970w, 115s, 1376s, 1651s, 2798w, 3108m, 3425w.

The data for X-ray can be acquired with diffractometer of SuperNova. For the analysis of strength data, it could be carried out through applying the software of CrysAlisPro, which was then converted to the files of HKL. And for the approach structural fashions, they were constructed with the direct method based program of SHELX, and then least-squares means based program of SHELXL-2014 was modified\(^{11}^{22}\). Via applying the overall non-hydrogen atoms, the anisotropic parameters could be mixed. Subsequently, the overall hydrogen atoms were fixed on carbon atoms geometrically that they are linked to by utilizing the commands of AFIX. The compounds’ refinement details along with parameters of crystallography were detailed calculated in the Table 1.

2.3 ELISA detection

In this current experiment, enzyme-linked immunosorbent assay detection kit was conducted for the assessment of the TNF-\(\alpha\) content and IL-1\(\beta\) content in plasma. This conduction was completely implemented in accordance with the instruments’ guidance, with only minor modifications. In a word, the hct116 colon cancer cells in logical growth phage were harvested and then implanted into the nude mouse, then the tumor resection was performed and the compound was applied for the indicated treatment with 5 mg/kg concentration. After treated by compounds, the plasma was harvested and the TNF-\(\alpha\) concentration and IL-1\(\beta\) concentration was detected by enzyme-linked
immunosorbent assay detection kit. This present investigation was implemented for 3 times and the outcomes were described as mean ± standard deviation.

2.4 Blood glucose determination

The inhibitory influence of synthetic 1 or 2 against the blood glucose was measured with blood glucose meter. This research was completely accomplished on the basis of the protocols, with only minor modifications. In a word, the hct116 colon cancer cells in logical growth phage were harvested and then implanted into the nude mouse, then the tumor resection was performed and the compound was applied to conduct the indicated treatment with 5 mg/kg concentration. Subsequently, we harvested β cells and then extracted overall RNA via the Reagent of TRIzol (Sigma, St. Louis, MO, USA). On the basis of the proposal of manufacturer, the RNA was transcripted reversely into the cDNA via the kit. SYBR Green Master Mix (Roche) was employed for the conduction of real time reverse transcription-polymerase chain reaction, and the measurement of insulin receptor relative expression on β cells was carried out through the real time reverse transcription-polymerase chain reaction, with the gapdh used as an internal control. With the $2^{-\Delta\Delta Ct}$ approach, the results could be calculated for 3 times.

2.6 Cell Counting Kit-8 assay

The Cell Counting Kit-8 assay was performed in this present research to measure the cytotoxicity of compounds 1 and 2. This experiment was finished totally in accordance with the manufactures’ protocols with some modifications. In brief, the colon cancer cells in the logical growth phage were collected and seeded into the 96 well plates at the concentration of 105 cells per well. The plate was
placed in the incubator at the condition of 37°C, 5% CO₂. The compounds 1 and 2 was then added into the wells for 48 h incubation. After that, the cell medium in the wells was discarded and the fresh medium containing CCK-8 reagent was added into the wells for further incubation. The absorbance of all wells was measured at the absorbance of 450 nm.

3 Results and Discussion

3.1 Crystal structures

In the P2₁/c space group of monoclinic system, complex 1 was crystallized, and 1’s asymmetric unit contains 6 coordinated molecules of H₂O, a totally deprotonated ligand of L⁵⁻, and 2.5 Co²⁺ ions. As exhibited in the Fig. 1a, all the Co atoms possess the geometries of distorted octahedron: where the Co1 atom is connected with 4 carboxylic acid oxygen atoms derived from 4 water oxygen atoms and 4 ligands of L; and the Co2 atom is coordinated via 3 water oxygen atoms and 3 carboxylic acid oxygen atoms in 3 ligands of L; while Co3 atom is connected with 3 water oxygen atoms and 3 carboxylic acid oxygen atoms originate from 2 ligands of L. The angles of O–Co–O are between 86.8° and 158.3°, and the distances of Co–O are in the range of 1.927 Å–2.526 Å. In complex 1, a L⁻⁻ ligand is connected with 7 Co⁵⁺ ions, where 5 carboxylic acid groups reflect the coordination patterns of monodentate (η¹μχ¹), bidentate chelating (η²μχ²) and bidentate bridging (η³μχ³) (Fig. 1b). 1 possesses the trinuclear clusters of [Co₂(μ₂-COO)₅(μ₂-COO)₃] with diverse central metal ions, nevertheless, 4 reveals a two-dimensional layered architecture on the basis of the Co₃ atoms and clusters extended through the ligands of L⁵⁻ (Fig. 1c). In cluster, the distance of Co···Co is 3.7137 Å. In topology, the cluster and L⁵⁻ can be viewed as the four-linked nodes, and thus, complex 1 creates the 2-nodal network, possessing the topology of [4·6·8] [4²·6³] (Fig. 1d)². In the P-1 space group of triclinic system, complex 2 was crystallized, and 2’s asymmetric unit includes a ligand of water, a totally deprotonated ligand of L⁵⁻, 2 isolated Cu²⁺ ions in crystallography, as well as a H₂N(Me)₂ counterion. As displayed in the Fig. 2a, the Cu1 atom is encircled by 5 carboxylic acid oxygen atoms derived from 4 diverse ligands of L⁵⁻, leading to the distorted geometry of trigonal bipyramid; and the Cu2 atom is pentacoordinated, and it is accomplished through 4 carboxylic acid oxygen atoms originate from 2 ligands of L⁵⁻ and an oxygen atom in one coordinated molecule of H₂O, creating the distorted geometry of tetragonal pyramid. The angles of O–Cu–O are between 86.8° and 189.0°, and the distances of Cu–O are in the range of 1.927(4) Å–2.038(4) Å. In complex 2, a L⁻⁻ ligand is linked to 6 Cu²⁺ ions, in which its 5 carboxylic acid groups with the coordination fashions of monodentate (η¹μχ¹), bidentate chelating (η²μχ²) and bidentate bridging (η³μχ³). 2 Cu1 atoms are linked to 2 carboxylic acid groups with the coordination fashions of monodentate (η¹μχ¹), bidentate chelating (η²μχ²) and bidentate bridging (η³μχ³) (Fig. 2c). 2 Cu1 atoms are linked to 2 carboxylic acid groups with the coordination fashions of monodentate (η¹μχ¹), bidentate chelating (η²μχ²) and bidentate bridging (η³μχ³) (Fig. 2d).

Fig. 1 (a) The coordination environment view for Co²⁺ ion in complex 1. (b) 1’s coordination fashion for ligand of L⁵⁻. (c) 1’s two-dimensional layered network. (d) 1’s four-linked network.
acids, thereby creating the binuclear cluster of \([\text{Cu}_2(\mu_2-\text{COO})_2(\mu_1-\text{COO})_4]\), and 4 carboxylic acids groups connect 2 Cu2 atoms, and generating the paddlewheel cluster of \([\text{Cu}_2(\mu_2-\text{COO})_4]\) (Fig. 2b). Such two types of clusters are alternately arranged in distinct ligands directions to produce a porous three-dimensional skeleton, which possesses the channels along axis c, with \(9.2 \times 10.6 \text{ Å}^2\) effective pore sizes (Fig. 2c). After the elimination of \(\text{H}_2\text{O}\) and \(\text{DMF}\) guest molecules, solvent accessible porosity can reach 44%. In topology, each ligand of \(\text{L}^2\) can be reduced as the four-linked node, and each cluster of the \([\text{Cu}_2(\mu_2-\text{COO})_2(\mu_1-\text{COO})_4]\) can be regarded as the six-linked node, therefore, complex 2 reveals a \(\langle 4,6 \rangle\)-linked three-dimensional network with the topology of \([4^4 \cdot 6^6 \cdot 8^3]_2\).

For the sake of the detection of products’ phase purity, we conducted the investigation of powder X-ray diffraction on our synthesized complexes (Fig. 3a). The peak position of simulated PXRD pattern is in consistent with that of the experiment, which reflects that the crystal architecture really represents the products of bulk crystal. The selective selection of crystal samples will lead to the difference of product strength. For the two compounds, the TGA was implemented for the investigation of their thermal stabilities (Fig. 3b). For complex 1, in the temperature range of 30-150°C, the significant weightlessness is 21.7 percent, this value is equivalent to the loss of 6 lattice and 12 coordinated molecules of \(\text{H}_2\text{O}\) with 21.8 percent calculated.

![Fig. 2](image_url) (a) The coordination environment view of Cu\(^{2+}\) ions in complex 2. (b) The images for the clusters of \([\text{Cu}_2(\mu_2-\text{COO})_4]\) and \([\text{Cu}_2(\mu_2-\text{COO})_2(\mu_1-\text{COO})_4]\) in complex 2. (c) 2’s three-dimensional structure. (d) 2’s \(\langle 4,6 \rangle\)-linked three-dimensional network.

![Fig. 3](image_url) (a) The PXRD fashions for the compounds. (b) The TGA diagrams for the two complexes.
value). From 30 to 200°C, complex 2 can release a lattice and a coordinated molecule of H2O, a H2N(Me)2 cation as well as a free molecule of DMF, with the weightlessness of 21.0 percent (and the calculated value is 21.2%). The two compounds’ TGA curves lose weight rapidly after in-depth heating, reflecting the collapse of the entire skeleton and the decomposition of organic ligands.

3.2 Compound significantly reduce the inflammatory cytokines
In the early after stage radical colon cancer surgery, there was usually combined with an evidently enhanced TNF-α and IL-1β level. Hence, in our experiment, the detection of enzyme-linked immunosorbent assay was conducted for the assessment of the content of TNF-α and IL-1β. As the outcomes reveal in the Fig. 4, we can find that there was an obviously enhanced TNF-α and IL-1β level in model group. Whereas, after complex 1 treatment, the levels of inflammatory cytokines were evidently decreased. However, 2 revealed only a little efficiency against the content of inflammatory cytokines.

3.3 Compound significantly reduce the glucose concentration time and dose dependently
1 possessed outstanding inhibitory effect on the content of TNF-α and IL-1β inflammatory cytokines. Nevertheless, compound’s inhibitory efficiency on the concentration of glucose was in-depth required to be studied. According to the results illustrated in Fig. 5, in model group, the concentration of glucose was evidently higher. After the exposure of 1, the enhanced concentration of glucose was obviously decreased. Nevertheless, 2 exhibited nearly no activity on the concentration of glucose.

3.4 Compound obviously increased the expression of the insulin receptor on the β cells
As we have revealed in Fig. 5, 1 exhibited superb inhibitory efficiency against the abnormal high level of the blood glucose concentration. So, how the compound exerts the biological activity remains to be discussed. The real time reverse transcription-polymerase chain reaction was performed in our investigation and the insulin receptor expression on β cells was detected. The outcomes displayed in the Fig. 6 indicated that in model group, there was a decreased insulin receptor level on β cells, and this level is obviously lower than that of control group. Nevertheless, 1 could evidently enhance the insulin receptor expression levels, but the 2 possesses no such activity.

3.5 Compounds exhibited no cytotoxicity on colon cells
Finally, the CCK-8 experiment was performed to evaluate the cytotoxicity of compounds 1 and 2 on colon cells. The results in Fig. 7 also indicated that compared with the normal cells, both compounds 1 and 2 showed inhibitory activity on the viability of FHC normal human colon cells. This result suggested that both compounds 1 and 2 exhibited little cytotoxicity, which have excellent safety.

4 Conclusion
To sum up, we have synthesized two coordination polymers containing Co(II) and Cu(II) by utilizing H5L, the symmetrical rigid polycarboxylic acid ligand with V-shape, leading to a variety kinds of coordination patterns of H5L and multifunctional skeletons. The two complexes acquired are completely investigated with the PXRD, thermogravi-

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**Fig. 4** Evidently decreased content of TNF-α and IL-1β inflammatory cytokines after treated by compound. The hct116 colon cancer cells were planted into the nude mouse, then the tumor resection was performed and the compound was employed to carry out the indicated treatment. The plasma was harvested and then the TNF-α and IL-1β content was detected via enzyme-linked immunosorbent assay detection kit. * means $p<0.05$, ** means $p<0.005$.  

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**Fig. 5** Evidently decreased content of TNF-α and IL-1β inflammatory cytokines after treated by compound. The hct116 colon cancer cells were planted into the nude mouse, then the tumor resection was performed and the compound was employed to carry out the indicated treatment. The plasma was harvested and then the TNF-α and IL-1β content was detected via enzyme-linked immunosorbent assay detection kit. * means $p<0.05$, ** means $p<0.005$.
metric analyses, the IR spectra as well as the diffraction of single crystal X-ray. The diffraction of single crystal X-ray suggests that 1 exhibits a two-dimensional structure on the basis of a cluster of $\{\text{Co}_3(\mu_2-\text{COO})_4(\mu_1-\text{COO})_2\}$ and 2 reveals a three-dimensional $(4,6)$-linked network on the basis of two binuclear clusters of $\{\text{Cu}_2(\mu_2-\text{COO})_4\}$ and $\{\text{Cu}_2(\mu_2-\text{COO})_2(\mu_1-\text{COO})_4\}$. The detection of the enzyme-linked immunosorbent assay displayed that 1 could obviously decrease the TNF-$\alpha$ level and IL-1$\beta$ level inflammatory cytokines, but not compound 2. Besides, the glucose concentration was reduced the exposure of 1, this is also stronger than 2. Additionally, we also revealed that 1 exhibited much more outstanding promotion efficiency on enhancing the insulin receptor expression on the $\beta$ cells. In the end, the results of the CCK-8 showed that both compounds 1 and 2 exhibited no cytotoxicity. Finally, we draw this conclusion, 1 re-

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**Fig. 5** Significantly reduced glucose concentration time and dose dependently after the compound treatment. The hct116 colon cancer cells was planted into the nude mouse, then the tumor resection was performed and the compound was employed to carry out the indicated treatment. The plasma could be harvested and the glucose concentration was measured at least three times. * means $p<0.05$, ** means $p<0.01$ and ***means $p<0.005$.  

**Fig. 6** Obviously enhanced insulin receptor expression on $\beta$ cells after treated by compound. The hct116 colon cancer cells was planted into the nude mouse, then the tumor resection was performed and the compound was applied to perform the indicated treatment. The $\beta$ cells could be harvested and the measurement for the insulin receptor expression on $\beta$ cells was conducted by real time reverse transcription-polymerase chain reaction. * means $p<0.05$, ** means $p<0.01$ and ***means $p<0.005$.  

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revealed much important application values on the insulin resistance of colon cancer patients by reducing the TNF-α and IL-1β levels, which has the protentional to be a clinical candidate.

Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

Data Availability

The data used to support the findings of this study are included within the article.

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Not applicable.

References

1) Cappell, M.S. Pathophysiology, clinical presentation, and management of colon cancer. *Gastroenterol. Clin. North Am.* **37**, 1-24 (2008).

2) Otani, K.; Kawai, K.; Hata, K.; Tanaka, T.; Nishikawa, T.; Sasaki, K.; Kaneko, M.; Murono, K.; Emoto, S.; Nozawa, H. Colon cancer with perforation. *Surg. Today* **49**, 15-20 (2019).

3) Loree, J.M.; Cheung, W.Y. Optimizing adjuvant therapy and survivorship care of stage III colon cancer. *Future Oncol.* **12**, 2021-2035 (2016).

4) Park, J.; Jiang, Q.; Feng, D.; Zhou, H.C. Controlled generation of singlet oxygen in living cells with tunable ratios of the photochromic switch in metal-organic frameworks. *Angew. Chemie - Int. Ed.* **1**, 1-7 (2016).

5) Li, J.X.; Du, Z.X.; Xiong, L.Y.; Fu, L.L.; Bo, W.B. Supramolecular isomerism in two nickel(II) coordination polymers constructed with the flexible 2-carboxyphenoxoacetate linker: Syntheses, structure analyses and magnetic properties. *J. Solid State Chem.* **293**, 121799 (2021).

6) Lu, W.; Yuan, D.; Makal, T.A.; Wei, Z.; Li, J.R.; Zhou, H.C. Highly porous metal-organic framework sustained with 12-connected nanoscopic octahedra. *Dalh. Trans.* **42**, 1708-1714 (2013).

7) Li, J.X.; Du, Z.X.; Zhang, L.L.; Liu, D.L.; Pan, Q.Y. Doubly mononuclear cocrystal and oxalato-bridged binuclear copper compounds containing flexible 2-((3,5,6-trichloropyridin-2-yl)oxy)acetate tectons: Synthesis, crystal analysis and magnetic properties. *Inorg. Chim. Acta* **512**, 119890 (2020).

8) Yilmaz, V.T.; Icsel, C.; Batmus, I.; Aydinlik, S.; Sahinturk, P.; Aygun, M. Structures and biochemical evaluation of silver(I)/5,5-diethylbarbiturate complexes with bis(diphenylphosphino)alkanes as potential antimicrobial and anticancer agents. *Eur. J. Med. Chem.* **139**, 901-916 (2017).

9) Li, J.X.; Du, Z.X.; Pan, Q.Y.; Zhang, L.L.; Liu, D.L. The first 3,5,6-trichloropyridine-2-oxyacetate bridged manganese coordination polymer with features of π-π stacking and halogen--halogen interactions: Synthesis, crystal analysis and magnetic properties. *Inorg. Chim. Acta* **509**, 119677 (2020).

10) Lillerud, K.P.; Obbeye, U.; Tilset, M. Designing heterogeneous catalysts by incorporating enzyme-like functionalities into MOFs. *Top. Catal.* **53**, 859-868 (2010).

11) Li, J.X.; Du, Z.X. A binuclear cadmium (II) cluster based on π-π stacking and halogen--halogen interactions: Synthesis, crystal analysis and fluorescent properties. *J. Clust. Sci.* **31**, 507-511 (2020).

12) Rancan, M.; Armelao, L. Exploiting dimensional variability in coordination polymers: Solvent promotes reversible conversion between 3D and chiral 1D architectures. *Chem. Commun.* **51**, 12947-12949 (2015).

13) Duan, C.; Su, Z.; Cao, Y.; Hu, L.; Fu, D.; Ma, J.; Zhang, Y. Synthesis of core-shell α-AlH3@Al(OH)3 nanocomposite with improved low-temperature dehydrogenating properties by mechanochemical mixing and ionic liquid treatment. *J. Clean. Prod.* **283**, 124635 (2021).

14) Zhang, H.M.; He, Y.C.; Yang, J.; Liu, Y.Y.; Ma, J.F. Ten coordination polymers constructed using an unprecedented azamacrocyclic octacarboxylate ligand 1,4,8,11-tetrazacyclododecane-N,N,N′,N″-tetramethylene-isophthalic acid: Syntheses, structures, and
photoluminescent properties. *Cryst. Growth Des.* **14**, 2307-2317 (2014).

15) Wang, K.; Ma, X.; Shao, D.; Geng, Z.; Zhang, Z.; Wang, Z. Coordination-induced assembly of coordination polymer submicrospheres: Promising antibacterial and *in vitro* anticancer activities. *Cryst. Growth Des.* **12**, 3786-3791 (2012).

16) Zhang, H.R.; Meng, T.; Liu, Y.C.; Chen, Z.F.; Liu, Y.N.; Liang, H. Synthesis, characterization and biological evaluation of a cobalt (II) complex with 5-chloro-8-hydroxyquinoline as anticancer agent. *Appl. Organomet. Chem.* **30**, 740-747 (2016).

17) Silva, T.F.S.; Martins, L.M.D.R.S.; Guedes da Silva, M.F.C.; Fernandes, A.R.; Silva, A.; Borralho, P.M.; Santos, S.; Rodrigues, C.M.P.; Pombeiro, A.J.L. Cobalt complexes bearing scorpionate ligands: Synthesis, characterization, cytotoxicity and DNA cleavage. *Dalt. Trans.* **41**, 12888-12897 (2012).

18) Raja, D.S.; Bhuvanesh, N.S.P.; Natarajan, K. A novel water soluble ligand bridged cobalt (ii) coordination polymer of 2-oxo-1,2-dihydroquinoline-3-carbaldehyde (isonicotinic) hydrazone: Evaluation of the DNA binding, protein interaction, radical scavenging and anticancer activity. *Dalt. Trans.* **41**, 4365-4377 (2012).

19) Alvarez, N.; Mendes, L.F.S.; Kramer, M.G.; Torre, M.H.; Costa-Filho, A.J.; Ellena, J.; Facchin, G. Development of copper (II)-diimine-iminodiacetate mixed ligand complexes as potential antitumor agents. *Inorg. Chim. Acta* **483**, 61-70 (2018).

20) Wang, K.; Ma, X.; Shao, D.; Geng, Z.; Zhang, Z.; Wang, Z. Coordination-induced assembly of coordination polymer submicrospheres: Promising antibacterial and *in vitro* anticancer activities. *Cryst. Growth Des.* **12**, 3786-3791 (2012).

21) Sheldrick, G.M. SHELXT-Integrated space-group and crystal-structure determination. *Acta Crystallogr. Sect. A Found. Adv.* **71**, 3-8 (2015).

22) Sheldrick, G.M. Crystal structure refinement with SHELXL. *Acta Crystallogr. Sect. C Struct. Chem.* **71**, 3-8 (2015).

23) Blatov, V.A.; Shevchenko, A.P.; Proserpio, D.M. Applied topological analysis of crystal structures with the program package ToposPro. *Cryst. Growth Des.* **14**, 3576-3586 (2014).