Functionalization of Two-Dimensional Coordination Polymer in Small Organic Matter Removal from Organic Wastewater

Billy Oktora Abdilah Fauzi1 · Mitsuru Kondo1,2 · Mohamed I. Elzagheid3 · Lydia Rhyman4,5 · Ponnadurai Ramasami4,5

Received: 19 January 2022 / Accepted: 29 June 2022 / Published online: 19 July 2022
© The Author(s), under exclusive licence to Springer Science+Business Media, LLC, part of Springer Nature 2022

Abstract

Multicobalt(II) two-dimensional layer coordination polymer \([\text{Co(bitbu-OMe}_2\text{NCS}_2\cdot2\text{MeOH}}] (\text{I})\) was synthesized using a bis-imidazole ligand having a steric hindrance, tert-butyl, and one methoxy group expressed by bitbu-OMe (bitbu-OMe = 1,1′-((5-tert-butyl-2-methoxybenzene-1,3-diyl)dimethanediyl)bis(1H-imidazole)). Since there are two methanol molecules trapped inside each void within I, the investigation of small organic matter removal from organic wastewater was conducted in order to reveal its ability in the purification process. The research findings indicate that I has the ability to capture methanol, acetone, acetonitrile, and tetrahydrofuran in organic wastewater with removal ratios of 29.17%, 63.22%, 42.77%, and 21.24%, respectively.

Keywords Bis-imidazole · Two-dimensional coordination polymer · Small organic matter removal

1 Introduction

Possessing clean water has long been a significant topic [1], and access to clean water is a key component of Sustainable Development Goal 6 [2]. Water pollution is caused by a variety of waste releases [3] from a variety of sources [4–7]. The creation of organic wastewater is one of the challenges that arise in chemical laboratory research [8–11]. In general, a chemical laboratory’s organic wastewater consists of used water and waste organic solvent mixtures [12]. Various efforts to recycle organic wastewater to generate clean water have been established, such as using zeolite as a purification agent to absorb organic matter dissolved in organic wastewater by leveraging its microporous [13–19].

Due to the unlimited variety of metal ions and bridging ligands involved in forming novel coordination polymers [20], the utilization of materials with voids, such as two-dimensional coordination polymers (CPs) [21], for organic wastewater treatment has become remarkable to research. Jiang et al. [22] reported that the graphene oxide-modified sponge coated with a hydrophobic porous coordination polymer namely USTC-6 synthesized from CuCl₂·2H₂O with 4,4′-(hexafluoroisopropylidene)diphthalic anhydride as the linker exhibited a remarkable ability in absorbing oil like gasoline and diesel oil, and organic solvent like acetone spilled into water. Some coordination polymers developed have also been reported in organic dyes adsorption in water. [(H₂L)₀.₅][Zn(1,2,3-BTA)(H₂O)]·2H₂O (1·2H₂O) one-dimensional anionic coordination polymer (L = N,N′-di(3-pyridyl)succinimide) exhibits a remarkable adsorption ability of an organic dye called Congo red [23]. [Zn(L)(rect tpch)₀.₅(H₂O)] (rect (regio cis, trans, trans)-tpch = tetrakis(4-pyridyl)cyclobutane), a two-dimensional coordination polymer prepared from an irradiation process using Hg lamp (250 W)
lenebis(methylene))bis(oxy)dibenoic acid; bpe = (E)-1,2-di(pyridin-4-yl)ethene), which was developed by Hu et al. [24], possesses an outstanding adsorption ability of some organic dyes, such as Congo red, methylene blue, rhodamine B over methyl orange from aqueous solutions. Because of the metal ions and ligands used, these molecules have piqued curiosity, and they should have no negative impacts on the human body or the environment. As a result, the creation of two-dimensional coordination polymers in the absorption process of small molecules [25, 26] as a purification agent has proven to be advantageous in the purification of organic wastewater. We reported on the synthesis and characterization of \([\text{Co(bitbu-OMe)}_2(\text{NCS})_2\cdot 2\text{MeOH}]_n\), a two-dimensional layered coordination polymer made from \(\text{Co(SCN)}_2\) and a bis-imidazole ligand with a steric hindrance tert-butyl and a methoxy group called bitbu-OMe, in which methanol molecules are encapsulated within its voids [27] (Fig. 1).

Given the foregoing, and in keeping with our research program on water purification [28–33], we present the functionalization of \([\text{Co(bitbu-OMe)}_2(\text{NCS})_2\cdot 2\text{MeOH}]_n\) (1), as well as its action in the purification of organic wastewater in the removal of small organic matter such as methanol, acetone, acetonitrile, and tetrahydrofuran before and after their removal treatment.

2 Experimental Sections

2.1 Materials and Methods

All of the solvents and reagents were commercially available and were used without further purification. On a Rigaku VariMax with a Saturn diffractometer, single-crystal X-ray structural diffraction data for 1 were acquired. On a Rigaku Smart Lab, powder X-ray Diffraction (PXRD) spectrum for 1 was gathered. On the Euro Vector EA3000, elemental analyses (CHN) for bitbu-OMe and 1 were performed. IR spectra for bitbu-OMe and 1 were collected in the 400–4000 cm\(^{-1}\) range using a PerkinElmer FT-IR Spectrometer Frontier. In the range of 300–800 nm, UV–Vis spectra for 1 were collected with a JASCO V-570 UV/Vis/NIR Spectrometer. On a Rigaku TG 8121, thermogravimetry (TG) for 1 was conducted. JEOL ECA-600 Spectrometer was used to generate nuclear magnetic resonance (NMR) spectra for bitbu-OMe and small organic matter such as methanol, acetone, acetonitrile, and tetrahydrofuran before and after their removal treatment.

2.2 Synthesis of 1

As previously reported [27], single crystals of 1 were produced in a straight tube using the liquid–liquid interface method [34]. A diluted 0.0259 g (0.080 mmol) 1,1’-[5-tert-butyl-2-methoxybenzene-1,3-diyl]dimethanediyl]bis(IH-imidazole) (bitbu-OMe) in 20 mL MeOH was prepared. Then, a diluted 0.014 g (0.080 mmol) Co(SCN)_2 in 20 mL
MeOH was prepared as well. 2 mL of each solution was taken, and these taken solutions were slowly added into a straight tube via the straight tube’s wall one by one. Pink crystals were obtained after 1 week of storage.

As previously described [27], the powder was made using the solvothermal method [34]. 1,1′-[5-tert-butyl-2-methoxybenzene-1,3-diyl]dimethanediyl]bis(1H-imidazole) bridging ligand (bitbu-OMe) (0.0648 g, 0.200 mmol) was diluted in 50 mL MeOH. In 50 mL MeOH, Co(SCN)₂ (0.035 g, 0.200 mmol) was diluted. In a 200 mL round bottom flask, these solutions were combined and swirled for 1 day. Later, with a yield of 0.0893 g (~50.73%), the light gray powder was obtained.

\[ \text{H} \] NMR for bitbu-OMe (600 MHz, DMSO-d₆): δ = 7.70 (s, 2H), 7.14 (s, 2H), 7.01 (s, 2H), 6.89 (s, 2H), 5.20 (s, 4H), 3.67 (s, 3H), 1.13 (s, 9H). Elemental analysis (EA) Calcd. For C₁₉H₂₄N₄O (bitbu-OMe) (324.42): C, 70.34; H, 7.46; N, 17.27. Found: C, 70.55; H, 7.34; N, 16.95. IR spectrum for bitbu-OMe (cm⁻¹) 2961 (m), 2904 (w), 2870 (w), 2829 (w), 1979 (w), 1789 (w), 1590 (w), 1485 (m), 1461 (m), 1431 (m), 1394 (m), 1364 (m), 1252 (m), 1225 (m), 1209 (s), 1144 (w), 1120 (w), 1096 (m), 1030 (w), 999 (m), 938 (m), 888 (m), 867 (w), 811 (w), 786 (m), 719 (w), 662 (m), 634 (w), 610 (m), 478 (w), 438 (w).

Elemental analysis (EA) Calcd. for C₄₂H₅₆CoN₁₀O₄S₂ (1) (888.01): C, 56.81; H, 6.36; N, 15.77. Found: C, 52.51; H, 5.54; N, 14.88. IR spectrum for 1 (cm⁻¹) 3647 (w), 3117 (w), 2969 (w), 2077 (w), 1630 (w), 1521 (w), 1492 (w), 1449 (w), 1406 (w), 1366 (w), 1284 (w), 1249 (w), 1216 (w), 1102 (m), 1046 (w), 1029 (m), 987 (m), 949 (w), 918 (w), 842 (w), 819 (w), 805 (w) 736 (m), 719 (w), 662 (m), 634 (w), 610 (m), 478 (w), 438 (w).

### 2.3 Crystal Structure Characterization of 1

VESTA software [35] was used to characterize the crystal structure for 1. Table 1 contains the crystallographic data for 1.

### 2.4 Small Organic Matters Removal Process

The removal of small organic matter in organic wastewater with 1 commenced with thermogravimetric analysis (TG analysis) to determine the optimum temperature for the desolvation process of voids in 1. UV/Vis spectra were recorded before and after the desolvation process to compare 1 powder with and without methanol molecules in the voids. In addition, the UV/Vis spectra for 1 were taken before and after the small organic matter removal treatment to distinguish the differences.

2,2-Dimethylpropan-1-ol (neopentyl alcohol, NPA) (0.018 g, 0.200 mmol) was added to 20 mL of D₂O to create the organic wastewater representative. Four vials of NPA solution were created (5 mL of solution for each vial). Each vial contained 0.400 mmol of each small organic matter (methanol, acetone, acetonitrile, and tetrahydrofuran). For ¹H NMR analysis, 0.500 mL of each small organic matter solution was put to the NMR tube.

The desolvated 1 powder (0.040 g, 0.05 mmol) was mixed with four small organic matter solutions to capture small organic matter. The desolvated 1 powder and small organic matter solutions were mixed at room temperature for one hour. A filter attached to the syringe was used to filter the mixes. For ¹H NMR analysis, 0.500 mL of each solution was put to the NMR tube.

The equation used for the small organic matter removal ratio was derived from the relative quantitative NMR (qNMR) [36], Eq. (1),

\[
\frac{n_x}{n_y} = \frac{I_x}{I_y} \frac{N_x}{N_y}
\]

where \(n_x/n_y\), \(I_x\), \(I_y\), \(N_x\), and \(N_y\) are molar ratio of two compounds, the integrated signal area of compound x, the integrated signal area of compound y, the number nuclei of compound x, and the number nuclei of compound y, respectively. Equation (1) was used to calculate the molarity of organic molecules after removal treatment (\(n_x\)) from

|  |  |
|---|---|
| **Table 1** Summary of crystallographic data and structure refinement parameters for 1 |  |
| Empirical formula | C₄₂H₅₆CoN₁₀O₄S₂ |
| Formula weight | 888.01 |
| Lattice | Monoclinic |
| a, Å | 9.9613(3) |
| b, Å | 23.9517(5) |
| c, Å | 10.2582(3) |
| \(\alpha^\circ\) | 90 |
| \(\beta^\circ\) | 90 |
| \(\gamma^\circ\) | 113.963(4) |
| V, Å³ | 2236.55(12) |
| Space group | \(P2_1/c\) (No. 14) |
| \(Z\) | 2 |
| \(\rho\) (calcd), g cm⁻³ | 1.319 |
| \(\mu\) (MoKα), mm⁻¹ | 0.529 |
| Radiateon (\(\lambda\),Å) | 0.71073 |
| Temp, K | 173.15 |
| Reflns collected | 6126 |
| Unique reflns | 5340 |
| Param refined | 273 |
| R1 [1>2\(\sigma\)] | 0.0556 |
| wR2 [all data] | 0.1672 |
| GOF | 1.064 |
molarity of organic molecules before removal treatment \((n_b)\), and by assuming the molarity of standard compound, the number nuclei of standard compound, the number nuclei of organic molecules before and after treatment to remain the same. The molar ratio of organic molecules before and after removal treatment was calculated using the Eq. (2).

\[
\frac{n_b}{n_a} = \frac{I_b}{I_a}
\]  

(2)

The percentage of organic molecules removal was calculated using the Eq. (3)

\[
\text{Percentage of organic molecules removal} = \left(\frac{I_b - I_a}{I_b}\right) \times 100\%
\]  

(3)

where \(I_b\) and \(I_a\) are the integrated signal area of organic molecules before and after removal treatment, respectively.

3 Result and Discussion

3.1 Synthesis and Characterization of \(1\)

The \(1\) is generated by mixing Co(SCN)\(_2\) salt with bitbu-OMe bridging ligand in a 1:2 ratio, according to the empirical formula of \(1\). Elemental analysis, IR spectra, UV–Vis spectra, powder X-ray diffraction, thermogravimetric analysis, and single-crystal X-ray diffraction were used to characterize the synthesized complex. Because the variation of the results for C, H, and N is higher than 0.4%, the CHN elemental analysis results for \(1\) do not match the calculated ones. However, since an element-agnostic deviation of 0.4% is not a realistic journal criterion for synthetic samples [37], elemental analysis results are not the only technique to validate the purity of a synthesized chemical. As a result, we could carry out more characterizations.

The FT-IR spectrum of bitbu-OMe exhibits extremely distinct bands in the region of 2800 and 3000 cm\(^{-1}\), which are attributed to asymmetric and symmetric stretching vibrations of the tert-butyl group of the bitbu-OMe. Strong bands at 1209 cm\(^{-1}\) and medium bands at 1485 cm\(^{-1}\) in the FT-IR spectrum of bitbu-OMe represent scissoring vibrations of H atoms on the benzene ring and scissoring vibrations of H atoms along with the imidazole rings and tert-butyl group, respectively (see Fig. S1). In comparison to the FT-IR spectrum of bitbu-OMe, the FT-IR spectrum of \(1\) has a relatively consistent band. It indicates that bitbu-OMe is indeed used to make \(1\) (see Fig. S2). The \(1\) powder’s powder X-ray diffraction (PXRD) pattern is highly consistent with \(1\) crystal’s simulated PXRD pattern (see Fig. S3a, b). It signifies that the compound in the \(1\) powder is the same as in the produced crystals.

The percentage by weight of methanol contained in \(1\) is calculated to be 7.23% using the empirical formula of \(1\). The thermogravimetric study shows a rapid mass drop of \(1\) up to 7.21% at 42.8 °C and a gradual mass decrease of \(1\) below 250 °C (see Fig. S4). It implies that below 45 °C, all methanol molecules are entirely eliminated, and the structure of \(1\) remains stable. The UV–Vis spectrum of \(1\) powder (initial/ before being heated below 45 °C) shows that \(1\) possesses the highest absorbance (approximately 0.3) at 300 nm, whereas the UV–Vis spectrum of \(1\) powder after being heated below 45 °C reveals that \(1\) has the highest absorbance (above 0.3) at 300 nm (see Fig. S5), and the \(1\) powder after being heated below 45 °C has a different color than that of the initial \(1\) powder (Fig. 3).

3.2 Crystal Structure Characterization of \(1\)

The single-crystal X-ray diffraction analysis reveals that \(1\) consists of two-dimensional layered coordination polymers with rhombic grid-style [20] crystallized in the monoclinic
system with the space group $P2_1/c$, as previously reported [27] (Fig. 4).

For the size of the void in 1, the single-crystal X-ray diffraction analysis reveals that 1 possesses voids where each void possesses an area of approximately 5.370 Å × 4.424 Å whose length and width are calculated based on the distance between C1 and C1* minus the van der Waals diameter of the carbon atom and the distance between N3 and N3* minus the van der Waals diameter of the nitrogen atom by considering the van der Waals modeling with 100% radius relativity, as previously reported [27] (Fig. 5).

3.3 Small Organic Matter Removal in Organic Wastewater Using 1

The study of encapsulating small organic matter in organic wastewater using 1 was conducted by calculating the ratio of the changes in the concentration of small organic matter and was interpreted from the changes in the integrated signal area of small organic matter obtained from the $^1$H NMR measurement. Neopentyl alcohol was used as a standard to calculate the removal ratio of small organic matter in organic wastewater. Neopentyl alcohol was used due to its size, which is relatively larger than the size of the void within 1. The van der Waals volume of neopentyl alcohol is approximately 87.01 Å$^3$, according to the van der Waals molecular volume calculation proposed by Bondi [38]. Assuming neopentyl alcohol is deemed to possess a spherical shape, the diameter of neopentyl alcohol is approximately 5.5 Å, calculated with the formula for the volume of a sphere. Therefore, the neopentyl alcohol was not captured by 1.

---

Fig. 3 a The 1 powder before being heated (initial). b The 1 powder after being heated (desolvated)

Fig. 4 Projection of 1 along $a$ axis showing the rhombic channels. Methanol molecules trapped in voids are omitted for clarity. Color codes: magenta, cobalt; cyan, nitrogen; black, carbon; red, oxygen; white, hydrogen; yellow, sulfur. Symmetry codes (i) x, y, z; (ii) −x, −y, −z; (iii) −x + 1/2, y + 1/2, −z + 1/2; (iv) x + 1/2, −y + 1/2, z + 1/2 (Color figure online)

Fig. 5 Calculation of the area of the void formed in 1. Two methanol molecules in the void are omitted for clarity. Color codes: magenta, cobalt; cyan, nitrogen; black, carbon; red, oxygen; white, hydrogen; yellow, sulfur. Symmetry codes (i) x, y, z; (ii) −x, −y, −z; (iii) −x + 1/2, y + 1/2, −z + 1/2; (iv) x + 1/2, −y + 1/2, z + 1/2 (Color figure online)
The van der Waals molecular volume and diameter of small organic matter such as methanol, acetone, acetonitrile, and tetrahydrofuran were calculated with the same formula as the van der Waals molecular volume and diameter of neopentyl alcohol described above. The van der Waals molecular volume of methanol, acetone, acetonitrile, and tetrahydrofuran was approximately 36.1 Å³, 64.85 Å³, 47.13 Å³, and 76.61 Å³, respectively. Hence, the van der Waals diameter of these molecules was approximately 4.1 Å, 4.99 Å, 4.48 Å, and 5.27 Å, respectively. Meanwhile, the ¹H NMR results reveal that the desolvated I powder possesses a capturing ability of methanol, acetone, acetonitrile, and tetrahydrofuran with the removal ratios of 29.17%, 63.22%, 42.77%, and 21.24%, respectively (see Fig. S6a–d). Technically, the smaller the van der Waals volume of the small organic matter is, the higher the capture capacity of I powder becomes. Possibly the voids are easier to capture tinier organic matter. In contrast, I possesses a capturing ability of acetone better than other organic matter despite being bigger than methanol. It possibly occurs because methanol possesses a strong interaction with water due to the presence of hydrogen bonding between hydroxy groups in methanol molecules and water molecules, so methanol is more likely to remain in water rather than being trapped by I. The low removal ratio of tetrahydrofuran seemed plausible due to its relatively large van der Waals volume and diameter. Interestingly, the color of I powder after small organic matter removal returned to the color of the initial I powder (Fig. 6), supported by the UV–Vis spectra of I powder after small organic matter removal where these spectra exhibit the highest absorbance (approximately 0.3) at 300 nm (see Fig. S7a–d).

4 Conclusions

Further to the synthesis of I, there are two methanol molecules encapsulated by each void within I and thus it became interesting to study the organic molecules removal in organic wastewater using I. Based on the experimental results, I has an ability to capture methanol, acetone, acetonitrile, and tetrahydrofuran with the removal ratios of 29.17%, 63.22%, 42.77%, and 21.24%, respectively. The findings of this research work can help towards the purification of organic wastewater.

5 Supplementary Data

‡ Crystal data for 1: formula = C₄₂H₅₆CoN₁₀O₄S₂, M = 888.01, lattice = ‘monoclinic’, a = 9.9613(3) Å, b = 23.9517(5) Å, c = 10.2582(3) Å, α = 90°, β = 113.963(4)°, γ = 90°, V = 2236.55(12) Å³, space group = P2₁/c (No. 14), Z = 2, ρ(calcld) = 1.319 g cm⁻³, μ(MoKα) = 0.529 mm⁻¹, ρ(moKα) = 0.529 mm⁻¹, radiateon = 0.71073 (λ, Å), temp = 173.15 K, reflns collected = 6126, unique reflns = 5340, param refined = 273, R1 [I > 2σ(I)] = 0.0556, wR2 [all data] = 0.1672, GOF = 1.064. CCDC-2121123 contains the supplementary crystallographic data for this work and can be obtained through www.ccdc.cam.ac.uk/data_request/cif.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10904-022-02435-5.

Acknowledgements The first author thanks M. K. of Shizuoka University for providing the opportunity to conduct the research and providing...
the laboratory facilities to conduct the measurement. The first author also thanks L. R. and P. R. for refining the manuscript.

**Author Contributions** MK conceived and supervised this research. BOAF carried out the experiment and analyses, drafted and refined the manuscript. MIE contributed to the write up and the analysis of the results. LR and PR refined the manuscript.

**Funding** This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

**Data Availability** All data generated or analyzed during this study are included in this published article [and its supplementary information files].

**Code Availability** Not applicable.

**Declarations**

**Conflict of interest** The authors have no conflicts of interest to declare that are relevant to the content of this article.

**Ethical Approval** Not applicable.

**References**

1. M. Khalifa, S. Bidaisee, The importance of clean water. Sch. J. Appl. Sci. Res. 1(7), 17–20 (2018)

2. U.N. Desa, Transforming our world: the 2030 agenda for sustainable development (2016). https://stg-wedocs.unep.org/bitstream/handle/20.500.11822/11125/unepwisiom1inf7sdg.pdf?sequence=1

3. M. Hasena, M.F. Malik, A. Javed, S. Arshad, N. Asif, S. Zulfiquar, J. Hanif, Water pollution and human health. Environ. Risk Assess. Remediat. 1(3), 16–19 (2017)

4. J.O. Ighalo, A.G. Adeniyi, J.A. Adeniran, S. Oginni. A systematic literature analysis of the nature and regional distribution of water pollution sources in Nigeria. J. Clean. Prod. 283, 124566 (2021). https://doi.org/10.1016/j.jclepro.2020.124566

5. J. Mateo-Sagasta, S.M. Zadeh, H. Turral, J. Burke, Water pollution from agriculture: a global review. Executive summary. Rome, Italy: FAO; Colombo, Sri Lanka: International Water Management Institute (IWMI); CGIAR Research Program on Water, Land, and Ecosystems (WLE) p. 35 (2017)

6. D. Pan, J. Tang, The effects of heterogeneous environmental regulations on water pollution control: quasi-natural experimental evidence from China. Sci. Total Environ. 751, 141550 (2021). https://doi.org/10.1016/j.scitotenv.2020.141550

7. A. Srivastava, B. Gupta, A. Majumder, A.K. Gupta, S.K. Nimbhorkar. A comprehensive review on the synthesis, performance, modifications, and regeneration of activated carbon for the adsorptive removal of various water pollutants. J. Environ. Chem. Eng. (2021). https://doi.org/10.1016/j.jece.2021.106177

8. I. Basturk, G. Varank, S. Murat-Hocaoglu, S. Yazici-Guvenc, E. Can-Guven, E.E. Oktem-Olgun, O. Canli, Simultaneous degradation of cephalixin, ciprofloxacin, and clarithromycin from medical laboratory wastewater by electro-Fenton process. J. Environ. Chem. Eng. 9(1), 104666 (2021). https://doi.org/10.1016/j.jece.2020.104666

9. R. Gulde, M. Rutsch, B. Clerc, J.E. Schollée, U. von Gunten, C.S. McArdell, Formation of transformation products during ozonation of secondary wastewater effluent and their fate in post-treatment: from laboratory-to full-scale. Water Res. 200, 117200 (2021). https://doi.org/10.1016/j.watres.2021.117200

10. M.H. Huang, Y.M. Li, G.W. Gu, Chemical composition of organic matters in domestic wastewater. Desalination 262(1–3), 36–42 (2010). https://doi.org/10.1016/j.desal.2010.05.037

11. E. Morgenroth, R. Kommedal, P. Harremoës, Processes and modeling of hydrolysis of particulate organic matter in aerobic wastewater treatment—a review. Water Sci. Technol. 45(6), 25–40 (2002). https://doi.org/10.2166/wst.2002.0091

12. Y.N. Liu, N. Liu, R. Qu, W. Zhang, Y. Wei, L. Feng, PG–PEI–Ag NPs-decorated membrane for pretreatment of laboratory wastewater: simultaneous removal of water-insoluble organic solvents and water-soluble anionic organic pollutants. Langmuir 35(24), 7680–7690 (2019). https://doi.org/10.1021/acs.langmuir.9b00515

13. N. Chaukura, W. Moyo, B.B. Mamba, T.I. Nkambule, Removal of dissolved organic matter from raw water using zero valent iron-carbonaceous conjugated microporous polymer nanocomposites. Phys. Chem. Earth A/B/C 107, 38–44 (2018). https://doi.org/10.1016/j.pce.2018.08.006

14. T. Wang, H. Liang, L. Bai, X. Zhu, Z. Gan, J. Xing, G. Li, T.M. Aminabhavi, Adsorption behavior of powdered activated carbon to control capacitive deionization fouling of organic matter. Chem. Eng. J. 384, 123277 (2020). https://doi.org/10.1016/j.cej.2019.123277

15. Y. Hu, C. Chen, L. Yang, J. Cui, Q. Hao, D. Sun. Handsy purifier based on bacterial cellulose and Ca-montmorillonite composites for efficient removal of dyes and antibiotics. Carbohydr. Polym. 222, 115017 (2019). https://doi.org/10.1016/j.carbpol.2019.115017

16. T. Wang, Z. Cheng, Y. Liu, W. Tang, T. Fang, B. Xing, Mechanistic understanding of highly selective adsorption of bisphenols on microporous-dominated nitrogen-doped framework carbon. Sci. Total Environ. 762, 143115 (2021). https://doi.org/10.1016/j.scitotenv.2020.143115

17. K. Gupta, O.P. Khatri, Fast and efficient adsorptive removal of organic dyes and active pharmaceutical ingredient by microporous carbon: effect of molecular size and charge. Chem. Eng. J. 378, 122218 (2019). https://doi.org/10.1016/j.cej.2019.122218

18. B. Wang, Q. Zhang, G. Xiong, F. Ding, Y. He, B. Ren, L. You, X. Fan, C. Hardacre, Y. Sun, Bakelite-type anionic microporous organic polymers with high capacity for selective adsorption of cationic dyes from water. Chem. Eng. J. 366, 404–414 (2019). https://doi.org/10.1016/j.cej.2019.02.089

19. G. Cai, P. Yan, L. Zhang, H.C. Zhou, H.L. Jiang, Metal–organic framework-based hierarchically porous materials: synthesis and applications. Chem. Rev. 121(20), 12278–12326 (2021). https://doi.org/10.1021/acs.chemrev.1c00243

20. A.Y. Robin, K.M. Fromm, Coordination polymer networks with O-and N-donors: what they are, why and how they are made. Coord. Chem. Rev. 250(15–16), 2127–2157 (2006). https://doi.org/10.1016/j.ccr.2006.02.013

21. K. Biradha, A. Ramanan, J.J. Vittal, Coordination polymers versus metal–organic frameworks. Cryst. Growth Des. 9(7), 2969–2970 (2009). https://doi.org/10.1021/cg801381p

22. Z.R. Jiang, J. Ge, Y.X. Zhou, Z.U. Wang, D. Chen, S.H. Yu, H.L. Jiang, Coating sponge with a hydrophobic porous coordination polymer containing a low-energy CF3-decorated surface for continuous pumping recovery of an oil spill from water. NPG Asia Mater. 8(3), e253–e253 (2016)

23. B. Wu, W.H. Zhang, Z.G. Ren, J.P. Lang, A 1D anionic coordination polymer showing superior Congo Red sorption and its dye composite exhibiting remarkably enhanced photocurrent response. Chem. Commun. 51(80), 14893–14896 (2015)
24. F.L. Hu, Y.X. Shi, H.H. Chen, J.P. Lang, A Zn(II) coordination polymer and its photocycloaddition product: syntheses, structures, selective luminescence sensing of iron(III) ions and selective absorption of dyes. Dalton Trans. 44(43), 18795–18803 (2015)

25. A. Gallego, C. Hermosa, O. Castillo, I. Berlanga, C.J. Gómez-García, E. Mateo-Martí, J.I. Martínez, F. Flores, C. Gómez-Navarro, J. Gómez-Herrero, S. Delgado, F. Zamora, Solvent-induced delamination of a multifunctional two dimensional coordination polymer. Adv. Mater. 25(15), 2141–2146 (2013). https://doi.org/10.1002/adma.201204676

26. N. Contreras-Pereda, P. Hayati, S. Suárez-García, L. Esrafilì, P. Retailleau, S. Benmansour, F. Novio, A. Morsali, D. Ruiz-Molina, Delamination of 2D coordination polymers: the role of solvent and ultrasound. Ultrason. Sonochem. 55, 186–195 (2019). https://doi.org/10.1016/j.ultsonch.2019.02.014

27. B.O.A. Fauzi, M. Kondo, Syntheses of novel coordination polymers using bis-imidazole ligand having steric hindrance and methoxy group. Online J. Chem.1(1), 29–37 (2021). https://doi.org/10.31586/ojc.2021.010104

28. M. Mochizuki, T. Inoue, K. Yamanishi, S. Koike, M. Kondo, L. Zhang, H. Aoki, Efficient removal of perchlorate ion from water by a water-insoluble M₂L₄ type compound. Dalton Trans. 43(48), 17924–17927 (2014). https://doi.org/10.1039/C4DT02900C

29. A. Murakami, K. Yamanishi, E. Sone, M. Kondo, Preferential removal of perchlorate ion from water using self-assembled constructions of cationic 3D coordination frameworks with methylene units. Chem. Lett. 44(7), 1007–1009 (2015). https://doi.org/10.1246/cl.150316

30. E. Sone, M. Sato, M. Mochizuki, K. Kamio, K. Yamanishi, M. Kondo, Cationic M₂L₄ cages for perchlorate removal from aqueous solutions and preferential perchlorate incorporation in hydrophilic solutions. CrystEngComm 18(26), 5004–5011 (2016). https://doi.org/10.1039/C6CE00267F

31. A. Kheddo, L. Rhyman, M.I. Elzaghied, P. Jeetah, P. Ramasami, Adsorption of synthetic dyed wastewater using activated carbon from rice husk. SN Appl. Sci. 2(12), 1–14 (2020). https://doi.org/10.1007/s42452-020-03922-5

32. E.H. Umukoro, M.G. Peleyeju, A.O. Idris, J.C. Ngila, N. Mababa, L. Rhyman, P. Ramasami, O.A. Arotiba, Photoelectrocatalytic application of palladium decorated zinc oxide-expanded graphite electrode for the removal of 4-nitrophenol: experimental and computational studies. RSC Adv. 8(19), 10255–10266 (2018). https://doi.org/10.1039/C8RA00180D

33. S. Vivekanandam, V. Muthunarayanan, S. Muniraj, L. Rhyman, I.A. Alswaidan, P. Ramasami, Ingenious bioorganic adsorbents for the removal of distillery based pigment-melanoidin: preparation and adsorption mechanism. J. Macromol. Sci. A 56(1), 52–62 (2019). https://doi.org/10.1080/10601325.2018.1527180

34. M. Tran, K. Kline, Y. Qin, Y. Shen, M.D. Green, S. Tongay, 2D coordination polymers: design guidelines and materials perspective. Appl. Phys. Rev. 6(4), 041311 (2019)

35. K. Momma, F. Izumi, VESTA: a three-dimensional visualization system for electronic and structural analysis. J. Appl. Crystallogr. 41(3), 653–658 (2008)

36. F. Malz, H. Jancke, Validation of quantitative NMR. J. Pharm. Biomed. Anal. 38(5), 813–823 (2005). https://doi.org/10.1016/j.jpba.2005.01.043

37. R.E. Kuveke, L. Barwise, Y. van Ingen, K. Vashisth, N. Roberts, S.S. Chitnis, J.L. Dutton, C.D. Martin, R.L. Melen, An international study evaluating elemental analysis (2022)

38. A.V. Bondi, van der Waals volumes and radii. J. Phys. Chem. 68(3), 441–451 (1964)

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.