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Synthesis, structural characterization, and DFT analysis of zinc(II) Schiff base complexes featuring noncovalent spodium bonds†

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In this study, we report the synthesis and comprehensive characterization of five novel zinc(II) complexes with Schiff base ligands: [Zn(HL¹)₂] (1), [Zn(HL²)₂·DMSO·2H₂O] (2A), [Zn(HL²)₂·DMF] (2B), [Zn₂(HL³)₄] (3), and [Zn₂(HL⁴)₄·H₂O] (4). SC-XRD confirms the structures of the complexes, revealing diverse coordination environments and noncovalent interactions, including spodium bonds. The role of hydroxyalkyl groups in stabilizing these complexes is highlighted, showing their contribution to both hydrogen and spodium bonds. Theoretical studies, including DFT geometry optimizations using periodic boundary conditions, QTAIM, and NCIPLOT analyses, elucidate the nature of these weak interactions. Natural bond orbital (NBO) analysis further demonstrates charge transfer from the lone pair of oxygen atoms to the Zn(II) centers, emphasizing the polarization of the zinc orbitals. These findings advance the understanding of spodium bonding in coordination chemistry and its role in stabilizing supramolecular assemblies.

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Introduction

Zinc plays a pivotal role in many biological, chemical, and material applications.^{1–8} Zinc coordination complexes are integral to biological processes such as enzymatic catalysis,^{9–11} structural stabilization in proteins,^{12–14} and zinc-finger motifs in gene regulation.^{15–17} In materials science, zinc complexes are widely explored for applications in luminescent devices,^{18–20} catalysis,^{21–24} and pharmaceuticals due to their unique coordination flexibility and ability to form diverse structural motifs.^{25–30}

Schiff-base ligands, synthesized by the condensation of aldehydes (or ketones) and amines, have long been recognized as versatile tools in coordination chemistry.^{31–37} Their ability to form stable complexes with transition metals,^{38–44} combined with their tunable electronic and steric properties, has led to their use in catalysis,^{45–48} magnetism,^{49–53} and medicinal chemistry.⁵⁴ Schiff-base zinc

complexes, in particular, offer an intriguing platform for exploring structural diversity and noncovalent interactions, which are key to understanding their functionality and potential applications.^{34–36,55–60}

Noncovalent interactions are fundamental to the assembly and stabilization of crystalline materials.^{37,61–64} These interactions, such as H-bonding, π stacking and σ -hole interactions (halogen bonding, chalcogen bonding, *etc.*) are pivotal in crystal engineering and supramolecular chemistry.^{43,65–72} They govern the packing, stability, and properties of solid-state materials, making them essential for the design of advanced materials and molecular devices.⁷³ The study of these interactions provides insights into the subtle balance of forces that determine molecular recognition, self-assembly, and the formation of supramolecular architectures.^{74–77}

Among noncovalent interactions, spodium bonds have recently emerged as a fascinating topic in crystal engineering.^{78–84} Spodium bonds involve attractive interactions between electrophilic sites on post-transition metals group 12 and nucleophilic atoms, such as oxygen or nitrogen. These interactions, which often exhibit directional characteristics akin to hydrogen or halogen bonds, are of particular interest due to their potential role in stabilizing supramolecular assemblies and influencing molecular packing in crystalline materials.^{85–87}

In this study, we report the synthesis, structure, and computational analyses of five zinc(II) complexes with Schiff base

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ligands. Using single-crystal X-ray diffraction, we identify spodium bonds as key interactions in two of the complexes. Theoretical studies, including periodic DFT calculations, quantum theory of atoms in molecules (QTAIM), and non-covalent interactions (NCI), were carried out to further characterize and confirm the nature of these interactions. Our findings contribute to the growing understanding of spodium bonding and its implications in crystal engineering and coordination chemistry.

Experimental

All starting materials and solvents were commercially available, of AR grade, and used as procured from Sigma-Aldrich. The details of the synthesis of ligands, H_2L^1 – H_2L^4 , are gathered in the ESI.†

Synthesis of the ligands

The details of the synthesis of ligands, H_2L^1 – H_2L^4 , are gathered in the ESI.†

Synthesis of the complexes

[Zn(HL¹)₂] (1). An acetonitrile (10 mL) solution of salicylaldehyde (0.11 mL, ~1 mmol) was refluxed with 2-aminobutan-1-ol (0.1 mL, ~1 mmol) for *ca.* 2 h, leading to the formation of a yellow Schiff base ligand, H_2L^1 . A few drops of acetonitrile were added to the reaction mixture to make the volume 20 mL. The acetonitrile solution (20 mL) of the ligand was added to the acetonitrile solution (5 mL) of anhydrous zinc(II) chloride (0.068 g, ~0.5 mmol) with stirring. Block-shaped yellow single crystals of complex **1** were collected by filtration after two weeks on slow evaporation.

Yield: (0.1439 g, ~64%) based on zinc(II) chloride. Anal. calc. for $C_{22}H_{28}N_2O_4Zn$ (FW: 449.85): C, 58.74; H, 6.27; N, 6.23. Found: C, 58.5; H, 6.1; N, 6.3%, FT-IR (KBr): ν_{max}/cm^{-1} 3576–3177 (O–H), 2961–2873 (C–H), 1613 (C=N), UV-vis, $\lambda_{max}(\text{MeOH})/nm$, 361 ($\epsilon/dm^3 \text{ mol}^{-1} \text{ cm}^{-1}$ 8700). δ_H (400 MHz; $CDCl_3$; Me_4Si) 8.28 (2H, s, HC=N), 7.33 (4H, t, $J = 8.1$ Hz, Ph), 7.17–6.57 (4H, m, Ph), 4.94 (2H, s, –OH), 4.01–3.11 (4H, m, –CH₂–), 2.32 (2H, m, –CH–), 1.32 (4H, m, –CH₂–), 0.93 (6H, t, $J = 7.4$ Hz, –CH₃).

[Zn(HL²)₂]-DMSO·2H₂O (2A). An acetonitrile (10 mL) solution of 3,5-dichlorosalicylaldehyde (~1 mmol, 0.191 g) was refluxed with 2-aminobutan-1-ol (0.1 mL, ~1 mmol) for *ca.* 2 h. A few drops of acetonitrile were added to the reaction mixture to make the volume 15 mL. The acetonitrile solution (15 mL) of the ligand (H_2L^2) was added to an acetonitrile solution (5 mL) of anhydrous zinc(II) chloride (0.068 g, ~0.5 mmol) with constant stirring at room temperature followed by the addition of DMSO solution (2 mL). After ten days, needle-shaped yellow crystals of complex **2A** were collected by filtration and allowed to dry in an open atmosphere.

Yield: (0.228 g, ~65%) based on zinc(II) chloride. Anal. calc. for $C_{24}H_{34}Cl_4N_2O_7SZn$ (FW: 701.78): C, 41.08; H, 4.88; N, 3.99; S, 4.57. Found: C, 41.1; H, 4.8; N, 4.2; S, 4.6%, FT-IR (KBr): $\nu_{max}/$

cm^{-1} 3535–3150 (OH), 2974–2917 (C–H), 1626 (C=N), $\lambda_{max}(\text{MeOH})/nm$, 379 ($\epsilon/dm^3 \text{ mol}^{-1} \text{ cm}^{-1}$ 102 600), δ_H (400 MHz; $CDCl_3$; Me_4Si) 8.20 (2H, s, –HC=N–), 7.58–7.28 (2H, m, Ph), 7.21–6.97 (2H, m, Ph), 3.66 (4H, d, $J = 57.0$ Hz, –CH₂–), 3.34 (2H, m, CH) 2.61 (6H, s, –CH₃), 1.25 (4H, m, –CH₂–), 0.93 (6H, t, $J = 7.7$ Hz, –CH₃), δ_C (101 MHz; $CDCl_3$; Me_4Si) 207.04 (s, CO), 169.78 (s, –HC=N–), 134.30 (s, Ph), 133.30 (s, Ph), 127.75 (s, Ph), 118.54 (s, Ph), 77.65 (s, $CDCl_3$), 77.24 (s, $CDCl_3$), 77.04 (s, $CDCl_3$), 76.72 (s, $CDCl_3$), 76.54 (s, $CDCl_3$), 64.65 (s, –CH₂–), 40.07 (s, –CH₃), 30.94 (s, –CH₂–), 25.02 (s, –CH₂–), 10.81 (s, –CH₃).

[Zn(HL²)₂]-DMF (2B). A methanol (10 mL) solution of 3,5-dichlorosalicylaldehyde (~1 mmol, 0.191 g) was refluxed with 2-aminobutan-1-ol (0.1 mL, ~1 mmol) for *ca.* 2 h. A few drops of methanol were added to the reaction mixture to make the volume 15 mL. The ligand H_2L^2 was not isolated and the methanol solution (15 mL) of the ligand was added to a methanol solution (5 mL) of zinc(II) acetate dihydrate (0.11 g, ~0.5 mmol) with constant stirring at room temperature followed by the addition of a few drops of DMF solution (2 mL). After ten days, yellow needle-shaped crystals of complex **2B** with X-ray quality clarity emerged at the beaker's bottom. These were gathered and allowed to dry naturally.

Yield: (0.2147 g, ~65%) based on zinc(II) acetate dihydrate. Anal. calc. for $C_{25}H_{31}Cl_4N_3O_5Zn$ (FW: 660.72): C, 45.45; H, 4.73; N, 6.36. Found: C, 45.4; H, 4.6; N, 6.5%, FT-IR (KBr): ν_{max}/cm^{-1} 3535–3150 (OH₂, OH), 2976–2856 (C–H), 1625 (C=N), $\lambda_{max}(\text{MeOH})/nm$, 381 ($\epsilon/dm^3 \text{ mol}^{-1} \text{ cm}^{-1}$ 35 000).

[Zn₂(HL³)₄] (3). Ethanolamine (~1 mmol, 0.06 mL) and 5-chloro-2-hydroxybenzaldehyde (~1 mmol, 0.156 g) in 15 mL acetonitrile were refluxed for *ca.* 2 h. A few drops of acetonitrile were added to the reaction mixture to make the volume 15 mL. The ligand was not isolated and the acetonitrile solution (15 mL) of the Schiff base ligand H_2L^3 was added to an acetonitrile solution (10 mL) of zinc(II) acetate dihydrate (0.11 g, ~0.5 mmol), with constant stirring until a light yellow solution was observed. To avoid precipitation, a few drops of DMSO were added (2 mL) to the reaction mixture and then it was kept in an open atmosphere to grow single crystals. After four weeks, single yellow crystals of X-ray quality were gathered.

Yield: (0.328 g, ~71%) based on zinc(II) acetate dihydrate. Anal. calc. for $C_{36}H_{36}Cl_4N_4O_8Zn_2$ (FW: 925.27): C, 46.73; H, 3.92; N, 6.06. Found: C, 46.6; H, 3.9; N, 6.2%, FT-IR (KBr): ν_{max}/cm^{-1} 3446–3003 (OH), 2941–2834 (C–H), 1626 (C=N). $\lambda_{max}(\text{MeOH})/nm$, 371 ($\epsilon/dm^3 \text{ mol}^{-1} \text{ cm}^{-1}$ 19 000), δ_H (400 MHz; $CDCl_3$; Me_4Si) 8.36 (1H, s, –CH=N–), 8.18 (3H, s, –CH=N–), 7.17 (4H, m, Ph), 6.86 (8H, d, Ph), 4.11–3.51 (12H, m, –CH₂–, –OH), 2.64 (8H, m, –CH₂–).

[Zn₂(HL⁴)₄]-H₂O (4). 3-Aminopropan-1-ol (~1 mmol, 0.08 mL) and 5-chloro-2-hydroxybenzaldehyde (~1 mmol, 0.156 g) in 20 mL methanol were refluxed for *ca.* 2 h to synthesize the Schiff base ligand, H_2L^4 . The ligand was not isolated and the methanol solution (20 mL) of H_2L^4 was added to a methanol solution (5 mL) of zinc(II) acetate dihydrate (0.11 g, ~0.5 mmol) with constant stirring and the stirring was continued for *ca.* 2 h. X-ray quality yellow block single crystals were collected after three weeks.

Table 1 Crystal data and refinement details of complexes 1–4

Complex	1	2A	2B	3	4
Formula	C ₂₂ H ₂₈ N ₂ O ₄ Zn	C ₂₄ H ₃₄ Cl ₄ N ₂ O ₇ SZn	C ₂₅ H ₃₁ Cl ₄ N ₃ O ₅ Zn	C ₃₆ H ₃₆ Cl ₄ N ₄ O ₈ Zn ₂	C ₄₀ H ₄₄ Cl ₄ N ₄ O ₉ Zn ₂
Formula weight	449.85	701.78	660.72	925.27	997.37
Temperature (K)	273	130	273	273	273
Crystal system	Monoclinic	Monoclinic	Triclinic	Monoclinic	Orthorhombic
Space group	<i>P</i> 2 ₁ / <i>c</i>	<i>P</i> 2 ₁ / <i>c</i>	<i>P</i> 1	<i>C</i> 2/ <i>c</i>	<i>P</i> ccn
<i>a</i> (Å)	11.7255(13)	11.9713(11)	7.3148(5)	27.2641(8)	21.993(2)
<i>b</i> (Å)	14.4835(16)	16.7097(15)	12.0737(8)	9.4294(3)	10.4162(10)
<i>c</i> (Å)	13.8775(15)	15.6498(15)	17.2426(12)	17.5738(5)	18.6268(19)
α	(90)	(90)	88.103(2)	(90)	(90)
β	99.984(3)	98.033(3)	82.599(2)	123.972(1)	(90)
γ	(90)	(90)	87.794(2)	(90)	(90)
<i>Z</i>	4	4	2	4	4
<i>V</i> (Å ³)	2321.1(4)	3099.8(5)	1508.40(18)	3746.8(2)	4267.1(7)
<i>d</i> _{calc} (g cm ⁻³)	1.287	1.504	1.455	1.640	1.553
μ (mm ⁻¹)	1.086	5.274	1.207	1.623	1.433
<i>F</i> (000)	944.0	1448.0	680.0	1888.0	2048.0
Total reflections	42 382	124 875	45 283	34 453	26 926
Unique reflections	5290	6213	5337	4213	3802
Observed data [<i>I</i> > 2 σ (<i>I</i>)]	3937	6040	4856	3511	2632
No. of parameters	278	408	378	285	271
<i>R</i> (int)	0.0529	0.0552	0.0617	0.0593	0.0496
χ^2 R1, ψ wR2 (all data)	0.0653, 0.1354	0.0413, 0.1087	0.0507, 0.1436	0.0438, 0.0904	0.0793, 0.1260
ξ R1, ψ wR2 [<i>I</i> > 2 σ (<i>I</i>)]	0.0457, 0.1232	0.0412, 0.1086	0.0424, 0.1284	0.0340, 0.0852	0.0464, 0.1025
CCDC no.	2405586	2405587	2405588	2405589	2405590

$$(\xi)R1 = \sum ||F_o| - |F_c|| / \sum |F_o|; (\psi)wR2 = \sum w(|F_o|^2 - |F_c|^2)^2 / (\sum w|F_o|^2)^{1/2}.$$

Yield: (0.403 g, ~81%) based on zinc(II) acetate dihydrate. Anal. calc. for C₄₀H₄₄N₄O₉Cl₄Zn₂ (FW: 997.37): C, 48.17; H, 4.45; N, 5.62. Found: C, 48.1; H, 4.4; N, 5.7%, FT-IR (KBr): ν_{\max} /cm⁻¹ 3449–3114 (O–H) 2940–2847 (C–H), 1626 (C=N), λ_{\max} (MeOH)/nm, 369 (ϵ /dm³ mol⁻¹ cm⁻¹ 200 000), δ_H (400 MHz; CDCl₃; Me₄Si) 8.20 (4H, s, –CH=N–), 7.28 (4H, s, Ph), 6.86 (8H, m, Ph), 3.83–3.48 (16H, m, –CH₂–), 1.98–1.67 (8H, m, –CH₂–), ¹³C NMR (101 MHz, CDCl₃) δ 207.08 (s, CO), 171.01 (s, –CH=N), 168.23 (s, C–O), 164.16 (s, C–O), 135.07 (s, Ph), 134.03 (s, Ph), 132.08 (s, Ph), 130.34 (s, Ph), 124.43 (s, Ph), 119.20 (s, Ph), 118.60 (s, Ph), 77.35 (s, CDCl₃), 77.23 (s, CDCl₃), 77.03 (s, CDCl₃), 76.71 (s, CDCl₃), 60.08 (s, –CH₂–), 40.97 (s, –CH₂–), 33.29 (s, –CH₂–).

Physical measurements

Elemental analysis (carbon, hydrogen and nitrogen) of the complexes was performed on a PerkinElmer 240C elemental analyzer. Elemental analysis for complex 2A was performed

using a ThermoFisher Scientific Flash Smart V CHNS/O analyzer. Infrared spectra in KBr (4500–500 cm⁻¹) were recorded using a PerkinElmer RXI FT-IR spectrophotometer. Absorption spectra in methanol were recorded on Duetta-1621 fluorescence and SHIMADZU UV-1800i spectrophotometers. Emission spectra in methanol were recorded on Duetta-1621 and PerkinElmer LS 55 fluorescence spectrophotometers. ¹H NMR and ¹³C NMR spectra were recorded using a BRUKER 400 MHz NMR spectrometer in CDCl₃ solvent. Powder X-ray diffraction patterns were recorded on well ground samples in the 2 θ range of 5–50° using a BRUKER D8 Advance X-ray diffractometer with Cu K α radiation (λ = 1.5418 Å). The details of Hirshfeld surface analysis are given in the ESI.†

X-ray crystallography

A 'Bruker D8 QUEST area detector' diffractometer equipped with graphite-monochromated Mo K α radiation (λ = 0.71073 Å) was used for data collection of complexes 1, 2A, 2B, 3 and

Table 2 Selected bond lengths (Å) of complexes 1–4

Bonds	Complex 1	Complex 2A	Complex 2B	Complex 3	Complex 4
Zn(1)–O(1)	1.909(2)	1.9999(16)	1.950(2)	2.0150(14)	2.119(3)
Zn(1)–N(1)	2.007(2)	2.0466(19)	2.011(3)	2.081(2)	2.060(3)
Zn(1)–O(1) ⁱⁱ	—	—	—	—	2.040(3)
Zn(1)–O(3)	1.9273(18)	1.9930(16)	1.950(2)	2.3582(16)	2.027(3)
Zn(1)–O(2)	—	2.3070(18)	2.524(2)	—	—
Zn(1)–N(2)	2.008(2)	2.0411(19)	2.046(2)	—	2.045(4)
Zn(2)–O(3)	—	—	—	1.9587(16)	—
Zn(2)–N(2)	—	—	—	1.986(2)	—

Symmetry transformation = ⁱⁱ = 1 – *x*, 1 – *y*, 1 – *z*.

Table 3 Selected bond angles (°) of complexes 1–4

Angles	Complex 1	Complex 2A	Complex 2B	Complex 3	Complex 4
O(1)–Zn(1)–N(1)	96.73(8)	89.31(7)	92.85(10)	90.50(7)	85.43(13)
O(1)–Zn(1)–O(1) ⁱ	—	—	—	100.18(6)	—
O(1)–Zn(1)–O(1) ⁱⁱ	—	—	—	—	76.53(12)
O(1)–Zn(1)–N(1) ⁱ	—	—	—	90.34(7)	—
N(1)–Zn(1)–N(1) ⁱ	—	—	—	178.69(7)	—
N(1)–Zn(1)–N(2)	121.38(9)	147.82(8)	143.10(11)	—	124.31(14)
O(1) ⁱⁱ –Zn(1)–O(3)	—	—	—	—	96.70(12)
O(1) ⁱⁱ –Zn(1)–N(1)	—	—	—	—	120.77(13)
O(1) ⁱ –Zn(1)–N(2)	—	—	—	—	113.00(13)
O(1)–Zn(1)–O(3)	116.37(8)	99.08(7)	108.29(9)	164.98(6)	172.74(12)
O(1)–Zn(1)–O(3) ⁱ	—	—	—	94.16(6)	—
O(1)–Zn(1)–O(2)	—	164.45(7)	154.74(9)	—	—
O(1)–Zn(1)–N(2)	114.97(9)	107.03(7)	103.92(10)	—	94.01(13)
O(3)–Zn(1)–O(3) ⁱ	—	—	—	71.96(6)	—
O(3)–Zn(1)–O(2)	—	87.55(6)	96.49(8)	—	—
O(3)–Zn(1)–O(4)	—	161.69(6)	—	—	—
O(3)–Zn(1)–N(1)	111.86(9)	114.41(7)	111.76(10)	93.89(7)	96.01(13)
O(3)–Zn(1)–N(1) ⁱ	—	—	—	85.04(7)	—
O(3)–Zn(1)–N(2)	96.86(9)	90.71(7)	94.04(9)	—	91.06(13)
O(2)–Zn(1)–O(4)	—	85.95(6)	—	—	—
O(2)–Zn(1)–N(1)	—	75.14(7)	72.93(9)	—	—
O(2)–Zn(1)–N(2)	—	86.81(7)	78.51(9)	—	—
O(4)–Zn(1)–N(2)	—	71.87(7)	—	—	—
O(4)–Zn(1)–N(1)	—	80.33(7)	—	—	—
O(3)–Zn(2)–N(2)	—	—	—	95.75(8)	—
O(3)–Zn(2)–O(3) ⁱ	—	—	—	90.04(7)	—
O(3)–Zn(2)–N(2) ⁱ	—	—	—	131.04(9)	—
N(2)–Zn(2)–N(2) ⁱ	—	—	—	115.27(8)	—

Symmetry transformation = ⁱ = 1 – x, y, 1.5 – z, ⁱⁱ = 1 – x, 1 – y, 1 – z.

4. The structures were solved by direct methods. Full-matrix least squares refinements on F^2 were done using the SHELXL-18/1 package.⁸⁸ Refinement of non-hydrogen atoms was done with anisotropic thermal parameters. Hydrogen atoms were constrained to ride on their parent atoms. The program SADABS was used for multi-scan empirical absorption corrections.⁸⁹ The crystallographic data and refinement details are summarised in Table 1. Selected bond lengths and angles are shown in Tables 2 and 3.

Theoretical methods

The X-ray geometries of complexes 2A and 3 were used as starting points for optimization under periodic boundary conditions (PBC) at the RI-BP86-D3/def2-TZVP level of theory.^{90–93} Geometry optimizations, energy calculations, wavefunction generation, and cube file creation were performed using the Turbomole 7.7 program.⁹⁴ The QTAIM⁹⁵ and NCIPlot⁹⁶

analyses were conducted at the same level of theory, utilizing the Multiwfn program⁹⁷ for calculations and VMD software⁹⁸ for visualization. For the NCIPlot analysis, the following settings were applied: $s = 0.45$, $\rho_{\text{cut-off}} = 0.04$ a.u., and a color scale of $-0.035 \leq \text{sign}(\lambda_2)\rho \leq 0.035$ a.u. The natural bond orbital (NBO)⁹⁹ analysis was performed using the NBO 7.0 program.¹⁰⁰

Results and discussion

Synthesis

The N,O donor Schiff bases (HL¹–HL⁴) were synthesized by refluxing the appropriate amines and salicylaldehyde



Scheme 1 Synthetic route to complex 1.



Scheme 2 Synthetic routes to complexes 2A and 2B.



Scheme 3 Synthetic route to complex 3.



Scheme 4 Synthetic route to complex 3.



Fig. 1 The perspective view of complex 1.



Fig. 2 Perspective view of the 1D supramolecular chain of complex 1. Only the relevant hydrogen atoms are shown for clarity.

derivatives in acetonitrile/methanol following the literature methods.^{59,101–109} The Schiff bases, so produced, were not isolated and not purified. These were used *in situ* for the syntheses of zinc(II) complexes $[\text{Zn}(\text{HL}^1)_2]$ (**1**), $[\text{Zn}(\text{HL}^2)_2]\cdot\text{DMSO}\cdot\text{H}_2\text{O}$ (**2A**), $[\text{Zn}(\text{HL}^2)_2]\cdot\text{DMF}$ (**2B**), $[\text{Zn}_2(\text{HL}^3)_4]$ (**3**) and $[\text{Zn}_2(\text{HL}^3)_4]\cdot\text{H}_2\text{O}$ (**4**) by adding zinc(II) chloride or zinc(II) acetate dihydrate with constant stirring for the formation of complexes **1**, **2A**, **2B**, **3** and **4** (in a 2:1 molar ratio). The use of drops of DMSO and DMF is essential to stabilize crystals of **2A** and **2B**, respectively. In the absence of DMSO or DMF, suitable single crystals of complexes **2A** or **2B** were not grown. This indicates the necessity of DMSO and DMF in the stabilization of the complexes. Synthetic routes to the complexes are shown in Schemes 1–4.

FT-IR spectroscopy

In the FT-IR spectrum of each complex, a distinct band for azomethine (C=N) stretching vibration appears at 1613–1626 cm^{-1} .^{85,110} Bands in the region of 3000–2890 cm^{-1} may be assigned to C–H stretching vibrations.^{37,111} The appearance of a broad band at around 3540–3100 cm^{-1} indicates the presence of O–H stretching vibration¹¹² of the hydroxyl group and lattice water molecule in each complex. The FT-IR spectra of the complexes are shown in Fig. S1–S5 (ESI†).

¹H and ¹³C NMR spectroscopy

The detailed information of ¹H and ¹³C NMR spectra of H_2L^1 – H_2L^4 is gathered in the ESI†. The ¹H NMR spectra of H_2L^1 , complex **1**, H_2L^2 , complex **2A**, H_2L^3 , complex **3**, H_2L^4 and complex **4** are shown in Fig. S6–S13 (ESI†), respectively. The ¹³C NMR spectra of H_2L^1 , H_2L^2 , complex **2A**, H_2L^3 , H_2L^4 and complex **4** are shown in Fig. S14–S19 (ESI†), respectively.

Electronic absorption spectroscopy

There is only one band in the electronic spectra of each complex in methanol (Fig. S20–S24 (ESI†)). The band at 361 nm (in **1**), 379 nm (in **2A**), 381 nm (in **2B**), 371 nm (in **3**) and

Table 4 O–H⋯O hydrogen bond distances and angles in complexes **1**, **2A**, **2B** and **3**

Complex	O–H⋯O	O–H (Å)	H⋯O (Å)	O–H⋯O (Å)	∠O–H⋯O (°)	Symmetry transformation
1	O(4)–H(4W)⋯O(4) ⁱⁱⁱ	0.820(3)	1.944	2.674(3)	147.9	ⁱⁱⁱ = <i>x</i> , 1.5 – <i>y</i> , $\frac{1}{2}$ + <i>z</i>
2A	O(4)–H(4)⋯O(5)	0.92(4)	1.74(4)	2.624(3)	160(3)	—
	O(2)–H(2)⋯O(6)	0.87(5)	1.80(5)	2.663(3)	173(4)	—
	O(6)–H(6B)⋯O(7)	0.83(5)	1.89(5)	2.724(3)	173(5)	—
	O(7)–H(7B)⋯O(1) ^{iv}	0.89(6)	2.04(7)	2.814(3)	145(6)	^{iv} = 1 – <i>x</i> , –1/2 + <i>y</i> , 1/2 – <i>z</i>
	O(7)–H(7A)⋯O(3) ^{iv}	0.88(5)	1.97(5)	2.762(3)	149(4)	—
	O(6) ⁱⁱ –H(6A) ⁱⁱ ⋯O(4)	0.88(3)	2.00(3)	2.871(3)	170(3)	ⁱⁱ = 1 – <i>x</i> , 1 – <i>y</i> , 1 – <i>z</i>
2B	O(4)–H(4)⋯O(3) ^{vi}	0.820	1.978	2.776(63)	164.3	^{vi} = –1 + <i>x</i> , <i>y</i> , <i>z</i>
	O(4)–H(4A)⋯O(3) ^{vii}	1.03(5)	1.75(5)	2.751(3)	164(4)	^{vii} = <i>x</i> , 1 – <i>y</i> , 1/2 + <i>z</i>
3	O(3)–H(3A)⋯O(1)	0.78(5)	1.92(5)	2.691(3)	173(4)	—

Table 5 Geometric parameters of the C–H⋯π interactions in complexes **1** and **2A**

Complex	C–H⋯π	H⋯π (Å)	C–H⋯π (Å)	∠C–H⋯C _g (°)	Symmetry transformation
1	C(16)–H(16)⋯Cg(1) ⁱⁱⁱ	2.748	3.980	148	ⁱⁱⁱ = <i>x</i> , 1.5 – <i>y</i> , 1/2 + <i>z</i>
2A	C(10)–H(10C)⋯Cg(2) ⁱⁱⁱ	2.908	3.658	137.07	—

Cg(1)ⁱⁱⁱ and Cg(2)ⁱⁱⁱ are centroids of the aromatic rings, R(1)ⁱⁱⁱ {C(1)ⁱⁱⁱ–C(2)ⁱⁱⁱ–C(3)ⁱⁱⁱ–C(4)ⁱⁱⁱ–C(5)ⁱⁱⁱ–C(6)ⁱⁱⁱ} and R(2)ⁱⁱⁱ {C(12)ⁱⁱⁱ–C(13)ⁱⁱⁱ–C(19)ⁱⁱⁱ–C(20)ⁱⁱⁱ–C(21)ⁱⁱⁱ–C(22)ⁱⁱⁱ}.

369 nm (in **4**) is assigned to either $\pi \rightarrow \pi^*$ or $n \rightarrow \pi^*$ transitions.^{59,113,114}

Structural aspects

Mononuclear zinc(II) complexes

[Zn(HL¹)₂] (**1**). Complex **1** consists of a discrete, mononuclear unit [Zn(HL¹)₂] (Fig. 1). The zinc(II) center is coordinated by two imine nitrogen atoms, N(1) and N(2), and two phenolate oxygen atoms, O(1) and O(3), of two tridentate N,O donor Schiff base ligands (HL¹)[–] producing a distorted tetrahedral structure. The τ_4 index is 0.867, which confirms that the geometry of the zinc(II) center is distorted tetrahedral {two largest ligand–metal–ligand angles are 121.38(9)° and 116.37(8)°}.¹¹⁵

Hydrogen atom H(4W) attached to oxygen atom O(4) of the Schiff base units forms a hydrogen bond with O(3)ⁱⁱⁱ of the symmetry related neighbouring molecule to form a 1D supramolecular chain (ⁱⁱⁱ = symmetry transformation = *x*, 1.5 – *y*, 1/2 + *z*) (Fig. 2). The details of O–H⋯O hydrogen bonding interactions are summarized in Table 4.

Hydrogen atom H(16) attached to carbon atom C(16) of the Schiff base unit is involved in C–H⋯π interactions with the aromatic ring, R(1)ⁱⁱⁱ [containing carbon atoms, C(1)ⁱⁱⁱ–C(2)ⁱⁱⁱ–C(3)ⁱⁱⁱ–C(4)ⁱⁱⁱ–C(5)ⁱⁱⁱ–C(6)ⁱⁱⁱ], ⁱⁱⁱ = symmetry transformation = *x*, 1.5 – *y*, $\frac{1}{2}$ + *z*], of the neighbouring molecule to form a 1D supramolecular chain (Fig. S25, ESI†). The geometric parameters of C–H⋯π interactions of complex **1** are summarized in Table 5.

[Zn(HL²)₂].DMSO.2H₂O (**2A**) and [Zn(HL²)₂].DMF (**2B**). Complexes **2A** and **2B** are similar in structures, only the lattice solvent molecules are different. Both consist of mononuclear units [Zn(HL¹)₂] (Fig. 3 and S26, (ESI†)). Two lattice water

molecules and one DMSO molecule are present in complex **2A**. On the other hand, one lattice DMF is present in complex **2B**. The zinc(II) center is coordinated by two imine nitrogen atoms [N(1), N(2)], two phenolate oxygen atoms [O(1), O(3)] of two tridentate N,O donor Schiff base ligands (HL²)[–] and one hydroxyl oxygen atom O(2) of a (HL²)[–] unit producing a 4 + 1 square pyramidal structure in each case (Fig. 3 and S26, (ESI†)). The square pyramidal geometry is confirmed by calculating the Addison parameters for both complexes (0.277 and 0.193 for complexes **2A** and **2B**, respectively).¹¹⁶

The saturated five-membered chelate ring [Zn(1)–N(1)–C(8)–C(11)–O(2)] represents a half-chair and an envelope conformation (Fig. S27 and S28, ESI†) with puckering parameters, $q = 0.412(2)$ Å; $\phi = 277.5(2)^\circ$ and $q = 0.462(4)$ Å; $\phi = 283.1(4)^\circ$ of complexes **2A** and **2B**, respectively.^{117,118}

Six O–H⋯O hydrogen bonding interactions involving lattice solvent (DMSO and water) and neighbouring

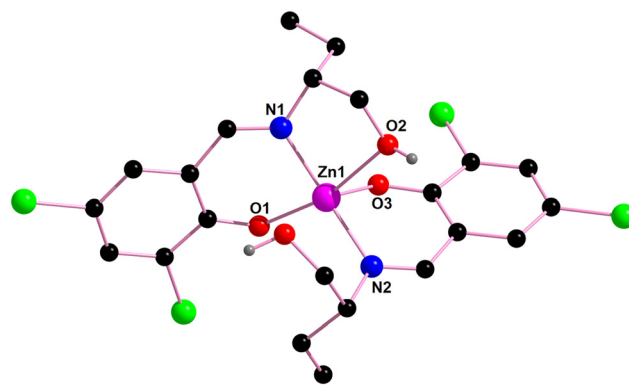
**Fig. 3** Perspective view of complex **2A**. Lattice water and DMSO are not shown for clarity.



Fig. 4 2D supramolecular framework of complex 2A, formed by O–H···O hydrogen bonding interactions.



Fig. 5 C–H··· π interactions of complex 2A. Only the relevant hydrogen atoms are shown for clarity.

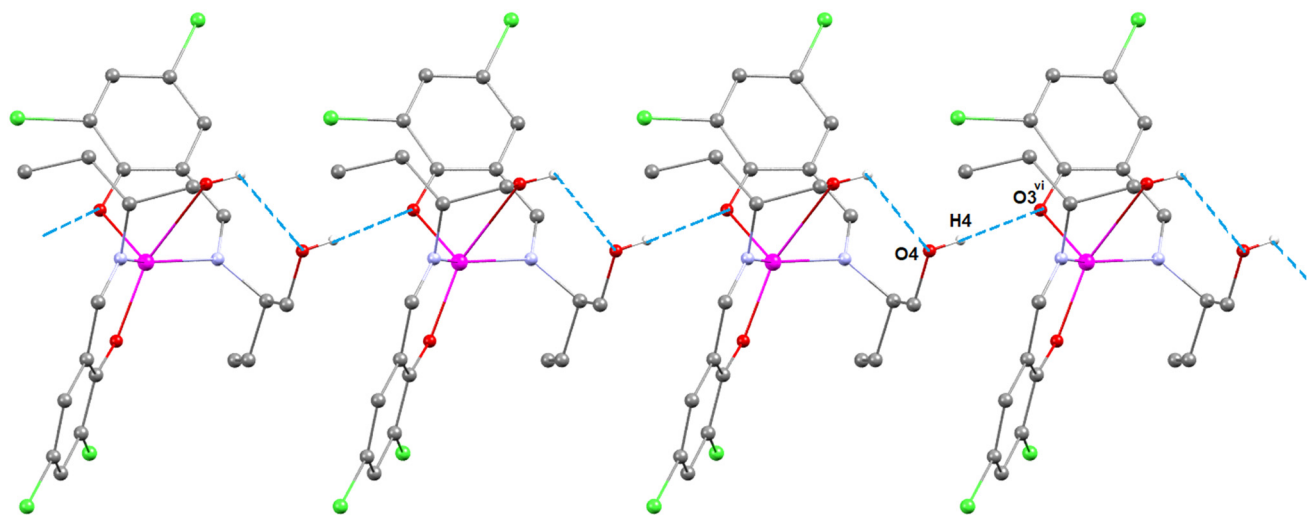


Fig. 6 Perspective view of the 1D supramolecular chain of complex **2B**, formed by O–H...O hydrogen bonding interactions.

molecules form a 2D framework of complex **2A** (Fig. 4). Hydrogen atoms H(2) and H(6B) attached to oxygen atoms O(2) and O(6) of the Schiff base unit and lattice water molecule respectively form hydrogen bonds with oxygen atoms O(6) and O(7), of the lattice water molecules. Hydrogen atoms H(7A) and H(7B) attached to oxygen atom O(7) of the lattice water molecule form hydrogen bonds with O(1)^{iv} and O(3)^{iv} of the Schiff base units of the symmetry related neighbouring molecule to form a two dimensional framework (symmetry transformation = ^{iv} = 1 - x, -1/2 + y, 1/2 + z). Hydrogen atom H(6A)ⁱⁱ attached to O(6)ⁱⁱ of the symmetry related lattice water molecule forms a hydrogen bond with oxygen atom O(4) of the Schiff base unit (symmetry transformation = ⁱⁱ = 1 - x, 1 - y, 1 - z). Hydrogen atom H(4) attached to oxygen atom O(4) of the Schiff base ligand forms a hydrogen bond with oxygen atom O(5) of the lattice DMSO molecule. The details of O–H...O hydrogen bonding interactions are gathered in Table 4.

One C–H... π interaction involving a symmetry related neighbouring aromatic ring with a hydrogen atom is observed

in complex **2A**. Hydrogen atom H(10C) attached to carbon atom C(10) of the Schiff base unit is involved in C–H... π interactions with the aromatic ring, R(2)ⁱⁱⁱ [containing carbon atoms, C(12)ⁱⁱⁱ–C(13)ⁱⁱⁱ–C(19)ⁱⁱⁱ–C(20)ⁱⁱⁱ–C(21)ⁱⁱⁱ–C(22)ⁱⁱⁱ, ⁱⁱⁱ = symmetry transformation = x, 1.5 - y, 1/2 + z], of the neighbouring molecule to form a 1D supramolecular chain (Fig. 5). The geometric parameters of C–H... π interactions of complex **2A** are gathered in Table 5.

Hydrogen atom H(4) attached to oxygen atom O(4) of the Schiff base unit forms a hydrogen bond with oxygen atom O(3)^{vi} of the symmetry related neighbouring molecule to form a 1D supramolecular chain of complex **2B** (Fig. 6). The details of O–H...O hydrogen bonding interactions are gathered in Table 4.

A π ... π stacking interaction is established between the aromatic ring, R(3) {C(12)–C(13)–C(14)–C(15)–C(16)–C(17)}, forming a π ... π stacking interaction with a symmetry related (^v = 1 - x, 1 - y, 2 - z) aromatic ring, R(3)^v {C(12)^v–C(13)^v–C(14)^v–C(15)^v–C(16)^v–C(17)^v}, of a neighbouring molecule to form a supramolecular dimer of complex **2B**, as shown Fig. 7.



Fig. 7 Perspective view of the supramolecular dimer of complex **2B**, formed by π ... π stacking interactions.

Table 6 Geometric features of the $\pi\cdots\pi$ stacking interactions in complexes **2B** and **4**

Complex	Cg(3) \cdots Cg(3) ^v /Cg(4) \cdots Cg(4) ^{viii} (Å)	Cg(3) \cdots Perp/Cg(4) \cdots Perp (Å)	α (°)	Slippage (Å)	Symmetry transformation
2B	3.7238(18)	3.4925(13)	0.00(15)	1.292	^v = 1 - x, 1 - y, 2 - z
4	3.609(3)	3.5723(18)	2.1(2)	3.380	^{viii} = 1.5 - x, 1.5 - y, z

Cg(3), Cg(3)^v, Cg(4) and Cg(4)^{viii} are centroids of the aromatic rings, R(3) {C(12)–C(13)–C(14)–C(15)–C(16)–C(17)}, R(3)^v {C(12)^v–C(13)^v–C(14)^v–C(15)^v–C(16)^v–C(17)^v}, R(4) {C(11)–C(12)–C(13)–C(14)–C(15)–C(16)} and R(4)^{viii} {C(11)^{viii}–C(12)^{viii}–C(13)^{viii}–C(14)^{viii}–C(15)^{viii}–C(16)^{viii}}, respectively. Cg(3) \cdots Cg(3)^v = distance between ring centroids, Cg(4) \cdots Cg(4)^{viii} = distance between ring centroids, Cg(3) \cdots Perp = perpendicular distance of Cg(3) on ring R(3)^v, Cg(4) \cdots Perp = perpendicular distance of Cg(4) on ring R(4)^{viii}, α = dihedral angle between planes R(3) and R(3)^v or planes R(4) and R(4)^{viii}.

The geometrical parameters of the $\pi\cdots\pi$ stacking interaction in complex **2B** are given in Table 6.

Dinuclear zinc(II) complexes

$[Zn_2(HL^3)_4]$ (**3**). Based on the determination of the X-ray crystal structure, complex **3** is centrosymmetric and crystallizes in the monoclinic space group *C2/c*. The perspective view of complex **3** along with a selective atom-numbering scheme is shown in Fig. 8. The dinuclear complex **3** contains two different types of zinc(II) centers. Zn(1) is distorted octahedral and Zn(2) is distorted tetrahedral. Both zinc(II) centers are bridged by phenoxo oxygen atoms O(3) and O(3)ⁱ of the N,O donor Schiff base ligands (HL³⁻). Here, two different binding sites of the Schiff base ligands (HL³⁻) have been observed, one is $\mu^2\text{-}\eta^2\text{:}\eta^1$ to form a Zn₂O₂ core and the other binding site is $\eta^1\text{:}\eta^1$. The hexa-coordinated Zn(1) center bonds with four phenoxo oxygen atoms [O(1), O(1)ⁱ, O(3), O(3)ⁱ] and two imine nitrogen atoms [N(1) and N(1)ⁱ] of four N,O donor Schiff base ligands (HL³⁻), to form a distorted octahedral geometry. On the other hand, the tetra-coordinated Zn(2) center bonds with two phenolate oxygen atoms [O(3) and O(3)ⁱ] and two imine nitrogen atoms [N(2) and N(2)ⁱ] of two Schiff base ligands (HL³⁻), to form a distorted tetrahedral geometry which is confirmed by the τ_4 index value (0.806) (where ⁱ = symmetry transformation = 1 - x, y, 1.5 - z).

Two different types of O–H \cdots O hydrogen bonding interactions are present in complex **3**. One is an



Fig. 8 Perspective view of complex **3** with selective atom numbering. Symmetry transformation ⁱ = 1 - x, y, 1.5 - z.

intramolecular hydrogen bond where hydrogen atom H(3A), attached to oxygen atom O(2) of the Schiff base, forms a hydrogen bond with oxygen atom O(1) of the Schiff base unit. In contrast, hydrogen atom H(4), attached to oxygen atom O(4) of the Schiff base unit, forms an intermolecular hydrogen bond with oxygen atom O(2)^{vii} of the symmetry related neighbouring molecule to form a 1D supramolecular chain (Fig. S29, ESI[†]) (symmetry transformation = ^{vii} = x, 1 - y, 1/2 + z). The details of O–H \cdots O hydrogen bonding interactions are gathered in Table 4.

$[Zn_2(HL^3)_4]\cdot H_2O$ (**4**). Single crystal X-ray diffraction analysis reveals that complex **4** is a discrete, centrosymmetric dinuclear molecule and crystallizes in the orthorhombic space group, *Pccn*. In complex **4**, two zinc(II) centers are present {Zn(1) and Zn(1)ⁱⁱ; ⁱⁱ = symmetry transformation = 1 - x, 1 - y, 1 - z}. The coordination polyhedron around the zinc(II) center is best described as a distorted trigonal bipyramidal geometry with a ZnN₂O₃ chromophore, furnished by two imine nitrogen atoms [N(1) and N(2)] and three phenolate oxygen atoms [O(1), O(1)ⁱⁱ, O(3)] of three tridentate Schiff base ligands (ⁱⁱ = symmetry transformation = 1 - x, 1 - y, 1 - z) (Fig. 9). The geometry around the zinc center, Zn(1), is a slightly distorted trigonal bipyramidal geometry with an Addison parameter of 0.806. The largest ligand–metal–ligand angles around the Zn(1) center are 172.7(1)° [O(1)–Zn(1)–O(3)] and 124.3(1)° [N(1)–Zn(1)–N(2)].



Fig. 9 Perspective view of complex **4** with selective atom numbering. Symmetry transformation ⁱⁱ = 1 - x, 1 - y, 1 - z.



Fig. 11 Emission spectra of 10^{-3} M Schiff base ligands $\{H_2L^1$ (excitation 397 nm, 446 nm) or H_2L^2 (excitation 419 nm, emission 479 nm) or H_2L^3 (excitation 397 nm, emission 454 nm) or H_2L^4 (excitation 397 nm, 453 nm)} in the presence of increasing concentration of free Zn^{2+} ions at room temperature.

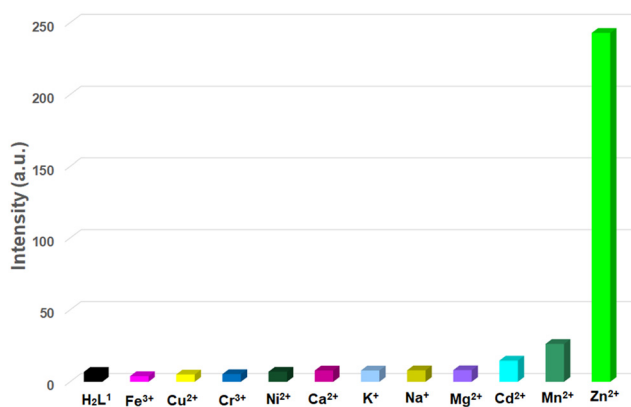


Fig. 12 Relative fluorescence intensity change profile of H_2L^1 in the presence of various cations (10^{-2} M) at room temperature (excitation at 446 nm).

The Stern-Volmer equation is employed to quantitatively assess the quenching efficiency of nitroaromatic compounds, $I_0/I = 1 + K_{SV}[Q]$, where K_{SV} is the quenching constant (M^{-1}), $[Q]$ is the molar concentration of the quencher, and I_0 and I are the luminescence intensities before and after quenching, respectively. When the concentration of the quencher is low, the Stern-Volmer plot of nitroaromatics is linear, in contrast, at higher concentration, it consequently deviates from linearity and turn upward (Fig. 15b), which may be due to the self-absorption.¹²¹ The Stern-Volmer quenching constant, K_{SV} , for complex **2A** has been calculated from the slope of the linearly fitted curve (inset in Fig. 15b), equal to $0.5 \times 10^4 M^{-1}$, and the limit of detection (LOD) value is 8.81×10^{-7} ($LOD = 3\sigma/k$, where σ = the standard deviation in the blank measurement,⁹⁶ and the slope (Fig. 16) from the plot (fluorescence intensity *versus* concentration of complex **2A**) gives k).



Fig. 13 Binding constants (K) of H_2L^1 , H_2L^2 , H_2L^3 and H_2L^4 , determined from the slopes of the plots (a)–(d), respectively.

Nitroaromatics are electron deficient compounds. Therefore, the ability of nitroaromatics to be used as quenchers may be explained as follows. Strong π - π



Fig. 14 Relative fluorescence intensity change profile of complex 2A in the presence and absence of various aromatic quenchers (10^{-2} M) at room temperature (excitation at 379 nm).

interactions may be established between the nitroaromatic compounds and the zinc-Schiff base complex, facilitating electron transfer from the excited state of the zinc complex to the ground state of the electron-deficient nitroaromatics.^{122–127} A schematic representation of electron transfer from a zinc-Schiff base complex (say complex 2A) to a nitroaromatic compound (*e.g.* nitrobenzene) is shown in Scheme 5a.

If the electron deficiency of the nitroaromatic ring is further increased by the incorporation of another electron withdrawing group in its *ortho* or *para* position (with respect to the nitro group), the electron deficiency in the aromatic ring will be further reduced, and therefore, the quenching efficiency of the nitroaromatic compound will obviously be increased. This is schematically illustrated in Scheme 5b, where 2-nitrobenzoic acid containing deactivating groups, $-NO_2$ and $-COOH$ (strong $-R$ effect), is used as the quencher. This explains why 2-nitrobenzoic acid acts as the best quencher.

In order to give experimental evidence of this binding mechanism of nitroaromatics with the complex in solution,



Fig. 15 (a) Fluorescence spectra of complex **2A** in MeOH (excitation wavelength of 379 nm and conc. of 10^{-4} M) with increasing concentration of 2-nitrobenzoic acid; (b) Stern-Volmer plot of complex **2A** with 2-nitrobenzoic acid in MeOH. The inset shows the linearly fitted Stern-Volmer plot with first six points.

^1H NMR titration was performed with varying amounts of 2-nitrobenzoic acid (0 and 5 equiv.) in CDCl_3 (Fig. 17). The shifting of aromatic protons to the downfield region with increasing concentrations of nitroaromatics clearly indicates that nitroaromatics withdraw electron density from the complex and shift the protons towards the deshielded region. Except for this shifting in peak positions, everything else remains practically constant in each step of this NMR titration.

PXRD patterns

The experimental powder X ray diffraction patterns of the bulk materials are in good agreement with the simulated XRD patterns from single-crystal X-ray diffraction, indicating

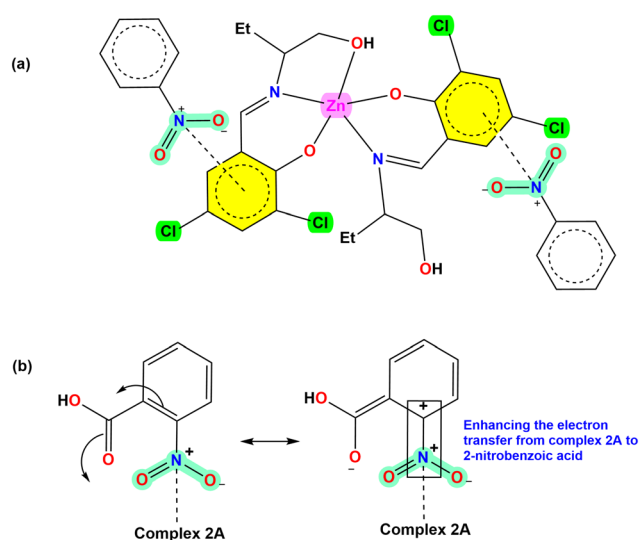


Fig. 16 Plot of limit of detection for complex **2A** towards 2-nitrobenzoic acid in MeOH solution.

the consistency of the bulk sample. The simulated PXRD patterns of the complexes are computed from the single crystal structural data. Fig. S39 (ESI †) shows the experimental and simulated XRD patterns for complex **1**. Fig. S40 (ESI †) shows the experimental and simulated XRD patterns for complexes **2A** and **2B**. Fig. S41 (ESI †) shows the experimental and simulated XRD patterns for complexes **3** and **4**.

DFT calculations

As described above, the zinc(II) metal centers exhibit distinct geometries and coordination indices, with the hydroxyalkyl groups of the Schiff-base ligands playing varying roles, as



Scheme 5 (a) Schematic representation of electron transfer from complex **2A** to 2-nitrobenzoic acid; (b) schematic representation of the canonical structures of 2-nitrobenzoic acid and its impact on the quenching mechanism.



Fig. 17 ^1H NMR spectra of complex **2A** with 0 and 5 equivalents of 2-nitrobenzoic acid in CDCl_3 .

detailed in Fig. 18. For instance, in the mononuclear complex **1**, the OH groups are positioned close to each other ($\text{O}\cdots\text{O}$ distance of 2.612 Å), indicating the formation of an $\text{OH}\cdots\text{O}$ hydrogen bond. A similar arrangement is observed in complex **2B**, where the uncoordinated hydroxyalkyl group interacts with the coordinated one. In contrast, in complex **2A**, which includes a crystallized DMSO molecule and two lattice water molecules, the coordinated hydroxyalkyl group forms a hydrogen bond with one water molecule, while the uncoordinated hydroxyalkyl group interacts with the DMSO molecule. This arrangement facilitates a $\text{Zn}\cdots\text{O}$ contact with a distance of 2.665 Å—significantly longer than the sum of covalent radii (1.88 Å) but shorter than the sum of Bondi's van der Waals radii (2.91 Å). This observation suggests the formation of a noncovalent spodium bond in this complex.

For the dinuclear complexes **3** and **4**, the positioning of the hydroxypropyl groups in complex **4** is likely governed by intramolecular hydrogen bonds. However, in complex **3**, the pseudotetrahedral $\text{Zn}(\text{II})$ atom establishes two symmetrically equivalent spodium bonds with the oxygen atoms of the hydroxypropyl groups, with a distance of 2.850 Å, which is close to Bondi's van der Waals radii ($\sum R_{\text{vdw}}$).

In this DFT study, we analyzed the spodium bonds in complexes **2A** and **3** using a combination of QTAIM and NCIPLOT analyses. Together, these methods are effective for visualizing interactions in real space and distinguishing between attractive and repulsive interactions based on the sign of the second eigenvalue of the Hessian of the electron density (ρ). Specifically, $\lambda_2 < 0$ indicates attractive interactions, represented by blue-green reduced density

gradient (RDG) isosurfaces, while $\lambda_2 > 0$ denotes repulsive interactions, shown as yellow-red RDG isosurfaces.

First, we optimized the geometries of complexes **2A** and **3** using periodic boundary conditions at the RI-BP86-D3/def2-

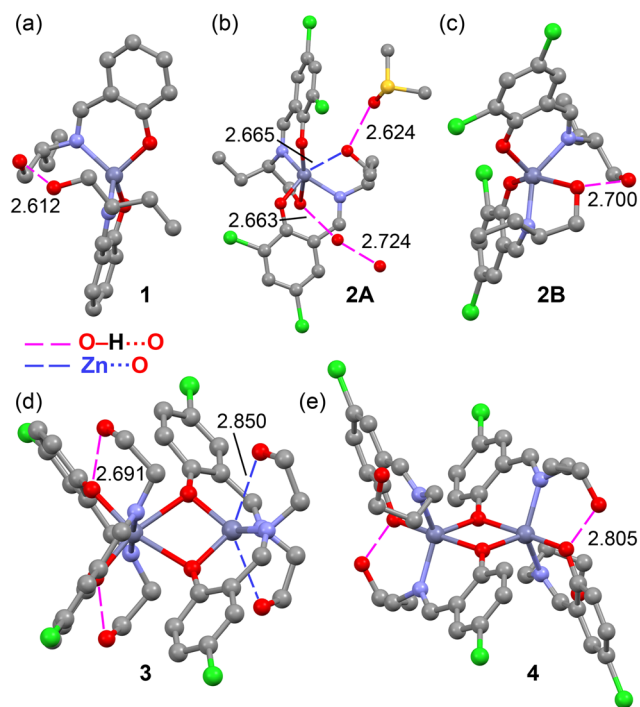


Fig. 18 Comparison of the X-ray geometries of complexes **1** (a), **2A** (b), **2B** (c), **3** (d) and **4** (e). Distances in Å. H-bonds in fuchsia and spodium bonds in dark blue dashed lines.



Fig. 19 Top: QAIM distribution of BCPs and bond paths linking the hydroxyl O-atom with Zn and H-atoms in complexes **2A** (a) and **3** (b). The superimposed RDG isosurfaces are also indicated ($s = 0.5$, $\rho_{\text{cut-off}} = 0.04$, color scale $-0.04 \text{ a.u.} \leq (\text{sign } \lambda_2)\rho \leq 0.04 \text{ a.u.}$). In complex **3**, the structure has been simplified for clarity, showing only the fragment comprising the Zn2 coordination sphere. Bottom: 2D-NCI plots for **2A** (a) and **3** (b) of reduced density gradient (RDG) vs. $(\text{sign } \lambda_2)\rho$ with indications of the spikes corresponding to the SpBs.

TZVP level of theory. The optimized geometries closely align with the experimental structures, with $\text{Zn} \cdots \text{O}$ distances showing slight deviations. In **2A**, the computed $\text{Zn} \cdots \text{O}$ distance is 2.784 Å, which is slightly longer than the experimental value, whereas in **3**, the theoretical $\text{Zn} \cdots \text{O}$ distance is 2.791 Å, slightly shorter than the experimental measurement. Other geometric parameters, such as bond angles and torsions, also exhibit good agreement. For example, in **2A**, the experimental $\text{O}(1)\text{-Zn}(1)\text{-N}(1)$ and $\text{O}(1)\text{-Zn}(1)\text{-O}(3)$ angles are $89.31(7)^\circ$ and $99.08(7)^\circ$, respectively, while the computed values are 87.8° and 99.4° . Similarly, in **3**, the experimental $\text{O}(1)\text{-Zn}(1)\text{-N}(1)$ and $\text{O}(1)\text{-Zn}(1)\text{-O}(3)$ angles are $90.5(7)^\circ$ and $164.98(6)^\circ$, whereas the theoretical values are 90.9° and 164.0° , respectively. These results confirm the reliability of the computational method in accurately reproducing the experimental structures. Subsequently, we performed QAIM and NCIPLOT analyses, confirming in both complexes the presence of spodium bonds. The O-atom of the hydroxy group is connected to the Zn-atom through a bond critical point (red sphere in Fig. 19) and a bond path (orange line), validating the existence of these interactions.

Additionally, the spodium bonds are characterized by a blue RDG isosurface in complex **2A** and green RDG

isosurfaces in complex **3**. This observation aligns with the shorter $\text{Zn} \cdots \text{O}$ distance in complex **2A**, indicating a stronger interaction compared to that in complex **3**. The SpBs in both complexes are also characterized by the corresponding spikes in the 2D-NCI plots of RDG vs. $(\text{sign } \lambda_2)\rho$, as represented in the bottom part of Fig. 19.

The QAIM parameters at the BCP that characterize the SpBs are given in Table 7, showing that they can be classified as weak noncovalent bonds. That is, in both complexes the density values at the BCPs are small ($< 0.016 \text{ a.u.}$) and the total energy density (H) values are close to zero. Moreover, the values of the Laplacian of ρ ($\nabla^2\rho$) are small and positive. The values of λ_2 are also small and negative, indicating weak attractive interactions.

The weak nature of the SpBs has been further confirmed by calculating the energy difference between two rotamers: one corresponding to the fully optimized geometry with the SpBs intact and the other with the C-CH₂OH bond rotated to disrupt the SpBs (see Fig. 20). For complex **2A**, the energy difference is $-2.4 \text{ kcal mol}^{-1}$, providing an estimate for the strength of a single SpB, while for complex **3**, the energy difference is $-4.9 \text{ kcal mol}^{-1}$, corresponding to the combined contribution of two SpB contacts. These results suggest that the interactions are weak and similar in

Table 7 QAIM in a.u. for the BCPs connecting the Zn atom to the O atom that characterize the SpBs represented in Fig. 18

Complex	BCP	$\rho(r)$	$G(r)$	$V(r)$	$H(r)$	$\nabla^2\rho(r)$	λ_2
2A	Zn1 \cdots O4	0.0157	0.0116	-0.0120	-0.0006	0.0437	-0.0124
3	Zn2 \cdots O4	0.0141	0.0110	-0.0111	-0.0001	0.0439	-0.0101



Fig. 20 Optimized structures of complexes **2A** (a) and **3** (b), indicating the energy differences between the rotamers where the Zn \cdots O interactions are disrupted. For complex **3**, the structure has been simplified for clarity, displaying only the fragment encompassing the Zn₂ coordination sphere.

strength in both systems, consistent with the comparable Zn \cdots O distances.

However, this finding contrasts with the NCIPlot analysis, which indicated that the SpB in complex **2A** is stronger. It is important to note that evaluating SpB interactions based on energy differences between rotamers is an approximation, as other factors may influence the dihedral preference around the C–CH₂OH bond, potentially affecting the calculated energy differences.

We also analyzed the spodium bonds (SpBs) in complexes **2A** and **3** using natural bond orbital (NBO) analysis to investigate the role of charge transfer in these interactions (see Fig. 21). The analysis reveals an interesting electron donation from the lone pair orbital on the O-atom to a lone valence orbital on the Zn atom. This LP(O) \rightarrow LV(Zn) charge transfer results in stabilization energies of 5.1 kcal mol⁻¹ for complex **2A** (one Zn \cdots O contact) and 6.8 kcal mol⁻¹ for complex **3** (two Zn \cdots O contacts). These findings align with the NCIPlot analysis, which showed a stronger interaction in complex **2A**, evidenced by a bluish RDG isosurface. This result also suggests that the energy of the SpBs in **3** is overestimated using the energy difference between the rotamers.

The NBO analysis further indicates that the lone valence molecular orbital receiving the electron donation corresponds to the empty 4s atomic orbital of Zn. In both complexes, this orbital is polarized toward the O-atoms, enhancing orbital overlap and facilitating the observed charge transfer. This polarization is consistent with the geometry and strength of the spodium bonds characterized in the QTAIM and NCIPlot analyses.

Conclusions

In this study, we have successfully synthesized and structurally characterized five novel zinc(II) Schiff base complexes, demonstrating diverse coordination environments and supramolecular architectures. The single-crystal X-ray diffraction analysis revealed that the complexes exhibit a range of geometries, from mononuclear tetrahedral to dinuclear distorted trigonal bipyramidal configurations. The presence of hydroxyalkyl groups and solvent molecules played a crucial role in stabilizing the crystal structures, particularly through the formation of hydrogen bonds and spodium bonds (Zn \cdots O). The identification of spodium bonds in complexes **2A** and **3** was supported by QTAIM and NCIPlot analyses, which confirmed the noncovalent nature of these interactions. The Zn \cdots O distances, slightly shorter than Bondi's van der Waals radii but longer than covalent radii, further emphasize the weak yet significant nature of these bonds. DFT studies using periodic boundary conditions provided excellent agreement with the experimental geometries, validating the computational approach and offering deeper insights into the electronic structure of these complexes. NBO analysis revealed that the stabilization of spodium bonds is primarily driven by LP(O) \rightarrow LV(Zn) charge transfer, where the lone pair of oxygen atoms donates electron density to the empty 4s orbital of the zinc center. This charge transfer mechanism, combined with the polarization of the zinc orbitals, contributes to the overall stability of the complexes. The findings of this study advance our understanding of spodium bonding in coordination chemistry and highlight its potential role in stabilizing supramolecular assemblies. These insights could be further explored in the design of new materials with applications in



Fig. 21 Plots of the NBOs involved in the LP(O) \rightarrow LV(Zn) charge transfer and the second order perturbation energies in complexes **2A** (a) and **3** (b). In complex **3**, the structure has been simplified for clarity, showing only the fragment comprising the Zn₂ coordination sphere.

catalysis, molecular recognition, sensing and the development of supramolecular frameworks. Future work could focus on the systematic investigation of spodium bonds in other metal complexes and their implications in crystal engineering and materials science.

Data availability

All data underlying the results are available as part of the article and no additional source data are required.

Conflicts of interest

There are no conflicts to declare.

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