

Heart-shaped {Cu₁₀}-added polyoxometalates for visible-light-driven hydrogen evolution and photothermal conversion

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ABSTRACT: A heart-shaped polyoxometalate, $\text{H}_{10}\text{LiK}_5[(\text{BO}(\text{OH})_2)_2(\text{B}_2\text{O}(\text{OH})_6)\text{Cu}_{10}(\text{OH})_4(\text{H}_2\text{Ge}_2\text{W}_2\text{O}_{15})(\text{GeW}_9\text{O}_{34})_2] \cdot 46\text{H}_2\text{O}$ (**1**), was successfully synthesized in this study. Its structure consists of a {B₄Cu₁₀} core integrated with {GeW₉} and {Ge₂W₂} fragments. Notably, the Cu–O–Cu bridge closure is indirectly precluded by steric hindrance originating from the specific orientation of the Jahn–Teller distortion, an unprecedented structural observation in polyoxometalate chemistry. **1** exhibits remarkable dual functionality, achieving a peak photocatalytic H₂ evolution rate of 8808.7 $\mu\text{mol} \cdot \text{g}^{-1} \cdot \text{h}^{-1}$ and photothermal conversion efficiency of 16.27% under 808 nm irradiation. These findings demonstrate the potential of **1** as a robust candidate for future synergistic solar energy conversion and photothermal applications.

KEYWORDS: polyoxometalates, visible-light-driven hydrogen evolution, copper, photothermal conversion

1 Introduction

Polyoxometalates (POMs) are a class of inorganic nanoclusters with well-defined structures and exceptional molecular-level tunability [1–6]. Owing to their structural modularity, tunable redox properties, strong Brønsted acidity, and rich electronic characteristics, POMs are promising candidates for advanced applications in catalysis, electrocatalysis, energy storage, biomedicine, and functional materials science [7–11]. POMs exhibit exceptional redox stability and a distinctive “electron sponge” effect [12, 13]. Furthermore, owing to their abundance of surface oxygen atoms, POMs are effective inorganic multidentate ligands that can induce the clustering or multinuclear assembly of additional metal centers [1]. By incorporating transition metals (TMs) into the POM framework for TM-added polyoxometalate (TMAP) formation, the structural robustness and stability of the POM scaffold can be synergistically combined with the intrinsic catalysis provided by the secondary TM sites. Driven by the necessity for a global energy transition, the development of dual-functional POM-based materials with synergistic photocatalytic and photothermal capabilities presents a pivotal strategy for maximizing solar energy harvesting [14]. In TMAP formation, the lacunary-directing synthetic (LDS) strategy is pivotal to precisely control the nuclearity

and configuration of the incorporated TM–O clusters. Classic lacunary precursors, such as trilacunary Keggin-type anions $\{\text{XW}_9\text{O}_{34}\}^{n-}$ (X = P, Si, Ge), possess highly reactive, coordinatively unsaturated oxygen sites within their defect cavities [15–17]. These sites exert a strong template effect and electrostatic attraction, effectively guiding the *in situ* aggregation of TM ions at lacunary positions. This aggregation enables the precise modulation of the central TM–O cluster while preserving the structural integrity of the POM framework. Recently, landmark TMAPs, such as $\{\text{Ni}_6\text{W}_9\}$ [18, 19], $\{\text{Cu}_6\text{W}_9\}$ [20], $\{\text{Cu}_8\text{W}_{18}\}$ [21, 22], $\{\text{Fe}_{13}\text{W}_{36}\}$ [23], and $\{\text{Co}_9\text{W}_{24}\}$ [24], as well as high-nuclearity TMAPs, including $\{\text{Co}_{19}\text{W}_{60}\}$ [25], $\{\text{Zr}_{24}\text{W}_{56}\}$ [26], $\{\text{Cu}_{26.5}\text{W}_{60.5}\}$ [27], and $\{\text{Ni}_{40}\text{W}_{72}\}$ [28, 29], have been successively synthesized. These structures strongly demonstrate the broad versatility and importance of the LDS strategy in forming TMAP nanoclusters.

Among the various TM centers, Cu-based compounds have garnered attention owing to their unique electronic configurations. Cu ions can undergo facile and reversible redox switching between Cu⁺ and Cu²⁺ states, resulting in exceptionally low activation energy barriers for key reactions, such as the photocatalytic H₂ evolution reaction and CO₂ reduction [30–32]. In addition, the d–d electronic transitions of Cu centers often produce strong optical absorption in the near-infrared (NIR) region, endowing these materials with excellent photothermal convergence. Consequently, the incorporation of multinuclear Cu ions into POMs is a highly promising strategy for the formation of bifunctional solar-energy-conversion materials that integrate efficient photocatalytic H₂ evolution with superior photothermal conversion effects. However, among the Cu-added POMs (CuAPs) reported to date, representative examples are primarily limited to lower-nuclearity

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Cu–O clusters, such as {Cu₄}, {Cu₆}, and {Cu₈}, as well as higher-nuclearity species, such as {Cu₁₃} and {Cu₁₄} [20, 33–36]. The development of decanuclear (Cu₁₀) or higher-nuclearity copper clusters faces significant challenges during synthesis and remains underexplored.

In this study, a heart-shaped CuAP, H₁₀LiK₅[(BO(OH)₂)₂(B₂O(OH)₆)Cu₁₀(OH)₄(H₂Ge₂W₂O₁₅)(GeW₉O₃₄)₂].46H₂O (**1**), was successfully synthesized using the LDS strategy and a hydrothermal reaction. The architecture is characterized by the integration of two {A-α-GeW₉} units, a C-type [(BO(OH)₂)₂(B₂O(OH)₆)Cu₁₀(OH)₄]¹²⁺ ({B₄Cu₁₀}) cluster, and a [H₂Ge₂W₂O₁₅]⁸⁻ fragment, providing a CuO₅/CuO₆ coordination ratio of 4:1. Photocatalytic H₂ evolution experiments revealed a remarkable H₂ evolution rate of 8808.7 μmol·g⁻¹·h⁻¹. Furthermore, the incorporation of Cu centers significantly enhanced NIR absorption, enabling efficient photothermal convergence under 808-nm laser irradiation.

2 Experimental

2.1 Materials and methods

The precursor Na₂K₈[A-α-GeW₉O₃₄].7H₂O ({GeW₉}) was prepared according to a previously reported procedure [37]. Other reagents and chemicals were obtained from commercial sources and used as received without further purification.

2.2 Synthesis of **1**

CuCl₂·2H₂O (0.127 g, 0.745 mmol), Na₂K₈[A-α-GeW₉O₃₄].7H₂O (0.940 g, 0.341 mmol), LiBO₂ (0.065 g, 1.306 mmol), and LiCl (0.730 g, 17.221 mmol) were mixed in 4 mL distilled water. The mixture was stirred for 2 h and then transferred to a 20 mL Teflon-lined autoclave to maintain a sealed hydrothermal environment. Subsequently, the autoclave was placed in an oven at 100 °C for 48 h. Upon reaction completion and cooling to room temperature, light-blue rod-shaped crystals were obtained via filtration and washed with distilled water. The product weight was 0.086 g (0.016 mmol), corresponding to a 15.81% yield (based on CuCl₂·2H₂O). The phase purity of **1** was confirmed via powder X-ray diffraction (PXRD; Fig. S1 in the Electronic Supplementary Material (ESM)). Elemental analysis (%) calculated for **1**: Li, 0.10; B, 0.59; K, 2.68; Cu, 8.70; Ge, 3.98; W, 50.34. Found: Li, 0.13; B, 0.52; K, 2.75; Cu, 8.57; Ge, 3.91; W, 51.05. Fourier transform infrared spectroscopy (FT-IR) (KBr tablet, cm⁻¹, Fig. S2 in the ESM): 1619(m), 1383(m), 1244(w), 1030(m), 942(s), 890(s), 773(s), and 707(s).

2.3 X-ray crystallography

The X-ray crystallography data for H₁₀LiK₅[(BO(OH)₂)₂(B₂O(OH)₆)Cu₁₀(OH)₄(H₂Ge₂W₂O₁₅)(GeW₉O₃₄)₂].46H₂O were obtained and loaded on XtaLAB Synergy R, DW system, HyPix diffractometer equipped with a graphite monochromator to isolate Cu-Kα (λ = 1.54056 Å) at 100 K. The structure was solved by the Intrinsic Phasing module of the SHELXT program and further refined by full-matrix least-squares analysis of F² using SHELXL, all within the Olex2 software [38–40]. The contribution of the disordered lattice water molecules to the crystal structure was evaluated using the Solvent Mask software [41]. Table 1 shows the refinement of the crystallographic data structure, which were submitted to The Cambridge Crystallographic Data Centre (CCDC 2531907). These data can be obtained for free at

Table 1 The crystallographic data for compound **1**

Compound	1
Formula	H ₁₁₈ B ₄ Cu ₁₀ Ge ₄ K ₅ LiO ₁₄₆ W ₂₀
Mr	7303.24
Crystal system	Monoclinic
Space group	C2/c
<i>a</i> (Å)	28.7165(4)
<i>b</i> (Å)	22.3003(2)
<i>c</i> (Å)	22.7479(4)
α (°)	90
β (°)	121.684(2)
γ (°)	90
<i>V</i> (Å ³)	12,396.3(4)
<i>Z</i>	4
<i>D_c</i> (g·cm ⁻³)	3.894
<i>F</i> (000)	13064.0
<i>T</i> (K)	100.0(3)
μ (mm ⁻¹)	38.885
Reflections collected	44,620
Reflections unique	12,513
Parameters	709
GOF on <i>F</i> ²	1.033
Final <i>R</i> indices (<i>I</i> > 2σ(<i>I</i>))	<i>R</i> ₁ = 0.0493 <i>wR</i> ₂ = 0.1353
<i>R</i> indices (all data) ^a	<i>R</i> ₁ = 0.0553 <i>wR</i> ₂ = 0.1406
CCDC number	2531907

$$^a R_1 = \sum ||F_o| - |F_c|| / \sum |F_o|, wR_2 = [\sum w(F_o^2 - F_c^2)^2 / \sum w(F_o^2)^2]^{1/2}$$

www.ccdc.cam.ac.uk/conts/retrieving.html or by sending an email to data_request@ccdc.cam.ac.uk, or by getting in touch with The Cambridge Crystallographic Data Centre, 12 Union Road, Cambridge CB21EZ, UK; Fax: +44-1223 336 033.

3 Results and discussion

3.1 Structural description

1 crystallizes in the monoclinic space group C2/c. **1** is a heart-shaped polyanionic cluster [(BO(OH)₂)₂(B₂O(OH)₆)Cu₁₀(OH)₄(H₂Ge₂W₂O₁₅)(GeW₉O₃₄)₂]¹⁶⁻ ({B₄Cu₁₀(Ge₂W₂)(GeW₉)₂}, Fig. 1(a) and Fig. S3 in the ESM). In this polyanionic cluster, two {A-α-GeW₉} units are linked to a C-shaped [(BO(OH)₂)₂B₂O₇Cu₁₀(OH)₄]⁶⁺ cluster ({B₄Cu₁₀}) and one [H₂Ge₂W₂O₁₅]⁸⁻ fragment ({Ge₂W₂}; Fig. 1(b)–1(d)). Furthermore, adjacent {B₄Cu₁₀(Ge₂W₂)(GeW₉)₂} units are connected via O15/O15A bridges to form a one-dimensional chain structure (Fig. S3(c) in the ESM). Bond valence sum (BVS) calculations were performed to evaluate the oxidation states and protonation sites of compound **1**. As shown in Table S1 in the ESM, the calculated BVS values show that the W, Cu, Ge, and O atoms are in the +6, +2, +4, and –2 oxidation states, respectively. Notably, the BVS values of O36, O38, O40, O42, O43, O50, and O52 are close to 1, suggesting that these oxygen atoms are protonated and exist as hydroxyl groups. Within the {B₄Cu₁₀} cluster, a C-shaped architecture is formed, with Cu–Cu distances ranging from 2.968 to 3.426 Å (Fig. 2(a)). The {Cu₁₀} unit adopts

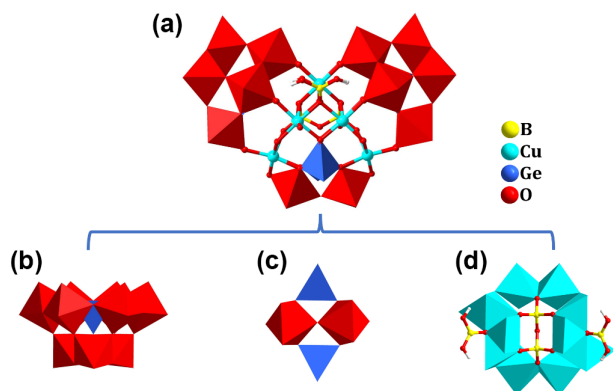


Figure 1 (a) Polyhedral representation of the polyanion $[(\text{BO}(\text{OH})_2)_2(\text{B}_2\text{O}(\text{OH})_6)\text{Cu}_{10}(\text{OH})_4(\text{H}_2\text{Ge}_2\text{W}_2\text{O}_{15})(\text{GeW}_9\text{O}_{34})_2]^{16-}$. (b) Polyhedral view of the $[\text{A}-\alpha\text{-GeW}_9\text{O}_{34}]^{10-}$ unit. (c) Polyhedral view of the $[\text{H}_2\text{Ge}_2\text{W}_2\text{O}_{15}]^{3-}$ fragment. (d) Polyhedral view of the $[(\text{BO}(\text{OH})_2)_2(\text{B}_2\text{O}(\text{OH})_6)\text{Cu}_{10}(\text{OH})_4]^{12+}$ cluster. Polyhedral color code: blue, GeO_4 ; red, WO_6 .

distorted square-pyramidal (CuO_5 for Cu1, Cu2, Cu3, and Cu5) and octahedral (CuO_6 for Cu4) coordination geometries in a 4:1 ratio, with Cu–O bond lengths varying between 1.915 and 2.615 Å (Fig. S4(a)–S4(e) in the ESM). In the C-shaped $\{\text{B}_4\text{Cu}_{10}\}$ cluster (Fig. 2(b)), the central B_2O_7 moiety features sp^3 hybridized boron atoms. Additionally, at both ends of the C-shaped cluster, two terminal $\text{BO}(\text{OH})_2$ units are attached via O51/O51A bridges, with the boron atoms exhibiting sp^2 hybridization (Fig. 2(c)). The back side of the C-shaped $\{\text{B}_4\text{Cu}_{10}\}$ cluster is embedded with a $\{\text{Ge}_2\text{W}_2\}$ unit, which further stabilizes the C-shaped architecture (Fig. S5 in the ESM). The $\{\text{Ge}_2\text{W}_2\}$ cluster is relatively uncommon; unlike the

conventional boat-shaped $\{\text{XW}_6\}$ -type clusters reported in Ref. [42], it adopts a distinctive bent or curved conformation.

Furthermore, **1** can be viewed as an assembly of two Dawson-like $\{\text{Cu}_6\text{BGeW}_9\}$ clusters combined via shared Cu atoms (Cu1/Cu1A; Figs. 3(a) and 3(c)). The Dawson-like $\{\text{Cu}_6\text{BGeW}_9\}$ and reported trilacunar $\{\text{P}_2\text{W}_{15}\}$ fragments are similar in size and configuration. However, a structural comparison (Fig. S6(a)–S6(d) in the ESM) reveals a shorter heteroatom distance in $\{\text{Cu}_6\text{BGeW}_9\}$ ($\{\text{GeO}_4\}\cdots\{\text{BO}_4\} = 3.8$ Å) than in $\{\text{P}_2\text{W}_{15}\}$ ($\{\text{PO}_4\}\cdots\{\text{PO}_4\} = 4.0$ Å). Furthermore, the Cu–O–Cu angles are narrower than the corresponding W–O–W angles. Notably, the Jahn–Teller effect leads to distinct structural outcomes. Unlike the conventional bond elongation observed in Cu2–Cu4, the Cu–O stretching directions of Cu1 and Cu1A are mutually opposed. This configuration results in a relatively short Cu1–Cu1A distance (3.654 Å, Fig. 3(b)). The resulting steric hindrance, dictated by the specific orientation of the Jahn–Teller distortion, prevents the Cu–O–Cu bridge closure. The spatial orientation of the Jahn–Teller effect at the Cu1/Cu1A centers creates an indirect barrier to Cu–O bond formation, which is an unprecedented finding in the field of POMs. Significantly, the C-shaped $\{\text{Cu}_{10}\}$ cluster in **1** is structurally distinct from previously documented sandwich-type CuAP ($\{\text{Cu}_4\}$, $\{\text{Cu}_5\}$, $\{\text{Cu}_6\}$, and $\{\text{Cu}_8\}$) clusters (Fig. 4). Thus, **1** is a prominent new member of the CuAP family.

3.2 Photocatalysis hydrogen evolution properties

The optical bandgap of **1** was 3.07 eV, as derived from the solid-state ultraviolet–visible light (UV–Vis) absorption data using the Kubelka–Munk equation (Fig. S7 in the ESM). This substantiates

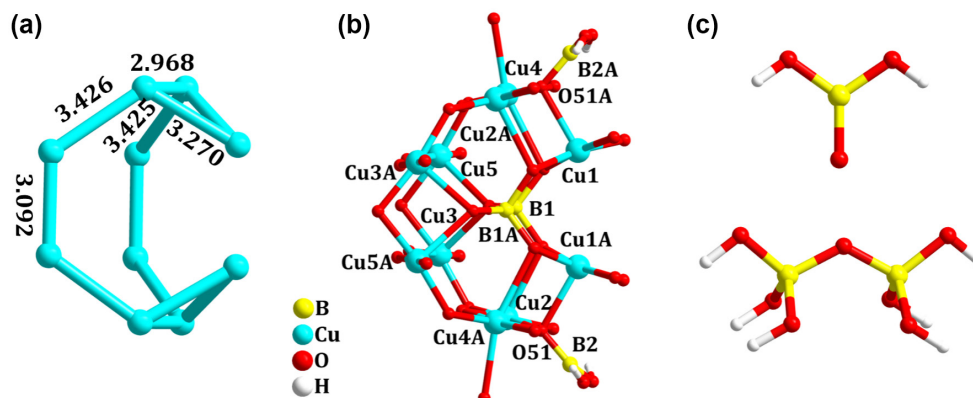


Figure 2 (a) Schematic view of the $\{\text{Cu}_{10}\}$ cluster. (b) Ball-and-stick model of the $\{\text{B}_4\text{Cu}_{10}\}$ cluster. (c) Ball-and-stick representations of the $\text{BO}(\text{OH})_2$ and $\text{B}_2\text{O}(\text{OH})_6$ fragments.

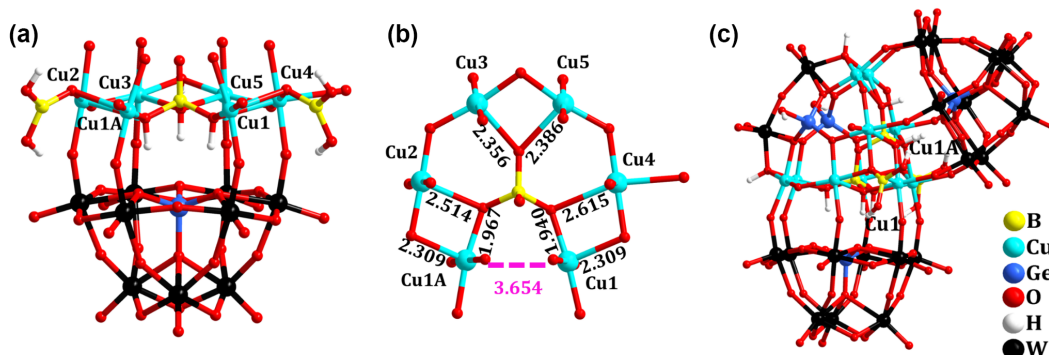


Figure 3 (a) Ball-and-stick model of the Dawson-like $\{\text{Cu}_6\text{BGeW}_9\}$ fragments. (b) Ball-and-stick representation of the $\{\text{Cu}_6\}$ cluster highlighting the Jahn–Teller distortion. (c) Ball-and-stick model of compound **1**.

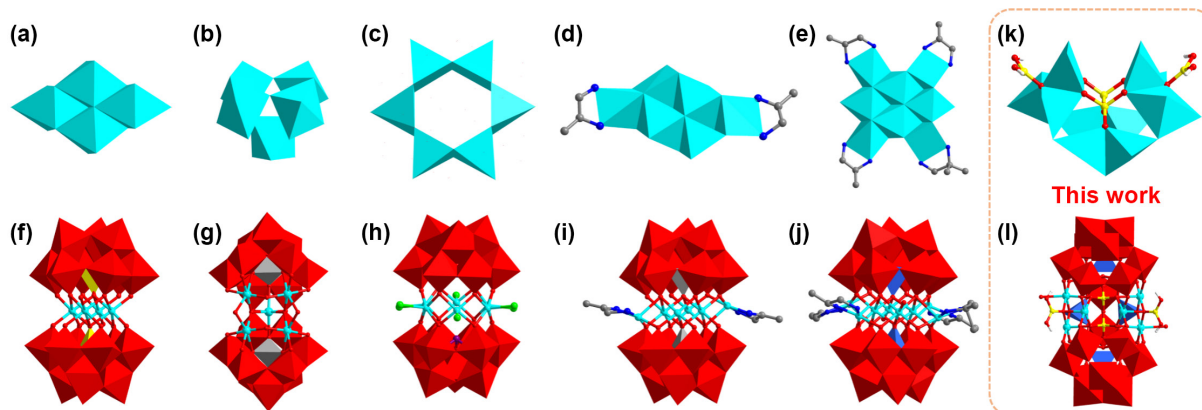


Figure 4 Polyhedral views of $\{Cu_4\}$ cluster ((a) and (f)); $\{Cu_5\}$ cluster ((b) and (g)); $\{Cu_6\}$ cluster ((c) and (h)); $\{Cu_6\}$ cluster ((d) and (i)); $\{Cu_8\}$ cluster ((e) and (j)); $\{Cu_{10}\}$ cluster ((k) and (l)). Atom color code: cyan, Cu; green, Cl; blue, N; grey, C; yellow, B; red, O.

the significant potential of **1** as a photocatalyst. Given that the electronic properties of POM can be effectively modulated via Cu incorporation, further analysis was performed on the application of CuAPs in photocatalysis. Photocatalytic H_2 evolution reactions were conducted under Vis irradiation ($\lambda = 400\text{--}800\text{ nm}$), and the performance of the compounds was subsequently evaluated in a three-component catalytic system.

Photocatalytic H_2 evolution experiments were performed using a Beijing Perfectlight PCX-50C multichannel photochemical reaction system equipped with a white light source. Typically, the reaction mixture consisted of a 6.0-mL dimethylformamide/ CH_3CN solution (1:3, v/v), containing **1** as the catalyst, $[Ir(ppy)_2(dtbbpy)] [PF_6]$ ($ppy = 2\text{-phenylpyridine}$; $dtbbpy = 5,5'\text{-di-tert-butyl-2,2'-bipyridine}$, Fig. S8 in the ESM) as the photosensitizer, triethanolamine (TEOA) as the sacrificial electron donor, and H_2O as the proton source. The reaction was conducted under LED

irradiation (10 W, 400–800 nm) at 25 °C. The generated H_2 was measured every 2 h using a gas chromatograph with a thermal conductivity detector. As shown in Fig. 5(a), a progressive increase in H_2 evolution was observed when the solution containing **1** was subjected to Vis irradiation, reaching a maximum yield of 95.70 μmol after 10 h (rate: 4785.08 $\mu\text{mol}\cdot\text{g}^{-1}\cdot\text{h}^{-1}$). H_2 evolution occurred only under Vis irradiation in the presence of the sacrificial agent and photosensitizer. To further validate the superior catalytic efficiency of **1**, control experiments were conducted under identical conditions using $\{GeW_9\}$, $CuCl_2\cdot 2H_2O$, or no catalyst, yielding significantly lower H_2 values of 7.57, 2.88, and 0.96 μmol , respectively. These results demonstrate that each component in the mixed solution is essential for Vis-driven H_2 evolution. The influence of catalyst dosage (1–3 mg) on the H_2 yield was systematically investigated (Fig. 5(b)). As the dosage of **1** increased, H_2 yields of 52.88, 95.70, and 264.26 μmol were achieved,

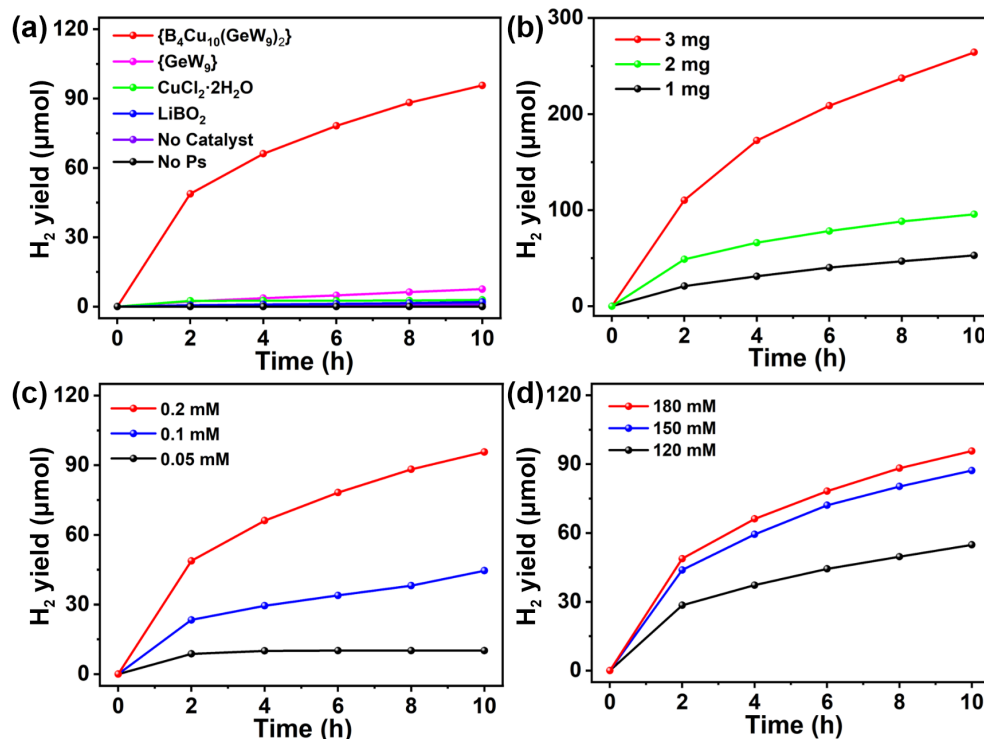


Figure 5 (a) Photocatalytic H_2 evolution under varying catalysts and reaction conditions. (b) Dependence of H_2 production on the dosage of **1** (1–3 mg). (c) Effect of photosensitizer concentration (0.05–0.2 mM) on H_2 evolution. (d) Effect of TEOA concentration (120–180 mM) on the H_2 evolution.

corresponding to H_2 evolution rates of 5288.0, 4785.0, and 8808.7 $\mu\text{mol}\cdot\text{g}^{-1}\cdot\text{h}^{-1}$, respectively. In comparison with previously reported POM-based catalysts (Table S2 in the ESM) [19, 22, 24, 25, 43–46], **1** exhibits competitive H_2 production. To further optimize photocatalytic efficiency, the effects of other experimental parameters were investigated. To optimize the multicomponent photocatalytic system and elucidate the roles of each component, we systematically investigated the effects of the photosensitizer and TEOA concentrations on the H_2 yield. As shown in Fig. 5(c) and 5(d), using **1** at a fixed dosage of 2 mg, the H_2 yield positively correlates with the photosensitizer (0.05–0.2 mM) and TEOA concentrations (120–180 mM). These results indicate that higher photosensitizer and TEOA concentrations within these ranges effectively promote light absorption and rapid electron replenishment, respectively.

Stability and recyclability are critical for heterogeneous catalysts. To assess these properties, **1** was thoroughly washed with deionized water and dried after each photocatalytic cycle. A marginal decline was observed in the H_2 yield after three consecutive cycles (Fig. S9 in the ESM), which may be due to inevitable catalyst loss during recovery and washing. Furthermore, the structural stability of **1** after cycling tests was confirmed by PXRD and FTIR spectra (Fig. S10(a) and S10(b) in the ESM), which do not show significant differences compared to those of fresh samples. Therefore, these results demonstrate that **1** shows excellent structural stability under catalytic conditions.

3.3 Photothermal conversion performance

In addition to enhancing the photocatalytic H_2 evolution of POMs, Cu incorporation enables the modulation of their absorption profiles. Specifically, TM addition effectively regulates POM absorption in the NIR region. Given the characteristic d–d transitions associated with Cu^{2+} , the NIR absorption of **1** is significantly influenced by Cu addition. An absorbance of 0.118 at 808 nm was recorded (Fig. 6), highlighting the potential of employing Cu^{2+} to tune the photothermal conversion efficiency of POM. Prompted by this robust NIR response and excellent stability of CuAP, the properties of **1** as an NIR-responsive photothermal agent were further investigated.

The photothermal conversion of **1** was systematically evaluated under 808-nm laser irradiation (Fig. S11 in the ESM). A solid sample of **1** was exposed to power densities ranging from 0.2 to 1.0 $\text{W}\cdot\text{cm}^{-2}$ for 90 s (Fig. 7(a)), resulting in a significant temperature

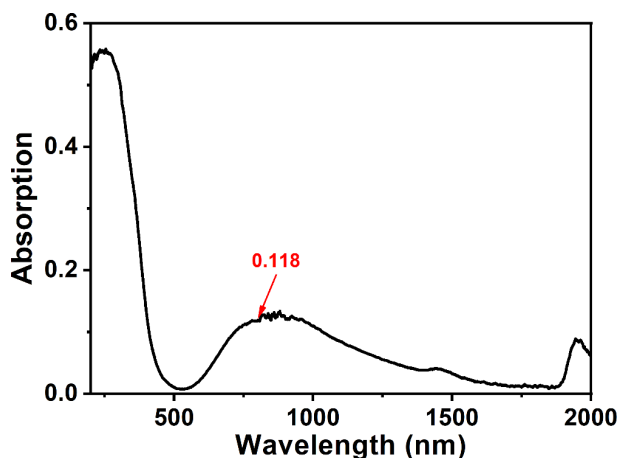


Figure 6 UV–Vis–NIR absorption spectrum of **1**.

increase from 26.6 to 117.7 °C. A linear correlation between temperature and laser power density was observed (Fig. S12(a) in the ESM), verifying that CuAP is capable of precise and stable thermal control. To assess material durability, cycling tests were performed over seven consecutive laser-on/off cycles (Fig. 7(b)); no significant attenuation was observed in the photothermal response, confirming the excellent thermal stability of **1** even at elevated temperatures. Furthermore, the photothermal conversion efficiency (η) was 16.27%, based on the system time constant (τ), which was calculated according to the method employed by Roper et al. [47] (Fig. S12(b) in the ESM). As summarized in Table S3 in the ESM, the temperature increase (ΔT) of **1** at 1.0 $\text{W}\cdot\text{cm}^{-2}$ is larger than those observed for previously reported materials [48–52]. The infrared imaging results at 1.0 $\text{W}\cdot\text{cm}^{-2}$ (Fig. 7(c)) indicate the potential of CuAPs in infrared thermal imaging. Collectively, these findings suggest that **1** is a promising solar-absorbing candidate for photothermal applications.

4 Conclusion

In summary, a novel heart-shaped POM, $\text{H}_{10}\text{LiK}_5[(\text{BO}(\text{OH})_2)_2(\text{B}_2\text{O}(\text{OH})_6)\text{Cu}_{10}(\text{OH})_4(\text{H}_2\text{Ge}_2\text{W}_2\text{O}_{15})(\text{GeW}_9\text{O}_{34})_2]\cdot 46\text{H}_2\text{O}$, was synthesized using the LDS strategy. Structural analysis revealed a unique $\{\text{B}_4\text{Cu}_{10}\}$ cluster encapsulated by $\{\text{GeW}_9\}$ and $\{\text{Ge}_2\text{W}_2\}$ fragments. Notably, the Cu–O–Cu bridge closure is indirectly precluded by steric hindrance arising from the specific orientation of the Jahn–Teller distortion, which is an unprecedented finding in the POM field. **1** exhibits excellent dual functionality, achieving a photocatalytic H_2 evolution rate of 8808.7 $\mu\text{mol}\cdot\text{g}^{-1}\cdot\text{h}^{-1}$ and an η of 16.27% under 808 nm irradiation. These results verify the potential of **1** as a robust candidate for synergistic solar energy conversion and photothermal applications. Furthermore, its structural novelty and dual-functional nature provide a blueprint for next-generation multifunctional materials, paving the way for advanced applications in photothermal-assisted catalysis and integrated solar-driven devices.

Electronic Supplementary Material: Supplementary material (including experimental section, additional structures, IR spectra, PXRD, and TGA) is available in the online version of this article at <https://doi.org/10.26599/POM.2026.9140150>.

Data availability

All data needed to support the conclusions in the paper are presented in the manuscript and the Electronic Supplementary Material. Additional data related to this paper may be requested from the corresponding author upon request.

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Declaration of competing interest

The authors have no competing interests to declare that are relevant to the content of this article. Author Guo-Yu Yang is the advisory board member of this journal, but he is not involved in the peer-

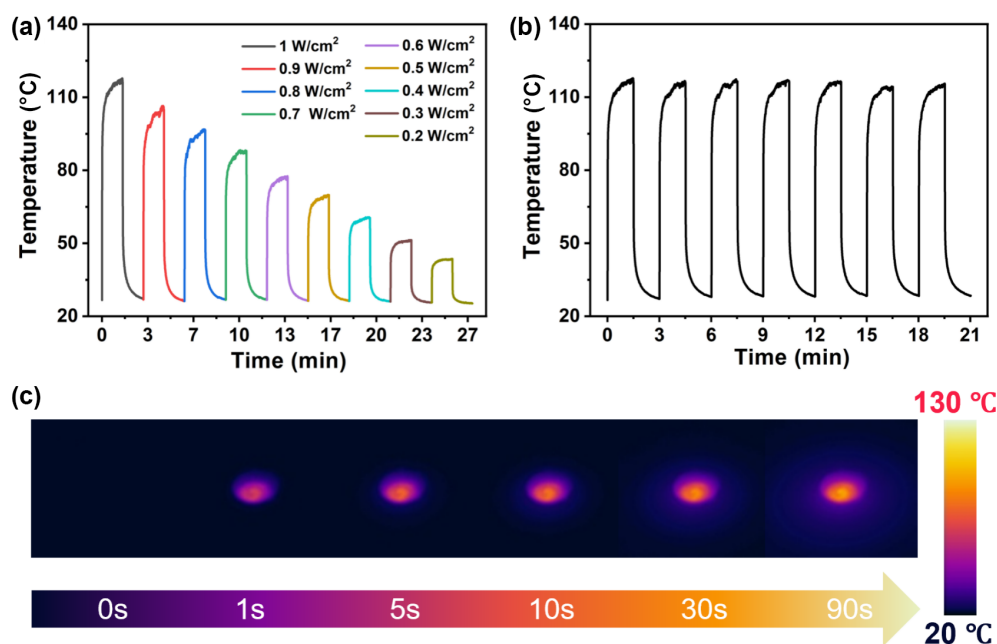


Figure 7 Photothermal conversion performance of **1**. (a) Linear relationship between temperature increment and power. (b) Photothermal conversion curves during heating and cooling cycles. (c) NIR thermal images of **1** powder under 808 nm laser irradiation ($1.0 \text{ W}\cdot\text{cm}^{-2}$).

review or decision of this article.

Author contribution statement

Z.-W. W.: Data curation, validation, writing manuscript, experimental design. G.-Y. Y.: Project administration, funding acquisition, writing manuscript. All the authors have approved the final manuscript.

Use of AI statement

None.

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