

An asymmetric naked-eye chemo-sensor for Cu²⁺ in aqueous solution



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ABSTRACT

We have synthesized a new asymmetric chemo-sensor (E)-4-((2-((2-hydroxybenzylidene)amino)phenyl)amino)-3-nitro-2H-chromen-2-one (**1**) based on the combination of 2-hydroxybenzaldehyde and precursor 4-((2-aminophenyl)amino)-3-nitro-2H-chromen-2-one. Receptor **1** showed a selective color change from colorless to yellow in the presence of Cu²⁺ in aqueous solution. The detection limit (18 μM) of **1** for Cu²⁺ is lower than that (30 μM) recommended by WHO in drinking water, and sensor **1** could be recyclable simply through treatment with a proper reagent such as EDTA.

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Much attention has been given in recent years to the development of chemosensors for heavy metal ions due to their environmental harm and biological importance [1–5]. Copper (II) ion, as the third most abundant transition metal in the human body, plays vital roles in many fundamental physiological processes in organisms. Copper dependent enzymes act as catalysts to help a number of body functions to provide energy for biochemical reactions, transform melanin for pigmentation of the skin, assist the formation of crosslinks in collagen and elastin, and thereby maintain and repair connective tissues [6,7]. However, copper ions can have detrimental effects on humans and animals when overexposed to Cu²⁺-polluted water. Excess exposure to high concentrations of Cu²⁺ has been implicated in the development of Alzheimer's and Parkinson's diseases [8,9]. The World Health Organization (WHO) has set the safe limit of copper in drinking water at 30 μM [10]. Therefore, reliable methods for determination of trace amounts of Cu²⁺ in biological and environmental samples have been developed [11]. However, many of them require sometimes complicated syntheses and expensive instruments, and some chemosensors are insoluble in aqueous solutions. For practical applications, it is necessary to develop Cu²⁺ sensors that are easily prepared and water-soluble, and shows easy detection without the help of instruments. Hence, colorimetric sensors are very attractive as simple-to-use and naked-eye diagnostic tools [12,13].

Coumarin derivatives are excellent chromogenic and fluorogenic dyes that are widely utilized as reporters in chemosensors [14], and a salicylaldehyde has been well known as the chromophores [15]. Therefore, we were interested in the combination of coumarin and salicylic groups to develop a novel chemosensor for detecting metal ions. The

resulting novel chemosensor (**1**) was easily prepared (Scheme 1) and showed an efficient detection of Cu²⁺ ion without the help of instruments.

Herein, we report on the synthesis, characterization and sensing properties of a new colorimetric receptor **1**, which displayed highly selective and sensitive colorimetric recognition toward Cu²⁺ by color change from colorless to yellow in aqueous solvent. The ratio of 1:1 for complex formation was proposed, based on Job plot, ESI-mass spectrometry analysis, and ¹H NMR titration. The detection limit of **1** for Cu²⁺ was 18 μM, which is below the WHO acceptable limit (30 μM) in drinking water.

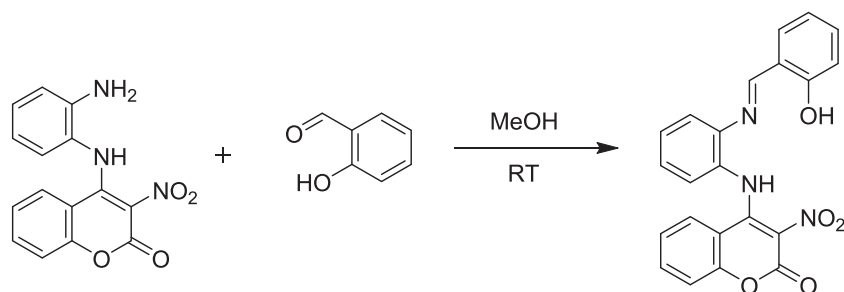
Receptor **1** was synthesized by coupling 4-((2-aminophenyl)amino)-3-nitro-2H-chromen-2-one with 2-hydroxybenzaldehyde with a 53% yield in absolute methanol (Scheme 1), and characterized by ¹H NMR, ¹³C NMR, ESI-mass spectrometry and elemental analysis. 4-((2-Aminophenyl)amino)-3-nitro-2H-chromen-2-one was synthesized according to the literature method [16].

The colorimetric selective sensing abilities of receptor **1** with various cations in a mixture of CH₃CN/bis-tris buffer (v/v, 4:6) were monitored by UV–vis absorption spectra (Fig. 1a). Only the addition of Cu²⁺ induced a distinct spectral change while other cations such as Na⁺, K⁺, Mg²⁺, Ca²⁺, Al³⁺, Ga³⁺, In³⁺, Cr³⁺, Mn²⁺, Fe²⁺, Fe³⁺, Co²⁺, Ni²⁺, Zn²⁺, Cd²⁺, and Pb²⁺ did not induce any spectral changes. Consistent with the change of UV–vis spectra, the solution of **1** resulted in an immediate color change from colorless to yellow with Cu²⁺ ion (Fig. 1b), indicating that receptor **1** can serve as a 'naked-eye' copper indicator in aqueous solution.

The UV–vis absorption spectral variation of sensor **1** was monitored during titration with different concentrations of Cu²⁺. As shown in Fig. 2, the increase in the absorption bands at 310 nm and 406 nm

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Scheme 1. Synthesis of receptor 1.

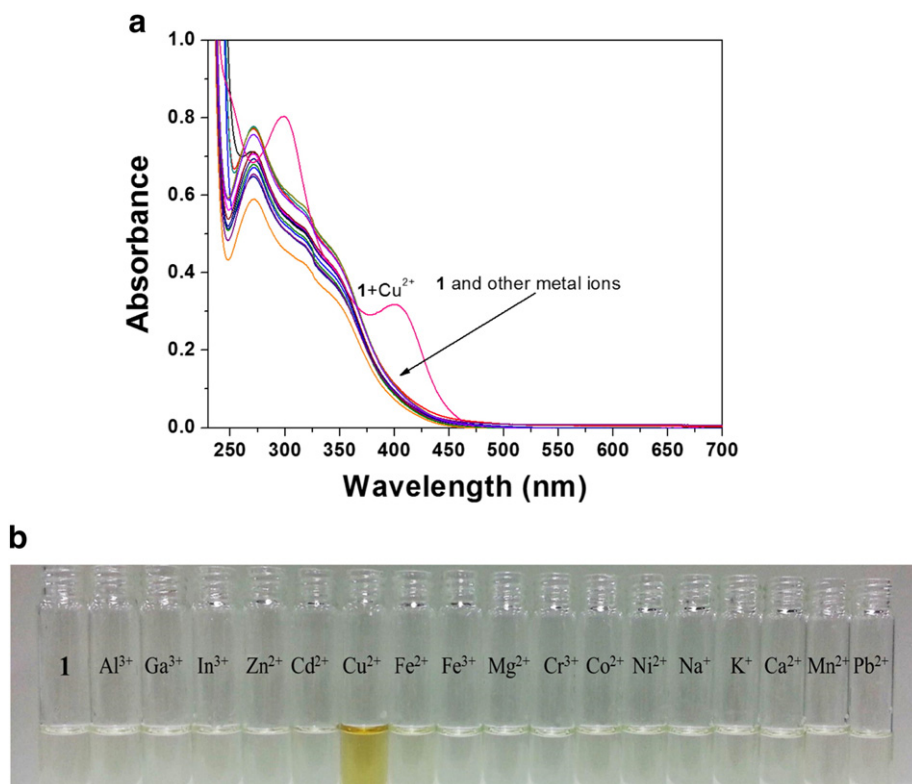


Fig. 1. (a) UV-vis spectral changes of receptor **1** (30 μM) upon the addition of various metal ions (4 equiv.) in CH_3CN /bis-tris buffer solution (v/v, 4:6). (b) The color changes of **1** (30 μM) upon addition of various metal ions (4 equiv.) in CH_3CN /bis-tris buffer solution (v/v, 4:6).

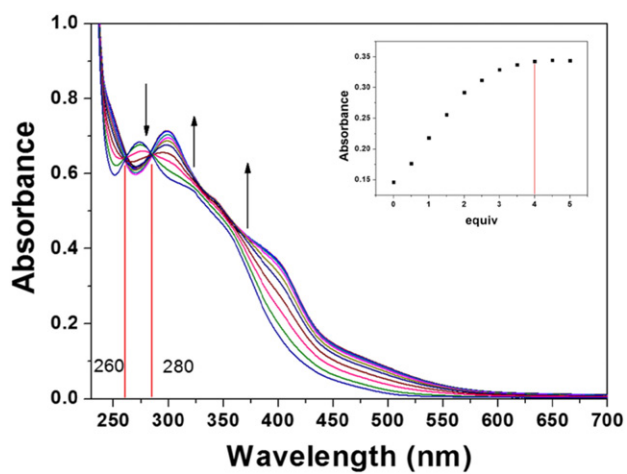


Fig. 2. UV-vis spectral changes of **1** (30 μM) upon addition of Cu^{2+} (up to 4 equiv.) in CH_3CN /bis-tris buffer solution (v/v, 4:6) at room temperature. Inset: Absorption at 406 nm versus the number of equiv. of Cu^{2+} added.

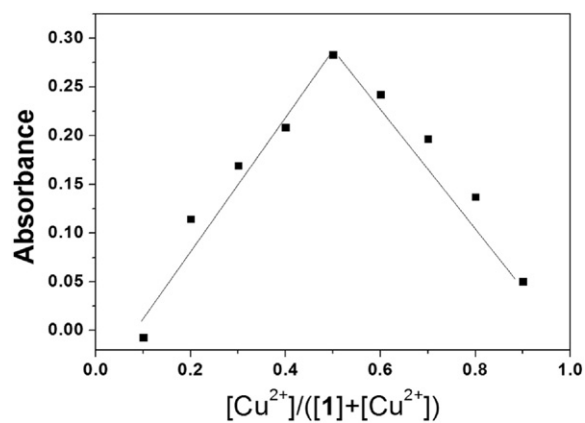
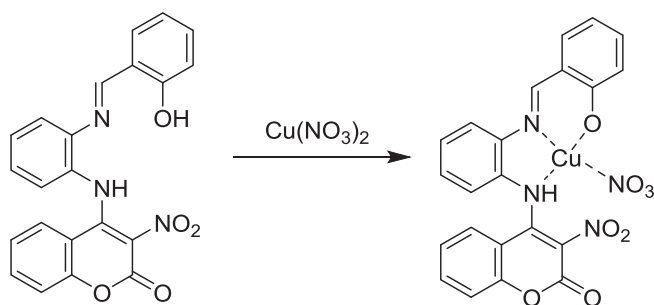


Fig. 3. Job plot for the binding of **1** with Cu^{2+} . Absorbance at 406 nm was plotted as a function of the molar ratio $[\text{Cu}^{2+}]/([\mathbf{1}] + [\text{Cu}^{2+}])$. The total concentration of Cu^{2+} with receptor **1** was 5.0×10^{-5} M.



Scheme 2. Proposed binding mode of 1-Cu²⁺ complex.

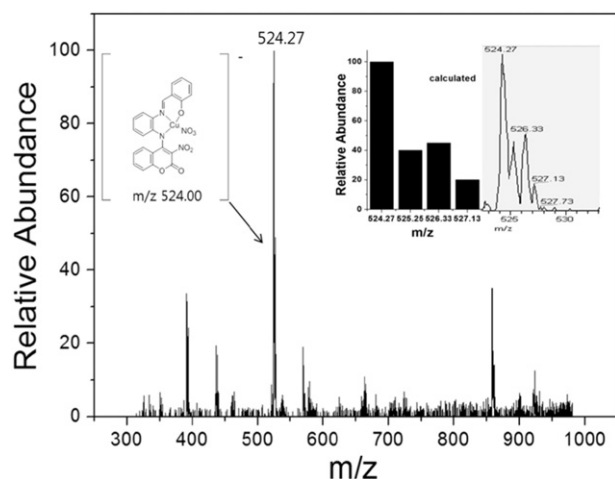


Fig. 4. Negative-ion electrospray ionization mass spectrum of **1** (50 μM) upon addition of Cu^{2+} (4 equiv.) in CH_3CN .

was observed upon the addition of Cu^{2+} , while the absorption band at 270 nm decreased gradually and reached minimum at 4 equiv. of Cu^{2+} . The isosbestic points at 260 nm and 280 nm were clearly observed, indicating the formation of a single species between receptor **1** and the Cu^{2+} . The yellow color of the solution observed upon addition of copper ions to receptor **1** might be attributed to the ligand-to-metal charge-transfer (LMCT) mechanism. The band with molar extinction coefficient in the thousands, $1.1 \times 10^4 \text{ M}^{-1} \text{ cm}^{-1}$ at 406 nm, is too large to be Cu-based d-d transitions and thus must be a ligand-based transition [17].

The Job plot [18] analysis revealed a 1:1 stoichiometric ratio between the Cu^{2+} ion and **1** (Fig. 3). The formation of **1**- Cu^{2+} adduct was further confirmed by ESI-mass spectrometry analysis. The negative ion mass spectrum indicated the 1:1 binding mode between **1** and Cu^{2+} [m/z 524.27; calcd, 524.00] as shown in Fig. 4. Based on the Job plot, ESI-mass spectrometry analysis, and the crystal structures of similar types of the copper complexes reported in the literature [19], we propose the structure of a 1:1 complex of **1** and Cu^{2+} as shown in Scheme 2.

The association constant (K_a) of **1** with Cu^{2+} ion was calculated by using the Benesi-Hildebrand equation [20] (Fig. S1). The K_a value was found to be $6.0 \times 10^3 \text{ M}^{-1}$, which is within the range of those (10^3 – 10^{12}) reported for Cu^{2+} sensing chemosensors [21]. The detection limit [22] of receptor **1** as a colorimetric sensor for the analysis of Cu^{2+} ions was found to be $18 \mu\text{M}$ (Fig. S2). The WHO has recommended the maximum limit of copper in drinking water to be $30 \mu\text{M}$ [10]. Therefore, receptor **1** could be used as a good indicator for monitoring Cu^{2+} ion in drinking water.

To further check the practical applicability of **1** as a copper ion chemosensor, competitive experiments were conducted by the addition of copper ions (4 equiv.) to the solution of **1** containing interfering cations viz. Na^+ , K^+ , Mg^{2+} , Ca^{2+} , Al^{3+} , Ga^{3+} , In^{3+} , Cr^{3+} , Mn^{2+} , Fe^{2+} , Fe^{3+} , Co^{2+} , Ni^{2+} , Zn^{2+} , Ag^+ , Cd^{2+} , Hg^{2+} , and Pb^{2+} (4 equiv.). The presence of interfering cations did not result in any significant change

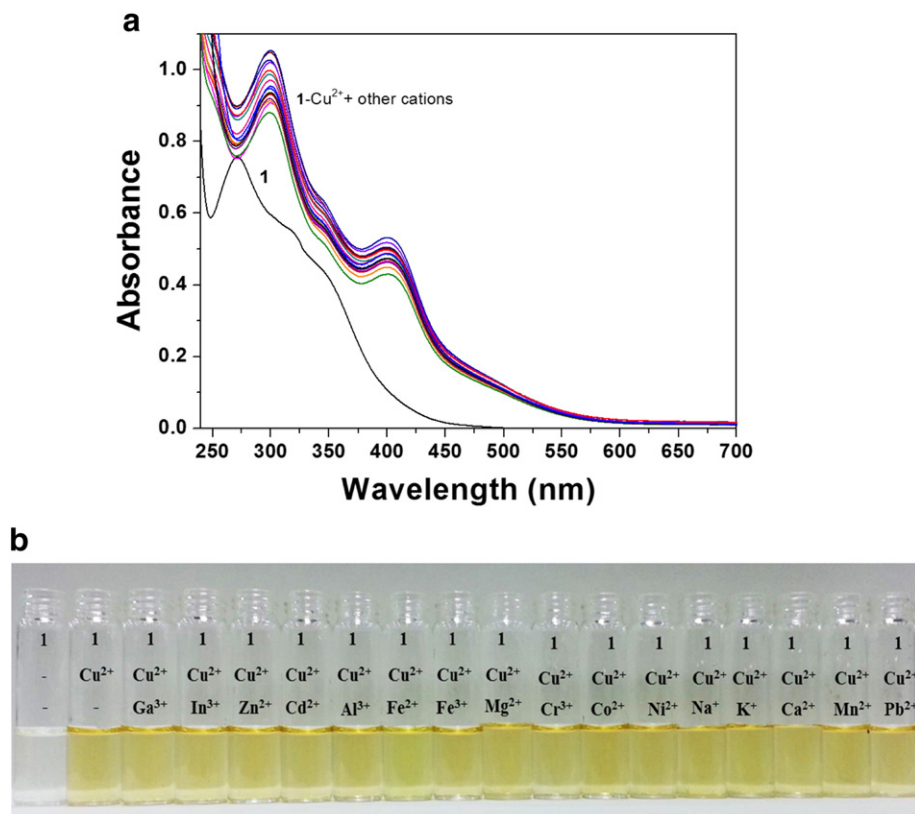


Fig. 5. (a) Competitive selectivity of **1** (30 μM) towards Cu^{2+} (4 equiv.) in the presence of other metal ions (4 equiv.). (b) Color changes of **1** (30 μM) in the presence of Cu^{2+} (4 equiv.) and other metal ions (4 equiv.).

in the UV–vis absorption as achieved by the addition of only Cu^{2+} to the solution of **1** (Fig. 5). Thus, receptor **1** could be used as a selective colorimetric sensor for Cu^{2+} in the presence of most competing metal ions.

To examine the reversibility of the proposed **1**– Cu^{2+} complex, ethylenediaminetetraacetic acid (EDTA) experiments were conducted in CH_3CN /bis-tris buffer (v/v, 4:6) solution (Fig. 6). After adding 4 equiv. of EDTA to **1**– Cu^{2+} solution, the solution color changed from yellow to colorless and the absorbance at 406 nm completely disappeared. This result demonstrates that the sensor **1** was regenerated through the demetallation reaction of **1**– Cu^{2+} complex by EDTA. Upon addition of Cu^{2+} into the solution again, the color and the absorbance were recovered, indicating that **1**– Cu^{2+} complex reformed. The color changes were almost reversible even after several cycles with the sequentially alternative addition of Cu^{2+} and EDTA. These results indicate that receptor **1** could be recyclable simply through treatment with a proper reagent such as EDTA.

The effect of pH on the absorption response of receptor **1** to Cu^{2+} ions was investigated in the pH range of 2 to 12 (Fig. 7). The color of the **1**– Cu^{2+} complex remained yellow between pH 6 and 12, but changed to colorless between pH 1 and 5. These results indicate that Cu^{2+} could be clearly detected by the naked eye or UV–Vis absorption measurements using receptor **1** over a wide pH range of 6.0–12.0, which includes the environmentally relevant range of pH 7.0–8.4.

In summary, we have reported a new asymmetric naked-eye chemo-sensor **1** for the detection of Cu^{2+} . Receptor **1** showed a highly selective colorimetric response to Cu^{2+} by changing its color from colorless to yellow immediately without any interference from other cations in a mixture of CH_3CN /bis-tris buffer solution (v/v, 4:6).

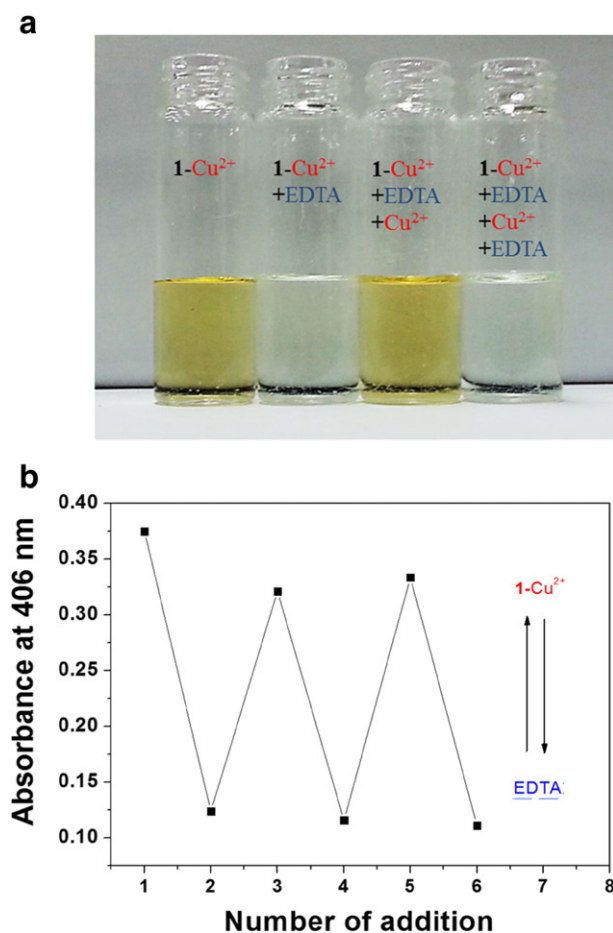


Fig. 6. (a) Colorimetric changes of **1** (30 μM) after the sequential addition of Cu^{2+} and EDTA in a mixture of CH_3CN /bis-tris buffer solution (v/v, 4:6). (b) Reversible changes in absorbance of **1** (30 μM) at 406 nm after the sequential addition of Cu^{2+} and EDTA.

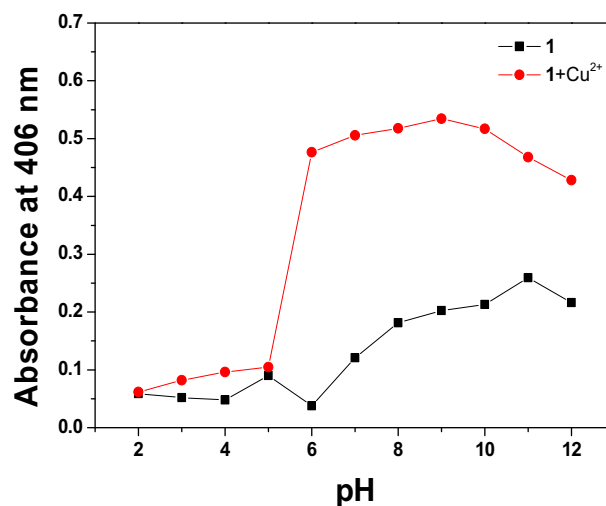


Fig. 7. UV–vis spectra of **1**– Cu^{2+} complex at various pH ranges (2–12) in CH_3CN /bis-tris buffer solution (v/v, 4:6).

Moreover, the receptor **1** enabled analysis of Cu^{2+} ions with a detection limit of 18 μM , which is below the WHO acceptable limit (30 μM) in drinking water. Furthermore, the addition of EDTA to the **1**– Cu^{2+} complex regenerated the free **1**, indicating that the sensor **1** could be recyclable simply through treatment with a proper reagent such as EDTA. Consequently, this chromogenic “naked-eye” chemosensor could be used for monitoring Cu^{2+} effectively in aqueous environment.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <http://dx.doi.org/10.1016/j.inoche.2014.11.016>.

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