

## Article

# Phenylthiadiazole-Based Schiff Base Fluorescent Chemosensor for the Detection of $\text{Al}^{3+}$ and $\text{Zn}^{2+}$ Ions

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## Abstract

Aluminum (Al) and zinc (Zn) are two of the most widely used metals in industry, and their excessive accumulation in the body has been linked to serious diseases like Alzheimer's, Parkinson's, and cancer. This highlights the need for effective ways to detect and measure them. In this study, we synthesized the fluorescent chemosensor **1**, which contains a Schiff base and a 1,3,4-thiadiazole ring in its structure, and evaluated its fluorescent response in the presence of various metal ions. The chemosensor enabled the selective quantification of  $\text{Al}^{3+}$  and  $\text{Zn}^{2+}$  ions through excitations at different wavelengths, yielding differentiated fluorescent emissions. For  $\text{Al}^{3+}$ , excitation at 370 nm generated a strong emission at 480 nm, whereas for  $\text{Zn}^{2+}$ , excitation at 320 nm led to a new small broad emission at 560 nm. We established detection limits of  $2.22 \times 10^{-6}$  M for  $\text{Al}^{3+}$  and  $1.62 \times 10^{-5}$  M for  $\text{Zn}^{2+}$ ; their binding stoichiometry was found to be 1:1 for  $\text{Al}^{3+}$  and 2:1 for  $\text{Zn}^{2+}$ , based on Job's plot analysis. These results show that chemosensor **1** is a promising tool for detecting  $\text{Al}^{3+}$  and  $\text{Zn}^{2+}$ .

**Keywords:** Schiff base; 1,3,4-thiadiazole; chemosensor;  $\text{Al}^{3+}$  /  $\text{Zn}^{2+}$ ; fluorescent



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## 1. Introduction

Aluminum (Al) is the third most abundant element after silicon and oxygen, and the most predominant metallic element in the Earth's crust [1,2]. As a metal, it exhibits several characteristics, such as high electrical conductivity, corrosion resistance, non-adsorptiveness, and low density, which enable its extensive use in everyday applications, including water treatment, kitchenware, vehicle and computer manufacturing, and medical devices [3]. However, it is also considered to be one of the most important environmental toxicants, and since it is a non-essential element for humans, its excessive accumulation in the body has been associated with various medical conditions, such as Alzheimer's disease, Parkinson's disease, Wilson syndrome, osteoporosis, osteomalacia, colic, gastrointestinal problems, kidney damage, and certain cancers, among others [4–8]. According to the WHO, the tolerable weekly intake of aluminum is estimated at 2 mg/kg of body weight, based on a non-observed adverse-effect level of 30 mg/kg per day [9]. Therefore, the detection of  $\text{Al}^{3+}$  in solution is crucial for both environmental and biomedical monitoring.

In contrast, zinc (Zn) is the fourth most consumed metal worldwide and is important due to its role in biological, environmental, and industrial contexts. Zinc's properties, which include its high corrosion resistance and ability to form alloys, make it invaluable for

galvanizing steel and in battery manufacturing [10]. Biologically,  $\text{Zn}^{2+}$  plays an important role in many physiological processes, including enzyme function, the immune response, and cellular metabolism [11]. However, overexposure to zinc has been linked to several diseases, including prostate cancer, neurodegenerative disorders, and oxidative stress conditions [12].

Several analytical methods for detecting  $\text{Al}^{3+}$  and  $\text{Zn}^{2+}$  ions have been reported, such as atomic absorption spectroscopy (AAS), inductively coupled plasma mass spectrometry (ICP-MS), and colorimetric techniques [13–15]. Despite their accuracy, these methods are often costly, time-consuming, and require specialized instrumentation and training. The detection of  $\text{Al}^{3+}$  ions is particularly challenging due to its poor coordination ability, strong hydration shell, and lack of distinct spectroscopic characteristics [16,17]. Zinc, although easier to coordinate than aluminum, may also suffer from interference by other bivalent or transition metals in complex matrices [18,19].

Numerous fluorescent chemosensors that are capable of selectively detecting  $\text{Al}^{3+}$  and  $\text{Zn}^{2+}$  ions have been developed over recent years, employing a variety of molecular scaffolds and sensing mechanisms. Schiff base derivatives, in particular, have been extensively studied due to their facile synthesis and strong coordination ability with metal ions, facilitating fluorescence “turn-on” responses [20–22]. Various mechanisms, such as excited-state intramolecular proton transfer (ESIPT), chelation-enhanced fluorescence (CHEF), and photoinduced electron transfer (PET), have been exploited to achieve high selectivity and sensitivity [23]. Despite these advances, challenges remain in designing dual chemosensors that can simultaneously detect  $\text{Al}^{3+}$  and  $\text{Zn}^{2+}$  ions with distinct fluorescence signals in aqueous media [21,24]. Furthermore, the interference from competing ions and the stability of the complexes are important factors that affect sensor performance [25]. Therefore, developing simple, robust, and selective solution-phase fluorescent probes remains an active and relevant area of research.

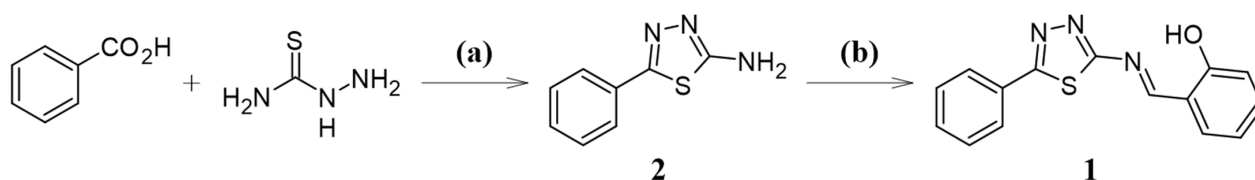
Among the various scaffolds explored for chemosensing, nitrogen-containing heterocyclics such as 1,3,4-thiadiazole have demonstrated notable fluorescence activity and coordination properties [26,27]. Fluorescent probes incorporating thiadiazole units have been used for selective  $\text{Al}^{3+}$  [28] and  $\text{Zn}^{2+}$  detection [29]. However, to the best of our knowledge, no dual-functional thiadiazole-based chemosensor capable of detecting both  $\text{Al}^{3+}$  and  $\text{Zn}^{2+}$  ions in solution with distinct responses has been reported to date.

Herein, we report a selective fluorescent “turn-on” probe, based on a 1,3,4-thiadiazole Schiff base derivative, which is capable of functioning as a dual-analyte chemosensor for the detection of  $\text{Al}^{3+}$  and  $\text{Zn}^{2+}$  ions in solution. This system demonstrates high selectivity and distinct emission behavior for each metal ion, and operates effectively under mild conditions, offering a practical alternative to more complex detection methodologies.

## 2. Materials and Methods

### 2.1. Synthesis of Ligand 1

The fluorescent probe shown in Scheme 1 was synthesized as previously reported [30,31]. The experimental procedure, along with the spectroscopic data, is provided in the Supplementary Materials (Figures S1–S4).



Reactives and conditions: (a) i)  $\text{POCl}_3$ , reflux, ii)  $\text{H}_2\text{O}$  reflux, iii)  $\text{NH}_4\text{OH}$   
 (b) salicylaldehyde, reflux

**Scheme 1.** Synthesis of ligand **1** from 2-amino-5-phenyl-1,3,4-thiadiazole (**2**).

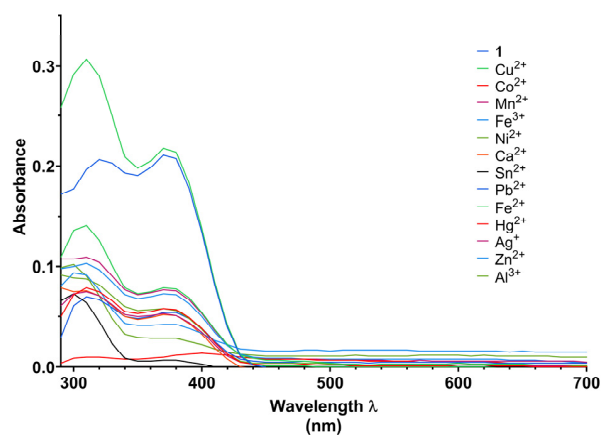
## 2.2. UV-Vis and Fluorescent Measurements

The thiadiazole **1** was dissolved in methanol to make a 2 mM stock solution. The stock solutions of the testing cation were prepared from  $\text{CuCl}_2 \cdot 2\text{H}_2\text{O}$ ,  $\text{CoCl}_2 \cdot 6\text{H}_2\text{O}$ ,  $\text{MnCl}_2 \cdot 4\text{H}_2\text{O}$ ,  $\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$ ,  $\text{NiCl}_2 \cdot 6\text{H}_2\text{O}$ ,  $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$ ,  $\text{SnCl}_2 \cdot 2\text{H}_2\text{O}$ ,  $\text{Pb}(\text{NO}_3)_2$ ,  $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$ ,  $\text{HgCl}_2$ ,  $\text{AgNO}_3$ ,  $\text{ZnCl}_2$ , and  $\text{AlCl}_3$ , dissolved in methanol (20 mM). All the solutions were stored at  $-20^\circ\text{C}$  and heated to room temperature before use. Prior to taking spectroscopic measurements, fresh solutions of the cations (1 mM) were prepared by diluting the stock solutions in methanol.

The UV-vis absorption and fluorescence emission spectra were determined with a 96-well plate using a microplate reader, the Cytation 5 (Agilent BioTek, Winooski, VT, USA) spectrophotometer. The absorption and emission spectra of sensor **1** in the presence of various metal ions were measured in methanol solvent in concentrations of 100  $\mu\text{M}$  and 25  $\mu\text{M}$ , respectively.

## 3. Results and Discussion

The UV-vis absorption spectrum of thiadiazole **1** was measured in methanol as solvent, and its behavior in the presence of various metal cations, such as  $\text{Cu}^{2+}$ ,  $\text{Co}^{2+}$ ,  $\text{Mn}^{2+}$ ,  $\text{Fe}^{3+}$ ,  $\text{Ni}^{2+}$ ,  $\text{Ca}^{2+}$ ,  $\text{Sn}^{2+}$ ,  $\text{Pb}^{2+}$ ,  $\text{Fe}^{2+}$ ,  $\text{Hg}^{2+}$ ,  $\text{Ag}^+$ ,  $\text{Zn}^{2+}$ , and  $\text{Al}^{3+}$  (25  $\mu\text{M}$  in methanol), was evaluated (Figure 1). The free ligand exhibited two main absorption bands at 320 and 370 nm. Upon the addition of metal ions to the ligand, both absorption bands decreased and a hypsochromic shift of the absorption band at 320 nm was observed (310 nm for  $\text{Cu}^{2+}$ ,  $\text{Co}^{2+}$ ,  $\text{Mn}^{2+}$ ,  $\text{Pb}^{2+}$ ,  $\text{Ag}^+$ , and  $\text{Zn}^{2+}$  ions, 300 nm for  $\text{Fe}^{3+}$ ,  $\text{Sn}^{2+}$  and  $\text{Al}^{3+}$  ions, and 290 nm for  $\text{Ni}^{2+}$  and  $\text{Ca}^{2+}$  ions). The main decrease in the absorption band at 370 nm was observed for  $\text{Sn}^{2+}$ ; however, this result suggested that **1** could not be used for the selective detection of any ions by absorbance.



**Figure 1.** UV-vis absorbance spectra of thiadiazole **1** (100  $\mu\text{M}$ ) in the presence of different metal ions ( $\text{Cu}^{2+}$ ,  $\text{Co}^{2+}$ ,  $\text{Mn}^{2+}$ ,  $\text{Fe}^{3+}$ ,  $\text{Ni}^{2+}$ ,  $\text{Ca}^{2+}$ ,  $\text{Sn}^{2+}$ ,  $\text{Pb}^{2+}$ ,  $\text{Fe}^{2+}$ ,  $\text{Hg}^{2+}$ ,  $\text{Ag}^+$ ,  $\text{Zn}^{2+}$ , and  $\text{Al}^{3+}$ ) (25  $\mu\text{M}$ ) in methanol solvent.

The fluorescence spectra of thiadiazole **1** were determined after excitation at both wavelengths, 320 and 370 nm. After excitation at 320 nm, a strong emission band at 380 nm was observed. In contrast, for excitation at 370 nm, a small broad emission band at 560 nm was observed (Figure 2). A 100  $\mu$ M methanolic solution of **1** was treated with various metal ions (25  $\mu$ M), and fluorescence was measured upon excitation at 320 nm. A moderate enhancement (30–40%) in the emission at 380 nm was observed in the presence of  $\text{Fe}^{3+}$ ,  $\text{Sn}^{2+}$ , and  $\text{Al}^{3+}$ , while other ions showed a negligible response. Notably,  $\text{Zn}^{2+}$  induced a distinct broad emission band centered at  $\lambda_{\text{em}} = 560$  nm (Figures 3A and S5), corresponding to a 5.7-fold increase in intensity at that wavelength, relative to the baseline of the free ligand. This enhancement, although moderate in absolute intensity, is highly selective and reproducible (Figure S6). Conversely, when it is excited at 370 nm, a strong emission is observed for  $\text{Al}^{3+}$ , with a maximum emission at 480 nm (Figure 3B), indicating that **1** exhibits an “off-on” mode in response to this ion, exhibiting a high sensitivity toward  $\text{Al}^{3+}$  over other metal ions that were used.

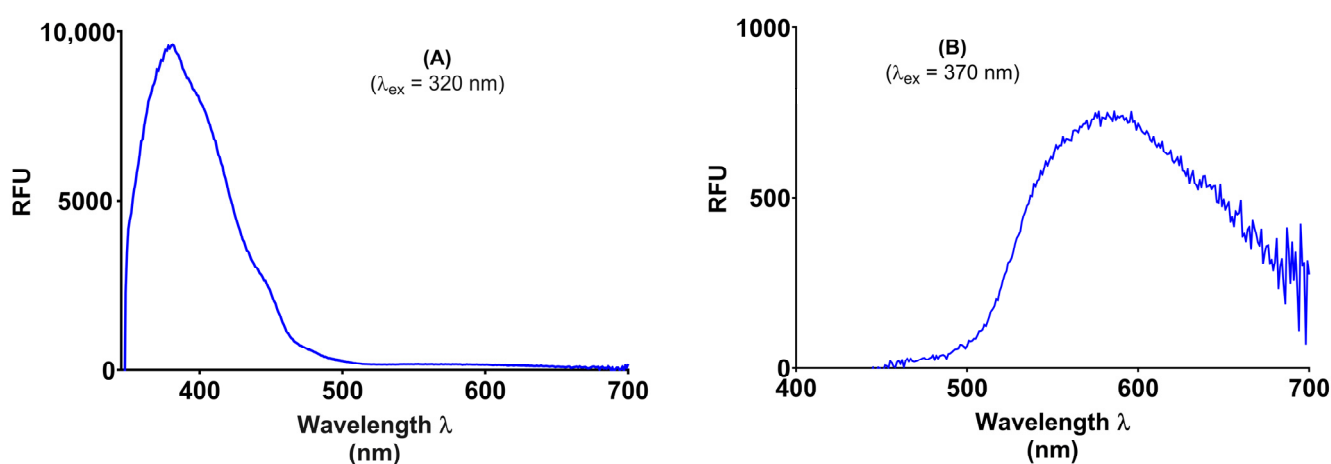


Figure 2. Fluorescence emission spectra of thiadiazole **1** (A)  $\lambda_{\text{ex}} = 320$  nm and (B)  $\lambda_{\text{ex}} = 370$  nm.

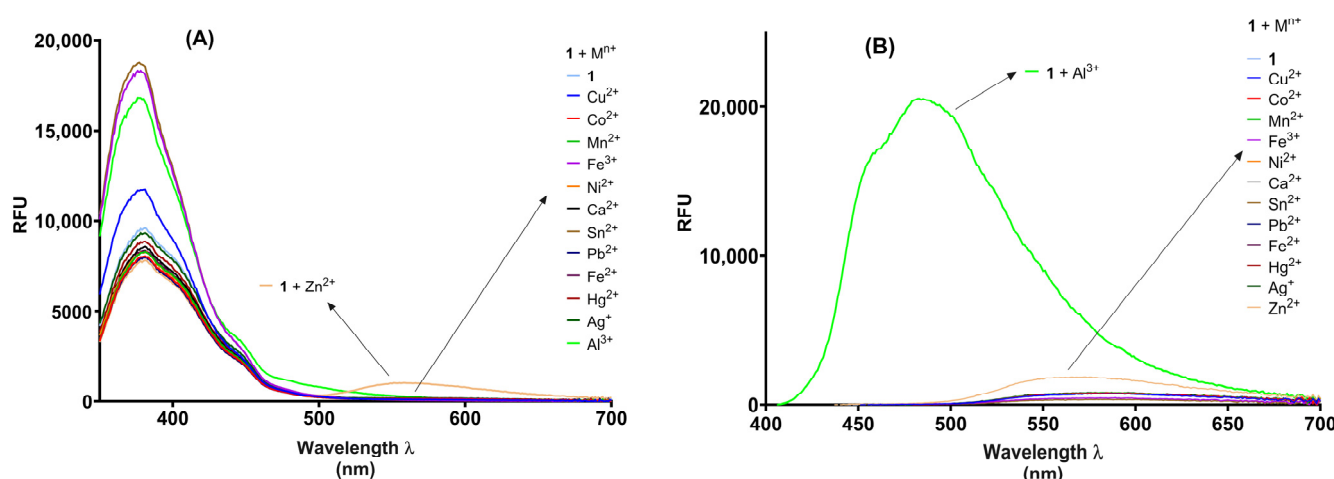


Figure 3. Fluorescence emission spectra of thiadiazole **1** (100  $\mu$ M) in the presence of different metal ions ( $\text{Cu}^{2+}$ ,  $\text{Co}^{2+}$ ,  $\text{Mn}^{2+}$ ,  $\text{Fe}^{3+}$ ,  $\text{Ni}^{2+}$ ,  $\text{Ca}^{2+}$ ,  $\text{Sn}^{2+}$ ,  $\text{Pb}^{2+}$ ,  $\text{Fe}^{2+}$ ,  $\text{Hg}^{2+}$ ,  $\text{Ag}^{+}$ ,  $\text{Zn}^{2+}$ , and  $\text{Al}^{3+}$ ) (25  $\mu$ M) in methanol solvent: (A)  $\lambda_{\text{ex}} = 320$  nm; (B)  $\lambda_{\text{ex}} = 370$  nm.

The fluorescent response of **1** was evaluated in the presence and absence of  $\text{Al}^{3+}$  (Figure S7) and  $\text{Zn}^{2+}$  (Figure S8) in various solvents. When excited at 320 nm and in the presence of  $\text{Al}^{3+}$ , the emission band at 380 nm was observed only in ethanol and methanol; however, the response in methanol was 13.77 times greater than that observed in ethanol.

No fluorescence was observed in the other solvents, except in the case of water, where the ligand only showed a broad signal with two maxima at 560 and 590 nm. When **1** was excited at 370 nm, no fluorescence was observed, except when using water. In this solvent, a broad emission band was observed again, with two maxima at 560 and 590 nm. In the presence of  $\text{Zn}^{2+}$  in ethanol and acetonitrile, an emission band was observed at 550 nm, accompanied by reductions in the intensity of the emission band by 45% and 36%, respectively, compared to the emission band observed at 560 nm in methanol. For both metal ions, the highest fluorescent response of chemosensor **1** was observed in methanol.

The fluorescent response of chemosensor **1** to  $\text{Al}^{3+}$  and  $\text{Zn}^{2+}$  was evaluated in a methanol–water system at varying ratios. For the **1**- $\text{Al}^{3+}$  complex, it was observed that the intensity of the fluorescence emission signal decreased as the water concentration increased, compared to a solution of pure methanol (Figure S9). At a 10% water concentration, the signal intensity dropped by 30% compared to pure methanol (Figure S10). As the water ratio increased, the fluorescence intensity declined significantly. This decrease in intensity may be due to the aggregation of compounds at higher water concentrations. This leads to an aggregation-caused quenching (ACQ) effect, which results in reduced fluorescence intensity [32].

In the case of  $\text{Zn}^{2+}$ , a similar decrease in fluorescence emission intensity was observed with increasing water concentration, but the reduction was more pronounced (Figure S11). In the presence of 10% water, the signal intensity decreased by 55% compared to that observed in pure methanol (Figure S12). When the water concentration exceeded 60%, the same broad emission signal observed in pure water began to appear, so complete fluorescence quenching was not observed.

The fluorescence response of **1** to various concentrations of  $\text{Al}^{3+}$  (0–200  $\mu\text{M}$ ) and  $\text{Zn}^{2+}$  (0–1000  $\mu\text{M}$ ) was investigated. With increasing concentrations of  $\text{Al}^{3+}$ , the fluorescence intensity at 480 nm of the solution gradually increased (Figure 4A). The chemosensor **1** showed a notable linear relationship ( $R^2 = 0.9986$ ) between the fluorescence intensity at 480 nm and the concentrations of  $\text{Al}^{3+}$  from 0 to 100  $\mu\text{M}$ , suggesting that this thiadiazole was potentially valuable for the quantitative determination of  $\text{Al}^{3+}$ . The same behavior was seen when detecting  $\text{Zn}^{2+}$  at 560 nm, showing a linear relationship of  $R^2 = 0.9992$  between the fluorescence intensity at 560 nm and  $\text{Zn}^{2+}$  concentrations ranging from 15 to 1000  $\mu\text{M}$  (Figure 4B). The detection limits ( $S/N = 3$ ) of chemosensor **1** were determined to be  $2.22 \times 10^{-6}$  M for  $\text{Al}^{3+}$  and  $1.62 \times 10^{-5}$  M for  $\text{Zn}^{2+}$ .

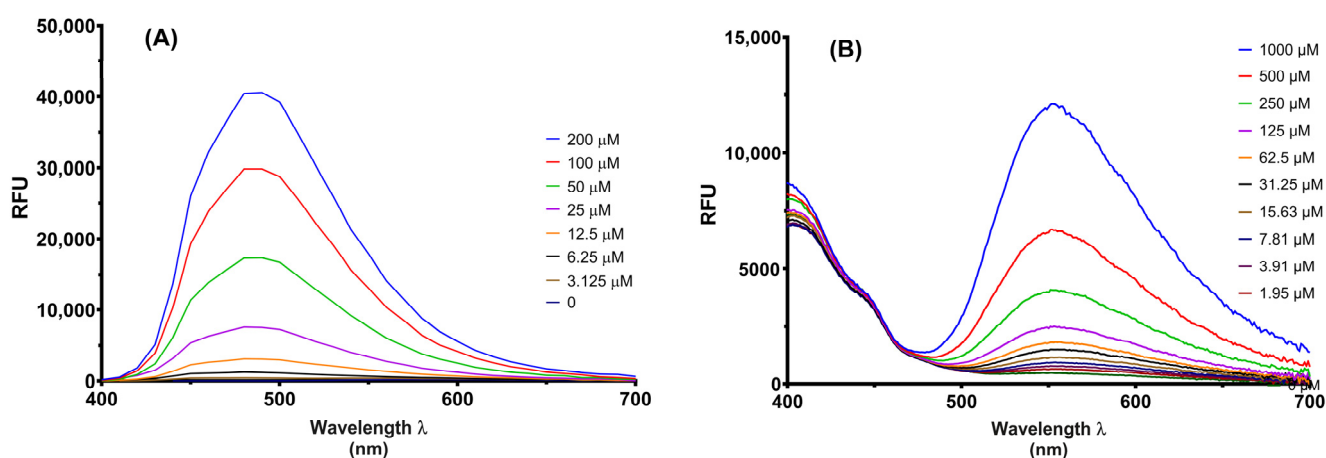
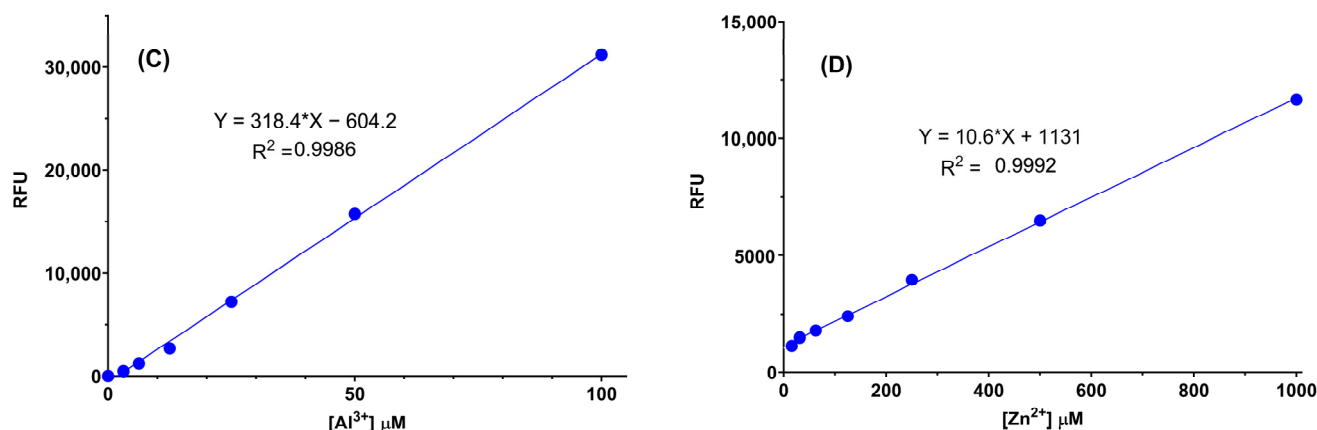
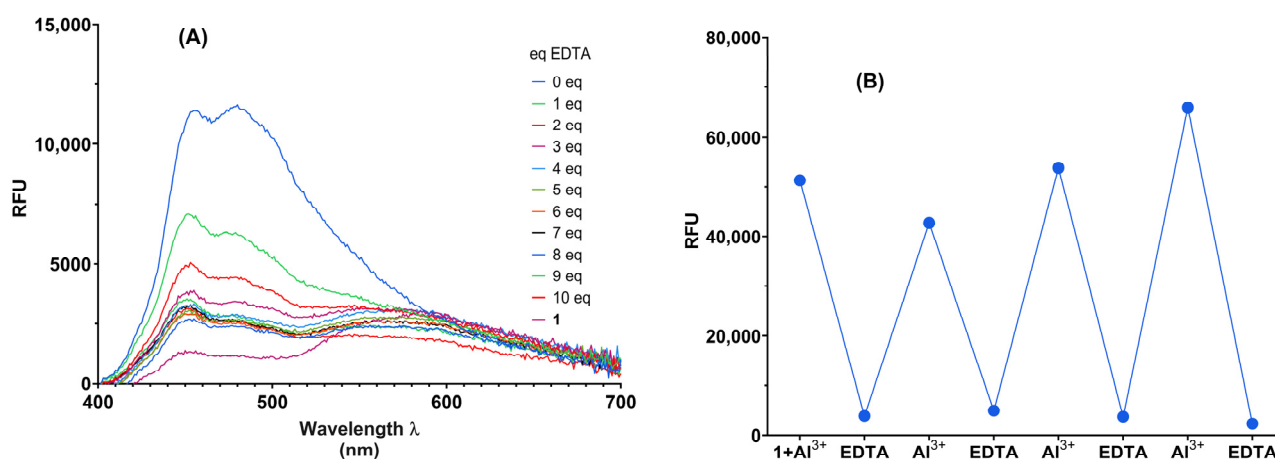


Figure 4. Cont.



**Figure 4.** Fluorescence emission spectra of thiadiazole **1** (100  $\mu\text{M}$ ) upon the addition of  $\text{Al}^{3+}$  ion (0–200  $\mu\text{M}$ ) in methanol solvent ( $\lambda_{\text{ex}} = 370 \text{ nm}$ ,  $\lambda_{\text{em}} = 480 \text{ nm}$ ) (A) and  $\text{Zn}^{2+}$  ion (0–1000  $\mu\text{M}$ ) in methanol solvent ( $\lambda_{\text{ex}} = 320 \text{ nm}$ ,  $\lambda_{\text{em}} = 560 \text{ nm}$ ) (B). Plots of fluorescence of **1** at 480 nm with  $\text{Al}^{3+}$  ions (0–100  $\mu\text{M}$ ) (C) and at 560 nm with  $\text{Zn}^{2+}$  ions (0–1000  $\mu\text{M}$ ) (D).

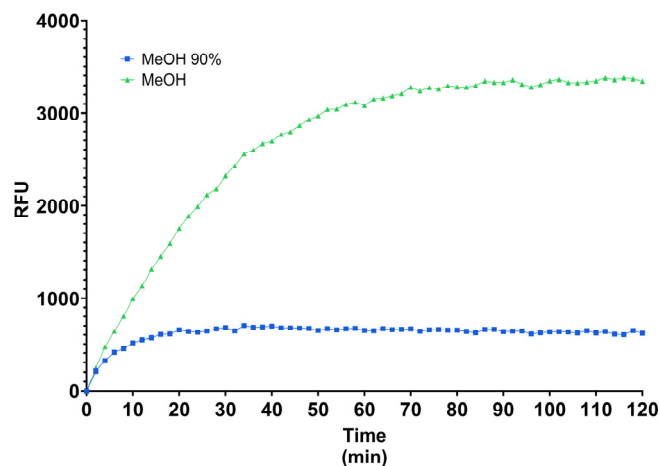
The reversibility of the chemosensor in the presence of  $\text{Al}^{3+}$  and  $\text{Zn}^{2+}$  was evaluated through a reversible experiment. When an EDTA solution (>4.0 eq) was added to the  $\text{Al}^{3+}$  complex, the chemosensor was released, resulting in a loss of fluorescence. Adding  $\text{Al}^{3+}$  ions along with the EDTA solution repeatedly led to an on–off fluorescence response, and this cycle was successfully repeated up to four times (Figure 5). Conversely, when an EDTA solution was added to the **1**– $\text{Zn}^{2+}$  complex, the fluorescence disappeared after the addition of one equivalent of EDTA. However, in contrast to what happened with  $\text{Al}^{3+}$ , the complex formed with  $\text{Zn}^{2+}$  was not reversible, since adding more  $\text{Zn}^{2+}$  ions did not restore the original fluorescence (see Figures S13 and S14).



**Figure 5.** Fluorescence emission spectra of thiadiazole **1** (100  $\mu\text{M}$ ) and the  $\text{Al}^{3+}$  ion (50  $\mu\text{M}$ ) in methanol–water (9:1) solvent ( $\lambda_{\text{ex}} = 370 \text{ nm}$ ) after the addition of EDTA solution (A). Fluorescence intensity of **1** at 480 nm by the alternate addition of  $\text{Al}^{3+}$  and EDTA (B).

Additionally, we evaluated the interaction time between chemosensor **1** and  $\text{Al}^{3+}$  in methanol and a methanol–water mixture (9:1). As shown in Figure 6, the fluorescence response of **1** to the  $\text{Al}^{3+}$  ion increases steadily with time after adding the chemosensor, and a gradual rise in the fluorescent signal occurs in both solvents; however, the fluorescence is higher in pure methanol, as expected. In methanol, the fluorescent signal increases progressively during the first 60 min, after which it stabilizes. Conversely, in the case of the methanol–water system (9:1), the fluorescent response stabilizes after the first 30 min

and remains constant throughout the remainder of the experiment. When compared to results in the literature, it can be observed that many probes exhibit response times that are often within seconds. However, probes with longer response times may still be suitable for applications where immediate detection is not critical, and signal stability is more important.



**Figure 6.** Response time spectra of fluorescent chemosensor **1** to  $\text{Al}^{3+}$  in methanol and methanol–water mixtures (9:1).

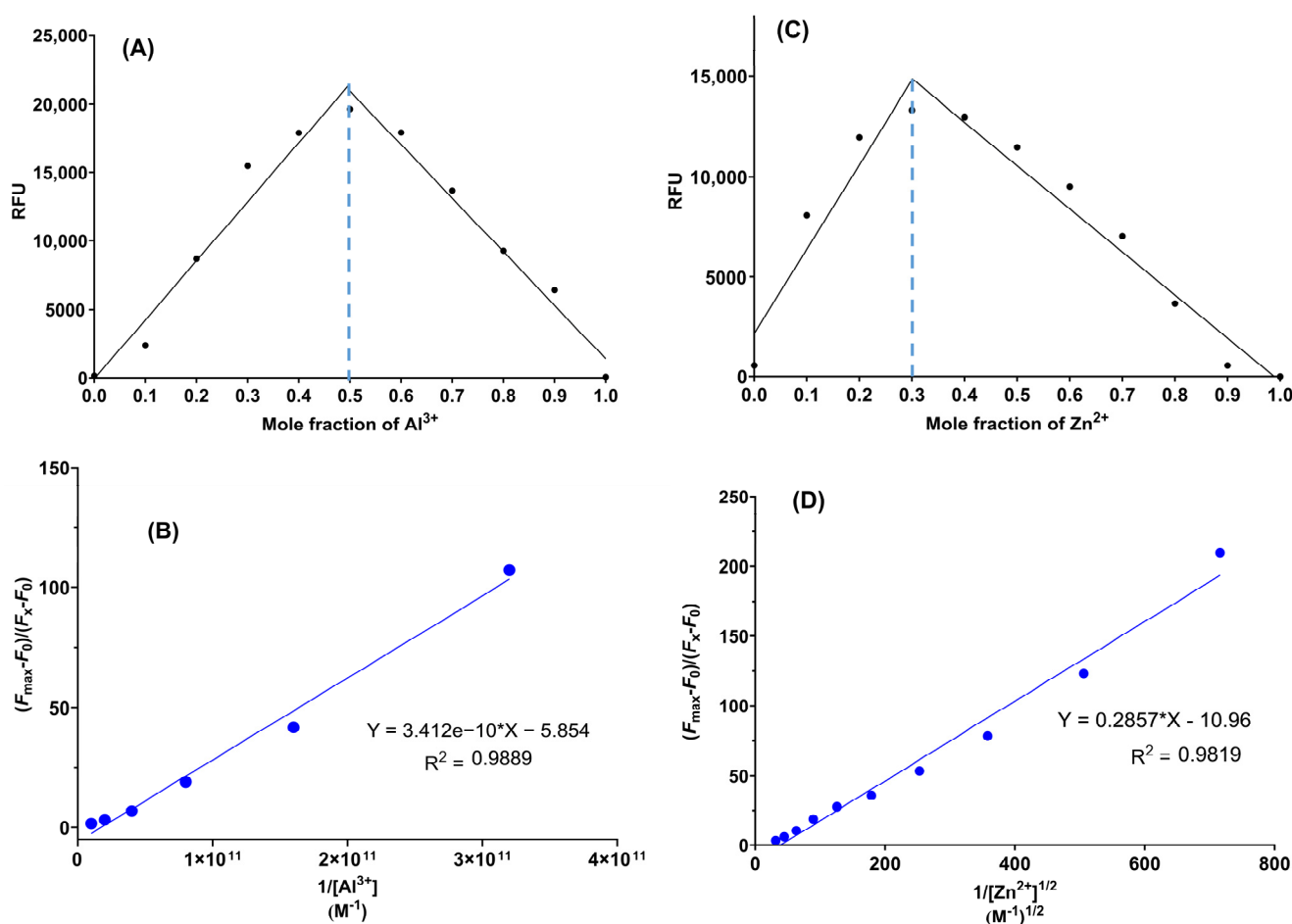
The combination mode between **1** and  $\text{Al}^{3+}$  and  $\text{Zn}^{2+}$  ions was investigated using Job's plot at 480 nm for  $\text{Al}^{3+}$  and 560 nm for  $\text{Zn}^{2+}$ . The fluorescence intensity reached its maximum value at 480 nm when the mole fraction of the  $\text{Al}^{3+}$  ion was 0.5 (Figure 7A). This suggests the formation of a 1:1 complex between the chemosensor and  $\text{Al}^{3+}$ . This finding contrasts with the report published by Manna et al., which indicated the formation of a 2:1 complex with this metal ion despite the similar ligand structure [28]. The difference in coordination modes between the two studies suggests variations in the binding affinity of the ligands for  $\text{Al}^{3+}$ , which may be attributed to factors such as electronic or solvation effects. Further studies are required to elucidate the precise mechanism behind this observation. Conversely, the fluorescence intensity of  $\text{Zn}^{2+}$  reached its maximum value at 560 nm when the mole fraction of the  $\text{Zn}^{2+}$  ion was about 0.30 (Figure 7C). This indicates the formation of a 2:1 complex between **1** and  $\text{Zn}^{2+}$ .

Linear fitting of the fluorescence titration profiles using a Benesi–Hildebrand plot was also examined using the following equation [33,34]:

$$\frac{F_{\max} - F_0}{F_X - F_0} = 1 + \frac{1}{K[M]^n} \quad (1)$$

where  $F_{\max}$ ,  $F_0$ , and  $F_X$  are the fluorescence intensities of the probe in the presence of a metal ion at saturation, free probe, and any intermediate metal ion concentration, respectively, and  $n$  is 1 for  $\text{Al}^{3+}$  and  $\frac{1}{2}$  for  $\text{Zn}^{2+}$ .

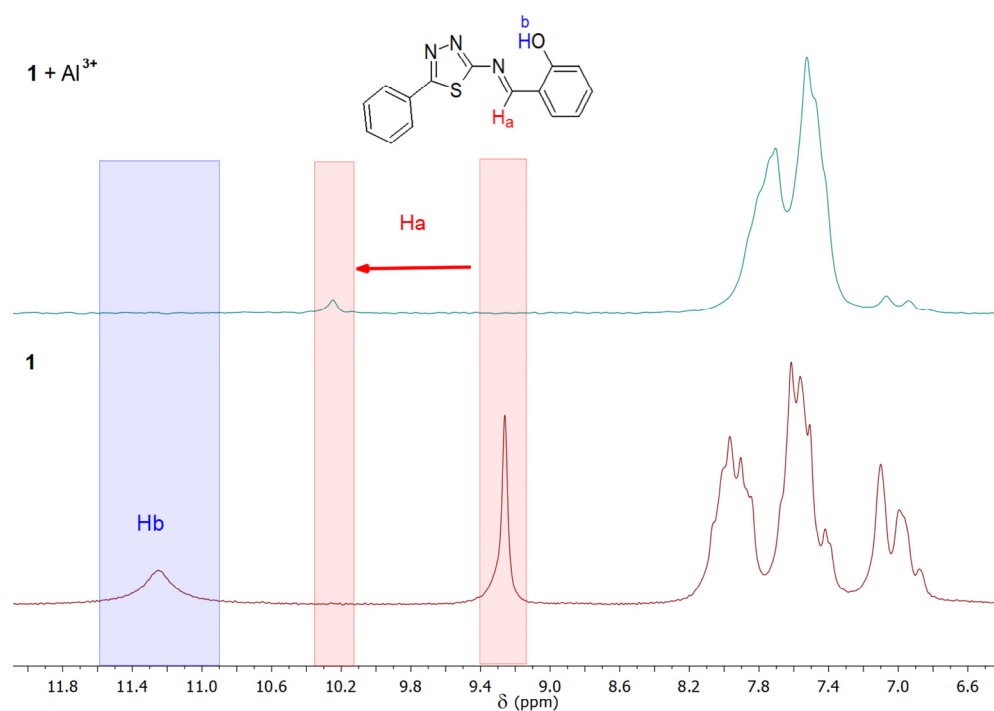
Plotting of  $(F_{\max} - F_0)/(F_X - F_0)$  versus  $1/[\text{Al}^{3+}]$  showed a linear relationship ( $R^2 = 0.9889$ ), which also strongly supports the 1:1 binding stoichiometry of **1** and  $\text{Al}^{3+}$  (Figure 7B), and the binding constant  $K$  was calculated to be  $2.93 \times 10^9 \text{ M}^{-1}$ . In the case of  $\text{Zn}^{2+}$ ,  $(F_{\max} - F_0)/(F_X - F_0)$  versus  $1/[\text{Zn}^{2+}]^{1/2}$  was plotted, also exhibiting a good linear relationship ( $R^2 = 0.9819$ ), which is expected in the case of 2:1 binding stoichiometry of **1** and  $\text{Zn}^{2+}$  (Figure 7C). The binding constant  $K$  for this ion is  $3.5 \text{ M}^{-2}$ .



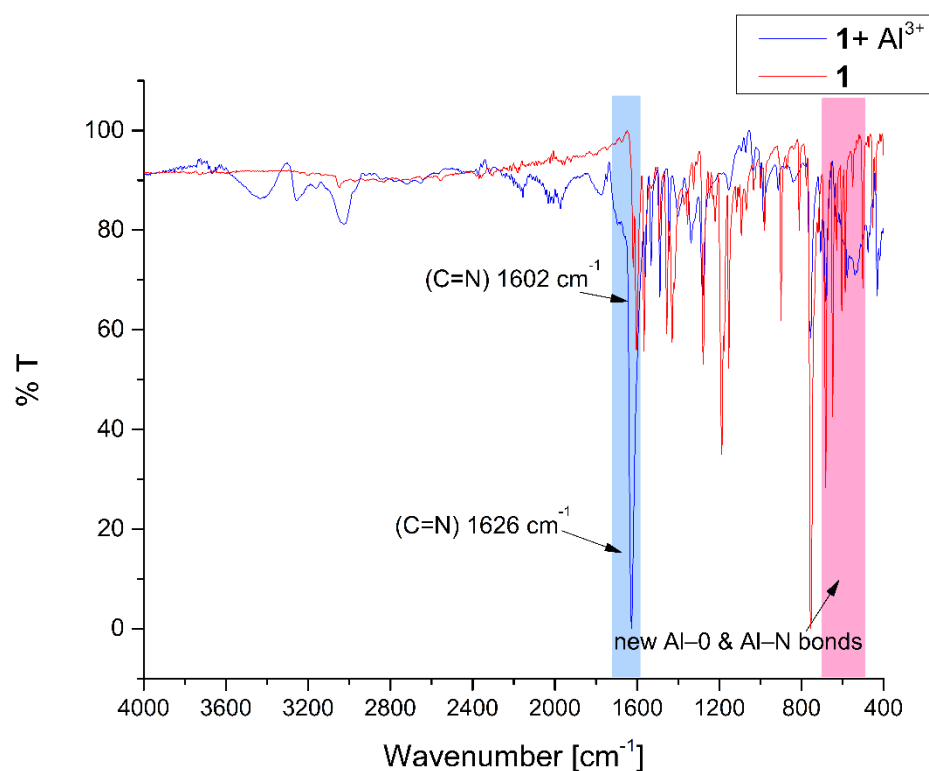
**Figure 7.** (A) Job's plot of thiadiazole 1 and  $\text{Al}^{3+}$  (the total concentration is 100  $\mu\text{M}$ ) ( $\lambda_{\text{ex}} = 370$  nm,  $\lambda_{\text{em}} = 480$  nm). (B) Benesi-Hildebrand plot (fluorescence at 480 nm) of thiadiazole 1, assuming 1:1 binding stoichiometry with  $\text{Al}^{3+}$ . (C) Job's plot of thiadiazole 1 and  $\text{Zn}^{2+}$  (the total concentration is 100  $\mu\text{M}$ ) ( $\lambda_{\text{ex}} = 320$  nm,  $\lambda_{\text{em}} = 560$  nm). (D) Benesi-Hildebrand plot (fluorescence at 560 nm) of  $\text{Zn}^{2+}$ , assuming 2:1 binding stoichiometry with thiadiazole 1.

To further understand the recognition mechanism of chemosensor 1 for  $\text{Al}^{3+}$ , studies using  $^1\text{H}$  NMR and Fourier transform infrared (FT-IR) spectroscopy were conducted. The  $^1\text{H}$  NMR spectra of chemosensor 1 were investigated in both the absence and presence of  $\text{Al}^{3+}$  in  $\text{DMSO-d}_6$ . As shown in Figure 8, when  $\text{Al}^{3+}$  was added to 1, the imine signal (Ha) at a chemical shift of 9.27 ppm shifted to 10.25 ppm. Also, the phenolic hydroxyl proton (Hb) was not seen, which suggests that the oxygen atom of the phenolic hydroxyl group and the nitrogen atom of the imine were involved in the coordination between chemosensor 1 and  $\text{Al}^{3+}$ .

In the IR spectra (Figure 9), the characteristic  $\text{C}=\text{N}$  stretching vibration observed at  $1602\text{ cm}^{-1}$  in the free ligand shifted to  $1626\text{ cm}^{-1}$  in the complex, which was consistent with metal coordination through the imine nitrogen. Simultaneously, the broad phenolic  $\text{O}-\text{H}$  band diminished, indicating deprotonation and coordination through the phenolic oxygen. The appearance of new bands in the  $400\text{--}500\text{ cm}^{-1}$  region, assignable to  $\text{Al}-\text{O}$  and  $\text{Al}-\text{N}$  vibrations, confirms the formation of a coordination complex.



**Figure 8.** Partial hydrogen spectra of compound **1** and **1 + Al<sup>3+</sup>**.



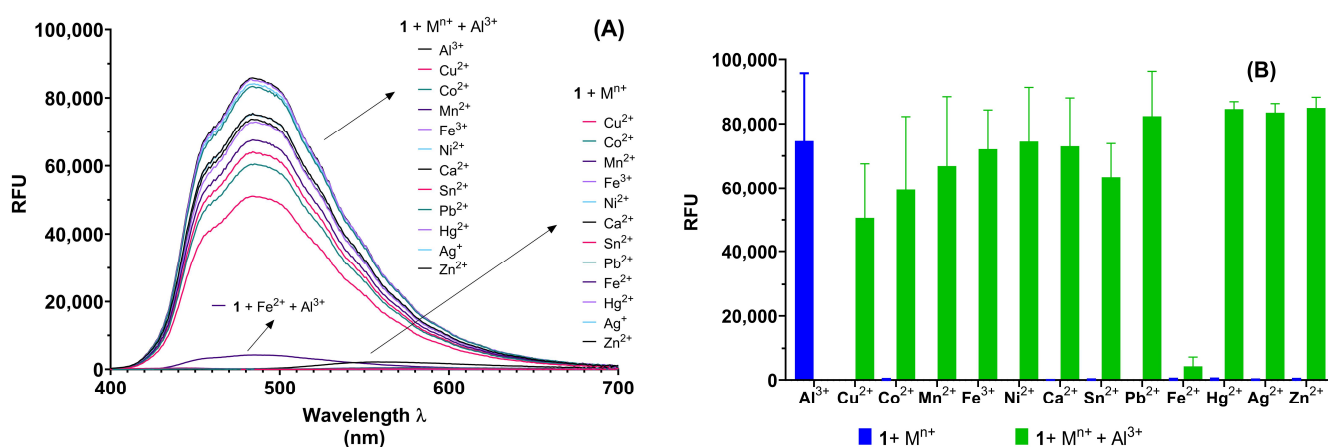
**Figure 9.** FTIR spectra of compound **1** and **1 + Al<sup>3+</sup>**.

Considering the bidentate nature of the ligand and the preference of  $\text{Al}^{3+}$  for six-coordinate geometries, the formation of an octahedral complex is proposed. The coordination sphere is plausibly completed by two chloride anions and one methanol molecule, resulting in a distorted octahedral arrangement stabilized by both electronic and steric factors.

The IR spectrum of the **1-Zn<sup>2+</sup>** complex (Figure S15) shows the appearance of new absorption bands at 454 and 551  $\text{cm}^{-1}$ , which are absent in the free ligand and can be

assigned to Zn–S vibrational modes. These bands indicate coordination through the sulfur atom of the benzothiazole moiety. Notably, the bands associated with the hydroxyl and imine groups remain largely unchanged, which is consistent with the absence of significant chemical shift variations in the  $^1\text{H}$  NMR spectrum of the complex (Figure S16), suggesting that these groups are not directly involved in coordination. In addition, the disappearance or shifts of specific ligand peaks (e.g., at 691 and 1418  $\text{cm}^{-1}$ ) further support complex formation. These results confirm metal–ligand coordination and are consistent with the formation of a 2:1 ligand-to-metal assembly, in which two ligand molecules chelate a single  $\text{Zn}^{2+}$  ion, predominantly via sulfur atoms. These features, combined with the  $d^{10}$  electronic configuration of  $\text{Zn}^{2+}$ , suggest a distorted tetrahedral geometry for the  $[\text{L}_2\text{Zn}]$  complex, as commonly observed in similar N,S-donor Schiff base zinc complexes [35,36].

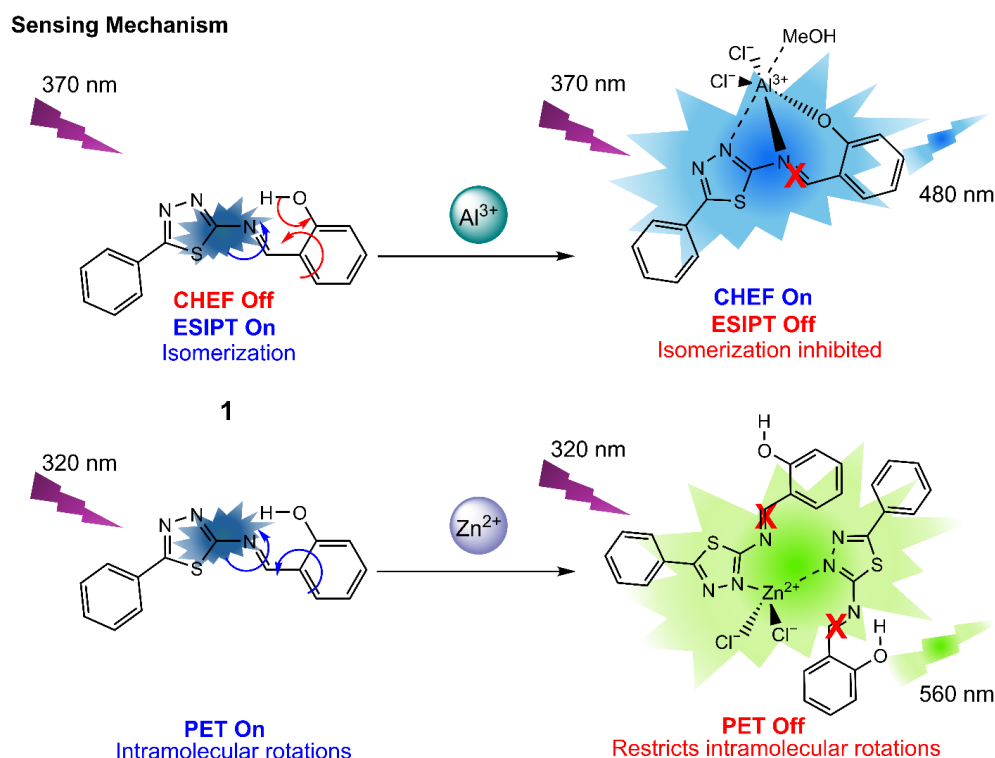
The selectivity of thiadiazole **1** (50  $\mu\text{M}$ ) for  $\text{Al}^{3+}$  over other metal ions (1.0 eq.) was evaluated by a competition experiment. The addition of  $\text{Al}^{3+}$  to the ligand–metal mixture generated a significant increase in fluorescence for almost all ions, reaching values close to those observed for the pure  $\text{Al}^{3+}$  ligand complex, except in the case of  $\text{Fe}^{2+}$  (Figure 10A). This pattern suggests that  $\text{Al}^{3+}$  displaces most other metals from the coordination site, forming a highly fluorescent complex, likely due to the ligand's higher affinity toward  $\text{Al}^{3+}$ , possibly due to its high charge, small radius, and tendency to rigid coordination geometries [37]. In the case of the **1**– $\text{Fe}^{2+}$  complex, the addition of  $\text{Al}^{3+}$  produced a fluorescence that was 17.8 times lower than that observed in the **1**– $\text{Al}^{3+}$  complex (Figure 10B). This suggests that the complex formed between the ligand and  $\text{Fe}^{2+}$  was much more stable, probably due to a stronger, specific, or irreversible coordination mode, which prevented the efficient displacement of  $\text{Fe}^{2+}$  by  $\text{Al}^{3+}$ .



**Figure 10.** Selectivity of the thiadiazole **1** (50  $\mu\text{M}$ ) toward 1 eq. of  $\text{Al}^{3+}$  and other metal ions ( $\text{Cu}^{2+}$ ,  $\text{Co}^{2+}$ ,  $\text{Mn}^{2+}$ ,  $\text{Fe}^{3+}$ ,  $\text{Ni}^{2+}$ ,  $\text{Ca}^{2+}$ ,  $\text{Sn}^{2+}$ ,  $\text{Pb}^{2+}$ ,  $\text{Fe}^{2+}$ ,  $\text{Hg}^{2+}$ ,  $\text{Ag}^{+}$ , and  $\text{Zn}^{2+}$ ). In these experiments, the fluorescence measurement was taken at  $\lambda_{\text{ex}} = 370$  nm in methanol at room temperature. (A) Emission spectra of thiadiazole **1** upon the addition of 1.0 eq. of various metal ions in the absence and presence of 1.0 eq. of the  $\text{Al}^{3+}$  ion. (B) Bars represent the final ( $I_{480 \text{ nm}}$ ) emission intensity. The blue bars represent the emission after the addition of various metal ions (1 eq.) to a solution of **1**. The green bars represent the emission after the addition of 1 eq. of  $\text{Al}^{3+}$  to the above solution.

When evaluating the selectivity of thiadiazole **1** (50 mM) for  $\text{Zn}^{2+}$  compared to other metal ions (1.0 eq.), a more limited selectivity profile was observed than that for  $\text{Al}^{3+}$  (Figure 11). This reduced selectivity was particularly evident when the metal ions formed more stable complexes with the ligand, which hindered the effective coordination of  $\text{Zn}^{2+}$ . For  $\text{Cu}^{2+}$ ,  $\text{Fe}^{3+}$ ,  $\text{Sn}^{2+}$ ,  $\text{Fe}^{2+}$ , and  $\text{Al}^{3+}$ , there was no significant increase in fluorescence at 560 nm after adding  $\text{Zn}^{2+}$ . The fluorescence emission was between 1.7 and 15.4 times lower than what was seen in the **1**– $\text{Zn}^{2+}$  complex. A similar effect occurred with  $\text{Co}^{2+}$  and  $\text{Ni}^{2+}$ ;





**Scheme 2.** The proposed mechanism of the sensing of  $\text{Zn}^{2+}$  and  $\text{Al}^{3+}$ .

Nevertheless, in the absence of competing ions, the  $1\text{-Zn}^{2+}$  complex exhibits a marked fluorescence enhancement compared to the free ligand, emission from which is otherwise suppressed. This turning-on behavior is attributable to a mechanism involving the inhibition of non-radiative deactivation pathways, particularly photo-induced electron transfer (PET). In the free ligand, fluorescence quenching is likely due to PET from the imine nitrogen lone pair to the excited chromophore, and possibly due to internal conversion, facilitated by conformational flexibility. Upon  $\text{Zn}^{2+}$  coordination, as suggested by the appearance of  $\text{Zn-N}$  vibrational modes in the IR spectrum (bands at  $454$  and  $551\text{ cm}^{-1}$ ) and the absence of significant chemical shift changes in the OH and  $\text{N=CH}$  signals in the  $^1\text{H}$  NMR spectrum, the metal center binds preferentially through the nitrogen atom of the benzothiazole ring (see Scheme 2). This interaction inhibits PET by reducing the electron-donating capacity of the nitrogen atom and rigidifies the structure, thereby enhancing conjugation and favoring radiative decay. This coordination-induced conformational restriction leads to increased fluorescence emission, which is consistent with the behavior observed in other  $\text{Zn}^{2+}$  complexes involving nitrogen donor atoms in similar heteroaromatic systems [36,42].

The use of compound **1** in real sample applications that involve  $\text{Zn}^{2+}$  is limited by its low selectivity for this metal ion compared to other metal ions. The literature, however, discusses several methods that could improve this selectivity. These methods include adding nanomaterials, making structural changes, altering functional groups, or using auxiliary receptors [43]. More research is necessary to understand the true capabilities of this chemosensor in relation to  $\text{Zn}^{2+}$ .

Chemosensor **1** was compared to other fluorescent probes made from salicylaldehyde for detecting  $\text{Al}^{3+}$ , as shown in Table S1 in the Supplementary Materials. The limits of detection (LOD) show that sensor **1** is in a good range, with values below the World Health Organization (WHO) guideline for drinking water, which is  $7.41\text{ }\mu\text{M}$  [44]. In contrast, analysis of the binding constants reveals that **1** exhibits a significantly higher affinity for  $\text{Al}^{3+}$  compared to the other probes, suggesting that it may be more effective for detecting this metal ion in solutions.

## 4. Conclusions

The fluorescent probe, 2-(2-hydroxybenzal)amino-5-phenyl-1,3,4-thiadiazole (**1**), shows potential for selectively detecting  $\text{Al}^{3+}$  and  $\text{Zn}^{2+}$  ions in methanol. This chemosensor allows the identification of these metal ions by displaying different fluorescence responses upon excitation at specific wavelengths. The excitation of **1** in the presence of  $\text{Al}^{3+}$  at 370 nm increases fluorescence emission at 480 nm, whereas excitation in the presence of  $\text{Zn}^{2+}$  at 320 nm results in a new emission band at 560 nm. Detection limits for  $\text{Al}^{3+}$  and  $\text{Zn}^{2+}$  were established at  $2.22 \times 10^{-6}$  M and  $1.62 \times 10^{-5}$  M, respectively. The binding stoichiometry differs between the two ions, forming a 1:1 complex with  $\text{Al}^{3+}$  and a 2:1 complex with  $\text{Zn}^{2+}$ , and the calculated binding constant for  $\text{Al}^{3+}$  is  $2.93 \times 10^9 \text{ M}^{-1}$ , and for  $\text{Zn}^{2+}$  is  $3.5 \text{ M}^{-2}$ .

Competitive experiments further show the ligand's preferential affinity for  $\text{Al}^{3+}$ , whereas interference from other metal ions limits  $\text{Zn}^{2+}$  coordination. These findings underscore the utility of thiadiazole **1** in metal detection, emphasizing the need for further research to optimize its selectivity and explore its applications in sensing technologies.

**Supplementary Materials:** The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/chemistry7040128/s1>: Synthesis of chemosensor **1**. Figure S1:  $^1\text{H}$ -NMR spectrum of **2**; Figure S2:  $^{13}\text{C}$ -NMR spectrum of **2**; Figure S3:  $^1\text{H}$ -NMR spectrum of **1**; Figure S4:  $^{13}\text{C}$ -NMR spectrum of **1**; Figure S5: Zoom of the fluorescence emission spectra ( $\lambda_{\text{ex}} = 320$  nm) of thiadiazole **1** (100  $\mu\text{M}$ ) in the presence of different metal ions ( $\text{Cu}^{2+}$ ,  $\text{Co}^{2+}$ ,  $\text{Mn}^{2+}$ ,  $\text{Fe}^{3+}$ ,  $\text{Ni}^{2+}$ ,  $\text{Ca}^{2+}$ ,  $\text{Sn}^{2+}$ ,  $\text{Pb}^{2+}$ ,  $\text{Fe}^{2+}$ ,  $\text{Hg}^{2+}$ ,  $\text{Ag}^{+}$ ,  $\text{Zn}^{2+}$ , and  $\text{Al}^{3+}$ ) (25  $\mu\text{M}$ ) in methanol solvent; Figure S6: Relative fluorescence emission of thiadiazole **1** (100  $\mu\text{M}$ ) in presence of different metal ions ( $\text{Cu}^{2+}$ ,  $\text{Co}^{2+}$ ,  $\text{Mn}^{2+}$ ,  $\text{Fe}^{3+}$ ,  $\text{Ni}^{2+}$ ,  $\text{Ca}^{2+}$ ,  $\text{Sn}^{2+}$ ,  $\text{Pb}^{2+}$ ,  $\text{Fe}^{2+}$ ,  $\text{Hg}^{2+}$ ,  $\text{Ag}^{+}$ ,  $\text{Zn}^{2+}$ , and  $\text{Al}^{3+}$ ) (25  $\mu\text{M}$ ) in methanol solvent. ( $\lambda_{\text{ex}} = 320$  nm;  $\lambda_{\text{em}} = 560$  nm); Figure S7: Fluorescence emission spectrum ( $\lambda_{\text{ex}} = 370$  nm) of thiadiazole **1** (100  $\mu\text{M}$ ) in the presence and absence of  $\text{Al}^{3+}$  (25  $\mu\text{M}$ ) in different solvents; Figure S8: Fluorescence emission spectrum ( $\lambda_{\text{ex}} = 320$  nm) of thiadiazole **1** (100  $\mu\text{M}$ ) in the presence and absence of  $\text{Zn}^{2+}$  (25  $\mu\text{M}$ ) in different solvents; Figure S9: Fluorescence emission spectrum ( $\lambda_{\text{ex}} = 370$  nm) of thiadiazole **1** (100  $\mu\text{M}$ ) in the presence of  $\text{Al}^{3+}$  (25  $\mu\text{M}$ ) as a function of the water fraction in the binary MeOH/water system; Figure S10: Fluorescence intensity vs. water fraction curve for thiadiazole **1** (100  $\mu\text{M}$ ) in the presence of  $\text{Al}^{3+}$  (25  $\mu\text{M}$ ); Figure S11: Fluorescence emission spectrum ( $\lambda_{\text{ex}} = 320$  nm) of thiadiazole **1** (100  $\mu\text{M}$ ) in the presence of  $\text{Zn}^{2+}$  (25  $\mu\text{M}$ ) as a function of the water fraction in the binary MeOH/water system; Figure S12: Fluorescence intensity vs. water fraction curve for thiadiazole **1** (100  $\mu\text{M}$ ) in the presence of  $\text{Zn}^{2+}$  (25  $\mu\text{M}$ ); Figure S13: Fluorescence emission spectra of thiadiazole **1** (100  $\mu\text{M}$ ) and  $\text{Al}^{3+}$  ion (25  $\mu\text{M}$ ) in methanol–water (9:1) solvent ( $\lambda_{\text{ex}} = 370$  nm) after the addition of EDTA solution; Figure S14: Fluorescence intensity of **1** at 560 nm by the alternate addition of  $\text{Zn}^{2+}$  and EDTA; Figure S15: FTIR spectra of compound **1** and **1** +  $\text{Zn}^{2+}$ ; Figure S16:  $^1\text{H}$ -NMR titration of compound **1** with  $\text{Zn}^{2+}$  in DMSO- $d_6$ . Table S1: Comparison of reported fluorescent probes derived from salicylaldehyde derivatives for  $\text{Al}^{3+}$  in this work.

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## Abbreviations

The following abbreviations are used in this manuscript:

|       |                                              |
|-------|----------------------------------------------|
| NMR   | Nuclear magnetic resonance                   |
| TMS   | Tetramethylsilane                            |
| PET   | Photo-induced electron transfer              |
| RIR   | Restricts intramolecular rotations           |
| CHEF  | Chelation-enhanced fluorescence              |
| ESIPT | Excited-state intramolecular proton transfer |
| IR    | Infrared spectra                             |

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