INTERNATIONAL JOURNAL OF CURRENT RESEARCH IN CHEMISTRY AND PHARMACEUTICAL SCIENCES
(p-ISSN: 2348-5213: e-ISSN: 2348-5221)
www.ijcrcps.com
(A Peer Reviewed, Referred, Indexed and Open Access Journal)
DOI: 10.22192/ijcrcps Coden: IJCROO(USA) Volume 9, Issue 6 - 2022

Review Article

DOI: http://dx.doi.org/10.22192/ijcrcps.2022.09.06.012

Schiff base based fluorescent probes for detecting physiologically relevant trace pollutant metal cations

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Abstract

The Schiff bases are nothing but the condensation product of various carbonyl compounds (either aldehydes or ketones) with different primary amines. These bases react with metal and oxo-metal cations to form stable metal chelates with absorb/fluoresce in UV or visible region of light. The development of chemical sensors made of Schiff bases has received attention during the past two decades because of their extensive use in environmental monitoring and clinical analysis in trace analysis for metal ions, organic pollutants and biological substances due to their simplicity, low cost, rapid photophysical response, high sensitivity, low detection limit etc. The detection of metal ions using Schiff bases can be performed in different ways such as spectrophotometry, spectrofluorimetry, gas chromatography, liquid chromatography and capillary electrophoresis. This review article presents and discusses a summary of colorimetric sensors that can detect metal cations in environmental samples.

Keywords: Schiff base, metal cation, sensor, colorimetric, fluorescent, chemical sensors

1. Introduction

In the human body, metal ions such as Ca^{2+}, Zn^{2+}, Fe^{2+}, Cu^{2+}, Mg^{2+}, Mn^{2+}, Co^{2+}, and Fe^{3+} have a variety of biological functions. For instance, calcium acid is necessary for healthy teeth and bones, a regular heartbeat, etc. Furthermore, everybody cell uses iron metal ions to produce hemoglobin, which is a component of blood cells. Together with iron, copper metal maintains the integrity of the immune system, blood vessels, and neurons. Besides these ions like Na^{+}, K^{+} are the most important ions for our nervous system [1-2]. Lethargy, hypertension, acute renal failure, liver and kidney damage for a brief period of time, diabetes, arthritis, liver cancer, heart failure, liver cirrhosis, Alzheimer's disease, kidney damage, and so on are just a few of the health issues that can arise from an excessive or insufficient consumption of these ions.

Because of this, it is now crucial to maintain or control the concentration of those ions in both the biological system and the environment [3]. The majority of toxic ions, such as Cd^{2+}, Hg^{2+}, Pb^{2+}, Mn^{2+}, Pd^{2+}, Cr^{2+}, Ni^{2+} appear to be pollutant metal ions and play a critical role in a variety of industrial operations including paper, food, textiles, pharmaceuticals, water treatment, refineries, battery manufactures and electronics [4-5]. In the past, various methods such as inductively coupled plasma atomic emission spectroscopy, inductively coupled plasma mass spectroscopy, electrochemical detection, ion chromatography, X-ray fluorescence spectrometry have been reported for metal ion detection [6-8]. Such methods do, however, have some drawbacks, including insufficient real-world applicability, pricey equipment, labourintensive processes, and intricate procedures. Recently, great emphasis has been made to creating fluorescent chemosensors for metal ion detection owing to their outstanding selectivity, sensitivity as well as short reaction time [9-11]. Fluorescent chemosensors have become more important in recent years due to their simple synthesis, customisable features, and on-site, quick, sensitive, and selective analyte detection [12-13]. Here, the detection of positive metal ions may cause a change in colour that is apparent, a change in colour in fluorescence, a shift in the intensity or wavelength of the emission (blue or red shift), or the emergence of new emission maxima [14-16]. Fluorescent chemosensors for metal ion detection generally contain Schiff base [17], pyridine [18], pyrene [19], anthracene [20], quinolone [21], naphthalene [22], urea [23], coumarin [24], phenolphthalein [25] and rhodamine [26] groups as the binding site. Schiff base-based sensors, among other fluorescent chemosensors, have demonstrated exceptional performance because of their synthesis and ability to simultaneously coordinate with single metal ions in an appropriate electrical and geometrical environment. Schiff bases, which provide nitrogen and oxygen atoms for coordination with metal ions, are frequently observed in hydrazone, acyl hydrazone, salicylimine, azine, and other groups [27-28]. The goal of the current study is to provide insight into the advancements made in colorimetric and fluorescent Schiff base sensors for the identification of metal ions that are threatening to biological systems. In this review, a thorough introduction to fluorescent Schiff base sensors for metal ion detection is given, along with an analysis of various approaches and mechanistic insights into the field. Practical uses of fluorescent Schiff base sensors in metal ion sensing, biomedical imaging, environmental monitoring, and other fields are then covered.

2. Chemistry of Schiff Base

One of the most often utilised families of organic molecules for synthetic intermediates and a valuable resource in the development of coordination chemistry is the Schiff base family [29]. Schiff base was initially introduced by Hugo Schiff [30]. He described the condensation of carbonyl compounds with primary amines. Imines, also known as Schiff bases sometimes, are a family of compounds having a carbon-nitrogen double bond that form when aldehydes and ketones react with primary amines. Wherein R1, R2, R3 might be either an aryl or an alkyl group. While Schiff bases with alkyl substituents are highly unstable, those with aryl substituents are far more stable and easier to synthesis. Aliphatic aldehyde Schiff bases are easily polymerized and relatively unstable. In contrast, aromatic aldehydes with an efficient conjugation have greater stability. Table-1: Permissible concentration levels of metals in drinking water by WHO and recommended daily amount (RDA) of metal ions in the human body [13].

3. Mechanistic details into metal ion detection

Generally speaking, metal ion detection requires interaction between the ion and the sensor. When the analyte and binding functional unit in Schiff base sensors interact, there may be a colorimetric and fluorescent colour shift that is apparent to the naked eye. However, a number of frequently employed mechanisms, such as FÖrster resonance energy transfer (FRET), photo-induced electron transfer (PET), exited-state intramolecular proton transfer (ESIPT), intra-/intermolecular charge transfer (ICT), inner filter effect (IFE), metal to ligand charge transfer (MLCT), ligand to metal charge transfer (LMCT), and CQN isomerization, may be responsible for the ratiometric fluorescence change and enhancement/quenching of emission intensity [3].

3.1 Self-assembly/disassembly

Fluorescence imaging and analyte detection are only two of the many uses for which self-assembled molecules are adaptable materials. In the literature, different methodologies such as self-assembly-disassembly driven detection of metal ions, metal ion-induced disassembly, self-assembly combined with the AIE phenomena etc. have been employed for fluorescence-based detection of metal ions [40-41]. The metal ion detection technique based on self-assembly and fluorescent Schiff base molecules will be covered in this section. Wu et al. developed pyrene-based Schiff base 1 with aggregated emission enhancement properties for fluorescence-based detection of Cu^{2+} [31]. In H_2O-DMF (1:1, v/v) solution, sensor 1 was weakly fluorescent (Table-2). In the presence of Cu^{2+}, sensor 1 displayed strong fluorescence enhancement (4.5 fold) at 455 nm. The recognition mechanism was attributed to Cu^{2+} induced self-assembly. TEM and SEM morphology results also supports the presence of Cu^{2+}.

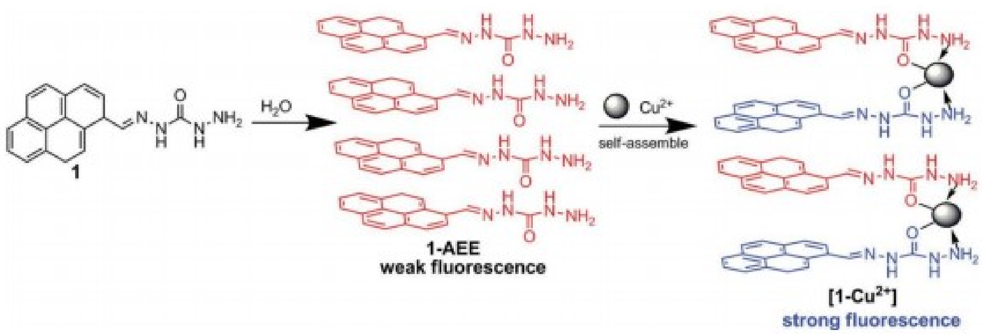

Fig. 1: Sensing mechanism of Cu^{2+} detection using sensor 1

3.2 Aggregation/disaggregation

Schiff base-based sensors are excellent AIE active molecules in which free rotation around the C=N bond is restricted upon coordination with metal ions, leading to emission change. These sensors emit poorly in diluted solutions, but they emit robustly when they aggregate in solution or in solid form with the help of probe-metal ion interaction. Fig. 1: Sensing mechanism of Cu^{2+} detection using sensor 1 Singh et al. developed probe 2 with AIE and ESIPT capabilities for Cu^{2+} detection in an aqueous solution (Fig. 2) [32]. Probe 2's fluorescence spectra showed green emission at 526 nm upon excitation at 390 nm, which was given to the AIE+ESIPT mechanism. Probe 2's emission spectrum showed quenching of emission intensity upon the gradual addition of increasing Cu^{2+} concentrations, and saturation was reached upon the addition of 1μM Cu^{2+}.

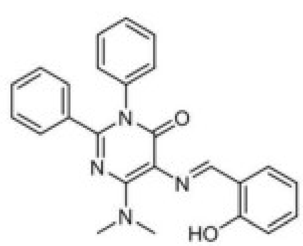

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Fig. 2: The chemical structure of sensor 2

3.3 Photoinduced electron transfer (PET)

In the process known as PET, electrons are transferred from the donor to the acceptor in an exited state. The PET process may be facilitated or hampered by the coordination of the metal ions with the Schiff base sensors, changing the emission.

Chakraborty et al. developed pyrene-based Schiff base 3 with AIE properties for fluorescence-based detection of Cu^{2+} (Fig. 3) [19]. Sensor 3 was found to be selective for Cu^{2+} with an LOD of 2.5 μM. Sensor 3 was weakly fluorescent because of the PET process between the imine bond and the pyrene ring. The complexation of sensor 3 with Cu^{2+} blocked the PET process and resulted in fluorescence enhancement.

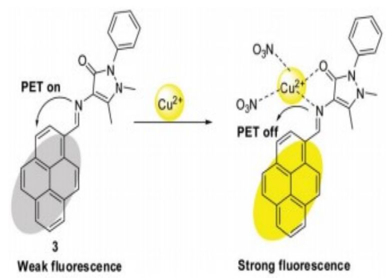

Fig. 3: PET-based mechanism for Cu^{2+} detection with sensor 3

3.4 Intra/intermolecular charge transfer (ICT)

The phenomenon of charge transfer, which can be intramolecular—where charge is redistributed within the excited molecule—or intermolecular—where charge is transferred from the excited donor molecule to the neighbouring acceptor molecule—is what allows the excited molecule to relax its energy during the ICT process.

Triazole-based Schiff base 4 was developed by Rout et al. as a turn-on fluorescence sensor for Pb^{2+} and Cu^{2+} detection (Fig. 4) [33]. The free sensor showed low fluorescence at 440 nm in methanol-tris buffer (1:1) media, which was explained by the PET process that transferred the triazole and imine moiety to the fluorophore. When those metal ions were present, sensor 4's fluorescence spectrum showed an increase in emission intensity, which was explained by the PET process being blocked and the ICT process being strengthened.

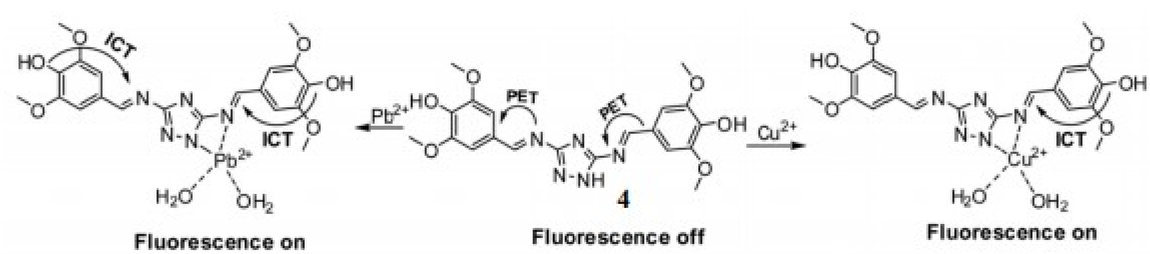

Fig. 4: ICT and PET based sensing mechanism for Pb^{2+} and Cu^{2+} detection sensor 4

3.5 Metal to Ligand Charge Transfer (MLCT)

Pannipara et al. developed an AIE-active Schiff base 5 as a turn-off sensor for Cu^{2+} detection (Fig.5) [34]. In the THF-H_2O (9:1, v/v) mixture, sensor 5 showed intense emission at 484 nm. Upon addition of Cu^{2+} to the solution of sensor 5, a significant decrease in fluorescence intensity was observed, attributed to metal to ligand charge transfer between Cu^{2+} and sensor 5, resulting in the CHEQ effect.

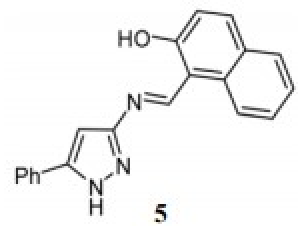

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Fig. 5: The chemical structure of sensor 5

3.6 Ligand to Metal Charge Transfer (LMCT)

Bhardwaj et al. developed chromone-based fluorescent organic nanoparticles (FON-6) for Cu^{2+} and CN^-detection in an aqueous medium [35]. When a higher concentration of Cu^{2+} was added, the fluorescence spectra of FON-6 gradually lost intensity at 512 nm, a phenomenon that was explained by the transfer of charge from ligand to metal. From the DFT method, for sensor 6, the HOMO was located on the naphthalene moiety and LUMO was in the whole sensor 6. But in the case of sensor-6-Cu^{2+} complex the LUMO was shifted towards metal centre, demonstrating ligand to metal charge transfer.

6

Fig. 6: The chemical structure of sensor 6

3.7 FÖrster resonance energy transfer (FRET)

FRET is a non-radiative process where energy transfer occurs from excited donors to acceptor molecules. The metal-Schiff base complexation may inhibit or trigger the FRET process resulting in emission change.

Yang et al. developed a novel method for Cu^{2+} detection through AIE and FRET strategy in an aqueous medium (Fig.: 7) [36]. The Schiff base sensor 7 exhibit AIE properties with green emission at 525 nm. In the presence of Cu^{2+}, sensor 7 undergoes fluorescence quenching.

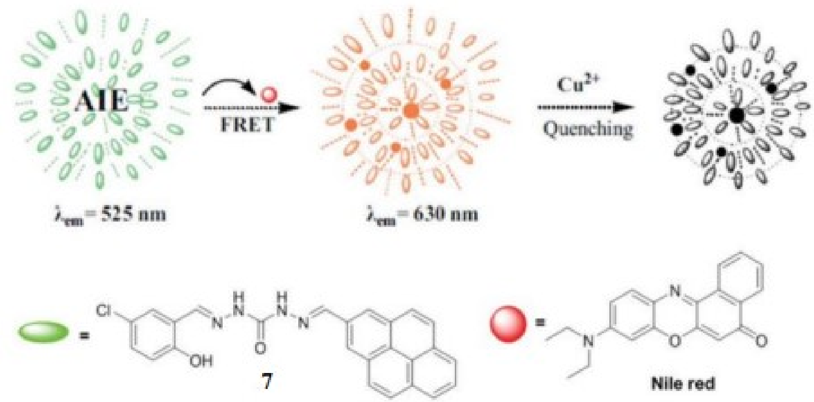

Fig.7: FRET-based sensing mechanism for Cu^{2+} detection with sensor 7

4. Conclusion

Metal ions are non-toxic up to a concentration set by the EPA and WHO. However, metal ions have demonstrated hazardous effects on human health and the environment due to a rise in their concentration brought on by industrialization and urbanisation. It is vital to detect them as a result.

Several Schiff base chemosensors were systematically studied to gain knowledge for the development of novel sensing technologies. Furthermore, the use of Schiff base probes for colorimetric metal ion detection offers up new possibilities for metal ion monitoring, especially at the industrial level. The methodical use of UV-visible, fluorescent, and colorimetric techniques has given researchers a foundation for simple technique handling. I think that fluorescent-based Schiff base sensors can be used as important materials in the near future and that their commercial availability is expected, despite the fact that they face numerous obstacles in terms of both exploratory and practical application.

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How to cite this article:
Sk Najmul Islam. (2022). Schiff base based fluorescent probes for detecting physiologically relevant trace pollutant metal cations. Int. J. Curr. Res. Chem. Pharm. Sci. 9(6): 99-106.
DOI: http://dx.doi.org/10.22192/ijcrcps.2022.09.06.012

