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RESEARCH ARTICLE OPEN ACCESS

# Evaluation of a New Methylimidazole-Containing Thiosemicarbazone as a Cu<sup>+</sup>/Cu<sup>2+</sup>-Targeting Ligand in the Context of Alzheimer's Disease

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## ABSTRACT

The binding of copper ions to amyloid- $\beta$  (A $\beta$ ) peptide leads to reactive oxygen species (ROS) formation and toxic soluble oligomers, contributing to oxidative stress in Alzheimer's disease (AD). Thus, studying compounds with moderate copper affinity is a promising strategy to prevent its interaction with A $\beta$  and reduce toxicity. Here, we evaluated a new tri-coordinating thiosemicarbazone (**HXE**) with chelating properties to regulate cuprotoxicity in AD. The ligand was nontoxic against HT-22 hippocampal neuronal cells and bound Cu<sup>+</sup> and Cu<sup>2+</sup> at pH 7.4, with affinity constants (log  $K_{\text{cond}}$ ) of 8.7 and 12.3, respectively, showing high selectivity over Zn<sup>2+</sup> (log  $K_{\text{app}} = 5.0$ ). In the presence of A $\beta$  and Cu<sup>2+</sup>, **HXE** formed stable ternary complexes at physiological pH. Ascorbate consumption and coumarin-3-carboxylic acid fluorescence assays showed that the ligand significantly reduces Cu(A $\beta$ <sub>16</sub>)-mediated ROS production. It also prevented Cu<sup>2+</sup>-induced modulation of A $\beta$ <sub>40</sub> self-assembly and restored the typical fibrillar structure of apo-A $\beta$ <sub>40</sub> aggregates. Overall, **HXE** effectively modulates metal-associated A $\beta$  toxicity and emerges as a promising candidate for AD bioinorganic management.

## 1 | Introduction

Copper is an essential trace element in biological systems, being required as a structural component, electron transporter agent and cofactor of redox enzymes, including Cu/Zn superoxide dismutase (SOD1) or cytochrome c oxidase, that play a critical role in antioxidant defense and mitochondrial respiratory chain, respectively [1, 2]. In the nervous system, this metal actively participates in neurotransmitter biosynthesis, cognitive processes and gene expression [3]. Copper homeostasis in the brain is finely

regulated by the action of transporters, enzymes and chaperones to ensure the proper distribution and avoid toxic accumulation [4–6]. Copper can be found either inertly bound to ceruloplasmin (Cp), representing 75–95% of the total amount, or as “non-Cp-Cu” (“free copper”) [7], when bound to coordinating biomolecules, such as Human Serum Albumin (HSA) that provides a higher lability and bioavailability of the metal [4, 8, 9]. The passage of this metal through the blood-brain barrier (BBB) is a highly selective process and depends on transporters such as CTR1, ATP7A, and ATP7B [4]. Disturbance in its homeostasis has been linked to

Christelle Hureau and Nicolás A. Rey contribute equally to the work

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several pathological conditions, as neurodegenerative disorders, cancer and cardiovascular diseases [4, 10].

In Alzheimer's disease (AD), growing evidence points to physiological metal ions (mainly Cu, Zn and Fe) imbalance as the main bioinorganic factor linked to this pathology's progression [11, 12, 7, 13]. Copper has been found to be present at high concentrations in senile plaques, one of the main hallmarks of the disease [14–16]. These insoluble deposits are mainly composed by aggregates of a 40–42 amino acid residues peptide, called amyloid- $\beta$  ( $A\beta$ ), derived from the pathological cleavage of the transmembrane amyloid precursor protein (APP) [17–21]. At pH around 7,  $A\beta$  forms stable complexes with Cu ions, and this interaction modulates the peptide's aggregation kinetics, shifting the equilibrium from the formation of insoluble fibrils to toxic soluble oligomers [22–26]. Furthermore, the  $Cu(A\beta)$  complex has a Cu-associated redox activity, cycling between  $Cu^+$  and  $Cu^{2+}$  states in the presence of molecular oxygen and biological reductants, such as ascorbate. This process culminates in the generation of reactive oxygen species (ROS), which contribute to neuronal oxidative stress, a central mechanism implicated in neurodegeneration [27, 28].

Therefore, the use of ligands (including some of the multitarget type) has emerged as a promising strategy to limit the interaction of  $A\beta$  with copper, relieving the toxicity mediated by  $Cu(A\beta)$  [5, 29–40]. However, to date, no chelating agent has shown satisfactory results in clinical trials, not even those that showed satisfactory *in vitro* results [41, 42]. It is worth noting that most of the proposed compounds so far have been designed to specifically target  $Cu^{2+}$ , not taking into consideration the crucial role of redox transition to  $Cu^+$  for the toxicity of the  $Cu(A\beta)$  complex [5]. At physiological pH,  $Cu^{2+}$  ions bind to  $A\beta$  with a square-planar geometry, through the imidazole (Im) rings of two His residues (His6 and either His13 or His14), the N-terminal amine and the carboxylate group of Asp1, with an affinity of  $10^9$ – $10^{10}$   $M^{-1}$  [43–46]. In turn,  $Cu^+$  is linearly coordinated to the peptide, involving two Im groups of His residues, with an affinity in the literature ranging from  $10^7$  to  $10^{10}$   $M^{-1}$  [46–49]. Thus, chelators that focus on both oxidative states of copper may be an attractive approach to interrupt the pathological redox cycles involved in  $A\beta$  neurotoxicity [50]. Besides, ligands that target  $Cu^{2+}$  face a challenge related to selectivity toward other metal ions present in the extracellular medium, mainly  $Zn^{2+}$ , that displays a similar preference for N/O-donors and is present at a higher concentration than copper in the synaptic cleft, reducing the compounds' efficacy [42, 51]. The difference in the coordination chemistry of the metal ions can be explored to design an improved chelator and overcome selectivity limitations.  $Cu^{2+}$  and  $Zn^{2+}$  are considered borderline acids based on Pearson's concept [52], showing a preference for intermediate bases, as those containing delocalized N/O-donors. However, due to the Jahn-Teller effect, copper tends to adopt square-planar or distorted octahedral geometries, whereas zinc has no electronic constraints and is thus usually found tetrahedrally coordinated. With respect to  $Cu^+$ , it has a softer character and preferably binds to soft donors, such as sulfur, in linear, trigonal planar or tetrahedral geometries.

Recently, some of us have shown interest in targeting  $Cu^+$  ions in the context of AD [50, 53–56]. Those compounds prove to be effective in removing copper from  $A\beta$ , lessening or stopping  $Cu(A\beta)$ -induced ROS production and showing satisfactory selec-

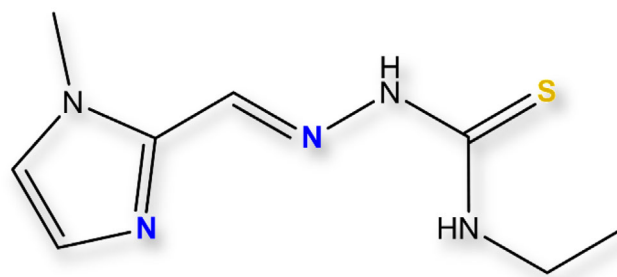


FIGURE 1 | HXE structure. Potential donor atoms are highlighted in color.

tivity toward  $Zn^{2+}$  [54, 56], encouraging the use of this strategy in the rational design of novel potential chelating agents for AD therapy. To be considered a promising drug candidate, a compound must meet several criteria: (i) ability to interrupt  $Cu(A\beta)$  redox cycle, (ii) rapid coordination kinetics [57, 58], (iii) capacity to abstract  $Cu^+/Cu^{2+}$  from  $A\beta$  or forming stable compound- $Cu-A\beta$  ternary complexes without compromising copper ions involved in physiological activities, and (iv) high selectivity over other metal ions abundant in the extracellular environment. Additionally, favorable pharmacokinetic properties, especially regarding toxicity and permeability through the BBB, are important criteria to fulfil if medical applications are foreseen [42].

Over the past years, some of us have extensively investigated *N*-acylhydrazones (NAHs) as a promising class for the management of metal-enhanced aggregopathies [59–64]. NAHs have demonstrated suitable affinity for  $Cu^{2+}$  and  $Zn^{2+}$ , being able to compete with amyloidogenic peptides without disrupting metal ion homeostasis in the organs of healthy Wistar rats [62]. More recently, a new family of NAHs derived from 1-methylimidazole-2-carboxaldehyde has shown improved properties [59, 65–69]. The inclusion of this five-membered nitrogen-containing ring into previously studied NAH structures proved effective in enhancing water solubility, hydrolytic stability, and reducing toxicity, while also helping to complete the coordination sphere of  $Cu^{2+}$ . Based on this, and aiming to target  $Cu^+$  ions in addition to  $Cu^{2+}$ , we propose in this work the replacement of the hydrazone moiety by a thiosemicarbazone group, to introduce a sulfur atom at the coordination site—a softer donor atom.

Thiosemicarbazones (TSCs) and their metal complexes are known in the literature for their wide range of biological properties: anticancer, antioxidant, antiinflammatory, antibacterial, and antiviral activities [70, 71]. In AD context, previous studies showed that TSCs derivatives have the ability to inhibit  $A\beta$  self or Cu-induced aggregation, antioxidant activity, acetylcholinesterase (AChE) activity, and have low toxicity in cell models and a suitable permeability through BBB [72–80]. Hence, we herein report an investigation into the therapeutic potential of a new TSC-1-methylimidazole-2-carboxaldehyde 4-ethyl-3-thiosemicarbazone—(HXE, Figure 1) containing a methylimidazole moiety, which was designed to target both biologically relevant oxidation states of copper in the context of AD. HXE was evaluated regarding its affinity for  $Cu^{2+}$  and  $Cu^+$  ions, selectivity relative to  $Zn^{2+}$  and the ability to reverse deleterious effects induced by  $Cu(A\beta)$ , including the generation of ROS and the metal-induced modulation of peptide aggregation.

## 2 | Materials and Methods

### 2.1 | Chemicals

Solvents and reactants were purchased from commercial sources in the higher purity available. Fresh stock solutions of **HXE** (5 mM, Milli-Q), ascorbate (5 mM, Milli-Q) and 3-CCA (2 mM, 200 mM phosphate buffer pH 7.4) were prepared at the beginning of each day. Stock solutions of  $\text{Cu}^{2+}$  and  $\text{Zn}^{2+}$  (0.1 M, water), from the salts  $\text{CuSO}_4 \cdot 5 \text{H}_2\text{O}$  and  $\text{ZnSO}_4 \cdot 1 \text{H}_2\text{O}$ , were used. BCA (bicinchoninic acid) (10 mM) was prepared by dissolution in Milli-Q water and the exact concentration was determined by UV-Vis titration with  $\text{CuSO}_4$  in the presence of 3 equivalents of ascorbate to obtain the  $\text{Cu}^+ [\text{Cu}(\text{BCA})_2]^{3-}$  complex ( $\epsilon_{562 \text{ nm}} = 8060 \pm 30 \text{ M}^{-1} \text{ cm}^{-1}$ , 50 mM HEPES pH 7.4). Tetrakis(acetonitrile)copper(I) tetrafluoroborate salt was bought from TCI. Stock solutions were prepared inside an argon flushed glove box by dissolving the powder in ACN or  $\text{ACN-d}_3$  for NMR experiments. The concentration was determined by UV-Vis titration with an excess of BCA in a 50 mM HEPES pH 7.4 solution. Stock solution of Thioflavin T (ThT) was prepared by dissolving the powder in Milli-Q and concentration was determined by UV-Vis ( $\epsilon_{412 \text{ nm}} = 33000 \text{ M}^{-1} \text{ cm}^{-1}$ ) [81].

GGH (sequence GGH-NH<sub>2</sub>),  $A\beta_{16}$  (sequence DAEFRHDSGY-EVHHQK-NH<sub>2</sub>) and  $A\beta_{40}$  (sequence DAEFRHDSGYEVHHQK-LVFFAEDVGSNKGAIIGLMVGGVV) peptides were bought from GeneCust or ApexBio with purity grade > 95%. Stock solutions of GGH and  $A\beta_{16}$  were prepared by the solubilization of the powder in Milli-Q water. For GGH, the concentration was determined by UV-Vis titration with  $\text{Cu}^{2+}$  until no change in *d-d* band (530 nm) was observed. For  $A\beta_{16}$ , the concentration of the stock was determined by the absorption of Tyr10 at 276 nm, corrected for the absorption at 300 nm ( $\epsilon_{276 \text{ nm}} = 1410 \text{ M}^{-1} \text{ cm}^{-1}$ , pH ~ 2) in UV-Vis [82].  $A\beta_{40}$  was monomerized and purified by FPLC before utilization following the previously reported protocol [83]. Concentration of the FPLC fractions of interest were determined in a 500 mM NaOH solution using the electronic absorption of deprotonated Tyr10 at 293 nm, corrected for the absorption at 360 nm ( $\epsilon_{293 \text{ nm}} = 2400 \text{ M}^{-1} \text{ cm}^{-1}$ , pH >13) [82].

### 2.2 | Instruments

Elemental analyses were performed in a Perkin Elmer 2400 Series II Flash Combustion Analyzer in duplicate at room temperature.

Infrared spectra were acquired on a Perkin Elmer FT-IR Frontier and Perkin Elmer Spectrum Two FT-IR spectrometers.

<sup>1</sup>H NMR spectra were recorded on a Bruker AvanceIII 400 or an Avance NEO 600 spectrometers at room temperature using dimethylsulfoxide ( $\text{DMSO-d}_6$ ) or aqueous solution with 10%  $\text{D}_2\text{O}$  as solvent. Suppression of the water signal was performed using excitation sculpting method. Crystallographic data of **HXE** and its  $\text{Cu}^{2+}$  complex were collected on a Rigaku XtaLAB Synergy Duaflex diffractometer using a PhotonJet X-ray source ( $\text{CuK } \alpha$ ,  $\lambda = 1.54184 \text{ \AA}$ ). An Oxford Cryosystems Cryostream cooling device was used to collect data at low temperature [100(2) K]. Potentiometric titrations were performed in a MOLSPIN pH-

meter equipped with a Metrohm 6.0234.100 combined glass electrode (Metrohm) in the pH range 2.5–11.5, while the dosing of the titrant was made with a computer-controlled MOL-ACS microburette.

EPR spectra were acquired using an Elexsys E-500 Bruker spectrometer operating at a microwave frequency of approximately 9.4 GHz with a modulation amplitude of 5G, 160 s of conversion time, 2 scans and 2500 to 3900 G as magnetic field range. The experiments were carried out at 120 K using a liquid nitrogen cryostat.

UV-Vis experiments were performed in a Hewlett Packard Agilent 5484 spectrophotometer under controlled temperature and continuous stirring (25°C, 800 rpm) using a 1 cm cuvette or, alternatively, in a Spectrostar nano (BMG Labtech) spectrophotometer using a 96 wells plate (Greiner, F-bottom, UV clear) at 25°C, stirring at 500 rpm for 10 s before each measurement. For cell viability experiments, a SpectraMax M5 spectrophotometer (Molecular Devices) was used.

Cyclic Voltammograms were acquired on an Autolab PGSTAT302N potentiostat controlled with GPES 4.9 software and using three electrodes: a glassy carbon electrode as working electrode, a platinum wire as counter electrode and a saturated calomel electrode (SCE) as reference.

Fluorescence experiments were performed in plates readers from BMG Labtech (ClarioStar, Omega, and Optima) using a 96 or 384 wells plate.

Electron Microscopy was performed in a Jeol JEM-1400, JEOL inc, Pea-body, MA, USA at 80 kV and images were taken with a digital camera (Ametek rio 9) at magnifications between 3000 and 12000.

### 2.3 | Syntheses

**HXE**—1-methylimidazole-2-carboxaldehyde 4-ethyl-3-thiosemicarbazone (**HXE**) was synthesized through the base Schiff condensation between 1-methylimidazole-2-carboxaldehyde (0,2212 g, 2.0 mmol) and 4-ethyl-3-thiosemicarbazide (0.2390 g, 2.0 mmol). Both reactants were dissolved in the minimal volume of ethanol and the thiosemicarbazide solution was dropped over the aldehyde. Reaction was catalyzed with HCl, resulting in a white precipitate, which was filtered and washed with cold ethanol. The reactional scheme can be found in Figure S1. White crystals were obtained through the recrystallization of the powder in an 80/20 EtOH/ $\text{H}_2\text{O}$  mixture.

White powder ( $\text{C}_8\text{H}_{14}\text{N}_5\text{SCl}$ ; **HXE**, HCl) Yield: 66%. M.W. = 247.75 g mol<sup>-1</sup>. Elemental analysis: Calculated – C: 38.8%, H: 5.7%, N: 28.3%, S: 12.9%. Experimental – C: 38.7%, H: 5.7%, N: 27.7%, S: 13.1%. Main IR bands (ATR, cm<sup>-1</sup>):  $\nu(\text{N-H})$  3213, 3162;  $\nu(\text{C} = \text{N})_{\text{azomethine}}$  1607;  $\nu(\text{C} = \text{S})$  805 (Figure S2).

<sup>1</sup>H NMR ( $\text{DMSO-d}_6$ ; ppm): 1.18 (t, 3H), 3.60 (m, 2H), 3.88 (s, 3H), 7.73 (d, 1H, <sup>3</sup>J = 1.9 Hz), 7.76 (d, 1H, <sup>3</sup>J = 1.9 Hz), 8.01 (d, 1H), 9.28 (t, 1H), 12.14 (s, 1H).

**[Cu(XE)Cl]**—0.2 mmol of ligand and CuSO<sub>4</sub> were solubilized in the least necessary volume of a mixture 80/20 EtOH/H<sub>2</sub>O. **HXE** solution, which showed an initial pH of 6, was adjusted to pH 8 and then dropwise added to the Cu<sup>2+</sup> solution. The system was kept under stirring at 50 °C for 1 h, resulting in a dark green solution with a green precipitate. The precipitate was separated by filtration and washed with cold ethanol. Part of the powder was then resolubilized in 80/20 EtOH/H<sub>2</sub>O and the solution was kept at room temperature for slow evaporation. Green needle crystals were obtained after two weeks.

Green powder (C<sub>8</sub>H<sub>12</sub>ClCuN<sub>5</sub>S). Yield: 28%. M.W. = 309.29 g mol<sup>-1</sup>. Main IR bands (ATR, cm<sup>-1</sup>): ν(N–H) 3324; ν(C = N) azomethine 1618; ν(C = S) 708 (Figure S2).

## 2.4 | X-Ray Diffraction

Omega scans were performed for data collection. An empirical absorption correction was applied and the structures were solved by intrinsic phasing method (ShelXT) [84]. All nonhydrogen atoms were refined anisotropically by means of least-squares procedures on F<sup>2</sup> with ShelXL. All the hydrogen atoms were refined isotropically at calculated positions using a riding model, except for the N-bound hydrogen atoms, which were located in different Fourier maps and refined freely. Deposition Numbers <a href="https://www.ccdc.cam.ac.uk/services/structures?id=https://doi.org/10.1002/chem.202502754">2477871 (for **HXE**) and 2477872 {for [Cu(XE)Cl]}</a> contain the supplementary crystallographic data for this paper. These data are provided free of charge by the joint Cambridge Crystallographic Data Centre and Fachinformationszentrum Karlsruhe <a href="http://www.ccdc.cam.ac.uk/structures">Access Structures service</a>.

## 2.5 | In Silico Calculations

Some pharmacological parameters such as cLog P, cLog S, PSA, Druglikeness, and Drug Score were calculated for **HXE** using Osiris Property Explorer: DataWarrior, software freely available for download at <http://www.organic-chemistry.org/prog/peo/>.

## 2.6 | Toxicity Against HT-22 Cells

**Cell Culture and Experimental Design**—HT-22 cells (mouse hippocampal neuronal cell line) were cultured in Dulbecco's Modified Eagle's Medium (DMEM; Sigma-Aldrich, D7777) supplemented with 10% fetal bovine serum (FBS; CRIPION, São Paulo, Brazil) and 100 IU mL<sup>-1</sup> penicillin/streptomycin (Sigma-Aldrich, P0781). Cells were maintained at 37 °C in a humidified atmosphere containing 5% CO<sub>2</sub> and 95% air. HT-22 cells were seeded at a density of 2 × 10<sup>4</sup> cells cm<sup>-2</sup> [85]. After 24 h, the cells were treated with **HXE** at concentrations of 5, 10, 20, 50, 100, or 200 μM for an additional 24 h.

**Cell Viability Assay**—Cell viability was assessed using the 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide (MTT) assay [86]. After 24 h of exposure, neuronal cells were incubated with 0.5 mg mL<sup>-1</sup> MTT (Sigma-Aldrich) for 3 h at 37 °C

in a 5% CO<sub>2</sub> atmosphere. Experiments were carried out in 96-well plates, and the formazan crystals formed by the reduction of MTT were dissolved in DMSO. Formazan absorbance was measured at a wavelength of 540 nm. Results are expressed as the percentage of control cells [85, 86]. Statistical analysis was performed using one-way ANOVA test.

## 2.7 | Potentiometric Titrations

Stock solutions of CuCl<sub>2</sub> and ZnCl<sub>2</sub> were prepared from analytical grade reagents and their concentrations were checked gravimetrically via the precipitation of oxinates. The other stock solutions (KOH, HCl, KCl, potassium hydrogen phthalate) were also prepared from analytical grade reagents.

The concentration and the deprotonation constants of the ligand and the stability of the Cu<sup>2+</sup> and Zn<sup>2+</sup> complexes were determined by pH-metric titration at 298.0 ± 0.1 K and at a constant ionic strength of 0.2 M KCl. All potentiometric measurements were carried out in 3.00 mL aqueous samples at 2 mM ligand concentration with a metal(II) ion-to-ligand ratio of 1:1. Titrations were performed using carbonate free stock solution of potassium hydroxide of accurately known concentration. During the experiments, argon was bubbled through the samples to ensure the absence of oxygen and carbon dioxide. The samples were stirred by a VELP Scientific magnetic stirrer. The recorded pH readings were converted to hydrogen ion concentration as described by Irving *et al.* [87]. Protonation constants of **HXE** and overall stability (log β<sub>pqr</sub>) constants of complexes were calculated by means of the general computational programs SUPERQUAD and PSEQUAD [88, 89], based on Equations (1) and (2):

$$pM + qH + rL = M_p H_q L_r \quad (1)$$

$$\beta_{pqr} = \frac{[M_p H_q L_r]}{[M]^p \cdot [H]^q \cdot [L]^r} \quad (2)$$

The concentration distribution curves were generated by the MEDUSA program using the protonation constants of the ligand and the stability constants of the Cu<sup>2+</sup> and Zn<sup>2+</sup> complexes at the same reactant concentrations as in the titrations [90].

## 2.8 | UV-Vis Titrations With Cu<sup>2+</sup> and Zn<sup>2+</sup>

**HXE** solution was diluted with Milli-Q to achieve a final concentration of 50 μM in HEPES (50 mM, pH 7.4). Substoichiometric (about 0.2 equiv. per **HXE**) ratio of Cu<sup>2+</sup> or Zn<sup>2+</sup> solutions were added to the ligand solution and the electronic absorption spectra were recorded after each addition. The apparent affinity constant (K<sub>app</sub>—in a buffered solution pH 7.4) for Zn<sup>2+</sup> was determined according to Table 1 and Equation (5):

$$K_{app} = \frac{\alpha}{1 - \alpha} \frac{1}{C_1 - \alpha C_0} \quad (3)$$

$$K_{app} C_0 \alpha^2 - (K_{app} C_0 + K_{app} C_1 + 1) \alpha + K_{app} C_1 = 0 \quad (4)$$

$$\alpha = \frac{-b + \sqrt{b^2 - 4ac}}{2a} \quad (5)$$

**TABLE 1** | Equilibrium for the formation of  $[\text{Zn}(\text{XE})(\text{H}_2\text{O})_x]^+$ .

	<b>HXE</b>	+	<b>Zn<sup>2+</sup></b>	⇌	<b><math>[\text{Zn}(\text{XE})(\text{H}_2\text{O})_x]^+</math></b>
Initial:	$C_0$		$C_1$		0
Equilibrium:	$C_0 - \alpha C_0$		$C_1 - \alpha C_0$		$\alpha C_0$

$$\text{For : } a = K_{app} C_0$$

$$b = -(KC_0 + KC_2 + C_1 - C_0)$$

$$b = -(K_{app} C_0 + K_{app} C_1 + 1)$$

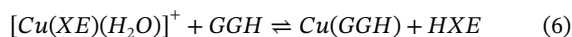
$$c = KC_2$$

$$c = K_{app} C_1$$

## 2.9 | Competition Assays

The affinity of the ligand for  $\text{Cu}^+$  and  $\text{Cu}^{2+}$  was determined by competition assays monitored by UV-Vis spectroscopy, aiming to estimate the conditional affinity constants ( $K_{cond}$ ), in which the effects of the buffer are neglected.

**Affinity for  $\text{Cu}^{2+}$** —Mixtures of  $[\text{Cu}(\text{XE})(\text{H}_2\text{O})]^+$  and the GGH peptide were prepared in a 50 mM HEPES pH 7.4 solution in a 96 wells plate, in triplicate, and the UV-Vis spectra of the samples were acquired with an interval of 15 min. The experiment was performed by the addition of different equivalents of GGH to the  $[\text{Cu}(\text{XE})(\text{H}_2\text{O})]^+$  solution. After the equilibrium shown in Equation (6) was reached, the progression of the reaction (i.e.,  $\alpha = [\text{Cu}(\text{GGH})]/[\text{Cu}^{2+}]_0$ ) was determined using the absorbance at 383 nm, related to the complex  $[\text{Cu}(\text{XE})(\text{H}_2\text{O})]^+$ , as demonstrated in Equation (7). Due to the presence of an excess of ligand in solution, the absence of free  $\text{Cu}^{2+}$  is assumed. The contribution of a ternary  $[\text{Cu}(\text{XE})(\text{Im}_{GGH})]^+$  complex was not considered in the fitting model. Given that the experimental data were well described by including only the two binary species, we supposed that the formation of the ternary complex does not significantly impact the estimation of the affinity constant. OBS.: throughout the manuscript, for the ternary species involving GGH or  $\text{A}\beta$ , we consider the net charge of Im rather than those of the peptides themselves for matter of simplicity.



The ratio between the conditional affinity of **HXE** and GGH for  $\text{Cu}^{2+}$  was calculated by fitting the experimental data with Equation (10) (Origin Software), where  $[\text{Cu}^{2+}]_0 = C_0$ ,  $[\text{HXE}]_0 = C_1$ ,  $[\text{GGH}]_0 = C_2$  and  $\beta$  is the stability constant for  $[\text{Cu}(\text{XE})(\text{H}_2\text{O})]^+$ .

$$\alpha = 1 - \frac{\text{Abs}_{383\text{nm}}}{\varepsilon_{383\text{nm}} [\text{Cu}(\text{XE})(\text{H}_2\text{O})]^+ C_0} \quad (7)$$

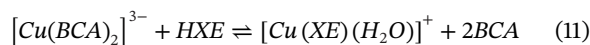
$$K = \frac{\beta}{K_{cond}^{HXE}} = \frac{\alpha}{1 - \alpha} \frac{C_1 - C_0 + \alpha C_0}{C_2 - \alpha C_0} \quad (8)$$

$$(K - 1) C_0 \alpha^2 - (KC_0 + KC_2 + C_1 - C_0) \alpha + KC_2 = 0 \quad (9)$$

$$\alpha = \frac{-b - \sqrt{b^2 - 4ac}}{2a} \quad (10)$$

$$\text{For : } a = (K - 1) C_0$$

**Affinity for  $\text{Cu}^+$**  — Competition experiment between  $[\text{Cu}(\text{BCA})_2]^{3-}$  and **HXE** was performed anaerobically in a 50 mM HEPES pH 7.4 solution by varying the concentration of **HXE** added. Solution of  $[\text{Cu}(\text{BCA})_2]^{3-}$  was prepared inside the glove box and one equivalent of  $\text{Na}_2\text{S}_2\text{O}_4$  was used to avoid oxidation of the metal. **HXE** was then added with a Hamilton syringe into the sealed cuvette equipped with a screw cap. The apparent affinity constant for  $[\text{Cu}(\text{XE})(\text{H}_2\text{O})]$  was determined by solving Equation (17) for each  $C_2$  value, where  $[\text{Cu}^+]_0 = C_0$ ,  $[\text{BCA}]_0 = C_1$ ,  $[\text{HXE}]_0 = C_2$ , and  $\beta_2$  is the stability constant for  $[\text{Cu}(\text{BCA})_2]^{3-}$ . The value reported corresponds to the mean and standard deviation between the different points.



$$[\text{Cu}(\text{BCA})_2]^{3-} = \alpha_{BCA} = \frac{\text{Abs}_{562\text{nm}}}{\varepsilon_{562\text{nm}} [\text{Cu}(\text{BCA})_2]^{3-}} \quad (12)$$

$$[\text{Cu}(\text{XE})(\text{H}_2\text{O})]^+ = C_0 - \alpha_{BCA} \quad (13)$$

$$[\text{BCA}] = C_1 - 2\alpha_{BCA} \quad (14)$$

$$[\text{HXE}] = C_2 - C_0 + \alpha_{BCA} \quad (15)$$

$$K_a^{HXE} = \beta_2 \frac{[\text{Cu}(\text{XE})(\text{H}_2\text{O})]^+}{[\text{HXE}]} \frac{[\text{BCA}]^2}{[\text{Cu}(\text{BCA})_2]^{3-}} \quad (16)$$

$$K_a^{HXE} = \beta_2 \frac{(C_0 - \alpha_{BCA})(C_1 - 2\alpha_{BCA})^2}{(C_2 - C_0 + \alpha_{BCA})\alpha_{BCA}} \quad (17)$$

## 2.10 | Cyclic Voltammetry Assays

A 50 mM HEPES pH 7.4 solution was used as the electrolyte solution in all experiments. Experiments were conducted under argon atmosphere, toward the reductive potential, with the initial potential of 0 mV and using 0.1 V s<sup>-1</sup> as scan rate. All potentials cited in this work will be given as function of the SCE.

## 2.11 | Copper Removal From $\text{A}\beta$

**UV-Vis**—Spectra of the ternary systems **HXE**,  $\text{Cu}^{2+}$  and  $\text{A}\beta_{16}$ /Imidazole (Im) were measured after the addition of 1.2 equivalent of **HXE** to a solution containing 1 equivalent of  $\text{Cu}^{2+}$  and 1.2 equivalents of  $\text{A}\beta_{16}$  peptide or 6.0 equivalents of Im. Experiments were performed in a 50 mM HEPES pH 7.4 solution.

A Savitzky-Golay smoothing was applied using a window of 50 points to reduce noise.

**EPR**—Samples were prepared in a 50 mM HEPES pH 7.4 solution with 10% glycerol to prevent the crystallization of the solvent and 1% DMSO to prevent precipitation in the lower temperature required for the experiment. Mixtures were made in 1500  $\mu$ L falcon tubes, with a final concentration of  $^{65}\text{Cu}^{2+}$  of 500  $\mu$ M. Different equivalents of HXE and/or  $A\beta$  peptide and/or Im were also added. Solutions were transferred to EPR quartz tubes and frozen in liquid nitrogen (77 K).

**NMR**—Samples were prepared in an Ar-saturated glove box in phosphate buffer (200 mM, pH 7.4 in  $\text{D}_2\text{O}$ ).  $A\beta_{16}$  (500  $\mu$ M in  $\text{D}_2\text{O}$ ) was first mixed with 2 eq. of  $\text{Na}_2\text{S}_2\text{O}_4$  (1 mM in  $\text{D}_2\text{O}$ ) and  $[\text{Cu}(\text{CH}_3\text{CN})_4]\text{BF}_4$  (490  $\mu$ M in  $\text{CD}_3\text{CN}$ , 3% of the final volume) in a Eppendorf tube. **HXE** (500  $\mu$ M, in  $\text{D}_2\text{O}$ ) was then added to the Eppendorf tube and 600  $\mu$ L of the solution was added to an NMR tube with J Young valve.

## 2.12 | Ascorbate Consumption Assay

The consumption of ascorbate (Asc) in the presence of Cu was monitored by UV-Vis. It mirrors the production of ROS in solution, as reported previously [56, 65]. Intensity of the Asc absorption band at  $\lambda = 265$  nm ( $\epsilon = 14500$  L mol $^{-1}$  cm $^{-1}$ ) was monitored as a function of time, with the background signal at  $\lambda = 800$  nm subtracted. Experiments with different concentrations of ligand, Zn and  $A\beta_{16}$  or imidazole (Im) were performed with a final concentration in the cuvette of: [Asc] = 100  $\mu$ M, [ $A\beta_{16}$ ] = 0 or 12  $\mu$ M, [Im] = 60  $\mu$ M, [ $\text{Cu}^{2+}$ ] = 10  $\mu$ M, [ $\text{Zn}^{2+}$ ] = 0, 12 or 120  $\mu$ M, [**HXE**] = 0, 12 or 60  $\mu$ M and [HEPES] = 100 mM, pH 7.4.  $\text{Cu}^{2+}$  is added to the solution of Asc (and peptide) generating  $\text{Cu}^+$ . The ligand is then added afterward the addition of  $\text{Cu}^{2+}$ , when absorbance reaches nearly 1 [55, 57, 91]. The Asc consumption rate was estimated from the slope of the plot of Asc concentration (determined by the ratio between the absorbance at 265 nm and the molar absorptivity,  $\epsilon = 14500$  M $^{-1}$  cm $^{-1}$ ) versus time (in seconds), using the first 300 s following ligand addition.

## 2.13 | HO $\cdot$ Production Mediated by Copper

Coumarin-3-carboxylic acid (3-CCA) was used as a probe to detect HO $\cdot$ , since the interaction of these leads to the formation of 7-hydroxy-coumarin-3-carboxylic acid (7-OH-CCA), which is fluorescent at 452 nm upon excitation at 395 nm. Fluorescence experiments were performed in a 96 wells plate at 25°C. The reaction was started with the addition of 20  $\mu$ L of a 5 mM aqueous solution of Asc into a 50 mM phosphate buffer pH 7.4 solution containing 3-CCA (0.5 mM), **HXE** (12  $\mu$ M),  $A\beta_{16}$  (12  $\mu$ M),  $\text{Zn}^{2+}$  (12  $\mu$ M), and  $\text{Cu}^{2+}$  (10  $\mu$ M), to a final volume of 200  $\mu$ L. The fluorescence was monitored with a 3 min interval during 90 min. Four replicates of each condition were added in the plate.

## 2.14 | Aggregation Kinetics of $A\beta_{40}$

Stock solutions of  $\text{CuSO}_4$  and  $\text{ZnSO}_4$  (0.3 mM, Milli-Q), **HXE** (0.1 mM, Milli-Q), ThT (250  $\mu$ M, Milli-Q), and  $A\beta_{40}$  (dilution of

the monomerized peptide solution with Milli-Q water to a final concentration of 40  $\mu$ M) were prepared. Self-assembly of  $A\beta_{40}$  in HEPES buffer pH 7.4 in the absence and presence of Cu or Zn and **HXE** was followed by the fluorescence of ThT ( $\lambda_{\text{ex}} = 440$  nm,  $\lambda_{\text{em}} = 490$  nm). ThT fluorescence increase can be considered a sigmoid curve described by Equation (18), where  $F_0$  and  $F_{\text{max}}$  are the initial and maximum fluorescence intensity, respectively, and  $k$  is the growth rate.  $t_{1/2}$  is defined as the time at which the fluorescence intensity reaches half of its maximum value.

$$F(t) = F_0 + \frac{F_{\text{max}} - F_0}{1 + e^{-k(t-t_{1/2})}} = F_0 + \frac{\Delta F}{1 + e^{-k(t-t_{1/2})}} \quad (18)$$

The experiments were performed at 37°C and with stirring at 200 rpm (double orbital) during 15 s before each cycle (10 min) in a 384 wells plate. The reactant addition was performed in the same order as listed here to achieve a final concentration of: [HEPES] = 100 mM, [EDTA] = 20 nM, [ThT] = 10  $\mu$ M, [**HXE**] = 0 or 20  $\mu$ M, [ $A\beta_{40}$ ] = 20  $\mu$ M and [Cu] = [Zn] = 0 or 18  $\mu$ M. Each condition was reproduced into six different wells. To ensure the reproducibility of the impact of **HXE** in the peptide self-assembly, the experiment was performed four times.

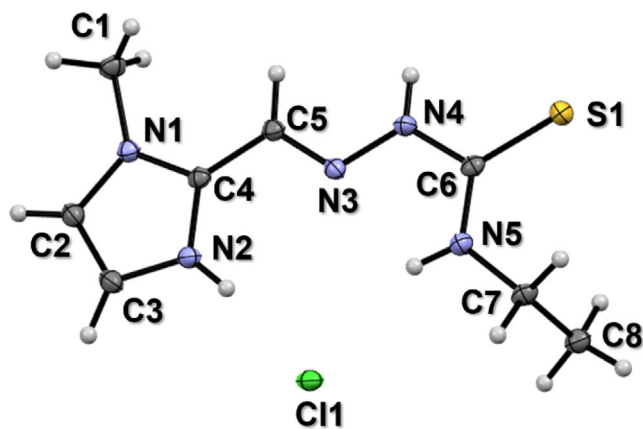
## 2.15 | Transmission Electron Microscopy (TEM)

Samples from different conditions were collected from 384-well plates after the ThT assays reached the fluorescence plateau (after approximately 2 days) and diluted 4 times. Formvar-coated grids (Delta Microscopies, France) were then prepared for microscopy using a conventional negative staining method. 5  $\mu$ L drop of sample was placed on the grid for 1 min, blotted and then stained with 3  $\mu$ L uranyl acetate (1%) for 1 min. The grids were then mounted and examined in a TEM. The images were then processed using GATAN software.

## 3 | Results and Discussion

### 3.1 | Syntheses and Characterization

**HXE** was synthesized as described in the experimental section, resulting in the precipitation of a white powder during the synthesis, corresponding to the hydrochloride form of the ligand, **HXE**, HCl. After solubilization of this powder in an 80/20 EtOH/ $\text{H}_2\text{O}$  mixture and slow evaporation of the solvent, white needle crystals were isolated. The protonation of the imidazole nitrogen occurs due to the acid catalysis used in the synthesis (see Figure S1). **HXE**, HCl crystallizes in the monoclinic system, space group  $\text{P}2_1/\text{c}$  and with four molecules and four chloride ions per unit cell. The structure of **HXE**, HCl is shown in Figure 2. An (*E*)-configuration regarding the  $\text{C}5=\text{N}3$  bond and *syn* conformation around the  $\text{N}4-\text{C}6$  are observed. The main crystal, data collection, and refinement parameters are given in Table S1, and some relevant bond distances and angles are reported in Table S2. The crystal network is stabilized through nonconventional hydrogen bonds involving the chloride ions,  $\text{N}2-\text{H}$  and  $\text{N}5-\text{H}$  from an **HXE** unit, as well as  $\text{N}4'-\text{H}$  from a second thiosemicarbazone unit. The geometric parameters associated to such interactions are listed in Table S3. No other interaction between the protonated, cationic



**FIGURE 2** | Ellipsoid plot of **HXE**, HCl. Ellipsoids drawn at 50% probability level.

**HXE**, HCl units, as for example  $\pi$ - $\pi$  stacking, is observed (Figure S3).

In solution, **HXE** can undergo a tautomeric equilibrium between thioamido and thioiminol forms (Figure 3), which provides a partial double bond character to the C6–N4 bond, restricting free rotation around it. Consequently, in addition to the classic geometric isomerism (*E*)- and (*Z*)- around the C5=N3 bond, **HXE** can also be described in terms of *anti* and *syn* conformations, according to the relative orientation between C6–S1 and N4–H bonds, which can be pointing to opposite sides or to the same side in the plane defined by the atoms H–N4–C6–S1 (Figure 4).

To characterize the ligand in solution,  $^1\text{H}$  NMR in DMSO- $d_6$  was performed, where two sets of signals were observed, corresponding, respectively, to 97% and 3% of the total amount of **HXE** (Figure S4). The major isomer was assigned as the (*E*)-isomer and the minor one, as the (*Z*)-isomer, based on the chemical shifts of the N4 proton, which appears at 12.14 and 13.42 ppm, respectively. This assignment is consistent with previous reports from our research group and the literature [61, 92–95]. A NOESY experiment allowed the attribution of the major species as the (*E*)-anti isomer (Figure S5). By the  $^1\text{H}$  spectrum, it is also possible to conclude that the ligand was obtained with a high purity.

The stability of **HXE** in a buffered solution (50 mM HEPES pH 7.4) was followed for 24 h by UV-Vis in order to evaluate possible hydrolysis of the C5–N3 bond. **HXE** shows a single intra-ligand transition at 324 nm ( $\epsilon = 3.17 \pm 0.05 \times 10^4 \text{ M}^{-1} \text{ cm}^{-1}$ ), which did not show any absorbance change during the experiment (data not shown), indicating the high stability of this ligand toward hydrolysis in an aqueous buffered solution at pH 7.4. This result is in accordance with the behavior observed for other methylimidazole containing ligands previously studied by our group [65, 67, 69].

Protonation constants of the ligand were determined by potentiometric titration in aqueous solution ( $I = 0.2 \text{ M}$ ,  $25^\circ\text{C}$ ). **HXE**, HCl shows two deprotonation sites. The most acidic one can be assigned to the protonated methylimidazole group (i.e.,  $\text{H}_2\text{XE}^+ \rightarrow \text{HXE} + \text{H}^+$ ,  $\text{p}K_a = 5.42$ ), while the higher  $\text{p}K_a$  value is related to deprotonation of the thioamide group at N4 ( $\text{HXE} \rightarrow \text{XE}^- +$

**TABLE 2** | Pharmacological parameters calculated for **HXE** using OSIRIS Property Explorer: DataWarrior™ software. MW: Molar weight, cLogP: Calculated octanol: Water partition coefficient (hydrophobicity/lipophobicity parameter), PSA: Polar surface area.

	MW (g mol <sup>-1</sup> )	cLog P	PSA (Å <sup>2</sup> )
Calculated	211.29	0.47	86.33
Expected range	200–450 [97]	0–3 [98]	< 90 [99–101]

$\text{H}^+$ ,  $\text{p}K_a = 11.09$ ). Therefore, at physiological pH, the ligand is in its neutral **HXE** form, being this the main species between pH 6 and 11 (Figure 5).

### 3.2 | Pharmacological Parameters and Toxicity

*In silico*, calculations of pharmacological parameters can be a useful tool to predict the bioavailability and permeability of new compounds. All the calculated parameters for **HXE** (Table 2) showed values in agreement with the expected range for drugs that aim to act in the CNS, according to Lipinski's rules [96].

Furthermore, **HXE** toxicity was evaluated in HT-22 cells. In that case, exposure to up to 200  $\mu\text{M}$  of ligand did not affect the viability of the hippocampal neuronal cell line, as assessed by the MTT assay [ $F(6, 27) = 1,284$ ,  $p = 0.2976$ ] (Figure S6).

### 3.3 | Binary Systems Between HXE and Cu<sup>+</sup>/Cu<sup>2+</sup> or Zn<sup>2+</sup> Ions

The interaction between **HXE** and Cu<sup>+</sup>/Cu<sup>2+</sup> or Zn<sup>2+</sup> were investigated in the solid state for Cu<sup>2+</sup> and in solution for the three ions, in order to assess their binding modes and affinities. In this context,  $[\text{Cu}(\text{XE})(\text{H}_2\text{O})]^+$ ,  $[\text{Cu}(\text{XE})(\text{H}_2\text{O})]$ , and  $[\text{Zn}(\text{XE})(\text{H}_2\text{O})_x]^+$  refer to the complexes formed *in situ* by mixing a ligand solution with the respective metal ions ( $\text{M} = \text{Cu}^{2+}$ ,  $\text{Cu}^+$ , or  $\text{Zn}^{2+}$ ) at neutral pH. Note that for Cu<sup>+</sup>, we employ the  $[\text{Cu}(\text{XE})(\text{H}_2\text{O})]$  notation for the sake of simplicity, but there is no data about its symmetry or showing that Cu<sup>+</sup> induce the deprotonation of **XE**, in contrast to Cu<sup>2+</sup> and Zn<sup>2+</sup> (see below).

We were able to isolate a monocrystal of the 1:1 complex,  $[\text{Cu}(\text{XE})\text{Cl}]$ , allowing the complete characterization of its structure in the solid state. The main crystal, data collection, and refinement parameters for  $[\text{Cu}(\text{XE})\text{Cl}]$  are given in Table S4. The complex adopts a square-planar geometry ( $\tau_4 = 0.14$ ) [102], in which the fully deprotonated form of the (*E*)-anti ligand binds to Cu<sup>2+</sup> *via* the methylimidazole and thiosemicarbazone moieties (N2, N3, and S1). This indicates that Cu<sup>2+</sup> binding induces deprotonation of **HXE**, which is coordinated in its thioiminolate form. The coordination sphere of Cu<sup>2+</sup> is completed by a chloride ion (Figure 6), resulting in the neutral complex  $[\text{Cu}(\text{XE})\text{Cl}]$ . It is worth noting that the binding of the chloro ligand is expected not to be kept in aqueous solution, where a water ligand will replace it in line with much higher concentration. Bond distances and angles around the metal center can be seen in Table S5. The decrease in the N4–C6 bond length and increase of C6–S1 is in full

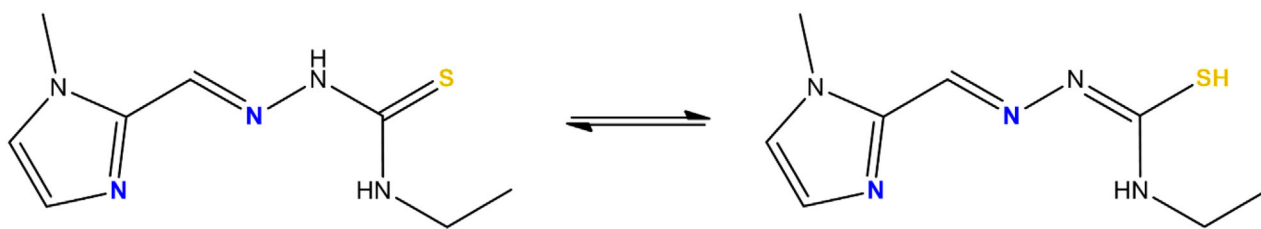


FIGURE 3 | Equilibrium between the thioamide and thioimino tautomers of HXE.

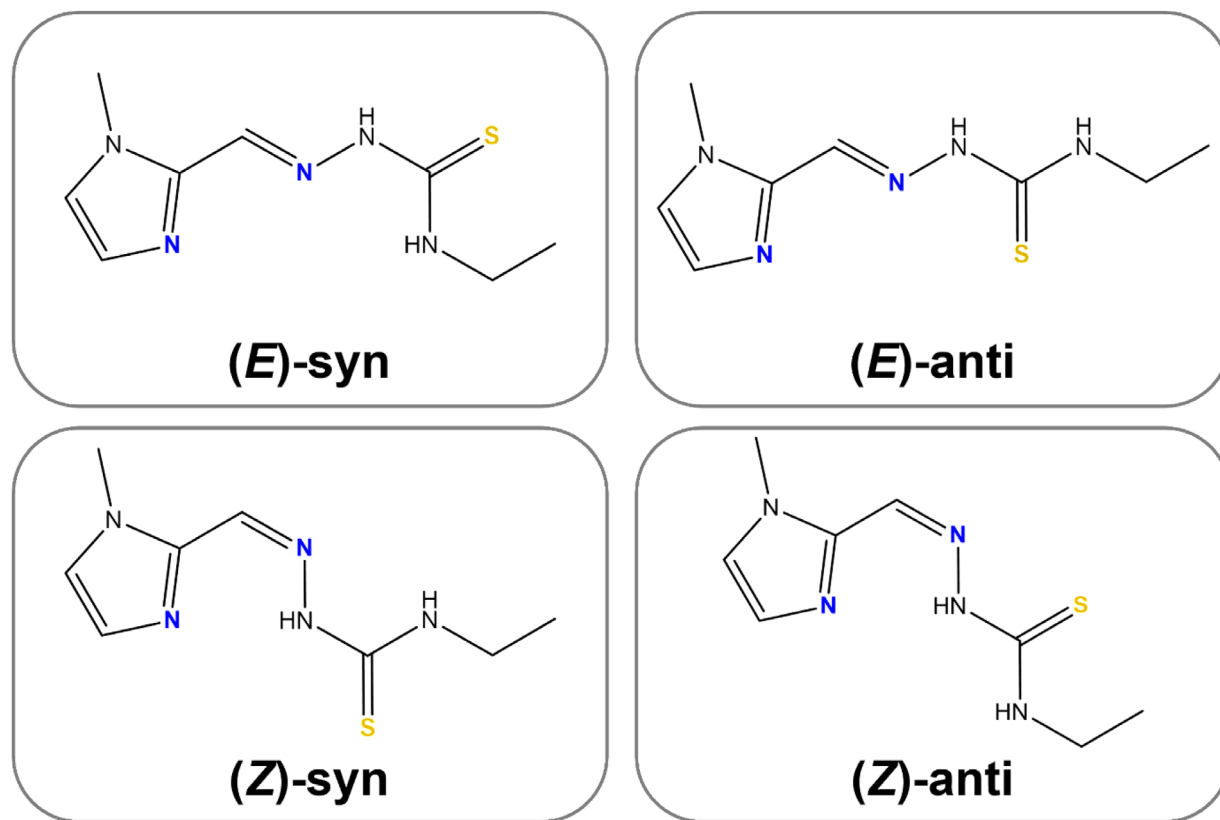


FIGURE 4 | Possible (*E*)/(*Z*) isomers and syn/anti conformers of HXE.

accordance with electron delocalization due to deprotonation of N4 (thioiminolate coordination).

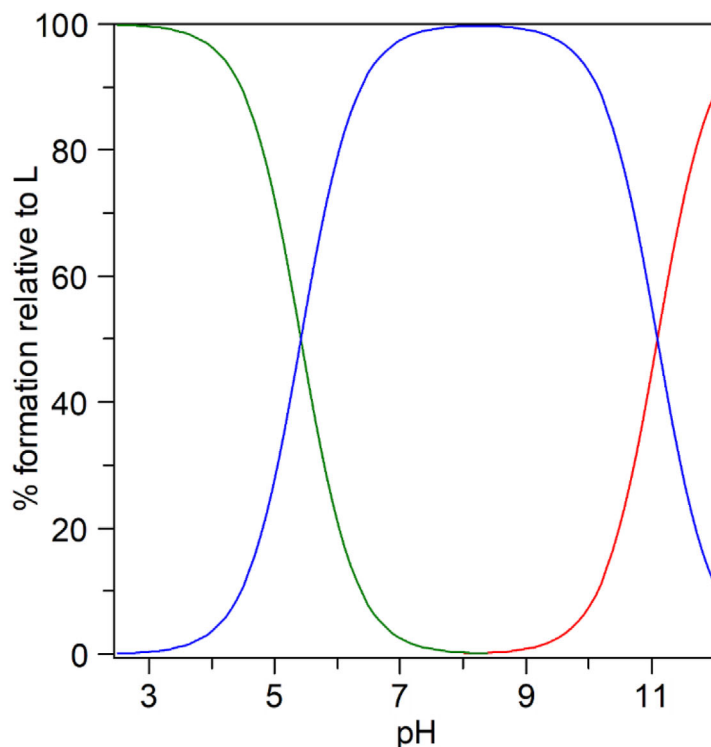
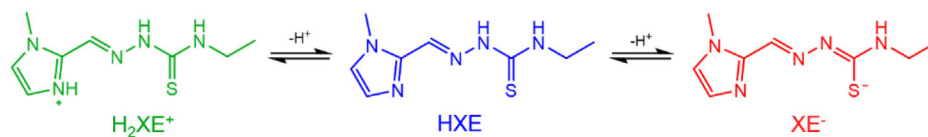
The formation of HXE-based complexes in the presence of equimolar amounts of Cu<sup>2+</sup> and Zn<sup>2+</sup> ions was further studied in aqueous solution by potentiometry. The stability constants calculated are listed in Table 3, in which the protonation constants of the ligand were included for comparison. The best fits (Figure S7) for the titration data were obtained for complex species ML<sup>+</sup> and MLH<sub>-1</sub> for Cu<sup>2+</sup> and MLH<sup>2+</sup>, ML<sup>+</sup>, and MLH<sub>-1</sub> for Zn<sup>2+</sup>. Simulated species distribution curves for a metal:ligand ratio of 1:1 are shown in Figure 7.

For Cu<sup>2+</sup>, the species ML<sup>+</sup>, [Cu(XE)(H<sub>2</sub>O)]<sup>+</sup>, in which the ligand is already fully deprotonated, starts to be formed below pH 3, dominates between pH 3 and ~9, and lasts until pH 10 (Figure 4A). This is, by far (>95%), the main complex present at physiological pH. Deprotonation of the equatorial coordinated water, leading to the neutral hydroxo complex MLH<sub>-1</sub>,

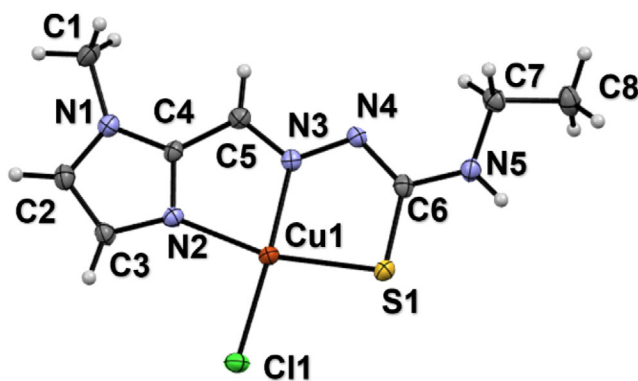
TABLE 3 | Protonation constants of the ligand and stability constants for its Cu<sup>2+</sup> and Zn<sup>2+</sup> complexes (standard deviations in parentheses). Experimental conditions: I (KCl) = 0.2 M, T = 298 K, and [HXE] = 2.0 mM. In the case of the stability constants, [Cu<sup>2+</sup>] or [Zn<sup>2+</sup>] = 2.0 mM.

Species	log β	
	Cu <sup>2+</sup>	Zn <sup>2+</sup>
H <sub>2</sub> L <sup>+</sup>	16.51(10)	
HL	11.09(7)	
MLH <sup>2+</sup>	–	13.89(15)
ML <sup>+</sup>	15.47(5)	9.02(3)
MLH <sub>-1</sub>	6.58(8)	0.84(5)

[Cu(XE)(OH)], occurs at a higher pH: pK<sub>a</sub> [Cu(XE)(H<sub>2</sub>O)]<sup>+</sup> / [Cu(XE)(OH)] = 8.89. It is worth noting that the CuL species formed from HXE is 3 orders of magnitude more stable (15.47 vs. 12.49) than the



**FIGURE 5** | Species distribution curves of the thiosemicarbazonic ligand **HXE** as a function of pH. Experimental conditions:  $I(\text{KCl}) = 0.2 \text{ M}$ ,  $T = 298 \text{ K}$ , and  $[\text{HXE}] = 2.0 \text{ mM}$ .



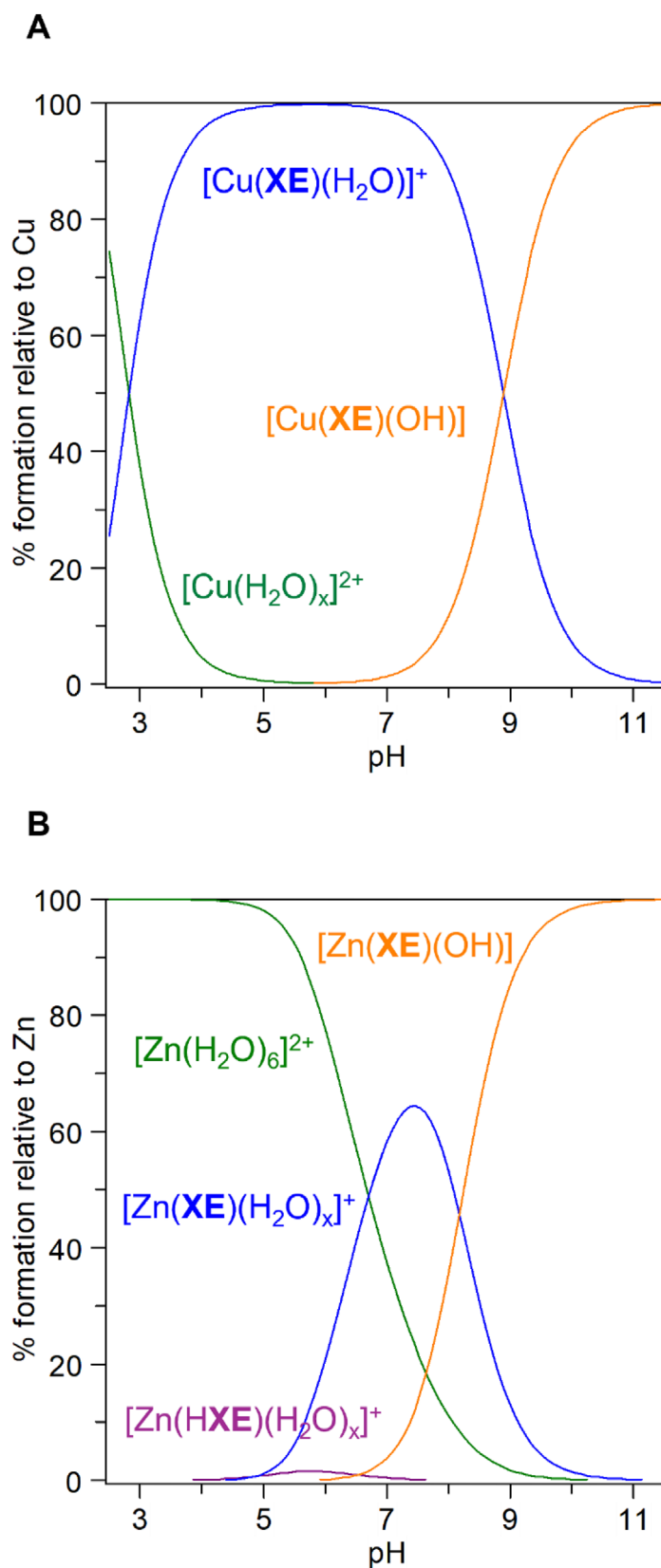
**FIGURE 6** | Ellipsoid plot of  $[\text{Cu}(\text{XE})\text{Cl}]$ . Ellipsoids drawn at 50% probability level.

corresponding one formed by the similar, tridentate ( $\text{N}_2\text{O}$ -donor) 1-methylimidazole-containing *N*-acylhydrazonic ligand **HX1Diox** [65], stressing the importance of the sulfur atom in the thiosemicarbazone **HXE** (which is a  $\text{N}_2\text{S}$ -donor) for the stabilization of the  $\text{Cu}^{2+}$  complex.

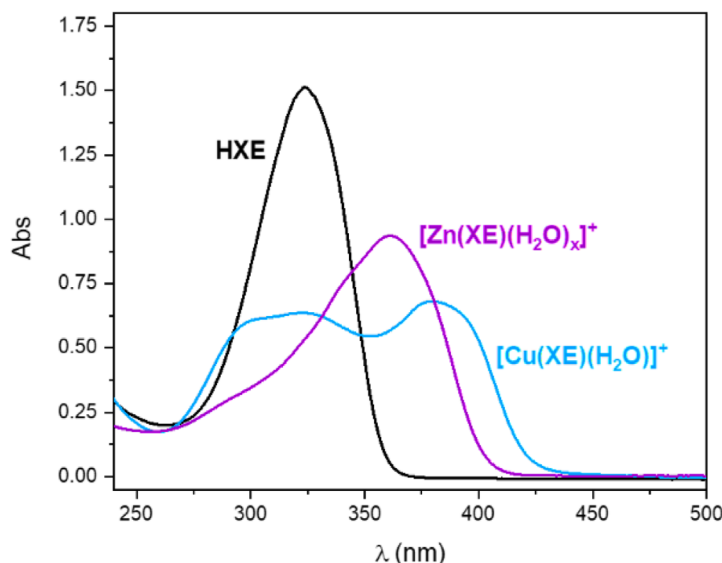
Different from  $\text{Cu}^{2+}$ , the formation of  $\text{Zn}^{2+}$  complexes only starts at pH around 5 (Figure 4B). In more acidic solutions,

the aquo complex  $[\text{Zn}(\text{H}_2\text{O})_6]^{2+}$  is virtually the unique  $\text{Zn}^{2+}$  existing form.  $\text{MLH}^{2+}$  is only marginally present.  $\text{ML}^+$  species  $[\text{Zn}(\text{XE})(\text{H}_2\text{O})_x]^+$ , on the other hand, dominates between pH 6.7 and 8.2, peaks at pH 7.5 (65%) and lasts until pH 9.5. By increasing the pH, deprotonation of a coordinated water molecule also occurs near pH 8.2, leading to the formation of the hydroxo complex  $[\text{Zn}(\text{XE})(\text{OH})]$ , in which coordinated water molecules were excluded for the sake of simplicity, starting at around pH 7. This species becomes predominant from pH 8.2 on. It is interesting to observe that the deprotonation of  $[\text{Zn}(\text{XE})(\text{H}_2\text{O})_x]^+$  occurs at a lower pH than that of  $[\text{Cu}(\text{XE})(\text{H}_2\text{O})]^+$ , which would not be expected based on the HSAB principle. However, although  $\text{Cu}^{2+}$  is usually considered a slightly stronger Lewis's acid than  $\text{Zn}^{2+}$ , this property is dependent on the coordination geometry and also on the nature of ligands. Mareque-Rivas *et al.*, for example, reported  $\text{pK}_a$  values ranging from 7.74 to 5.99 for coordinated water in a series of zinc(II) complexes containing ligands derived from tpa [tris(pyridylmethyl)amine] [103]. Moreover,  $\text{Zn}^{2+}$  forms more stable complexes with softer donors (as **HXE**) than with the harder ones, and this may affect the ability of coordinated water to undergo deprotonation.

The spectroscopic profile of the ligand and its  $\text{Cu}^{2+}$  and  $\text{Zn}^{2+}$  complexes formed *in situ* at pH 7.4 were investigated through UV-Vis (Figure 8). Upon coordination with one equivalent of



**FIGURE 7** | Species distribution curves of complexes formed in (A) 1:1  $\text{Cu}^{2+}$ :HXE and (B) 1:1  $\text{Zn}^{2+}$ :HXE system as a function of pH. Simulation conditions:  $[\text{HXE}] = 50 \mu\text{M}$ ,  $[\text{Cu}^{2+}] = [\text{Zn}^{2+}] = 50 \mu\text{M}$ .



**FIGURE 8** | UV-Vis spectra of **HXE** and its  $\text{Cu}^{2+}$  and  $\text{Zn}^{2+}$  complexes.  $[\text{HXE}] = [\text{Cu}^{2+}] = 50 \mu\text{M}$ ,  $[\text{Zn}^{2+}] = 250 \mu\text{M}$  in 50 mM HEPES pH 7.4.

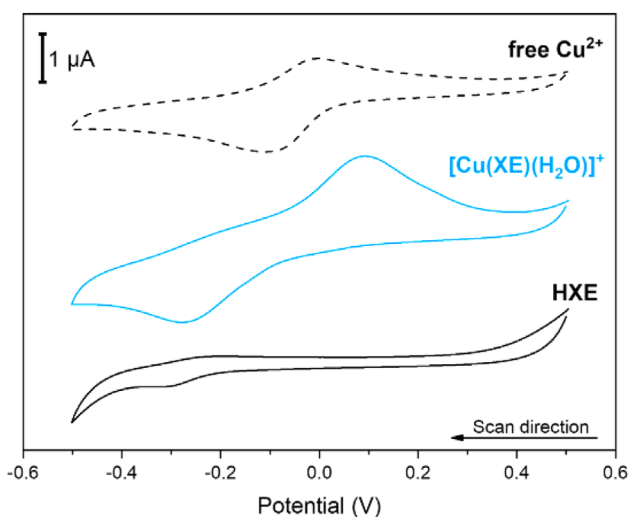
**TABLE 4** | UV-Vis parameters for complexes  $[\text{Cu}(\text{XE})(\text{H}_2\text{O})]^+$  and  $[\text{Zn}(\text{XE})(\text{H}_2\text{O})_x]^+$  in 50 mM HEPES pH 7.4 solution.

	$\lambda_{\text{max}}$ (nm)	$\epsilon$ ( $\text{M}^{-1} \text{cm}^{-1}$ )	Transition
<b>HXE</b>	324	31700	Intra-ligand
$[\text{Cu}(\text{XE})(\text{H}_2\text{O})]^+$	383	13680	LMCT
	626	164	<i>d-d</i>
$[\text{Zn}(\text{XE})(\text{H}_2\text{O})_x]^+$	362	19690	LMCT

either  $\text{Cu}^{2+}$  or  $\text{Zn}^{2+}$ , the intra-ligand band of **HXE** at 324 nm decreases in intensity, and a new LMCT band emerges at 383 nm and 362 nm, respectively. The maximum absorption wavelengths, molar absorptivities, and the corresponding transition assignments for **HXE** and its  $\text{Cu}^{2+}$  and  $\text{Zn}^{2+}$  complexes are summarized in Table 4.

**HXE** and  $[\text{Cu}(\text{XE})(\text{H}_2\text{O})]^+$  were also electrochemically evaluated in a buffered solution pH 7.4 (Figure 9). **HXE** shows a weak reduction process around -250 mV (*vs.* SCE). With the addition of  $\text{Cu}^{2+}$ , a process displaying  $E_{\text{pa}} = +90$  mV and  $E_{\text{pc}} = -270$  mV is observed, in which peak-to-peak separation indicates electrochemical irreversibility. When compared with “free”  $\text{Cu}^{2+}$  in buffer, an increase in  $\Delta E$  due to the coordination of **HXE** is observed, going from approximately 93 in “free copper” to 360 mV in the complex, showing that the ligand makes the redox cycle between  $\text{Cu}^{2+/+}$  sluggish. The increase in the scan rate (Figure S8A) causes an increase in the separation between the anodic and cathodic peaks ( $\Delta E$ ), which depends linearly on the square root of the scan rate (Figure S8B), indicating a diffusion controlled process [104]. The irreversibility of the process may originate from different geometries between  $\text{Cu}^{2+}$  and  $\text{Cu}^+$  bound to **HXE**.

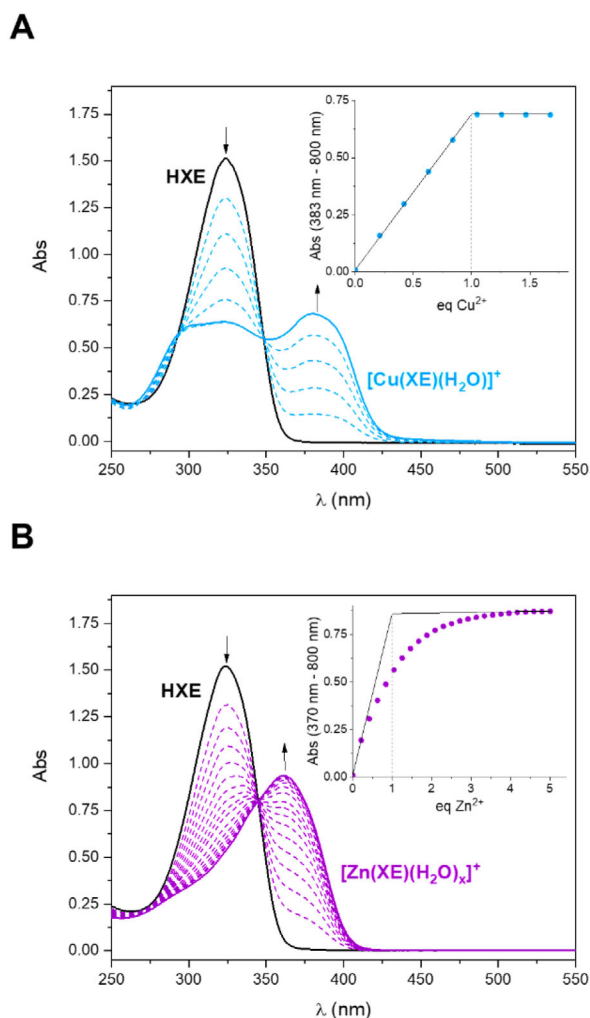
UV-Vis titrations of  $\text{Cu}^{2+}$  and  $\text{Zn}^{2+}$  over a **HXE** solution were performed in order to confirm the stoichiometry and apparent affinity of the complex formed *in situ* at physiological pH ( $\log K_{\text{app}}$ ) and deduce the selectivity of the ligand. The electronic spectra for both metal ions are shown in Figure 10. The com-



**FIGURE 9** | (A) Voltammograms of free  $\text{Cu}^{2+}$  (black dotted line),  $[\text{Cu}(\text{XE})(\text{H}_2\text{O})]^+$  (light blue line) and **HXE** (black line) in 50 mM HEPES pH 7.4 with a scan rate of  $100 \text{ mV s}^{-1}$ . Electrodes: glassy carbon (WE) platinum wire (CE), and saturated calomel electrode (RE).

plexation of the metal ions can be followed by the appearance of the LMCT band centered at 383 nm ( $\epsilon = 13680 \text{ M}^{-1} \text{cm}^{-1}$ ) for  $\text{Cu}^{2+}$  and 362 nm ( $\epsilon = 19690 \text{ M}^{-1} \text{cm}^{-1}$ ) for  $\text{Zn}^{2+}$ . For both metal ions, the formation of 1:1 complexes under these conditions is observed (see inset in Figure 10). For  $\text{Cu}^{2+}$ , the concentration range used for the experiments does not allow to have an equilibrated reaction and, thus, the affinity cannot be determined. In contrast, the apparent affinity for  $\text{Zn}^{2+}$  could be evaluated as described in the methodology section (Figure S9), obtaining  $\log K_{\text{app}} \{[\text{Zn}(\text{XE})(\text{H}_2\text{O})_x]^+\} = 5.0 \pm 0.1$ .

To determine the conditional affinity of **HXE** for  $\text{Cu}^{2+}$  ions at pH 7.4, competition assay was performed using the well-known ATCUN (Amino-Terminal Cu and Ni binding motif) peptide GGH [105–107]. This peptide binds  $\text{Cu}^{2+}$  with a square planar geometry through four nitrogen atoms (the terminal amine, the



**FIGURE 10** | UV-Vis spectra of **HXE** solution after the addition of increasing amounts of (A)  $\text{Cu}^{2+}$  and (B)  $\text{Zn}^{2+}$ .  $[\text{HXE}] = 50 \mu\text{M}$  in 50 mM HEPES pH 7.4.

$\text{N}^{\delta}$  of the Im ring of histidine at the third position and the two deprotonated amides in peptide backbone in between) [107, 108]. A value of 12.7 for  $\log K_{\text{GGH-Cu}}$  was determined by Noormägi *et al.* using competition with HSA and monitored by LC-ICP-MS [109]. This value is consistent with the binding constant previously determined by a thorough potentiometric study, showing a value of  $12.215 \pm 0.001$  at pH 7.4 but for the nonamidated GGH peptide [110]. Our experimental design involved the addition of different GGH equivalents to a buffered  $[\text{Cu}(\text{XE})(\text{H}_2\text{O})]^+$  solution (pH 7.4). Progression of the reaction, that is  $[\text{Cu}(\text{GGH})]/C_0$ , was determined by the disappearance of the absorbance at 383 nm relative to  $[\text{Cu}(\text{XE})(\text{H}_2\text{O})]^+$  complex. Equilibrium was reached after 180 min (Figure S10). The spectra resulting of successive additions of competitor are shown in Figure 11. Progression of the reaction for each mixture was then plotted in function of the number of equivalents of peptide and the experimental data was fitted using the respective quadratic equation to determine the stability constant of  $[\text{Cu}(\text{XE})(\text{H}_2\text{O})]^+$ , obtaining  $\log K_{\text{cond}} = 12.3 \pm 0.1$ .

For both  $\text{Cu}^{2+}$  and  $\text{Zn}^{2+}$ , the apparent and conditional affinity constants determined by direct titration and competition

experiments, respectively, are in agreement with those deduced from the potentiometric titration (11.8 and 5.4, respectively, at pH 7.4).

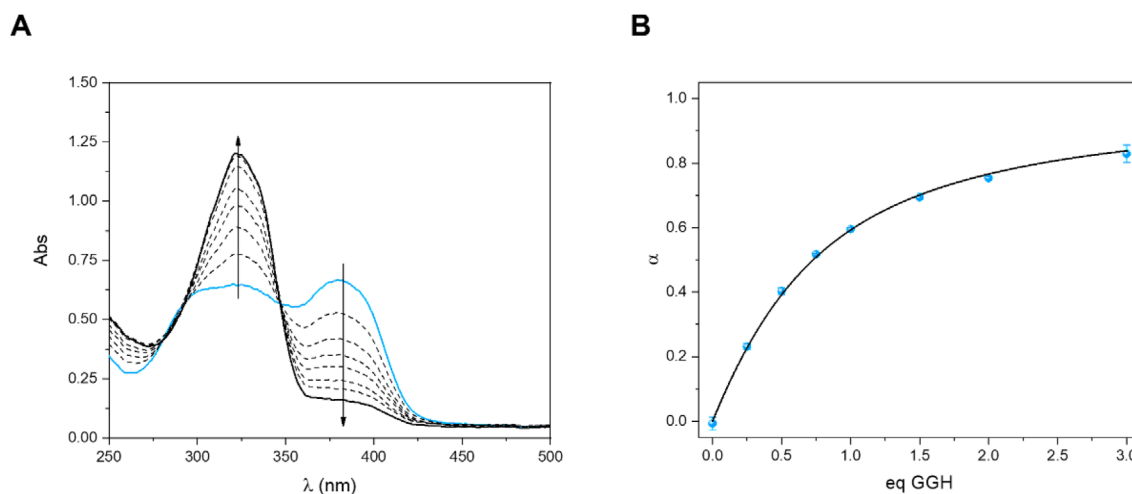
To estimate the affinity of **HXE** toward  $\text{Cu}^+$ , competition with the well-known BCA ligand was performed. BCA forms an  $\text{ML}_2$  complex with  $\text{Cu}^+$ , with an affinity of  $\log \beta_2 = 14.7$  or 17.2 [111, 112]. With the addition of **HXE**, a decrease in the characteristic absorption at 562 nm, related to  $[\text{Cu}(\text{BCA})_2]^{3-}$ , is observed (Figure S11). Absorbance at this wavelength was used to calculate the percentual of  $\text{Cu}^+$  that remains bound to BCA. The apparent stability of  $[\text{Cu}(\text{XE})(\text{H}_2\text{O})]^+$  could be determined as described in Equation (17), resulting in a value of  $\log K_{\text{app}} = 8.7 \pm 0.1$  or  $11.2 \pm 0.1$ , based on either affinity values reported for the BCA complex.

All affinity constants determined for **HXE** in this work and the ones found in the literature for  $\text{A}\beta$  are summarized in Table 5. Since the values reported in literature for the BCA competitor differ ( $\log \beta_2 = 14.7$  or 17.2), the resulting affinities of **HXE** or  $\text{A}\beta$  change accordingly. Hence, to directly compare the  $\text{Cu}^+$  affinity for **HXE** and  $\text{A}\beta$ , either reference value (14.7 or 17.2) was used. This leads to the same difference of  $\text{Cu}^+$  affinity between them, *id est*, between one and two orders of magnitude (8.7 vs. 6.9, and 11.2 vs. 10). On the other hand, **HXE** has an affinity for  $\text{Cu}^{2+}$  approximately 100–1000 times greater than that of  $\text{A}\beta$ . With respect to selectivity [ $s = K_{\text{app}}(\text{M})/K_{\text{app}}(\text{Zn}^{2+})$ , where  $\text{M} = \text{Cu}^{2+}$  or  $\text{Cu}^+$ ], the  $\text{Cu}^{2+}$  versus  $\text{Zn}^{2+}$  selectivity of **HXE** is about 1000 times higher and the  $\text{Cu}^+$  versus  $\text{Zn}^{2+}$  selectivity is about 100 times higher compared to the peptide.

Based on the evaluated affinity values, the **HXE** ligand is expected to remove  $\text{Cu}^+$  and  $\text{Cu}^{2+}$ , but not  $\text{Zn}^{2+}$  from the corresponding  $\text{A}\beta$  complexes. It is worth noting that, for both oxidative states of copper, **HXE** is not expected to effectively compete for the metal ion against their main biological transporters: HSA, in the case of  $\text{Cu}^{2+}$  ( $K_d \sim 10^{-13}$  M) [110], and Ctr1, in the case of  $\text{Cu}^+$  ( $K_d \sim 10^{-14}$  M) [116].

### 3.4 | Copper Removal From $\text{A}\beta_{16}$ by **HXE**

Once the affinity of **HXE** for metal ions was evaluated, the ability of the ligand to abstract the metal ion from  $\text{A}\beta$  peptide was directly studied by UV-Vis and EPR for  $\text{Cu}^{2+}$  (Figure 12A, 12B). By UV-Vis, both  $\text{Cu}^{2+}(\text{A}\beta_{16})$  and  $[\text{Cu}(\text{XE})(\text{H}_2\text{O})]^+$  show a *d-d* band centered at  $\sim 630$  nm. The addition of **HXE** to a  $\text{Cu}^{2+}(\text{A}\beta)$  solution results in a shift of this band to  $\sim 595$  nm, which could suggest the formation of a ternary complex. EPR spectra of **HXE** added to  $\text{Cu}^{2+}(\text{A}\beta_{16})$  shows a different profile when compared to the complexes of reference, with the total disappearance of  $\text{Cu}^{2+}(\text{A}\beta_{16})$  signatures and the appearance of a new signature close to those observed for the  $[\text{Cu}(\text{XE})(\text{H}_2\text{O})]^+$  species, but meaningfully different. Hence, the formation of the ternary species  $[\text{Cu}(\text{XE})(\text{Im}_{\text{A}\beta})]^+$  is inferred. To confirm the formation of a ternary complex in which the equatorial coordination of  $[\text{Cu}(\text{XE})(\text{H}_2\text{O})]^+$  is completed by an Im ring from one of the His residues of  $\text{A}\beta$ , further experiments were performed using Im in the place of the peptide. In that case, through both techniques, similar behaviors were observed (Figure 12C, 12D), confirming the formation of a ternary complex under the experimental conditions used. The spectroscopy



**FIGURE 11** | (A) Selected UV-Vis spectra of a solution of  $[\text{Cu}(\text{XE})(\text{H}_2\text{O})]^+$  with the addition of different equivalents of GGH. (B) Progression of  $\text{Cu}(\text{GGH})$  formation as a function of the number of equivalents of competitor and theoretical curve (best fit). Mean and standard variation between the replicates are shown.  $[\text{HXE}] = 50 \mu\text{M}$ ,  $[\text{Cu}^{2+}] = 45 \mu\text{M}$  in 50 mM HEPES pH 7.4.

**TABLE 5** | Copper and zinc binding affinities with HXE and  $\text{A}\beta$  peptide.

Metal ion	HXE		$\text{A}\beta$ Log $K_{\text{app}}$
	Log $K_{\text{app}}$	Experimental conditions	
$\text{Cu}^{2+}$	$12.3 \pm 0.1$	by competition with the GGH peptide (50 mM HEPES pH 7.4)	9 – 10 [43–46]
	11.8	by potentiometric titration (at pH 7.4)	
$\text{Cu}^+$	$8.7 \pm 0.1$	by competition with BCA (50 mM HEPES pH 7.4 0.3% ACN)	6.9 [47]
	$11.2 \pm 0.1$		~10 [46, 48, 49]
$\text{Zn}^{2+}$	$5.0 \pm 0.1$	by spectrophotometric titration (50 mM HEPES pH 7.4)	5 – 6 [113–115]
	5.4	by potentiometric titration (at pH 7.4)	

**TABLE 6** | UV-Vis and EPR parameters obtained for the binary systems  $\text{Cu}^{2+}(\text{A}\beta_{16})$  and  $[\text{Cu}(\text{XE})(\text{H}_2\text{O})]^+$  and the ternary systems  $[\text{Cu}(\text{XE})(\text{Im}_{\text{A}\beta_{16}})]^+$  and  $[\text{Cu}(\text{XE})(\text{Im})]^+$ , in a 50 mM HEPES pH 7.4 1% DMSO 10% glycerol solution.

	UV-Vis			EPR	
	$\lambda_{\text{max}}$ (nm)	$\epsilon$ ( $\text{M}^{-1} \text{cm}^{-1}$ )	Transition	$g_{\text{II}}$	$A_{\text{II}}$ ( $10^{-4} \text{cm}^{-1}$ )
$[\text{Cu}(\text{XE})(\text{H}_2\text{O})]^+$	383	13680	LMCT	2.20	189
	626	164	<i>d-d</i>		
$[\text{Cu}(\text{XE})(\text{Im})]^+$	604	208	<i>d-d</i>	2.19	212
$[\text{Cu}(\text{XE})(\text{Im}_{\text{A}\beta_{16}})]^+$	591	169	<i>d-d</i>	2.19	209
$\text{Cu}^{2+}(\text{A}\beta_{16})$	633	108	<i>d-d</i>	2.26	218

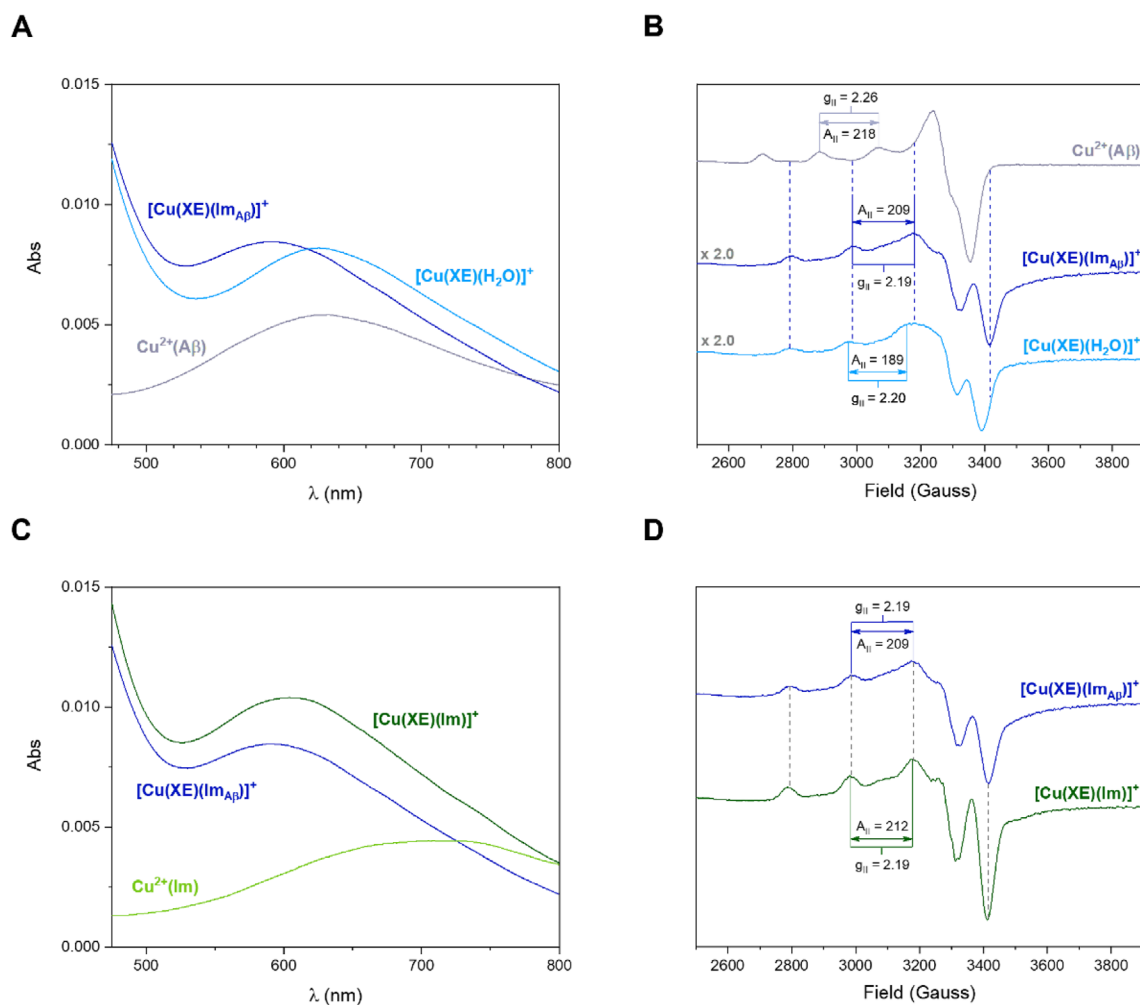
parameters for all the species mentioned above are summarized in Table 6. Proposed structure for  $[\text{Cu}(\text{XE})(\text{Im}_{\text{A}\beta})]^+$  is shown in Figure S12.

Competition for  $\text{Cu}^+$  between  $\text{A}\beta_{16}$  and HXE was monitored by  $^1\text{H}$  NMR (Figure 13). As previously described [28, 56, 117, 118],  $\text{Cu}^+$  coordination to  $\text{A}\beta_{16}$  induces a clear de-shielding of the histidine proton signals involved in metal binding (observed at ~ 6.85, 6.92, and 7.72 ppm for the apo-peptide). However, upon addition of 1 equivalent of HXE, the position of the signals corresponding to the apo- $\text{A}\beta_{16}$  are fully restored.

$[\text{A}\beta_{16}] = [\text{HXE}] = 500 \mu\text{M}$ ,  $[\text{Cu}^+] = 490 \mu\text{M}$  in 200 mM phosphate buffer pH 7.4 97%  $\text{D}_2\text{O}$  3%  $\text{ACN}-d_3$  in the presence of 2 equivalents of sodium dithionite.

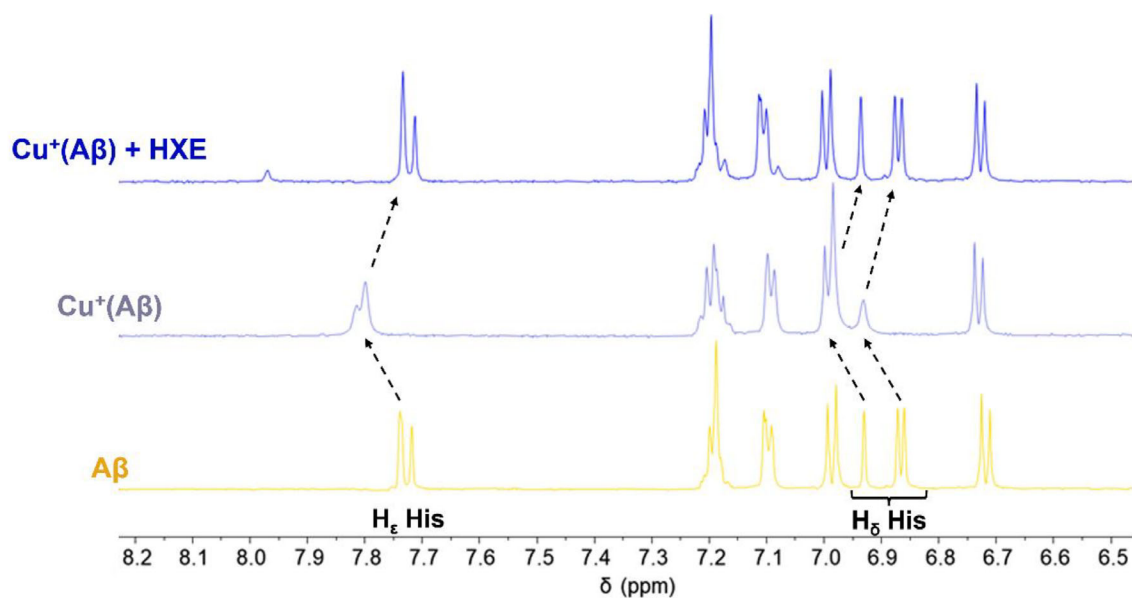
Solutions were prepared anaerobically in an argon purged glove box.

These results highlight HXE efficiency in preventing  $\text{Cu}(\text{A}\beta)$  interactions, fully removing  $\text{Cu}^+$  from the peptide and, instead, forming a ternary  $[\text{Cu}(\text{XE})(\text{Im}_{\text{A}\beta})]^+$  complex with  $\text{Cu}^{2+}$ , indicating a potential ability to mitigate  $\text{Cu}$ -induced  $\text{A}\beta$  toxicity.



**FIGURE 12** | Comparison of UV-Vis and low-temperature (120 K) X-band EPR spectra of  $[\text{Cu}(\text{XE})(\text{Im}_{\text{A}\beta})]^+$  with the binary systems (A and B, respectively) and with the ternary system  $[\text{Cu}(\text{XE})(\text{Im})]^+$  (C and D) at pH 7.4. UV-Vis:  $[\text{HXE}] = [\text{A}\beta] = 60 \mu\text{M}$ ,  $[\text{Im}] = 300 \mu\text{M}$ ,  $[\text{Cu}^{2+}] = 50 \mu\text{M}$  in 50 mM HEPES pH 7.4.

EPR:  $[\text{HXE}] = [\text{A}\beta] = 600 \mu\text{M}$ ,  $[\text{Im}] = 3000 \mu\text{M}$ ,  $[\text{Cu}^{2+}] = 500 \mu\text{M}$  in 50 mM HEPES pH 7.4 1% DMSO 10% glycerol.



**FIGURE 13** |  $^1\text{H}$  NMR spectra of  $\text{A}\beta_{16}$  (yellow),  $\text{Cu}^+(\text{A}\beta_{16})$  (grey) and  $\text{Cu}^+(\text{A}\beta_{16}) + \text{HXE}$  (blue).

### 3.5 | ROS Production in the Presence of HXE

Oxidation of Asc by  $\text{Cu}^{2+}$  or  $\text{Cu}(\text{A}\beta_{16})$  leads to the formation of  $\text{Cu}^+$  in solution, which, in aerobic conditions, acts as a catalyst in the formation of ROS through the stepwise and incomplete reduction of dioxygen. Thus, the loss of the characteristic Asc absorption at 265 nm has been widely used to mirror the production of ROS mediated by  $\text{Cu}^{2+}$  or  $\text{Cu}(\text{A}\beta_{16})$  and to assess the ability of ligands to prevent this process [28, 46, 55, 56, 60, 65, 67, 91, 119–122]. In the presence of  $\text{A}\beta$  and copper, the total consumption of Asc (initially at 100  $\mu\text{M}$ ) occurs after approximately 1500 s after the addition of the metal ion (Figure 14A—grey dotted curve) [56]. Herein, **HXE** was added to an ongoing Asc consumption reaction, when the absorbance was equal to 1. With the addition of 1 equivalent of **HXE** into this system, a significant decrease in the rate of Asc consumption is observed, resulting in a 10-fold slower ROS production. (Figure 14A—dark blue curve).

It is worth noting that, in the experiment performed in the absence of  $\text{A}\beta$  (Figure 14A—light blue curve), the same rate of Asc consumption is observed, in line with the previously observed complete  $\text{Cu}^+$  removal from  $\text{A}\beta$ . In addition, this rate is much lower than that of “free copper” (about 20x faster than for the complex  $[\text{Cu}(\text{XE})(\text{H}_2\text{O})]^+$ ). This agrees with a much more sluggish redox process of copper when bound to **HXE**, as previously detected by cyclic voltammetry. In the case of  $\text{Cu}^{2+}$ , that is present at some extent in the medium, the rate of Asc consumption was similar in the absence or presence of  $\text{A}\beta$ , indicating that the ternary species  $[\text{Cu}(\text{XE})(\text{Im}_{\text{A}\beta})]^+$  characterized by UV-Vis and EPR has the same ability to consume Asc than  $[\text{Cu}(\text{XE})(\text{H}_2\text{O})]^+$  and/or that the concentration of the ternary species in the Asc consumption experiments is too low to have an impact in the ROS generation process. Based on the fact that the ternary species was still detected by UV-Vis at 20  $\mu\text{M}$  concentration (Figure S13), the first hypothesis is preferred.

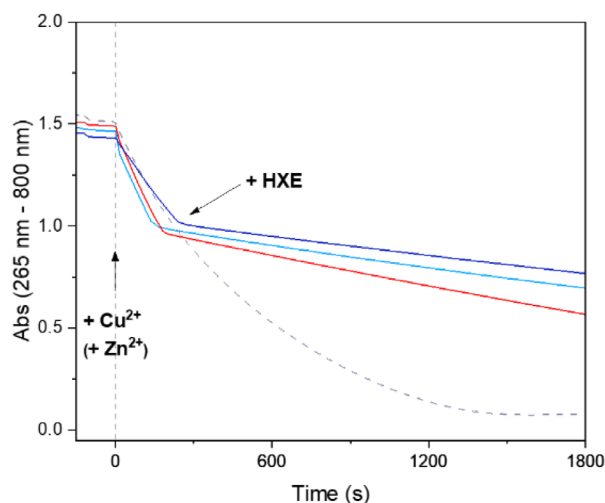
The experiment was also performed in the presence of 10 equivalents of zinc ions as a competitor for the ligand (Figure 14A—red curve). In this case, an increase in the rate of Asc consumption is observed, nearly twice as fast as in the absence of  $\text{Zn}^{2+}$ , although still significantly slower than the control containing only  $\text{Cu}(\text{A}\beta_{16})$ .

Furthermore, the generation of hydroxyl radicals ( $\text{HO}^\bullet$ ) mediated by copper was indirectly monitored by the formation of the fluorescent product 7-OH-CCA over time in the presence of the metal ion, 3-CCA and Asc (Figure 14B). In this case, in the presence of 1 equivalent of **HXE**, a significant decrease in  $\text{HO}^\bullet$  production was observed and neither  $\text{A}\beta$  nor  $\text{Zn}^{2+}$  affected the **HXE** ability to lessen  $\text{HO}^\bullet$  formation. These results are entirely consistent with those obtained in the Asc assay, demonstrating that **HXE** effectively reduces  $\text{Cu}(\text{A}\beta_{16})$ -induced ROS generation.

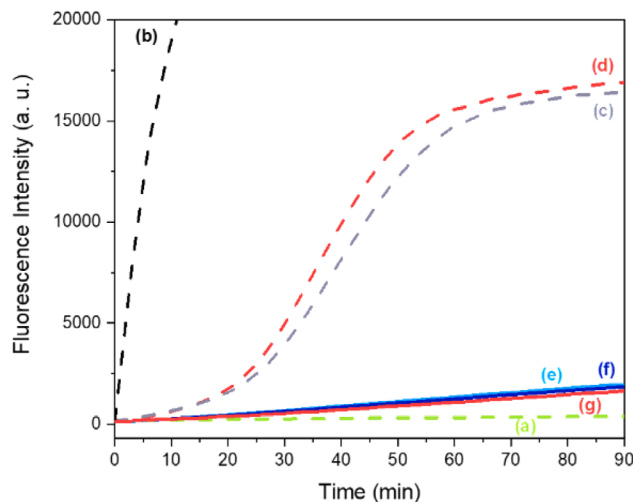
### 3.6 | Impact of HXE on the $\text{A}\beta_{40}$ Aggregation Modulated by $\text{Cu}^{2+}$ and $\text{Zn}^{2+}$

Finally, the effect of **HXE** on the aggregation of  $\text{A}\beta_{40}$  was evaluated in the absence and presence of  $\text{Cu}^{2+}$  and  $\text{Zn}^{2+}$  using ThT as the classical fluorescent reporter, that allows to monitor the kinetics of self-assembly of the peptide (Figure 15A) [123–

## A

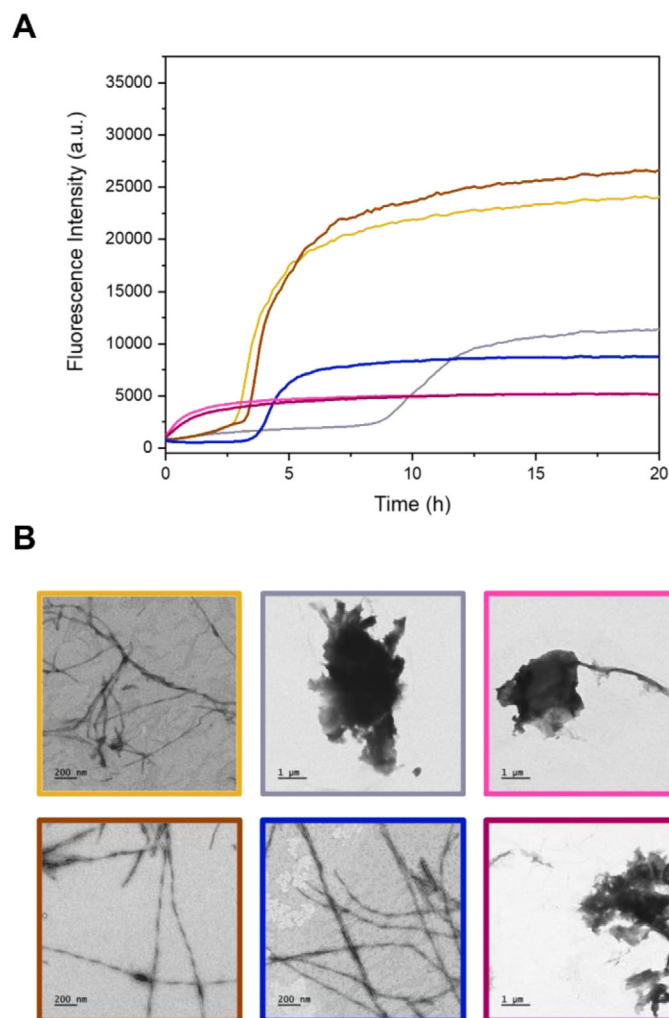


## B



**FIGURE 14** | (A) Ascorbate consumption for:  $\text{Cu}(\text{A}\beta_{16})$  (grey dotted curve),  $[\text{Cu}(\text{XE})(\text{H}_2\text{O})]^+$  (light blue curve),  $\text{Cu}(\text{A}\beta_{16})$  + 1 equivalent **HXE** (dark blue curve) and  $\text{Cu}(\text{A}\beta_{16})$  + 10 equivalents  $\text{Zn}^{2+}$  + 1 equivalent **HXE** (red curve). Ascorbate is first added, then the  $\text{A}\beta$  peptide, and the metal ions. **HXE** is added when the absorbance reaches about 1.0.  $[\text{HXE}] = [\text{A}\beta_{16}] = 12 \mu\text{M}$ ,  $[\text{Cu}^{2+}] = 10 \mu\text{M}$ ,  $[\text{Zn}^{2+}] = 120 \mu\text{M}$ ,  $[\text{Asc}] = 100 \mu\text{M}$  in 100 mM HEPES pH 7.4. (B) Fluorescence curve of the formation of 7-OH-CCA induced by  $\text{Cu}^{2+}$ . (a) Control - 3-CCA + Asc, (b) Cu, (c)  $\text{Cu}(\text{A}\beta_{16})$ , (d)  $\text{Cu}(\text{A}\beta_{16})$  +  $\text{Zn}^{2+}$ , (e)  $[\text{Cu}(\text{XE})(\text{H}_2\text{O})]^+$ , (f)  $\text{Cu}(\text{A}\beta_{16})$  + **HXE** and (g)  $\text{Cu}(\text{A}\beta_{16})$  +  $\text{Zn}^{2+}$  + **HXE**.  $[\text{HXE}] = [\text{A}\beta_{16}] = [\text{Zn}^{2+}] = 12 \mu\text{M}$ ,  $[\text{Cu}^{2+}] = 10 \mu\text{M}$ ,  $[\text{Asc}] = 500 \mu\text{M}$ ,  $[3\text{-CCA}] = 500 \mu\text{M}$  in 50 mM phosphate buffer pH 7.4.

127], and through TEM [67, 128–131], in order to characterize the morphology of the aggregates (Figure 15B). For the apo-peptide, a sigmoidal ThT curve is obtained, along with the formation of long and twisted fibrils as observed by TEM. With the addition of **HXE** on  $\text{A}\beta_{40}$ , no difference in the aggregation kinetics or in the microscopy image is observed, which leads to the hypothesis that the ligand does not interact with the apo-peptide. The kinetics of  $\text{Cu}^{2+}(\text{A}\beta_{40})$  displays a different profile. As



**FIGURE 15** | (A) Average of aggregation kinetic curves and (B) corresponding TEM images of Aβ<sub>40</sub> (yellow), Cu<sup>2+</sup>(Aβ<sub>40</sub>) (grey), Zn<sup>2+</sup>(Aβ<sub>40</sub>) (violet), Aβ<sub>40</sub> + HXE (brown), Cu<sup>2+</sup>(Aβ<sub>40</sub>) + HXE (blue) and Zn<sup>2+</sup>(Aβ<sub>40</sub>) + HXE (pink) in 100 mM HEPES pH 7.4. [Aβ] = [HXE] = 20 μM, [Cu<sup>2+</sup>/Zn<sup>2+</sup>] = 18 μM, [ThT] = 10 μM and [EDTA] = 20 nM.

already observed in other studies, the presence of 0.9 equivalent of Cu<sup>2+</sup> promoted a two-step process with a first rapid and weak ThT fluorescence increase and a second sigmoidal process that occurs later compared to the apo-Aβ [132–134]. The decrease in the fluorescence intensity were related to the stabilization of more amorphous aggregates, as also observed in TEM images [23, 24, 26, 135, 136]. The addition of 1 equivalent of HXE on the Cu<sup>2+</sup>(Aβ<sub>40</sub>) system leads to a sigmoidal curve with a similar  $t_{1/2}$  as apo-Aβ but with a level of final ThT fluorescence intensity that is about 40% of that observed for the apo-Aβ. Additionally, in the presence of HXE, fibrillar aggregates are recovered. This may be related to the formation of a ternary species, [Cu(XE)(Im<sub>Aβ</sub>)]<sup>+</sup>, that was detected by UV-Vis when using the Aβ<sub>16</sub> fragment at similar concentration (Figure S13). The formation of the ternary species may leave to Aβ its ability to self-assemble but to a slightly different morphology with distinct response to ThT. Note that the possibility of having inner-filter effect has been ruled out based on the low absorptivity of the HXE-based Cu<sup>2+</sup> complexes in the dedicated wavelength range. The recovery of the kinetics parameters and fibrillar structure induced by HXE indicates that the ligand can modulate the Cu<sup>2+</sup>(Aβ<sub>40</sub>) aggregation pathway, deflecting it from the generation of soluble oligomeric species,

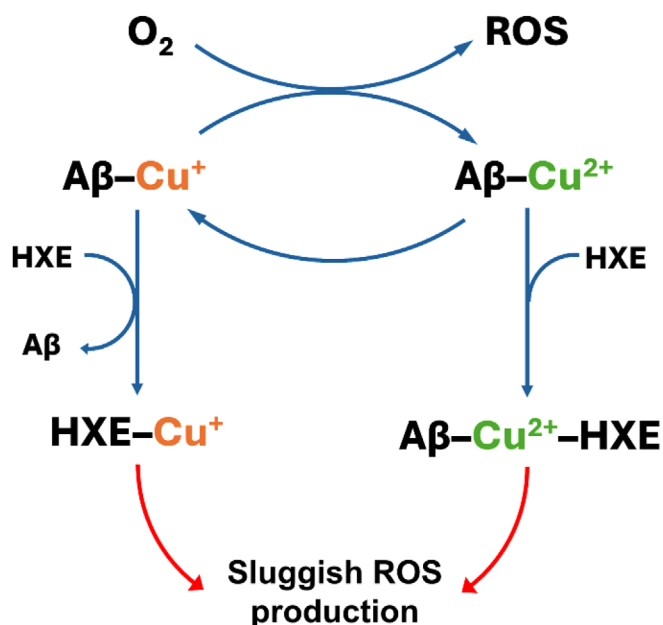
widely described as the most neurotoxic forms, and promoting the formation of mature fibrils, which exhibit reduced cellular toxicity [137].

In presence of Zn<sup>2+</sup>, Aβ aggregation data similar to those reported in the literature were obtained, with a rapid nonsigmoidal process [24, 81, 133, 138]. The addition of HXE did not impact Zn<sup>2+</sup>(Aβ<sub>40</sub>) aggregation kinetics or resulting aggregates morphology, in line with a weaker to similar affinity for Zn<sup>2+</sup> of the HXE versus the Aβ ligands (Table 5).

Kinetic curves of all replicates are shown in Figures S14, S15 and the respective kinetic parameters can be found in Table S6.

#### 4 | Conclusions

High extracellular levels of copper have been widely associated with the progression of AD [11]. In particular, the interaction between Cu ions and the Aβ peptide favors the formation of toxic aggregates and the generation of ROS due to the cycling between Cu<sup>+</sup> and Cu<sup>2+</sup> [27]. In this context, chelating agents



**FIGURE 16** | Overview of Cu<sup>+</sup>/Cu<sup>2+</sup> chelation by HXE and its impact on Aβ(Cu)-mediated ROS generation.

have been proposed as a promising therapeutic approach to prevent this interaction [5, 32–34, 37, 40]. However, to date, no chelating agent has shown significant clinical efficacy [42, 51], with most being designed to specifically target Cu<sup>2+</sup>. In this work, we report the synthesis and characterization, both in the solid state and in solution, of a new 1-methylimidazole-containing thiosemicarbazone (HXE). Due to the presence of the biocompatible imidazole group, the compound shows a good solubility in aqueous medium and low toxicity, as demonstrated against HT-22 mouse hippocampal neuronal cells. In addition, all pharmacokinetic parameters predicted *in silico* are within the expected values for compounds with the potential to cross the BBB. HXE forms 1:1 complexes in pseudo-physiological solution with Cu<sup>2+</sup>, Cu<sup>+</sup>, and Zn<sup>2+</sup>, presenting the respective affinity constants of log  $K_{app}$  = 12.3, 8.7 and 5.0. These values indicate that the ligand is highly selective for both oxidation states of copper over zinc, a characteristic which is extremely important, given the high concentration of zinc present in the synaptic cleft. HXE has an affinity for Cu<sup>2+</sup> approximately 100–1000 times greater than that of Aβ. Regarding Cu<sup>+</sup>, the difference is between one and two orders of magnitude in favor of our ligand. HXE is, in fact, very efficient in modulating Cu(Aβ) interactions, fully removing Cu<sup>+</sup> from the peptide and, instead, forming a ternary [Cu(XE)(Im<sub>Aβ</sub>)]<sup>+</sup> complex with Cu<sup>2+</sup>. Ternary complexes may be involved in an alternative mechanism of metal passivation, and their formation can be considered, in many respects, desirable. The group of Mi Hee Lim, for example, described ternary complexes of Cu<sup>2+</sup>(Aβ) with bidentate chemical regulators that can specifically modulate Cu-induced Aβ aggregation [139, 140]. Consistent with the HXE properties demonstrated in this study (Figure 16), the ligand was able to significantly reduce Cu(Aβ)-mediated ROS production, even in the presence of 10 equivalents of zinc. HXE also restored the half-time ( $t_{1/2}$ ) of Cu<sup>2+</sup>(Aβ<sub>40</sub>) aggregation to levels comparable to that of the apo form of the peptide and induced the formation of fibrillar structures typical of those of apo-Aβ aggregates.

Together, our results demonstrate that the new thiosemicarbazone HXE presents a promising profile to modulate Cu<sup>+</sup>(Aβ) and Cu<sup>2+</sup>(Aβ) interactions, thus mitigating Cu-induced Aβ toxicity. In this sense, this work contributes not only to the understanding of the bioinorganic mechanisms of AD, but also to the development of ligands with novel structural motifs and a real therapeutic potential.

### Authors Contribution

CH, NAR, CE: Conceptualization; BM, CE, CH: Writing, Formal analysis, Investigation, Review & editing; AG, MVC, AB, SML, JO, CK: Writing, Formal analysis, Investigation; NAR, CH: Resources.

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### Conflicts of Interest

The authors declare no conflict of interest.

### Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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### Supporting Information

Additional supporting information can be found online in the Supporting Information section.

**Supporting File 1:** chem70495-sup-0001-SuppMat.pdf.