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Arylhydrazone ligands as Cu-protectors and -catalysis promoters in the azide–alkyne cycloaddition reaction†

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A series of water soluble copper(II) complexes, $[Cu(\kappa O^1O^2N\text{-}H_2L^1)(H_2O)_2]\cdot 2H_2O$ (**2**), $[Cu(\kappa O\text{-}H_3L^1)_2(H_2O)_4]$ (**3**), $[Cu(\kappa O\text{-}H_4L^2)_2(H_2O)_4]$ (**5**) and $[Cu(H_2O)_6]\cdot 2H_2L^3\cdot 2(CH_3)_2NCHO$ (**7**), were prepared by the reaction of $Cu(NO_3)_2\cdot 3H_2O$ with sodium (*Z*)-2-(2-(1-amino-1,3-dioxobutan-2-ylidene)hydrazineyl)benzenesulfonate, $[Na(\mu_4\text{-}1{:}2\kappa O^1,2\kappa O^2,3\kappa O^3,4\kappa O^4\text{-}H_3L^1)]_n$ (**1**; for **2** and **3**), sodium (*Z*)-3-(2-(1-amino-1,3-dioxobutan-2-ylidene)hydrazineyl)-4-hydroxybenzene-sulfonate, $[Na(\mu\text{-}1\kappa O^1,2\kappa O^2\text{-}H_4L^2)]_2$ (**4**; for **5**) or sodium (*Z*)-2-(2-(1,3-dioxo-1-(phenylamino)butan-2-ylidene)hydrazineyl)naphthalene-1-sulfonate, $[Na(\mu\text{-}1\kappa O^1O^2,2\kappa O^3\text{-}H_2L^3)(CH_3OH)_2]_2$ (**6**; for **7**). Compounds **1–7** were fully characterized, also by single-crystal X-ray diffraction analysis, and applied as homogeneous catalysts for the azide–alkyne cycloaddition (AAC) reaction to afford 1,4-disubstituted 1,2,3-triazoles. A structure–catalytic activity relationship has been recognized for the first time on the basis of the occurrence of resonance- and charge-assisted hydrogen bond interactions (RAHB and CAHB), in charge and ligand binding modes, enabling the catalytic activity of the compounds to be ordered as follows: $Cu(NO_3)_2 \ll$ **7** (complex salt with RAHB and CAHB) < **3** (with RAHB and CAHB) < **5** (with RAHB) < **2** (neither RAHB nor CAHB). Complex **2**, without such non-covalent interactions, was found to be the most efficient catalyst for the AAC reaction, affording up to 98% product yield after being placed for 15 min, at 125 °C, in a water/acetonitrile mixture under low power (10 W) MW irradiation.

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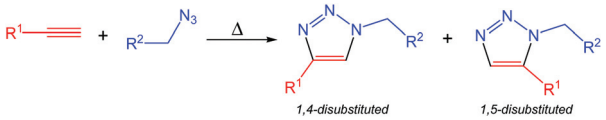
1. Introduction

The azide–alkyne cycloaddition (AAC) reaction (or the Huisgen 1,3-dipolar cycloaddition reaction)[1] leading to the formation of 1,4- or 1,5-disubstituted 1,2,3-triazole derivatives (Scheme 1) has been extensively studied in recent years due to the industrial applications of such products as dyes, corrosion inhibitors, photostabilizers and agrochemicals,[2] in addition to their antiparasitic, antiplatelet, anticancer, antimicrobial, antimalarial, anti-inflammatory, and HIV-1 reverse transcriptase inhibitory properties, among others.[3] The non-catalyzed 1,3-dipolar cycloaddition of organic azides and alkynes is usually slow, requires an elevated temperature and affords a mixture of the 1,4- and 1,5-regioisomers (Scheme 1). The catalytic 1,3-dipolar cycloaddition reaction of azides and terminal alkynes by copper(I) or ruthenium(II) complexes can be completely regioselective and represents a powerful method for the rapid assembly of 1,4-disubstituted-1,2,3-triazoles[4] or 1,5-disubstituted-1,2,3-triazoles.[5] The metal complex catalyzed AAC reaction fulfils the "click criteria"[1c,d] since it meets the conditions of quantitative yields, regioselective conversions, progression under mild conditions with high rates in benign solvents, modularity, broadness of scope, simple work-up or purification steps, *etc.*[4b,6–9] In comparison with the use of other metal complexes, the Cu(I)-promoted AAC reaction has been largely explored because the method is cheap and easy to handle and provides virtually quantitative yields.[4]

There have been several reports of using a Cu(II) species for catalyzing the AAC without adding any reducing agent or



Scheme 1 1,3-Dipolar cycloaddition of organic azides and alkynes.

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base.[8e,9a,g–p] The first example of using solely a Cu(II) salt (copper acetate) for the AAC reaction was reported in 2006,[9g] evidencing the relevant direct participation of Cu(II) in this catalytic process.[4b,9q] Thereafter, several spectroscopic, mechanistic and DFT studies[8e,9r–t] on different Cu(II) salts and complexes clearly showed that Cu(I) species are generated in a short induction period from alkyne–alkyne homocoupling (known as the Glaser reaction),[9u] and are responsible for the progress of the AAC reaction.

The role of the ligands as stabilizers of the copper oxidation state, modulating and increasing the reactivity, has also been revealed.[10a]

Oxygen-based and mixed *N*,*O*-ligands have scarcely been investigated for the AAC reactions, where most of the reported examples were found to be inactive,[10b] require an inert atmosphere[10c] or use a stoichiometric amount of metal.[10d] In addition, the development of the Cu-catalysed 1,3-dipolar cycloaddition reaction in water instead of an organic solvent will contribute to a cleaner green chemistry process.[4b,9] However, catalytic processes in water medium require water-soluble metal catalysts having suitable ligands, *e.g.*, with hydrophilic functionalities.

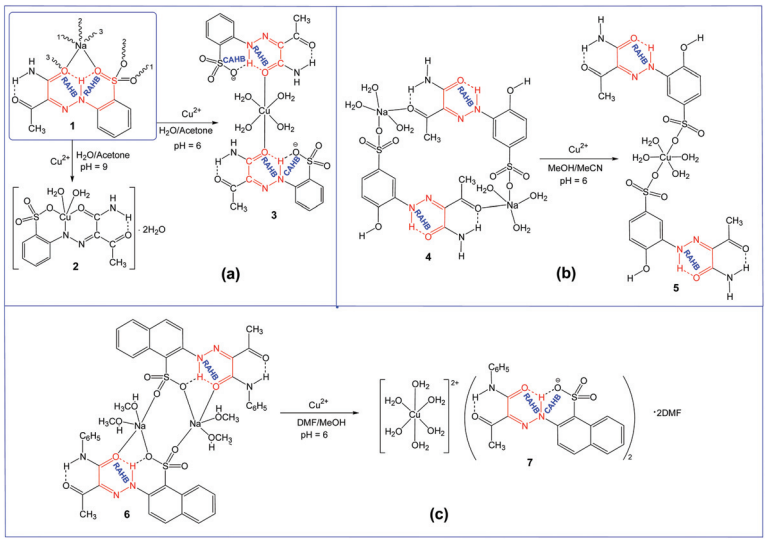
Arylhydrazones of active methylene compounds (AHAMCs) functionalized with carboxylic or sulfonic group(s) have effectively served as versatile ligands in the synthesis of water-soluble copper(II) complexes, thereafter applied as catalysts in oxidation and C–C coupling reactions in aqueous medium.[10e–i] In pursuit of such research work, in this paper we focused on the synthesis of novel water-soluble Cu(II)-AHAMCs complexes with the hydrazone ligands holding a sulfonic group (Scheme 2), their full characterization and the study of their catalytic activity towards the 1,3-dipolar cycloaddition reaction under MW irradiation. We observed an unprecedented relationship between resonance- and charge-assisted hydrogen bonds (RAHB and CAHB, respectively) of the compounds, measured in the solid state, with their catalytic performances.

2. Results and discussion

2.1. Synthesis and characterization of compounds 1–7

Sodium salts of (*Z*)-2-(2-(1-amino-1,3-dioxobutan-2-ylidene) hydrazineyl)benzenesulfonate, $[Na(\mu_4\text{-}1{:}2\kappa O^1,2\kappa O^2,3\kappa O^3,4\kappa O^4\text{-}H_3L^1)]_n$ (**1**), (*Z*)-3-(2-(1-amino-1,3-dioxobutan-2-ylidene)hydrazineyl)-4-hydroxybenzenesulfonate, $[Na(\mu\text{-}1\kappa O^1,2\kappa O^2\text{-}H_4L^2)]_2$ (**4**) and (*Z*)-2-(2-(1,3-dioxo-1-(phenylamino)butan-2-ylidene) hydrazineyl)naphthalene-1-sulfonate, $[Na(\mu\text{-}1\kappa O^1O^2,2\kappa O^3\text{-}H_2L^3)(CH_3OH)_2]_2$ (**6**) (Scheme 2), were prepared by the Japp–Klingemann method[10f–i] by the reaction of aryldiazonium chlorides and β-diketones (3-oxobutanamide or 3-oxo-*N*-phenylbutanamide) in a sodium hydroxide water solution. Reaction of **1** with $Cu(NO_3)_2{\cdot}3H_2O$ in a water–acetone (1 : 5) mixture in the presence or absence of NH_4OH solution (pH 9) leads to $[Cu(\kappa O^1O^2N\text{-}H_2L^1)(H_2O)_2]{\cdot}2H_2O$ (**2**) or $[Cu(\kappa O\text{-}H_3L^1)_2(H_2O)_4]$ (**3**), respectively (Scheme 2). Treatment of **4** or **6** with the same copper salt in a MeOH/MeCN (1 : 2) mixture or a DMF/MeOH (1 : 20) mixture produces $[Cu(\kappa O\text{-}H_4L^2)_2(H_2O)_4]$ (**5**) or $[Cu(H_2O)_6]{\cdot}2H_2L^3{\cdot}2(CH_3)_2NCHO$ (**7**), in this order. The compounds were characterized by elemental analysis, ESI-MS, IR spectroscopy and single crystal X-ray diffraction (see below). They are soluble in water and DMSO and are insoluble in NCMe or chlorinated solvents; the pro-ligands **1**, **4**, and **6** and complex **5** are soluble in MeOH, the latter being also soluble in DMF as in the case of **2** and **3**.

Compounds **1**, **4** and **6** are stabilized in DMSO-d_6 solution in the hydrazone form, as reported for analogues.[10e–i] In fact, ^{1}H-NMR spectra of **1**, **4** and **6** in DMSO-d_6 solution at room temperature show only one signal at δ 14.58, 14.68 and 14.88 respectively, which is assigned to the proton bound to



Scheme 2 Synthesis of water-soluble copper(II) complexes.

the nitrogen atom adjacent to the aryl unit (=N–NH– hydrazone form). The chemical shifts at *ca.* 14 ppm are characteristic of resonance assisted hydrogen bonds (RAHB), while the weak N–H···O bonds are known to display the δ_{N-H} values at the δ range of 7–9 ppm.[10e–i] In the IR spectra, the ν(N–H) and ν(C=O) vibrations of **2** (3183 and 1603 cm^{-1}) and **3** (3108 and 1638 cm^{-1}) are significantly shifted in relation to the corresponding signals of **1** (3138 and 1657 cm^{-1}), the same occurring for **5** (3193 and 1599 cm^{-1}) relative to **4** (3080 and 1606 cm^{-1}) and for **7** (3241 and 1652 cm^{-1}) as compared to **6** (3198 and 1648 cm^{-1}). The following ESI-MS fragmentation peaks were identified: m/z = 284.0 $[H_3L^1]^-$ (for **1**), 383.9 $[Mr - 2H_2O + H]^+$ (for **2**), 67.8 $[Cu(H_2O)_4]^{2+}$ and 284.2 $[H_3L^1]^-$ (for **3**), 300.0 $[H_4L^2]^-$ (for **4**), 67.8 $[Cu(H_2O)_4]^{2+}$ and 300.2 $[H_4L^2]^-$ (for **5**), 410.3 $[H_2L^3]^-$ (for **6**) and 85.8 $[Cu(H_2O)_6]^{2+}$ and 410.5 $[H_2L^3]^-$ (for **7**), accounting for the existence of ionic species in solution, under ESI-MS conditions. Elemental analysis and X-ray crystallography results (Fig. 1) are also in agreement with the proposed formulations.

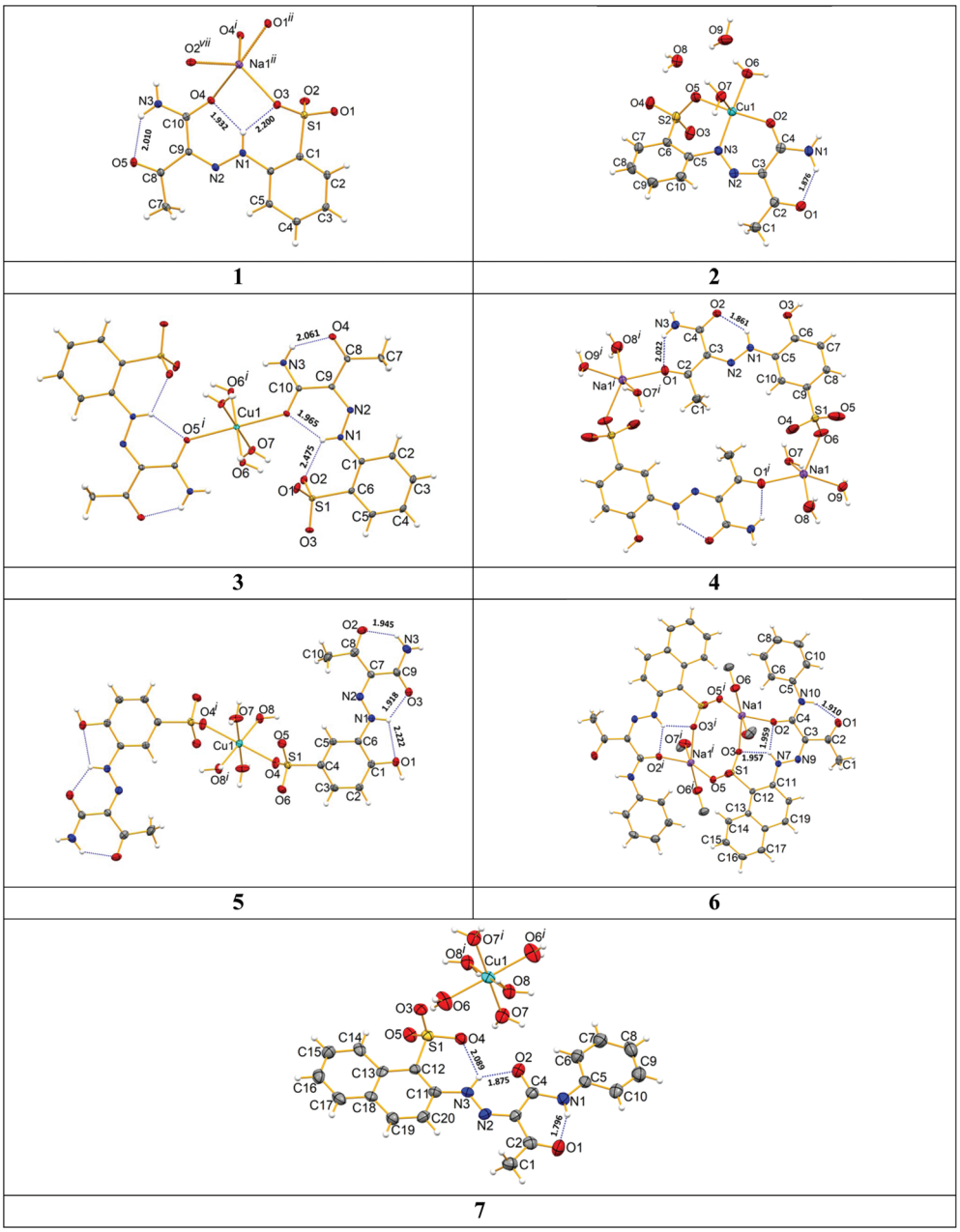


Fig. 1 Ellipsoid plots of **1–7** (drawn at the 30% probability level) with partial atom numbering schemes. The protons of the coordinated methanol in **6** and the DMF molecule in **7** are omitted for clarity. Intramolecular H-bond interactions are shown as dashed blue lines with the O(or N)···H distances in Å. Symmetry operations to generate equivalent atoms: (i) 2 – *x*, –*y*, 1 – *z*; (ii) 2 – *x*, –*y*, 2 – *z*; (vii) 1 + *x*, *y*, *z* (**1**; see also Fig. S1†). (i) –*x*, 1 – *y*, 1 – *z* (**3**). (i) 1 – *x*, –*y*, 2 – *z* (**4**). (i) 2 – *x*, 1 – *y*, 1 – *z* (**5**). (i) 1 – *x*, –*y*, 1 – *z* (**6**). (i) 2 – *x*, –*y*, 1 – *z* (**7**).

2.2. Single crystal X-ray diffraction analysis

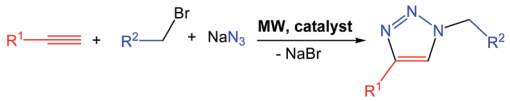
Single crystal X-ray diffraction analysis revealed that the Cu(II) compounds are all monomeric with the metal cations presenting square pyramidal (**2**, τ_5 = 0.14) or octahedral (**3**, **5**) geometries, while those of Na(I) are dimeric (**4** and **6**) or polymeric (**1**), with the metals displaying distorted trigonal bipyramid (**1**, τ_5 = 0.67) or almost perfect square pyramidal conformations [τ_5 = 0.03 (**4**), 0.00 (**6**)]. The compounds have all-O settings around the cations, except **2** where the hydrazone ligand is deprotonated and forces the metal to present a NO_4, instead of an *all*-O, coordination environment. In the remaining compounds the hydrazone ligands are not deprotonated, the positive charges of the metals being balanced exclusively by the sulfonate-centered negative charge (Scheme 2 and Fig. 1). In the 2D polymeric structure of **1** the hydrazone is the sole ligand with the three $O_{sulfonate}$ atoms and the O_{amide}, engaged in coordination to Na(I). For the remaining compounds, water (in **2**–**5**) or methanol molecules (in **6**) are co-ligands. Complexes **3** and **5** hold the $\{Cu^{2+}(H_2O)_4\}$ unit, connecting two organic ligand moieties; however, in the former such binding of L to the cation is through the O_{amide} oxygen, and in the latter it is through the $O_{sulfonate}$.

The NN distances (Table S2,† *ca.* 1.30 Å) are typical single bonds. The M–O_{amide} bond distances (*ca.* 2.30–2.32, Table S2†) are shorter than the M–$O_{sulfonate}$ ones (between 2.33 and 2.39 Å), except for **1** where the reverse is detected (Table S2†). Probably resulting from deprotonation of the ligand, compound **2** is the one that presents the shortest M–O bonds involving that species.

The compounds show several medium to strong intra- and intermolecular hydrogen bond interactions (Table S3 and Fig. S1–S7†), in particular those presenting coordinated water (**2**–**5** and **7**) or methanol (**6**) molecules. Despite the use of a strong base in the syntheses of the arylhydrazone species (see the Experimental), the RAHB, Resonance-Assisted Hydrogen Bond, involving the hydrazone hydrogen interaction with the *O*-sulfonate and/or *O*-carbonyl moiety, is presented in **1**, **4** and **6** (Scheme 2). In these RAHB systems the N···O distances of (Table S3†) 2.823 and 2.602 (for **1**), 2.570 (for **4**) and 2.640 Å (for **6**) confirm strong intramolecular donor–acceptor interactions (Fig. 1).[11] The added NH_4OH conceivably weakens the RAHB systems in **1** on its reaction with $Cu(NO_3)_2{\cdot}3H_2O$ in a water–acetone (1 : 5) mixture, leading to deprotonation of the hydrazone and affording **2**. In the absence of NH_4OH the copper(II) complex **3** is obtained, which has both RAHB and CAHB (Charge-Assisted Hydrogen Bond) systems with donor···acceptor distances of 2.603 and 3.037, respectively. The RAHB systems of the sodium salts of arylhydrazones **4** and **6** (also CAHB for this latter one) were not destroyed by interaction with the Cu(II) salt to give **5** and **7** (Scheme 2 and Fig. 1), in this order, although with a slight weakening when going from **4** to **5**, and a strengthening when comparing **6** and **7**. In contrast, the CAHB interaction in **7** is stronger than that in **6** (2.668 *versus* 2.639 Å, Table S3†).

2.3. Catalytic activity

The catalytic activities of compounds **1**–**7** were tested for the 1,3-dipolar cycloaddition of ethynylbenzene with benzyl bromide in the presence of NaN_3 (Scheme 3) under microwave irradiation in a H_2O/MeCN (v/v, 1/1) mixture and at 125 °C (Table 1, entries 1–7). No reaction takes place in the absence of any metal species or under solvent-free conditions, even in the presence of the arylhydrazone sodium salts **1**, **4** and **6** (Table 1, entries 1, 4 and 6). In contrast, the Cu(II) complexes **2**, **3**, **5** and **7** are active catalysts for the reaction under study to afford 1,4-disubstituted 1,2,3-triazoles, but their catalytic activities strongly depend on their structures, the former being the most active and the latter the least active one (Table 1, compare entries 2, 3, 5 and 7). Only a small amount of 1-benzyl-4-



Scheme 3 Microwave assisted 1,3-dipolar cycloaddition of alkynes with substituted benzyl bromides in the presence of NaN_3 and a catalyst.

Table 1 Optimization of the parameters of the 1,3-dipolar cycloaddition reaction between ethynylbenzene and benzyl bromide in the presence of NaN_3 with **1**–**7** as catalysts[a]

Entry	Catalyst	Amount of catalyst[b] (mol%)	Solvent	Time (min)	Yield[c] (%)
1	**1**	3	H_2O : MeCN	15	—
2	**2**	3	H_2O : MeCN	15	80.3
3	**3**	3	H_2O : MeCN	15	50.4
4	**4**	3	H_2O : MeCN	15	—
5	**5**	3	H_2O : MeCN	15	66.4
6	**6**	3	H_2O : MeCN	15	—
7	**7**	3	H_2O : MeCN	15	29.6
8	—	—	H_2O : MeCN	15	—
9	—	—	Solvent free	15	—
10	$Cu(NO_3)_2{\cdot}3H_2O$	3	H_2O : MeCN	15	7.2
11	**2**	1	H_2O : MeCN	15	34.8
12	**2**	5	H_2O : MeCN	15	80.3
13[d]	**2**	3	H_2O : MeCN	15	61.9
14[e]	**2**	3	H_2O : MeCN	15	78.1
15	**2**	3	H_2O : MeCN	5	51.2
16	**2**	3	H_2O : MeCN	30	80.4
17	**2**	3	H_2O	15	74.1
18	**2**	3	MeCN	15	11.7
19	**2**	3	H_2O : Dioxane	15	55.6
20	**2**	3	H_2O : ^{t}BuOH	15	57.8
21	**2**	3	H_2O : ^{i}PrOH	15	60.0
22	**2**	3	H_2O : EtOH	15	63.3
23	**2**	3	H_2O : MeOH	15	66.4
24	**2**	3	Solvent free	15	Traces (<5)
25[f]	**2**	3	H_2O : MeCN	24 h	51.3

[a] Reaction conditions: Ethynylbenzene (0.33 mmol, 1.1 equiv.), benzyl bromide (0.30 mmol, 1 equiv., limiting reactant), sodium azide (0.33 mmol, 1.1 equiv.), 1.5 mL of solvent (1 : 1 in the case of solvent mixtures), MW irradiation (10 W), 125 °C. [b] Calculated on the basis of benzyl bromide. [c] Isolated yield; calculated on the basis of benzyl bromide. [d] Reaction performed at 70 °C. [e] Reaction performed at 150 °C. [f] Reaction performed under conventional heating (100 °C).

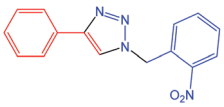
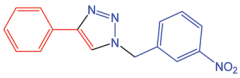
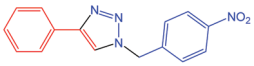
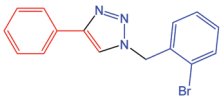
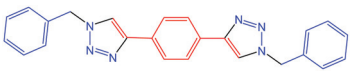
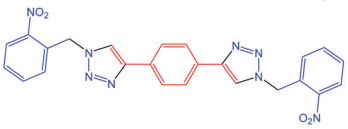
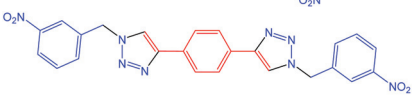
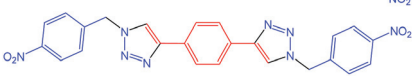
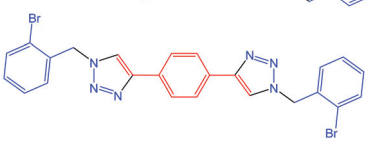
phenyl-1*H*-1,2,3-triazole (7.2%) was obtained in the presence of $Cu(NO_3)_2{\cdot}3H_2O$ under the same reaction conditions (Table 1, entries 8–10). Using **2** as a catalyst for the reaction under study, the increase of its loading up to 3 mol% resulted in a marked yield improvement (Table 1, entries 2, 11 and 12) but further increase of the amount had no effect. The temperature of 125 °C is considered the best for the reaction (Table 1, compare entries 2, 13 and 14) as well as the reaction time of 15 min (Table 1, compare entries 2, 15 and 16). Using MeCN as the sole solvent had an inhibiting effect possibly due to the lack of solubility of NaN_3 and of the catalyst in this solvent (Table 1, entry 18). With water alone we obtained comparatively better yields, but utilizing a water : MeCN mixture led to higher conversions, probably as a result of enhancement of reactant miscibility (Table 1, entries 2 and 17). Apart from MeCN several other organic co-solvents have been tested *viz.* dioxane, ^{t}BuOH, ^{i}PrOH, EtOH and MeOH (Table 1, entries 2 and 19–23), with the H_2O/dioxane mixture falling well below the others (56% yield, Table 1, entry 19) and the H_2O/MeCN revealing to be the best combination (80% yield, Table 1, entry 2). The 1,3-dipolar cycloaddition does not occur under solvent-free conditions (Table 1, entry 24), whereas conventional heating (oil bath, 100 °C) hampers the reactions in comparison with MW irradiation (Table 1, entry 25) in the presence of catalyst **2**.

Under the above optimized experimental conditions, we explored the versatility of catalyst **2** for the 1,3-dipolar cycloaddition of ethynylbenzene or 1,4-diethynylbenzene with substituted benzyl bromides in the presence of NaN_3, and the results are summarized in Table 2. All the substrates produced the expected 1,4-disubstituted 1,2,3-triazoles in good to excellent yields and selectivity. The presence of the strong electron-acceptor nitro group at the phenyl group of benzyl bromide enhances the reaction (97% yield *versus* 80%, entry 1 of Table 2 *versus* entry 2 of Table 1), but its position (*ortho*, *meta* or *para*) appears to have no effect on the yield of the corresponding 1,4-disubstituted 1,2,3-triazole (Table 2, entries 1–3). However, the Br substituent, with a much weaker electron withdrawing ability, has only a low promoting effect (82%, entry 4 of Table 2 *versus* entry 2 of Table 1). When using 1,4-diethynylbenzene instead of ethynylbenzene as a substrate, the reaction is not so effective (Table 2, entries 5–9). All isolated 1,4-disubstituted 1,2,3-triazoles were fully characterized by elemental analysis and NMR spectroscopy (see the ESI†).

Most of the protocols for the synthesis of 1,4-disubstituted 1,2,3-triazoles use long reaction times,[6d,f] toxic solvents (*e.g.* THF and toluene),[9e] costly reagents (Au, Ag, Ir, and Ln complexes),[6d] and may occur in a multistep manner.[6e,9e] Our method is straightforward, uses inexpensive reagents, is performed in aqueous medium and under MW irradiation, achieving conversions that are comparable to other related systems.[12a,b] In addition, our experimental conditions are relatively milder as only 10 W of MW irradiation were applied in a shorter time and in the absence of reducing agents. In terms of the obtained high yields and regioselectivities for AAC reactions, the efficiency of our complexes as catalysts is comparable with those of other reported copper complexes bearing phosphines,[12c–f] tris(triazolyl)methanols,[12b,g] tris(pyrazolyl)methanes[12h,i] and N-heterocyclic carbenes.[12i–k] However, our water soluble AHAMCs have an important advantage over these ligands as they are easily prepared from readily available and cheap starting materials using a very simple and mild synthetic protocol, in addition to their high stability in air and water and under several reaction conditions. Moreover, all catalysts of this study exhibit good solubility in water and using water-soluble catalysts simplified their separation from the hydrophobic product (1,4-disubstituted 1,2,3-triazole). This fact is relevant for the industrial application of homogeneous catalysis since an easy way for catalyst separation can lower the economical and environmental costs of the chemical process.

The discussion of the effect of the structure on the catalytic activity of the compounds, with the aiming of finding a structure–catalytic activity relationship, is not straightforward.

Table 2 1,3-Dipolar cycloaddition of ethynylbenzene or 1,4-diethynylbenzene with substituted benzyl bromides in the presence of NaN_3 catalysed by 3 mol% of **2**[a]

Entry	Product	Yield[b], %
1		97
2		98
3		99
4		82
5		77
6		86
7		88
8		91
9		75

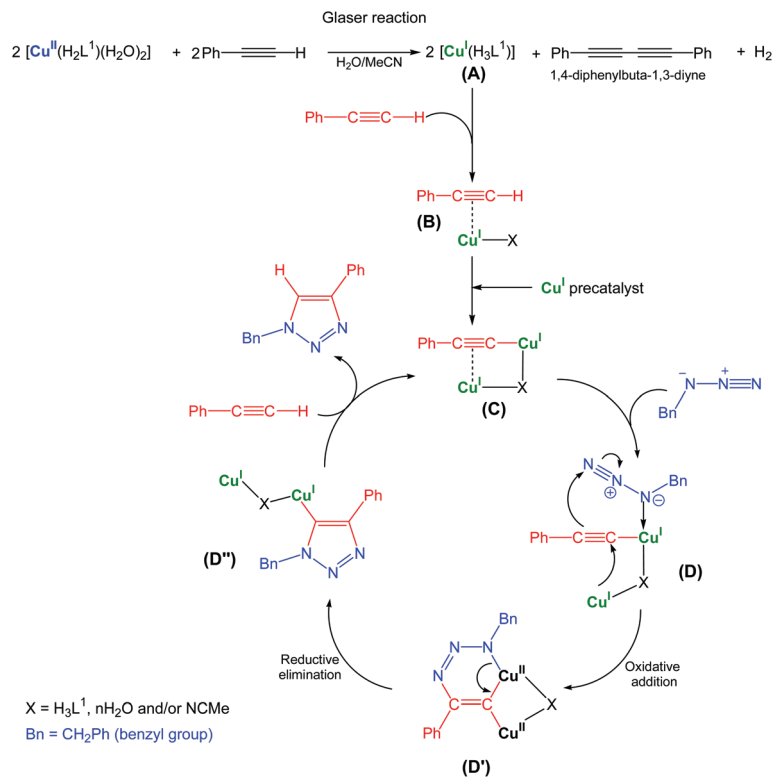
[a] Reaction conditions: 3.0 mol% of catalyst **2**, ethynylbenzene (0.33 mmol, 1.1 equiv.) or 1,4-diethynylbenzene (0.33 mmol, 1.1 equiv.), substituted benzyl bromides (0.30 mmol, 1 equiv. or 0.60 mmol, 2 equiv., limiting reactant), sodium azide (0.33 mmol, 1.1 equiv. or 0.63 mmol, 2.1 equiv.), 1.5 mL H_2O/MeCN (1 : 1), MW irradiation (10 W), 125 °C, 15 min. [b] Isolated yield; calculated on the basis of substituted benzyl bromide.

Considering that dissolution in water of the copper(II) nitrate salt should lead to the formation of the hexaaqua complex and that a low catalytic activity is observed, we believe that the catalytic activity is promoted by the hydrazone ligand. The low activity of the complex salt **7** can be related to the enforced stabilization of the hydrazone anion simultaneously through RAHB and CAHB, which hampers its coordination to copper; despite their detection in the solid state, these interactions can also occur in water solution. Since compounds **2**, **3** and **5** are more catalytically active than **7**, coordination of the hydrazone species to the metal cation has been proved to favour the catalysis. Moreover, the RAHB and CAHB contacts in the coordinated hydrazone in **3** inhibit its performance, which is lower than that of complex **5** in view of the non-existent CAHB system in the latter. Compound **2**, the most active catalyst, lacks both H-contact interactions. However, other types of factors of the catalytic activity can be considered on the basis of the expected mechanism, as discussed below.

A conceivable mechanism for the CuAAC reaction catalysed by **2** is depicted in Scheme 4, taking into consideration a collection of key mechanistic aspects based on reported computational and experimental studies,[13] in particular: (i) alkyne–alkyne homocoupling with the generation of a Cu(I) species (**A**), in an initial short induction period (Glaser reaction),[9u] which is the one responsible for the catalytic reaction progress; (ii) π-coordination of the ethynylbenzene to the Cu(I) site (**B**) promoting CH-acidity of the terminal alkyne and the formation of the σ, π-coordinated acetylide in a di-Cu(I) intermediate (**C**);[3a,b,g] (iii) involvement of dinuclear species (**C** and **D**s) despite the mononuclear nature of the precatalyst;[13f,h] (iv) acetylide–azide coupling upon oxidative addition followed by reductive elimination steps; and (v) the role of the arylhydrazone ligand acting as a stabilizer of the Cu(I) centre and as proton acceptor/donor species. The primary participation of the azide molecule by coordination to **2** in the aforementioned induction period of formation of the Cu(I) active catalyst should not be disregarded, as well as the recognised facile binding of azide to Cu(II) relatively to Cu(I) compounds.[13i]

To find some evidence for the involvement of some of the aforementioned species in our system, reactions were performed under ESI-MS$^+$, namely by mixing complex **2** (0.2 mmol) and ethynylbenzene (1 mmol) in a 1 : 1 water : acetonitrile solution, and by mixing the reaction components using the amounts specified in Table 1, entry 12.

The ESI-MS$^+$ spectrum of the first mixture is shown in Fig. S21† and shows evidence for the occurrence of the Glaser reaction indicated in Scheme 4, *viz.*, the product of the alkyne–alkyne homocoupling reaction $\{PhC{\equiv}C{-}C{\equiv}CPh + H_2O + H\}^+$ (*m*/*z* 221) and the formation of $\{Cu^I(H_3L^1)\}^+$ (*m*/*z* 347), together with the related solvated groups $\{Cu^I(H_3L^1) + H_2O\}^+$ (*m*/*z* 365), $\{Cu^I(H_3L^1) + MeCN\}^+$ (*m*/*z* 388) and $\{Cu^I(H_3L^1) + H_2O + MeCN\}^+$ (*m*/*z* 406), all these revealing variants of intermediate **A**; the peak at *m*/*z* 449 can correspond to $\{Cu^I(H_3L^1)(PhCCH)\}^+$ (intermediate **B**). This experiment also shows evidence for the formation, under ESI-MS$^+$ conditions, of a dinuclear species involving solely the protonated hydrazone ligand $\{Cu^I_2(H_3L^1) +$



Scheme 4 Postulated mechanism of the Cu–AAC reaction.

H_2O + MeCN$\}^+$ (*m*/*z* 468) and of another dinuclear species with acetylene $\{Cu^I_2(H_3L^1)(PhC{\equiv}CH)_2 + 3H_2O + MeCN\}^+$ (*m*/*z* 709).

The set of fragmentation peaks in the ESI-MS$^+$ spectrum of the second mixture (Fig. S22†) allowed the identification of the triazole product (*m*/*z* 236), as well as the hydrated sodium salt of the ligand $\{H_3L^1 + Na + H_2O\}^+$ (*m*/*z* 326). Evidence for the coordination of the organic azide is given by $\{Cu^I(H_3L^1)(PhCH_2N_3) + 3H_2O\}^+$ (*m*/*z* 533). The identified dinuclear species include $\{Cu^I_2(H_3L^1) + H_2O\}^+$ (*m*/*z* 426), a variant of structure **C** $\{Cu^I_2(H_3L^1)(PhC{\equiv}CH) + H_2O + MeCN\}^+$ (*m*/*z* 570) and a structure of **D** type, $\{Cu^I_2(PhCH_2N_3PhCCH)_2 + 2H_2O\}^+$ (*m*/*z* 633).

On the basis of the proposed mechanism which involves an oxidative addition step to the metal, the highest activity of catalyst **2** is consistent with the expected most favourable occurrence of such a type of reaction in this case, in view of the lower charge (in comparison with **7**) and of the direct coordination of the anionic sulfonate group (**2** and **5** in contrast to **3**, all with the same charge). In accord, the lowest activity of **7** is due to the cationic character of the copper centre and the absence of electron donation by the hydrazine species which is uncoordinated.

3. Conclusions

Novel water-soluble copper(II) complexes (**2**, **3**, **5** and **7**) containing *ortho*-sulfonic functionalized arylhydrazones of β-diketones were synthesized from the corresponding arylhydrazone sodium salts (**1**, **4** and **6**). The reaction is shown to strongly depend on the pH of the medium and solvents used in the synthesis. All the compounds were fully characterized, also by single-crystal X-ray diffraction analysis, and tested as catalysts in the 1,3-dipolar cycloaddition of ethynylbenzene and 1,4-diethynylbenzene with substituted benzyl bromides in the presence of NaN_3 (AAC reaction) in a water/acetonitrile mixture under microwave irradiation.

While none of the sodium precursors is a catalyst, the copper(II) species are affective catalysts for the reaction and their activity was shown to be highly dependent (i) on the simultaneous presence of the arylhydrazone moiety and the Cu(II) cation, (ii) on the concurrent existence of RAHB and CAHB in the structure of the catalyst, and (iii) on the charge of the complex and the nature of the coordinating group of the hydrazone ligand. Hence, in this work we have established, for the first time, a structure–catalytic activity relationship that follows the order: $Cu(NO_3)_2 \ll$ **7** (complex salt with positive charge at the copper complex and uncoordinated hydrazone stabilized by RAHB and CAHB) < **3** (neutral, with hydrazone stabilized by RAHB and CAHB, and coordinated *via* a neutral binding group) < **5** (neutral, with hydrazone stabilized by RAHB and coordinated *via* the anionic sulfonate group) < **2** (neutral, with hydrazone without RAHB and CAHB, and coordinated *via* the anionic sulfonate group, apart from *N*,*O*-coordination). Complex **2** was thus found to be the most efficient catalyst for the 1,3-dipolar cycloaddition, yielding selectively 1,4-disubstituted 1,2,3-triazoles in yields up to 98% after being placed for 15 min at 125 °C under low power (10 W) MW irradiation.

ESI-MS$^+$ analysis of the catalytic reaction mixture using **2** as a pre-catalyst supported the generation of the catalytically active Cu(I) species and the alkyne–alkyne coupling, in what is considered as the induction period for this reaction. These experiments also showed the formation of dinuclear species involving the hydrazone, the alkyne, or both the alkyne and the organic azide (or the dipolar cycloaddition product). The detection of the free hydrazone suggests ligand decoordination to some extent and explains the loss of activity of the complex.

This protocol provides the first example of using Cu(II)–arylhydrazone complexes as homogeneous catalysts for the AAC reaction, following a facile synthetic procedure with inexpensive reagents and being applied to various substrates. The generality of this research direction is worth exploring.

4. Experimental

4.1. Materials and general procedures

All synthetic procedures were performed in air. Reagents and solvents were obtained from commercial sources and used without further purification. Infrared spectra (4000–650 cm^{-1}) were recorded on a Cary 630 FTIR spectrometer; wavenumbers are reported in cm^{-1}; abbreviations: s, strong; m, medium; w, weak. Elemental analyses (C, H, and N) were carried out by the Microanalytical service of the Instituto Superior Técnico. Electrospray mass spectra (ESI-Ms) were obtained using a Varian 500-MS LC Ion Trap mass spectrometer equipped with an electrospray ion source. For electrospray ionization, the drying gas and the flow rate were optimized according to the sample with 35 p.s.i. nebulizer pressure. The scanning was performed from *m*/*z* 0 to 2000. All compounds were observed in both the negative and positive modes (capillary voltage = 80–105 V). ^{1}H, ^{13}C and DEPT NMR spectra were obtained in DMSO-d_6 using a Bruker Advance 400 MHz spectrometer at ambient temperature. Chemical shifts δ are quoted in ppm. All spectra were internally referenced to residual protio-solvent resonance and are reported relative to $SiMe_4$. Assignments of ^{1}H and ^{13}C signals rely on *g*-COSY and/or *g*-HSQC experiments. The MW irradiation was performed on a focused microwave Anton Paar Monowave 300 reactor (10 W), using a 10 mL capacity reaction tube with a 13 mm internal diameter, fitted with a rotational system and an IR temperature detector.

4.2. Synthesis of arylhydrazone ligands

The sodium salts of arylhydrazone ligands (**1**, **4** and **6**) were prepared using the Japp–Klingemann synthetic protocol in two steps:[11] (i) *Diazotization of aromatic amine.* 10 mmol of the respective aniline and 0.20 g (5 mmol) of NaOH were dissolved in 20 mL of water. The solution was cooled to 0–5 °C; then 0.69 g (10 mmol) of $NaNO_2$ were added. After 5 minutes of stirring, 2 mL HCl were added slowly over 30 minutes in 0.1 mL portions, while the temperature was maintained at 0–5 °C

during the whole time. (ii) *Azocoupling.* 10 mmol of the β-diketone compound and 0.40 g (10 mmol) of NaOH were dissolved in 30 mL of a water–ethanol (1 : 2) mixture. This solution was then added to the suspension of diazonium salt (see the first step) in portions under vigorous stirring. Catalytic amounts of sodium acetate (*ca.* 0.10 g) were added; then the prepared mixture was stirred for an additional 1 h where it warmed gradually to reach room temperature.

The produced solids were then filtered, washed repeatedly with ethanol and dried at 40 °C under vacuum. Crystals suitable for X-ray measurements were obtained upon recrystallization from methanol.

Compounds **1**, **4** and **6** are soluble in water, methanol and DMSO and are insoluble in NCMe and chlorinated solvents.

$[Na(\mu_4\text{-}1{:}2\kappa O^1,2\kappa O^2,3\kappa O^3,4\kappa O^4\text{-}H_3L^1)]_n$ (**1**): yield = 92% (2.83 g). Elemental analysis calcd (%) for $C_{10}H_{10}N_3NaO_5S$ (*Mr* = 307.26 g mol^{-1}): C 39.09, H 3.28, N 13.68, S 10.44. Found: C 39.72, H 3.38, N 12.17, S 10.23. FTIR (KBr): ν (cm^{-1}) = 3371 s, 3305 m, 3253 m, 3196 w, 3138 m, 1657 s, 1643 s, 1576 m, 1559 m, 1513 s, 1441 m, 1418 m, 1355 m, 1308 w, 1230 s, 1190 s, 1133 s, 1084 s, 1052 m, 1038 m, 1017 s, 940 m, 862 w, 793 m, 758 m, 709 m. ESI-MS$^-$ in MeCN (*m*/*z* assignment, % intensity): 591 ($[Na(H_3L^1)_2]^-$, 9%), 284 ($[H_3L^1]^-$, 100). ESI-MS$^+$ in MeCN (*m*/*z* assignment, % intensity): 371 ($[Na_2(H_3L^1)(MeCN)]^+$, 100), 330 ($[Na_2(H_3L^1)]^+$, 78). ^{1}H NMR (400 MHz, DMSO-d_6), δ: 14.58 (s, 1H, N–N*H*), 8.32 (s, 1H, C(O)–N–*H*···O), 7.75–7.67 (m, 2H, Ar–H and 1H, C(O)–N–*H*), 7.42 (dd, J_1 = 9.6 Hz, J_2 = 1.2 Hz, 1 H, Ar–H), 7.11 (dd, J_1 = 10 Hz, J_2 = 1.2 Hz, 1 H, Ar–H), 2.45 (s, 3H, CH_3). ^{13}C{^{1}H} NMR (400 MHz, DMSO-d_6) δ: 198.07 (H_3C–*C*═O), 164.14 (H_2N–*C*═O), 138.71 (HN–C_{quat}–Ph), 135.21 (*C*═N), 130.25 (H*C*–Ph), 128.03 (S–C_{quat}–Ph), 127.44 (H*C*–Ph), 123.40 (H*C*–Ph), 115.40 (H*C*–Ph), 26.07 (*C*H_3). DEPT (400 MHz, DMSO-d_6) δ: 130.00, 127.19, 123.15, 115.15, 25.82.

$[Na(\mu\text{-}1\kappa O^1,2\kappa O^2\text{-}H_4L^2)]_2$ (**4**): yield = 86% (3.25 g). Elemental analysis calcd (%) for $C_{10}H_{16}N_3NaO_9S$ (*Mr* = 377.30 g mol^{-1}): C 31.83, H 4.27, N 11.14, S 8.50. Found: C 31.59, H 4.12, N 10.60, S 7.94. FTIR (KBr): ν (cm^{-1}) = 3417 s, 3287 m, 3080 w, 1667 m, 1635 m, 1606 m, 1531 m, 1444 w, 1421 w, 1395 w, 1355 m, 1312 m, 1292 m, 1254 m, 1234 m, 1182 s, 1127 m, 1087 s, 1032 s, 948 m, 827 w, 807 m, 784 w, 698 s. ESI-MS$^-$ in MeOH (*m*/*z* assignment, % intensity): 623 ($[Na(H_4L^2)_2]^-$, 15%), 300 ($[H_4L^2]^-$, 100). ESI-MS$^+$ in MeOH (*m*/*z* assignment, % intensity): 1315 ($[Na_5(H_4L^2)_4]^+$, 53), 992 ($[Na_4(H_4L^2)_3]^+$, 100), 669 ($[Na_3(H_4L^2)_2]^+$, 54), 346 ($[Na_2(H_4L^2)]^+$, 60). ^{1}H NMR (400 MHz, DMSO-d_6) δ: 14.68 (s, 1H, N–N*H*), 8.57 (s, 1H, C(O)–N–*H*···O), 7.91 (s, 1H, C(O)–N–*H*), 7.81 (s, 1H, HN–C–C*H*), 7.26 (d, *J* = 12 Hz, 1H, SC–C*H*–CH), 6.86 (d, *J* = 12 Hz, 1 H, HO–C–C*H*), 2.44 (s, 3H, CH_3). ^{13}C{^{1}H} NMR (400 MHz, DMSO-d_6) δ: 197.63 (H_3C–*C*═O), 165.93 (H_2N–*C*═O), 146.75 (HO–C_{quat}–Ph), 140.20 (*C*═N), 128.70 (HN–C_{quat}–Ph), 126.81 (S–C_{quat}–Ph), 122.85 (SC–*C*H–CH), 114.67 (HO–C–*C*H), 111.97 (N–C_{quat}–*C*H), 25.77 (*C*H_3). DEPT (400 MHz, DMSO-d_6) δ: 122.60, 114.42, 111.71, 25.52.

$[Na(\mu\text{-}1\kappa O^1\kappa O^2,2\kappa O^3\text{-}H_2L^3)(CH_3OH)_2]_2$ (**6**): yield = 94% (4.67 g). Elemental analysis calcd (%) for $C_{22}H_{24}N_3NaO_7S$ (*Mr* = 497.50 g mol^{-1}): C 53.11, H 4.86, N 8.45, S 6.45. Found: C 53.72, H 3.97, N 8.33, S 6.47. FTIR (KBr): ν (cm^{-1}) = 3380 m, 3198 w, 3100 w, 1648 m, 1594 m, 1559 m, 1484 s, 1441 m, 1424 m, 1354 m, 1314 w, 1280 w, 1254 w, 1222 m, 1179 s, 1138 w, 1046 s, 945 m, 885 m, 810 m, 770 w, 735 m, 695 m, 660 m. ESI-MS$^-$ in MeOH (*m*/*z* assignment, % intensity): 410 ($[H_2L^3]^-$, 100). ESI-MS$^+$ in MeOH (*m*/*z* assignment, % intensity): 889 ($[Na_3(H_2L^3)_2]^+$, 89), 456 ($[Na_2(H_2L^3)]^+$, 100). ^{1}H NMR (400 MHz, DMSO-d_6) δ: 14.88 (s, 1H, N–N*H*), 11.03 (s, 1H, C(O)–N*H*), 8.09–7.15 (m, 11H, Ar–H), 2.56 (s, 3H, CH_3). ^{13}C{^{1}H} NMR (400 MHz, DMSO-d_6) δ: 198.20 (H_3C–*C*═O), 160.53 (N–*C*═O), 137.89 (N–NH–C_{quat}), 136.47 (C(O)–NH–C_{quat}), 131.37 (H*C*–Ph), 1 30.73 (NNHCCHCH–C_{quat}), 130.64 (*C*═N), 130.38 (SC–C_{quat}–C_{quat}), 129.06 (H*C*–Ph), 128.76 (H*C*–Ph), 128.03 (H*C*–Ph), 127.51 (S–C_{quat}), 126.62 (H*C*–Ph), 124.83 (H*C*–Ph), 124.26 (H*C*–Ph), 120.19 (H*C*–Ph), 115.19 (H*C*–Ph), 26.11 (*C*H_3). DEPT (400 MHz, DMSO-d_6) δ: 131.12, 128.80, 128.51, 127.78, 126.37, 124.58, 124.01, 119.93, 114.94, 25.86.

4.3. Synthesis of complexes

Synthesis of 2 and 3. Compound **1** (0.31 g, 1 mmol) was dissolved in 20 mL of a water–acetone (1 : 5) mixture (1.5 mL of 0.1 M NH_4OH solution was also added to increase the pH up to 9, in the case of **2**); then $Cu(NO_3)_2{\cdot}3H_2O$ (0.24 g, 1 mmol) was added to the reaction mixture. The obtained dark green or green (in the case of **3**) solution was stirred for 1 h and then left in the open air at room temperature for slow evaporation to afford **2** or **3** as green crystals suitable for X-ray measurements.

Compounds **2** and **3** have a good solubility in water, DMF and DMSO, and are insoluble in MeOH, NCMe and in chlorinated solvents.

$[Cu(\kappa O^1O^2N\text{-}H_2L^1)(H_2O)_2]{\cdot}2H_2O$ (**2**): yield = 91% (0.38 g, based on Cu). Elemental analysis calcd (%) for $C_{10}H_{17}CuN_3O_9S$ (*Mr* = 418.87 g mol^{-1}): C 28.67, H 4.09, N 10.03, S 7.66. Found: C 29.24, H 3.84, N 10.51, S 7.64. FTIR (KBr): ν (cm^{-1}) = 3310 Br s, 3183 s, 1603 s, 1390 m, 1352 s, 1320 m, 1300 w, 1277 w, 1223 s, 1188 m, 1136 s, 1084 m, 1055 w, 1012 s, 948 m, 908 w, 868 w, 807 m, 758 s, 741 w, 721 m, 669 w. ESI-MS$^-$ in H_2O (*m*/*z* assignment, % intensity): 630 ($[Cu(H_2L^1)(H_3L^1)]^-$, 100), 284 ($[H_3L^1]^-$, 61). ESI-MS$^+$ in H_2O (*m*/*z* assignment, % intensity): 712 ($[H\{Cu(H_2L^1)\}_2(H_2O)]^+$, 82), 694 ($[H\{Cu(H_2L^1)\}_2]^+$, 49), 364 ($[H\{Cu(H_2L^1)\}(H_2O)]^+$, 100), 347 ($[H\{Cu(H_2L^1)\}]^+$, 13), 286 ($[H(H_4L^1)]^+$, 8).

$[Cu(\kappa O\text{-}H_3L^1)_2(H_2O)_4]$ (**3**): yield = 83% (0.29 g, based on Cu). Elemental analysis calcd (%) for $C_{20}H_{28}CuN_6O_{14}S_2$ (*Mr* = 704.14 g mol^{-1}): C 34.11, H 4.01, N 11.94, S 9.11. Found: C 33.89, H 3.79, N 11.80, S 9.32. FTIR (KBr): ν (cm^{-1}) = 3457 m, 3313 m, 3108 s, 1638 s, 1571 m, 1551 w, 1517 s, 1450 m, 1416 m, 1355 m, 1315 w, 1243 s, 1165 s, 1133 s, 1084 m, 1052 w, 1018 s, 946 m, 862 w, 793 m, 755 s, 712 s. ESI-MS$^-$ in H_2O (*m*/*z* assignment, % intensity): 915 ($[Cu(H_3L^1)_3]^-$, 12%), 630 ($[Cu(H_3L^1)(H_2L^1)]^-$, 83), 284 ($[H_3L^1]^-$, 100). ESI-MS$^+$ in H_2O (*m*/*z* assignment, % intensity): 1611 ($[Cu_3(H_3L^1)_5]^+$, 67), 980 ($[Cu_2(H_3L^1)_3]^+$, 79), 347 ($[Cu(H_3L^1)]^+$, 100), 286 ($[H(H_4L^1)]^+$, 12).

Synthesis of 5. Compound **4** (0.38 g, 1 mmol) was dissolved in a MeOH/MeCN (1 : 2) (20 mL) mixture, and $Cu(NO_3)_2{\cdot}3H_2O$ (0.12 g, 0.5 mmol) was added. The produced solution was stirred under reflux for 3 h. The obtained green product was filtered off, washed repeatedly with ethanol and dried under vacuum. Crystals of **5** suitable for X-ray measurements were obtained by allowing the filtrate to stand at room temperature for slow evaporation.

Compound **5** is soluble in water, methanol, DMF and DMSO and is insoluble in NCMe and chlorinated solvents.

$[Cu(\kappa O\text{-}H_4L^2)_2(H_2O)_4]$ (**5**): yield = 71% (0.26 g, based on Cu). Elemental analysis calcd (%) for $C_{20}H_{28}CuN_6O_{16}S_2$ (*Mr* = 736.14 g mol^{-1}): C 32.63, H 3.83, N 11.42, S 8.71; found: C 33.23, H 3.80, N 11.28, S 8.87. FTIR (KBr): ν (cm^{-1}) = 3193 s, 1599 s, 1519 m, 1470 m, 1406 s, 1352 m, 1280 s, 1233 m, 1156 s, 1087 m, 1032 s, 977 m, 931 m, 876 m, 844 w, 819 w, 770 w, 695 m. ESI-MS^- in H_2O (*m*/*z* assignment, % intensity): 300 ($[H_4L^2]^-$, 100). ESI-MS^+ in H_2O (*m*/*z* assignment, % intensity): 1028 ($[Cu_2(H_4L^2)_3]^+$, 62), 363 ($[Cu(H_4L^2)]^+$, 100).

Synthesis of 7. $Cu(NO_3)_2{\cdot}3H_2O$ (0.06 g, 0.25 mmol) was added to a solution of **6** (0.25 g, 0.5 mmol) in 20 mL of water. The obtained solution was stirred under reflux for 5 min. The obtained green product was filtered off, dried under vacuum, and recrystallized from a mixture of DMF/MeOH (1 : 20) solutions to afford **7** as crystals suitable for X-ray measurements.

Compound **7** is soluble in water and DMSO and is insoluble in MeOH, DMF, NCMe and chlorinated solvents.

$[Cu(H_2O)_6]{\cdot}2H_2L^3{\cdot}2(CH_3)_2NCHO$ (**7**): yield = 81% (0.23 g, based on Cu). Elemental analysis calcd (%) for $C_{46}H_{58}CuN_8O_{18}S_2$ (*Mr* = 1138.67 g mol^{-1}): C 48.52, H 5.13, N 9.84, S 5.63. Found: C 48.11, H 4.88, N 8.62, S 6.30. FTIR (KBr): ν (cm^{-1}) = 3241 m, 1652 m, 1638 m, 1615 w, 1594 m, 1560 m, 1485 s, 1442 m, 1427 m, 1413 m, 1361 m, 1295 m, 1254 m, 1179 s, 1156 s, 1139 s, 1061 m, 1044 s, 986 w, 957 m, 885 w, 850 w, 807 m, 770 w, 744 m, 703 m, 663 m. ESI-MS^- in MeOH (*m*/*z* assignment, % intensity): 410 ($[H_2L^3]^-$, 100). ESI-MS^+ in MeOH (*m*/*z* assignment, % intensity): 473 ($[Cu(H_2L^3)]^+$, 100).

4.4. X-ray structure determination

X-ray quality single crystals of the compounds were mounted in a nylon loop and measured at ambient temperature. Intensity data were collected using a Bruker AXS-KAPPA APEX II PHOTON 100 diffractometer with graphite monochromated Mo-Kα (0.71069 Å) radiation. Data were collected using omega scans of 0.5° per frame and full sphere of data were obtained. Cell parameters were retrieved using Bruker SMART software and refined using Bruker SAINT[14] on all the observed reflections. Absorption corrections were applied using the SADABS program.[15] The structures were solved by direct methods using the SIR97 software package[16] and refined with SHELXL-2014/7.[17] Calculations were performed using the WinGX System Version 2014-1.[18] The hydrogen atoms of water, hydrazine or amine groups were found in the difference Fourier map and the isotropic thermal parameters were set at 1.5 times the average thermal parameters of the belonging oxygen or nitrogen atoms, frequently with their distances restrained using the DFIX command. Coordinates of hydrogen atoms bonded to carbon atoms were included in the refinement using the riding-model approximation with the $U_{iso}(H)$ defined as $1.2U_{eq}$ of the parent aromatic atoms, and $1.5U_{eq}$ of the parent carbon atoms for methyl. Least-squares refinements with anisotropic thermal motion parameters for all the non-hydrogen atoms were employed. In **4** the oxygen atoms of the sulfonate group were disordered over two positions with occupancies of 0.53 and 0.47% and were refined with the use of PART instruction. Despite the low-quality data for **7** resulting from low diffracting crystals, the final refinement parameters are reasonably good; the structure proves the composition of the sample and is included in this study for comparative purposes. Crystallographic data are given in Table S1 (ESI†); selected bond lengths and angles are given in Table S2† and hydrogen-bond interactions in Table S3.† The structures with partial numbering schemes are shown in Fig. 1.

Crystallographic data for the structural analysis have been deposited to the Cambridge Crystallographic Data Center [CCDC 1857654 (for **1**), 1857660 (for **2**), 1857658 (for **3**), 1857655 (for **4**), 1857656 (for **5**), 1857657 (for **6**) and 1857659 (for **7**)†].

4.5. General procedure for the three-component azide alkyne cycloaddition reaction

A mixture of the respective substituted benzyl bromide (0.30 mmol, 1 equiv.), ethynylbenzene (0.33 mmol, 1.1 equiv.), NaN_3 (0.33 mmol, 1.1 equiv.), the catalyst (1–5 mol%) and 1.5 mL of solvent was charged to a 10 mL pyrex vial equipped with a magnetic stirring bar. The vial was then tightly sealed and placed in the microwave reactor to be irradiated (10 W) at 125 °C for the periods of time indicated in Table 1 and Scheme 3. A precipitate was formed; the reaction mixture was cooled to ambient temperature and diluted with 7 mL of water. The product was filtered off, washed repeatedly with petroleum ether and dried under vacuum. In the case of 1,4-diethynylbenzene as a substrate (Table 2), the reactions were performed according to the general procedure described above except that 0.60 mmol of the respective benzyl bromide derivative, 0.33 mmol of 1,4-diethynylbenzene and 0.62 mmol of sodium azide were used. The ^1H, ^{13}C and DEPT NMR spectroscopic data of all 1,4-disubstituted 1,2,3-triazole products are reported in the ESI.†

ESI-Ms^+ analysis of the catalytic reaction mixtures. Mixture 1: (Complex **2** + ethynylbenzene).

1 mmol of ethynylbenzene and 0.2 mmol of complex **2** (20 mol%) were mixed in a 2 mL mixture of water and acetonitrile (1 : 1). The obtained mixture was left at room temperature for 1 h, and then subjected to the ESI-Ms^+ analysis.

ESI-MS^+ (*m*/*z* assignment, % intensity): 449 ($[Cu\{H_3L^1\}\{PhC{\equiv}CH\}]^+$, 12), 406 ($\{Cu^I(H_3L^1) + MeCN\}^+$, (7), 388 ($\{Cu^I(H_3L^1) + MeCN\}^+$, 14), 365 ($\{Cu^I(H_3L^1) + H_2O\}^+$, 12), 347 ($[Cu^I\{H_3L^1\}]^+$, 7), 221 ($[\{PhC{\equiv}C\text{–}C{\equiv}CPh + H_2O + H\}]^+$, 4), 144 ($[\{PhC{\equiv}CH + MeCN\} + H]^+$, 100).

Mixture 2: (Complex **2** + ethynylbenzene + NaN_3 + Benzyl bromide).

Benzyl bromide (0.30 mmol, 1 equiv.), ethynylbenzene (0.33 mmol, 1.1 equiv.), NaN_3 (0.33 mmol, 1.1 equiv.) and the complex **2** (0.015 mmol, 5 mol%) were added to a 1.5 mL solution of water and acetonitrile (1 : 1). The obtained mixture was left at room temperature for 1 h and then subjected to ESI-MS$^+$ analysis.

ESI-MS$^+$ (*m*/*z* assignment, % intensity): 633 $\{Cu^I_2(PhCH_2N_3PhCCH)_2 + 2H_2O\}^+$, (6), 570 $(\{Cu^I_2(H_3L^1)(PhCCH) + H_2O + MeCN\}^+$, 3) 533 $(\{Cu^I(H_3L^1)(PhCH_2N_3) + 3H_2O\}^+$, 24), 471 $([Cu\{NaH_2L^1\}\{PhC{\equiv}CH\}]^+$, 12), 426 $(\{Cu^I_2(H_3L^1) + H_2O\}^+$, 27), 326 $([\{NaH_3L^1 + H_2O + H\}]^+$, 100), 236 $([M_{triazol} + H]^+$, 4).

Conflicts of interest

There are no conflicts to declare.

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References

1 (*a*) R. Huisgen, *Angew. Chem., Int. Ed. Engl.*, 1963, **2**, 565–598; (*b*) R. Huisgen, *Angew. Chem., Int. Ed. Engl.*, 1963, **2**, 633–645; (*c*) H. C. Kolb, M. G. Finn and K. B. Sharpless, *Angew. Chem., Int. Ed.*, 2001, **40**, 2004–2021; (*d*) V. V. Rostovtsev, L. G. Green, V. V. Fokin and K. B. Sharpless, *Angew. Chem., Int. Ed.*, 2002, **114**, 2708–2711.

2 (*a*) W.-Q. Fan and A. R. Katritzky, in *Comprehensive Heterocyclic Chemistry II*, ed. A. R. Katritzky, C. W. Rees and E. F. V. Scriven, Elsevier Science, Oxford, U.K., 1996, pp. 1–126; (*b*) N. H. Morgan, *Eur. Pat. Appl*, EP437979A219910742, 1991; (*c*) S. Kantheti, R. Narayan and K. V. S. N. Raju, *RSC Adv.*, 2015, **5**, 3687–3708; (*d*) J.-F. Lutz, *Angew. Chem., Int. Ed.*, 2007, **46**, 1018–1025.

3 (*a*) B. Schulze and U. S. Schubert, *Chem. Soc. Rev.*, 2014, **43**, 2522–2571; (*b*) S. B. Ferreira, A. C. R. Sodero, M. F. C. Cardoso, E. S. Lima, C. R. Kaiser, F. P. Silva and V. F. Ferreira, *J. Med. Chem.*, 2010, **53**, 2364–2375; (*c*) H. C. Kolb and K. B. Sharpless, *Drug Discovery Today*, 2003, **8**, 1128–1137; (*d*) F. de C. da Silva, M. C. B. V. de Souza, I. I. P. Frugulhetti, H. C. Castro, S. L. de O. Souza, T. M. L. de Souza, D. Q. Rodrigues, A. M. T. Souza, P. A. Abreu, F. Passamani, C. R. Rodrigues and V. F. Ferreira, *Eur. J. Med. Chem.*, 2009, **44**, 373–383; (*e*) S. A. Bakunov, S. M. Bakunova, T. Wenzler, M. Ghebru, K. A. Werbovetz, R. Brun and R. R. Tidwell, *J. Med. Chem.*, 2010, **53**, 254–272; (*f*) A. C. Cunha, J. M. Figueiredo, J. L. M. Tributino, A. L. P. Miranda, H. C. Castro, R. B. Zingali, C. A. M. Fraga, M. C. B. V. de Souza, V. F. Ferreira and E. J. Barreiro, *Bioorg. Med. Chem.*, 2003, **11**, 2051–2059; (*g*) T.-H. Fu, Y. Li, H. D. Thaker, R. W. Scott and G. N. Tew, *ACS Med. Chem. Lett.*, 2013, **4**, 841–845; (*h*) N. Boechat, V. F. Ferreira, S. B. Ferreira, M. de L. G. Ferreira, F. de C. da Silva, M. M. Bastos, M. dos S. Costa, M. C. S. Lourenço, A. C. Pinto, A. U. Krettli, A. C. Aguiar, B. M. Teixeira, N. V. da Silva, P. R. C. Martins, F. A. F. M. Bezerra, A. L. S. Camilo, G. P. da Silva and C. C. P. Costa, *J. Med. Chem.*, 2011, **54**, 5988–5999; (*i*) D. K. Nasirova, A. V. Malkova, K. B. Polyanskii, K. Y. Yankina, P. N.-A. Amoyaw, I. A. Kolesnik, A. V. Kletskov, I. A. Godovikov, E. V. Nikitina and F. I. Zubkov, *Tetrahedron Lett.*, 2017, **58**, 4384–4387; (*j*) F. Reck, F. Zhou, M. Girardot, G. Kern, C. J. Eyermann, N. J. Hales, R. R. Ramsay and M. B. Gravestock, *J. Med. Chem.*, 2005, **48**, 499–506; (*k*) D. Y. Vandyshev, K. S. Shikhaliev, A. Y. Potapov, M. Y. Krysin, F. I. Zubkov and L. V. Sapronova, *Beilstein J. Org. Chem.*, 2017, **13**, 2561–2568; (*l*) H. Elamari, R. Slimi, G. G. Chabot, L. Quentin, D. Scherman and C. Girard, *Eur. J. Med. Chem.*, 2013, **60**, 360–364; (*m*) W.-T. Li, W.-H. Wu, C.-H. Tang, R. Tai and S.-T. Chen, *ACS Comb. Sci.*, 2011, **13**, 72–78; (*n*) K. K. Borisova, E. V. Nikitina, R. A. Novikov, V. N. Khrustalev, P. V. Dorovatovskii, Y. V. Zubavichus, M. L. Kuznetsov, V. P. Zaytsev, A. V. Varlamov and F. I. Zubkov, *Chem. Commun.*, 2018, **54**, 2850–2853; (*o*) S. Shafi, M. Mahboob Alam, N. Mulakayala, C. Mulakayala, G. Vanaja, A. M. Kalle, R. Pallu and M. S. Alam, *Eur. J. Med. Chem.*, 2012, **49**, 324–333; (*p*) A. A. Shetnev and F. I. Zubkov, *Chem. Heterocycl. Compd.*, 2017, **53**, 495–497; (*q*) I. V. Ledenyova, A. V. Falaleev, K. S. Shikhaliev, E. A. Ryzhkova and F. I. Zubkov, *Russ. J. Gen. Chem.*, 2018, **88**, 73–79; (*r*) V. Patil, W. Guerrant, P. C. Chen, B. Gryder, D. B. Benicewicz, S. I. Khan, B. L. Tekwani and A. K. Oyelere, *Bioorg. Med. Chem.*, 2010, **18**, 415–425; (*s*) Beena, N. Kumar, R. K. Rohilla, N. Roy and D. S. Rawat, *Bioorg. Med. Chem. Lett.*, 2009, **19**, 1396–1398; (*t*) M. J. Genin, D. A. Allwine, D. J. Anderson, M. R. Barbachyn, D. E. Emmert, S. A. Garmon, D. R. Graber, K. C. Grega, J. B. Hester, D. K. Hutchinson, J. Morris, R. J. Reischer, C. W. Ford, G. E. Zurenko, J. C. Hamel, R. D. Schaadt, D. Stapert and B. H. Yagi, *J. Med. Chem.*, 2000, **43**, 953–970.

4 (*a*) P. L. Golas and K. Matyjaszewski, *Chem. Soc. Rev.*, 2010, **39**, 1338–1354; (*b*) J. E. Hein and V. V. Fokin, *Chem. Soc. Rev.*, 2010, **39**, 1302–1315; (*c*) L. Liang and D. Astruc, *Coord. Chem. Rev.*, 2011, **255**, 2933–2945; (*d*) H.-B. Chen, N. Abeyrathna and Y. Liao, *Tetrahedron Lett.*, 2014, **55**, 6575–6576; (*e*) S. Saha, K. Biswas and B. Basu, *Tetrahedron*

Lett., 2018, **59**, 2541–2545; (*f*) Z. Gonda and Z. Novák, *Dalton Trans.*, 2010, **39**, 726–729; (*g*) S. J. Bent, M. F. Mahon and R. L. Webster, *Dalton Trans.*, 2015, **44**, 10253–10258; (*h*) A. Taher, D. Nandi, R. U. Islam, M. Choudhary and K. Mallick, *RSC Adv.*, 2015, **5**, 47275–47283.

5 (*a*) L. Zhang, X. Chen, P. Xue, H. H. Y. Sun, I. D. Williams, K. B. Sharpless, V. V. Fokin and G. Jia, *J. Am. Chem. Soc.*, 2005, **127**, 15998–15999; (*b*) A. Tam, U. Arnold, M. B. Soellner and R. T. Raines, *J. Am. Chem. Soc.*, 2007, **129**, 12670–12671; (*c*) M. M. Majireck and S. M. Weinreb, *J. Org. Chem.*, 2006, **71**, 8680–8683; (*d*) L. K. Rasmussen, B. C. Boren and V. V. Fokin, *Org. Lett.*, 2007, **9**, 5337–5339; (*e*) B. C. Boren, S. Narayan, L. K. Rasmussen, L. Zhang, H. Zhao, Z. Lin, G. Jia and V. V. Fokin, *J. Am. Chem. Soc.*, 2008, **130**, 8923–8930; (*f*) J. R. Johansson, P. Lincoln, B. Nordén and N. Kann, *J. Org. Chem.*, 2011, **76**, 2355–2359; (*g*) D. Wang, L. Salmon, J. Ruiz and D. Astruc, *Chem. Commun.*, 2013, **49**, 6956–6958; (*h*) E. Engholm, N. Stuhr-Hansen and O. Blixt, *Tetrahedron Lett.*, 2017, **58**, 2272–2275; (*i*) N. Zabarska, A. Stumper and S. Rau, *Dalton Trans.*, 2016, **45**, 2338–2351.

6 (*a*) J. Kalisiak, K. B. Sharpless and V. V. Fokin, *Org. Lett.*, 2008, **10**, 3171–3174; (*b*) S. R. Chavan, K. S. Gavale, K. M. Kamble, S. S. Pingale and D. D. Dhavale, *Tetrahedron*, 2017, **73**, 365–372; (*c*) J. N. S. Rao and R. Raghunathan, *Tetrahedron Lett.*, 2015, **56**, 2669–2673; (*d*) C. Wang, D. Ikhlef, S. Kahlal, J.-Y. Saillard and D. Astruc, *Coord. Chem. Rev.*, 2016, **316**, 1–20; (*e*) U. Pradere, V. Roy, T. R. McBrayer, R. F. Schinazi and L. A. Agrofoglio, *Tetrahedron*, 2008, **64**, 9044–9051; (*f*) V. Aragão-Leoneti, V. L. Campo, A. S. Gomes, R. A. Field and I. Carvalho, *Tetrahedron*, 2010, **66**, 9475–9492; (*g*) X. Chen, C.-W. Lu, Y. Huang and D. V. McGrath, *Tetrahedron*, 2015, **71**, 9154–9160; (*h*) Y. Kitamura, R. Sakamoto, T. Shiraishi, H. Oguri, S. Ohno and Y. Kitade, *Tetrahedron*, 2016, **72**, 4016–4021.

7 (*a*) M. S. Singh, S. Chowdhury and S. Koley, *Tetrahedron*, 2016, **72**, 5257–5283; (*b*) S. R. Chavan, K. S. Gavale, K. M. Kamble, S. S. Pingale and D. D. Dhavale, *Tetrahedron*, 2017, **73**, 365–372; (*c*) A. Ray, K. Manoj, M. M. Bhadbhade, R. Mukhopadhyay and A. Bhattacharjya, *Tetrahedron Lett.*, 2006, **47**, 2775–2778; (*d*) N. W. Smith, B. P. Polenz, S. B. Johnson and S. V. Dzyuba, *Tetrahedron Lett.*, 2010, **51**, 550–553; (*e*) J. González, V. M. Pérez, D. O. Jiménez, G. Lopez-Valdez, D. Corona and E. Cuevas-Yañez, *Tetrahedron Lett.*, 2011, **52**, 3514–3517; (*f*) H. A. Stefani, H. A. Canduzini and F. Manarin, *Tetrahedron Lett.*, 2011, **52**, 6086–6090.

8 (*a*) K. C. Majumdar and S. Ganai, *Tetrahedron Lett.*, 2013, **54**, 6192–6195; (*b*) G. T. Mukosera, T. P. Adams, R. F. Rothbarth, H. Langat, S. Akanda, R. G. Barkley, R. D. Dolewski, J. V. Ruppel and N. L. Snyder, *Tetrahedron Lett.*, 2015, **56**, 73–77; (*c*) A. R. Powers, I. Ghiviriga, K. A. Abboud and A. S. Veige, *Dalton Trans.*, 2015, **44**, 14747–14752; (*d*) Y.-C. Wang, Y.-Y. Xie, H.-E. Qu, H.-S. Wang, Y.-M. Pan and F.-P. Huang, *J. Org. Chem.*, 2014, **79**, 4463–4469; (*e*) K. Kamata, Y. Nakagawa, K. Yamaguchi and N. Mizuno, *J. Am. Chem. Soc.*, 2008, **130**, 15304–15310.

9 (*a*) Y. Masuyama, K. Yoshikawa, N. Suzuki, K. Hara and A. Fukuoka, *Tetrahedron Lett.*, 2011, **52**, 6916–6918; (*b*) P. W. Szafrański, P. Kasza and M. T. Cegła, *Tetrahedron Lett.*, 2015, **56**, 6244–6247; (*c*) A. A. Ali, M. Chetia and D. Sarma, *Tetrahedron Lett.*, 2016, **57**, 1711–1714; (*d*) R. U. Islam, A. Taher, M. Choudhary, M. J. Witcomb and K. Mallick, *Dalton Trans.*, 2015, **44**, 1341–1349; (*e*) E. Haldón, M. C. Nicasio and P. J. Pérez, *Org. Biomol. Chem.*, 2015, **13**, 9528–9550; (*f*) M. A. Morozova, M. S. Yusubov, B. Kratochvil, V. Eigner, A. A. Bondarev, A. Yoshimura, A. Saito, V. V. Zhdankin, M. E. Trusova and P. S. Postnikov, *Org. Chem. Front.*, 2017, **4**, 978–985; (*g*) K. R. Reddy, K. Rajgopal and M. L. Kantam, *Synlett*, 2006, 957–959; (*h*) M. Vashist, K. Kushwaha, R. Kaushik and S. C. Jain, *RSC Adv.*, 2014, **4**, 23679–23684; (*i*) L. Cao, C. Liu, X. Tang, X. Yin and B. Zhang, *Tetrahedron Lett.*, 2014, **55**, 5033–5037; (*j*) C. Zhou, J. Zhang, P. Liu, J. Xie and B. Dai, *RSC Adv.*, 2015, **5**, 6661–6665; (*k*) S. Layek, S. Kumari, Anuradha, B. Agrahari, R. Ganguly and D. D. Pathak, *Inorg. Chim. Acta*, 2016, **453**, 735–741; (*l*) M. Amini, A. Bayrami, M. N. Marashi, A. Arab, A. Ellern and L. K. Woo, *Inorg. Chim. Acta*, 2016, **443**, 22–27; (*m*) M. Bagherzadeh, A. Bayrami, R. Kia, M. Amini, L. J. K. Cook and P. R. Raithby, *Inorg. Chim. Acta*, 2017, **466**, 398–404; (*n*) B. Kaboudin, R. Mostafalu and T. Yokomatsu, *Green Chem.*, 2013, **15**, 2266–2274; (*o*) I. Jlalia, F. Gallier, N. Brodie-Linder, J. Uziel, J. Augé and N. Lubin-Germain, *J. Mol. Catal. A: Chem.*, 2014, **393**, 56–61; (*p*) H. Sharghi, P. Shiri and M. Aberi, *Catal. Lett.*, 2017, **147**, 2844–2862; (*q*) M. Meldal and C. W. Tomøe, *Chem. Rev.*, 2008, **108**, 2952–3015; (*r*) W. S. Brotherton, H. A. Michaels, J. T. Simmons, R. J. Clark, N. S. Dalal and L. Zhu, *Org. Lett.*, 2009, **11**, 4954–4957; (*s*) K. Yamaguchi, T. Oishi, T. Katayama and N. Mizuno, *Chem. – Eur. J.*, 2009, **15**, 10464–10472; (*t*) G.-C. Kuang, P. M. Guha, W. S. Brotherton, J. T. Simmons, L. A. Stankee, B. T. Nguyen, R. J. Clark and L. Zhu, *J. Am. Chem. Soc.*, 2011, **133**, 13984–14001; (*u*) P. Siemsen, R. C. Livingston and F. Diederich, *Angew. Chem., Int. Ed.*, 2000, **39**, 2632–2657.

10 (*a*) S. Díez-González, *Catal. Sci. Technol.*, 2011, **1**, 166–178; (*b*) B. Gerard, J. Ryan, A. B. Beeler and J. A. Porco, *Tetrahedron*, 2006, **62**, 6405–6411; (*c*) K. Tanaka, C. Kageyama and K. Fukase, *Tetrahedron Lett.*, 2007, **48**, 6475–6479; (*d*) V. Aucagne, K. D. Hänni, D. A. Leigh, P. J. Lusby and D. B. Walker, *J. Am. Chem. Soc.*, 2006, **128**, 2186–2187; (*e*) K. T. Mahmudov, M. N. Kopylovich, A. Sabbatini, M. G. B. Drew, L. M. D. R. S. Martins, C. Pettinari and A. J. L. Pombeiro, *Inorg. Chem.*, 2014, **53**, 9946–9958; (*f*) R. Jlassi, A. P. C. Ribeiro, M. F. C. Guedes da Silva, K. T. Mahmudov, M. N. Kopylovich, T. B. Anisimova, H. Naïli, G. A. O. Tiago and A. J. L. Pombeiro, *Eur. J. Inorg. Chem.*, 2014, **2014**, 4541–4550; (*g*) K. T. Mahmudov, M. F. C. Guedes da Silva, M. Sutradhar, M. N. Kopylovich,

F. E. Huseynov, N. T. Shamilov, A. A. Voronina, T. M. Buslaeva and A. J. L. Pombeiro, *Dalton Trans.*, 2015, **44**, 5602–5610; (*h*) A. V. Gurbanov, A. M. Maharramov, F. I. Zubkov, A. M. Saifutdinov and F. I. Guseinov, *Aust. J. Chem.*, 2018, **71**, 190–194; (*i*) A. G. Mahmoud, K. T. Mahmudov, M. F. C. Guedes da Silva and A. J. L. Pombeiro, *RSC Adv.*, 2016, **6**, 54263–54269.

11 (*a*) G. Mahmoudi, E. Zangrando, M. P. Mitoraj, A. V. Gurbanov, F. I. Zubkov, M. Moosavifar, I. A. Konyaeva, A. M. Kirillov and D. A. Safin, *New J. Chem.*, 2018, **42**, 4959–4971; (*b*) G. Mahmoudi, F. A. Afkhami, A. Castiñeiras, I. García-Santos, A. Gurbanov, F. I. Zubkov, M. P. Mitoraj, M. Kukułka, F. Sagan, D. W. Szczepanik, I. A. Konyaeva and D. A. Safin, *Inorg. Chem.*, 2018, **57**, 4395–4408; (*c*) G. Mahmoudi, J. K. Zaręba, A. V. Gurbanov, A. Bauzá, F. I. Zubkov, M. Kubicki, V. Stilinović, V. Kinzhybalo and A. Frontera, *Eur. J. Inorg. Chem.*, 2017, **2017**, 4763–4772; (*d*) F. Akbari Afkhami, G. Mahmoudi, A. V. Gurbanov, F. I. Zubkov, F. Qu, A. Gupta and D. A. Safin, *Dalton Trans.*, 2017, **46**, 14888–14896.

12 (*a*) P. Appukkuttan, W. Dehaen, V. V. Fokin and E. Van der Eycken, *Org. Lett.*, 2004, **6**, 4223–4225; (*b*) S. Özçubukçu, E. Ozkal, C. Jimeno and M. A. Pericàs, *Org. Lett.*, 2009, **11**, 4680–4683; (*c*) J. García-Álvarez, J. Díez, J. Gimeno, F. J. Suárez and C. Vincent, *Eur. J. Inorg. Chem.*, 2012, 5854–5863; (*d*) S. Lal and S. Díez-González, *J. Org. Chem.*, 2011, **76**, 2367–2373; (*e*) J. García-Álvarez, J. Díez and J. Gimeno, *Green Chem.*, 2010, **12**, 2127–2130; (*f*) A. G. Mahmoud, M. F. C. Guedes da Silva, J. Sokolnicki, P. Smoleński and A. J. L. Pombeiro, *Dalton Trans.*, 2018, **47**, 7290–7299; (*g*) E. Ozkal, S. Özçubukçu, C. Jimeno and M. A. Pericàs, *Catal. Sci. Technol.*, 2012, **2**, 195–200; (*h*) I. Cano, E. álvarez, M. C. Nicasio and P. J. Pérez, *J. Am. Chem. Soc.*, 2011, **133**, 191–193; (*i*) A. G. Mahmoud, L. M. D. R. S. Martins, M. F. C. Guedes da Silva and A. J. L. Pombeiro, *Inorg. Chim. Acta*, 2018, **483**, 371–378; (*j*) S. Díez-González, A. Correa, L. Cavallo and S. P. Nolan, *Chem. – Eur. J.*, 2006, **12**, 7558–7564; (*k*) S. Díez-González and S. P. Nolan, *Angew. Chem., Int. Ed.*, 2008, **120**, 9013–9016; (*l*) S. Díez-González, E. D. Stevens and S. P. Nolan, *Chem. Commun.*, 2008, 4747–4749.

13 (*a*) M. Ahlquist and V. V. Fokin, *Organometallics*, 2007, **26**, 4389–4391; (*b*) F. Himo, T. Lovell, R. Hilgraf, V. V. Rostovtsev, L. Noodleman, K. B. Sharpless and V. V. Fokin, *J. Am. Chem. Soc.*, 2005, **127**, 210–216; (*c*) B. F. Straub, *Chem. Commun.*, 2007, 3868–3870; (*d*) V. O. Rodionov, V. V. Fokin and M. G. Finn, *Angew. Chem., Int. Ed.*, 2005, **44**, 2210–2215; (*e*) C. Nolte, P. Mayer and B. F. Straub, *Angew. Chem., Int. Ed.*, 2007, **46**, 2101–2103; (*f*) B. T. Worrell, J. A. Malik and V. V. Fokin, *Science*, 2013, **340**, 457–460; (*g*) J. J. Eisch, H. Gopal and S.-G. Rhee, *J. Org. Chem.*, 1975, **40**, 2064–2069; (*h*) A. L. Schöffler, A. Makarem, F. Rominger and B. F. Straub, *Beilstein J. Org. Chem.*, 2016, **12**, 1566–1572; (*i*) L. Zhu, C. J. Brassard, X. Zhang, P. M. Guha and R. J. Clark, *Chem. Rec.*, 2016, **16**, 1501–1517; (*j*) L. Jin, D. R. Tolentino, M. Melaimi and G. Bertrand, *Sci. Adv.*, 2015, **1**, e1500304–e1500304; (*k*) C. Iacobucci, S. Reale, J.-F. Gal and F. De Angelis, *Angew. Chem., Int. Ed.*, 2015, **54**, 3065–3068.

14 Bruker, *APEX2*, Bruker AXS Inc., Madison, Wisconsin, USA, 2012.

15 G. M. Sheldrick, *SADABS. Program for Empirical Absorption Correction*, University of Gottingen, Germany, 2000.

16 A. Altomare, M. C. Burla, M. Camalli, G. L. Cascarano, C. Giacovazzo, A. Guagliardi, A. G. G. Moliterni, G. Polidori and R. Spagna, *J. Appl. Crystallogr.*, 1999, **32**, 115–119.

17 G. M. Sheldrick, Crystal structure refinement with SHELXL, *Acta Crystallogr., Sect. C: Struct. Chem.*, 2015, **71**, 3–8.

18 L. J. Farrugia, *J. Appl. Crystallogr.*, 2012, **45**, 849–854.

