

# Group 11 Tris(pyrazolyl)methane Complexes: Structural Features and Catalytic Applications

EReceived 00th January 20xx,  
Accepted 00th January 20xx

José María Muñoz-Molina<sup>a</sup>, Tomás R. Belderrain<sup>a</sup>, Pedro J. Pérez<sup>a,\*</sup>

DOI: 10.1039/x0xx00000x

Tris(pyrazolyl)methane ligands (Tpm<sup>x</sup>) have been for years a step behind their highly popular boron-anionic analogues, the tris(pyrazolyl)borate ligands (Tp<sup>x</sup>). However, in the last decade the development of new members of this family of ligands has boosted a number of contributions in their use in coordination chemistry. This fact has also triggered the application of metal-Tpm<sup>x</sup> complexes as catalysts for a range of organic transformations, particularly with group 11 metals. The main structural features of Tpm<sup>x</sup>M (M = Cu, Ag, Au) complexes and their success as catalysts in a variety of reactions under homogeneous or heterogenous conditions are presented.

## 1. Introduction

Scorpionate ligands, a name coined by Trofimenko for ligands containing three pyrazolyl fragments, constitute a very important type of N-donor tridentate ligands.<sup>1</sup> Two main families (Figure 1) dominate the chemistry employing these molecules, i.e. the anionic tris(pyrazolyl)borates<sup>2</sup> (Tp<sup>x</sup>) and the neutral tris(pyrazolyl)methanes<sup>3</sup> (Tpm<sup>x</sup>). The synthesis of the latter was first described by Trofimenko,<sup>4</sup> albeit is somewhat more intricate than that of the former, precluding its development until Elguero reported efficient preparations of several tris(pyrazolyl)alkanes in the 80s of the last century.<sup>5</sup> This work propelled other groups to develop a second generation of ligands.<sup>6</sup> The use of phase transfer reaction conditions introduced by Reger<sup>7</sup> led to a significant improvement in the synthetic procedures. Since then, a number of contributions regarding the preparation of transition metal complexes bearing these Tpm<sup>x</sup> ligands as well as their use in catalytic reactions have increased significantly.

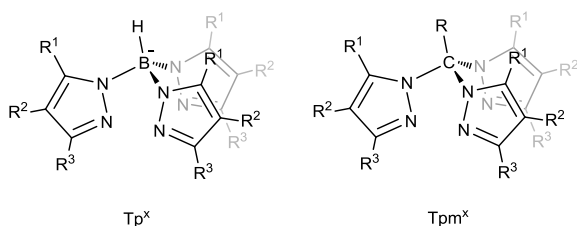


Fig. 1 Tp<sup>x</sup> and Tpm<sup>x</sup> ligands.

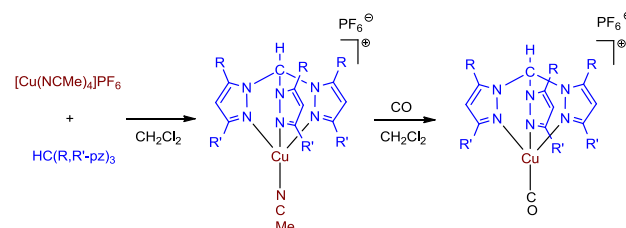
This contribution provides an overview of the main structural features of Tpm<sup>x</sup>-complexes with coinage metals, with special emphasis on their steric and electronic properties which can be modulated by installing functional groups in the pyrazolyl rings or the apical carbon atom, leading to a variety of coordination modes

of this type of ligand. Additionally, the different catalytic applications promoted by those complexes are discussed: a number of organic transformations such as carbene and nitrene transfer, cycloadditions, oxidation and cross-couplings will be shown.

## 2. Group 11 Tris(pyrazolyl)methane Complexes: Structural Features

### 2.1. Copper complexes

The first examples of copper(I) complexes bearing tris(pyrazolyl)methane ligands (Tpm<sup>x</sup>) was reported by Reger in 1996.<sup>8</sup> The reaction of [Cu(NCMe)<sub>4</sub>]PF<sub>6</sub> with equimolar amounts of a series of substituted Tpm<sup>x</sup> ligands gave the corresponding [HC(R,R',R''-pz)<sub>3</sub>]Cu(NCMe)PF<sub>6</sub> four-coordinate complexes. Their corresponding CO adducts [HC(R,R',R''-pz)<sub>3</sub>]Cu(CO)PF<sub>6</sub> were prepared by reaction with carbon monoxide (Scheme 1). The carbonyl stretching frequencies (ν<sub>CO</sub>) of the latter complexes can be used to estimate



Scheme 1 First copper complexes with tris(pyrazolyl)methane ligands.

Table 1 Carbonyl stretching frequencies (ν<sub>CO</sub>) for [HB(R,R',R'')<sub>3</sub>]Cu(CO) and [HC(R,R',R'')<sub>3</sub>]Cu(CO)<sup>+</sup> complexes.<sup>8,9</sup>

Complex	ν(CO) (cm <sup>-1</sup> )	Complex	ν(CO) (cm <sup>-1</sup> )
[HB(Me <sub>2</sub> -pz) <sub>3</sub> ]Cu(CO)	2066	[{HC(Me <sub>2</sub> -pz) <sub>3</sub> ]Cu(CO)] <sup>+</sup>	2113
[HB( <sup>i</sup> Pr <sub>2</sub> -pz) <sub>3</sub> ]Cu(CO)	2056	[{HC( <sup>i</sup> Pr <sub>2</sub> -pz) <sub>3</sub> ]Cu(CO)] <sup>+</sup>	2107
[HB(Ph <sub>2</sub> -pz) <sub>3</sub> ]Cu(CO)	2086	[{HC(3-Ph-pz) <sub>3</sub> ]Cu(CO)] <sup>+</sup>	2104
[HB(3- <sup>i</sup> Bu-pz) <sub>3</sub> ]Cu(CO)	2069	[{HC(3- <sup>i</sup> Bu-pz) <sub>3</sub> ]Cu(CO)] <sup>+</sup>	2100

<sup>a</sup> Laboratorio de Catálisis Homogénea, Unidad Asociada al CSIC, CIQSO-Centro de Investigación en Química Sostenible and Departamento de Química, Universidad de Huelva, 21007 Huelva, Spain.

the electronic effects of the Tpm<sup>x</sup> ligands. Interestingly, those values are higher than the corresponding for the analogous Tp<sup>x</sup>-containing neutral complexes<sup>9</sup> (Table 1). This can be correlated with a weaker  $\pi$  back-bonding from the copper center to the CO ligand in the case of the Tpm<sup>x</sup> derivatives.

The structures of the acetonitrile and carbonyl four-coordinate adducts<sup>8</sup> ([Tpm<sup>x</sup>CuL]<sup>+</sup>) are very similar to those previously reported for the neutral analogs, [Tp<sup>x</sup>CuL] complexes.<sup>9,10</sup> However, the formation of complexes with different copper-Tpm<sup>x</sup> stoichiometry depends on the steric influence of the trispyrazolylmethane ligand and the nature of the counterion. For example, when iodide ions are present, the steric hindrance at the 3-position of the pyrazolyl rings determines the structure adopted by the cationic complexes.<sup>11</sup> Thus, the bulky Tpm<sup>Ms</sup> (HC(3-Ms-pz)<sub>3</sub>) prevents the coordination of the iodine atom to the Cu(I) center, favoring the acetonitrile adduct (Fig. 2a), whereas less hindered Tpm\* (HC(3,5-Me<sub>2</sub>-pz)<sub>3</sub>) or Tpm (HC(pz)<sub>3</sub>) ligands yield the neutral complex [Tpm<sup>x</sup>CuI] or the open-structure complex with  $\kappa^1$ - $\kappa^1$ - $\kappa^0$  coordination mode of the Tpm ligand, respectively (Fig. 2b).

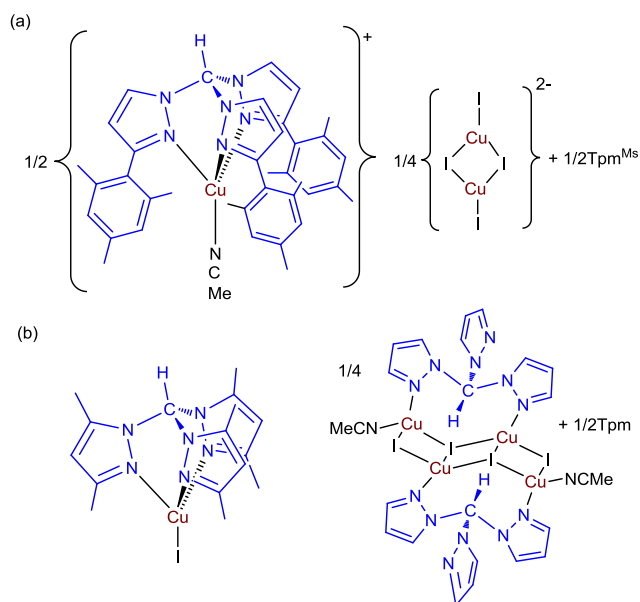


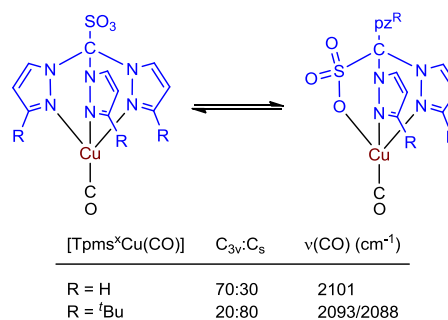
Fig. 2. Structures of Tpm<sup>x</sup>-copper(I) complexes.

In addition, some other cationic complexes of general formula [Tpm<sup>x</sup>CuL]X have been synthesized, with L being *N,N'*-dimethylimidazole selone (dmise) and thione (dmit),<sup>12</sup> tertiary monodentate phosphines (PTA = 1,3,5-triaza-7-phosphaadamantane, PCN = tris(cyanoethyl)phosphine),<sup>13</sup> perchlorate,<sup>9b</sup> isocyanide,<sup>14</sup> nitrosyl,<sup>15</sup> nitrite,<sup>16</sup> and cyanamides.<sup>17</sup>

The structurally related tris(pyrazolyl)methanesulfonate (Tpms<sup>x</sup>) ligand was used by Santini to synthesize the complex [TpmsCu(PPh<sub>3</sub>)] (Tpms = O<sub>3</sub>SC(pz)<sub>3</sub>) as the first example of the  $\kappa^3$ -N,N,O coordination mode of Tpms<sup>x</sup> ligands.<sup>18</sup> Shortly after, Kläui reported the adducts [TpmsCu(CO)] and [Tpms<sup>tBu</sup>Cu(CO)] (Tpms<sup>tBu</sup> = O<sub>3</sub>SC(3-<sup>t</sup>Bu-pz)<sub>3</sub>).<sup>19</sup> In solution, both N,N,N and N,N,O coordination modes are present. In the case of [Tpms<sup>tBu</sup>Cu(CO)], the C<sub>s</sub>-symmetrical isomer is favorable, whereas the N,N,N coordination mode (C<sub>3v</sub>) is preferred in the case of [TpmsCu(CO)] (Scheme 2). The different behaviour of the Tpms<sup>tBu</sup> ligand was explained as the

result of the repulsion between the *tert*-butyl groups and the carbonyl ligand. The  $\nu_{\text{CO}}$  of the latter complexes were determined in the solid state. The anionic Tpms<sup>x</sup> ligands are stronger donors compared to the neutral Tpm<sup>x</sup> ligands, although they are weaker donors than the Tp<sup>x</sup> ligands.

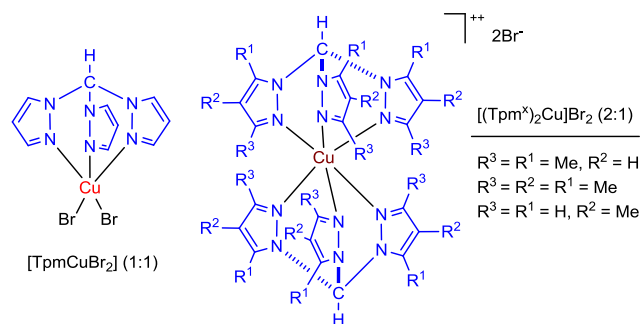
More recently, Pombeiro described a series of copper(II) complexes bearing the ligand Tpms<sup>Ph</sup> (O<sub>3</sub>SC(3-Ph-pz)<sub>3</sub>).<sup>20</sup> They found that the aforementioned tripodal coordination flexibility of the ligand toward the copper atom depends not only on the steric factors, but also on the electronic preferences of the metal center. Thus, complexes containing *N*-donor ancillary ligands (i.e.



Scheme 2. Equilibrium between the N,N,N mode (C<sub>3v</sub>) and the N,N,O mode (C<sub>s</sub>) (R = H, <sup>t</sup>Bu), and the  $\nu_{\text{CO}}$  values (cm<sup>-1</sup>) of carbonyl-copper(II) complexes.

acetonitrile) with a stronger electron-donor ability display the  $\kappa^3$ -N,N,O coordination mode, whereas those complexes bearing ligands with a  $\pi$ -acceptor character (i.e. phosphines) tend to adopt the  $\kappa^3$ -N,N,N capping coordination.

A variety of Cu(II) complexes have been described since the complexes [TpmCuX<sub>2</sub>] (X = Cl or Br) were reported by Mesubi and Anumba in 1985.<sup>21</sup> The reaction between copper(II) salts and an excess of the Tpm ligand yields complexes of general formula [Tpm<sup>x</sup>CuX<sub>2</sub>], [Tpm<sup>x</sup>CuX]X, [(CuX<sub>2</sub>)<sub>3</sub>(Tpm<sup>x</sup>)<sub>2</sub>] or [(Tpm<sup>x</sup>)<sub>2</sub>Cu]X<sub>2</sub>.<sup>22</sup> Pettinari worked on the synthesis of a wide range of [TpmCu<sup>II</sup>] complexes, using different copper(II) salts CuX<sub>2</sub> (X = ClO<sub>4</sub>, NO<sub>3</sub>, Cl, Br or CH<sub>3</sub>COO) and varying the position and the number of methyl substituents on the pyrazol rings: HC(pz)<sub>3</sub>, HC(4-Me-pz)<sub>3</sub>, HC(3,5-Me<sub>2</sub>-pz)<sub>3</sub>, HC(3,4,5-Me<sub>3</sub>-pz)<sub>3</sub> or HC(3-Me-pz)<sub>2</sub>(5-Me-pz). They found



Scheme 3 Structures of the 1:1 and 2:1 Tpm<sup>x</sup>-bromide copper(II) complexes.

that the metal to ligand stoichiometry depends on the steric bulk of the ligand and mainly on the nature of the counterion X.<sup>23</sup> For instance, the reaction of CuBr<sub>2</sub> with the Tpm ligand gives the complex [TpmCuBr<sub>2</sub>], with a 1:1 ligand to metal stoichiometry regardless the reaction conditions and the metal to ligand ratio employed. In the case of methyl substituted Tpm<sup>x</sup> ligands, the

formation of complexes  $[(\text{Tpm}^x)_2\text{Cu}]\text{X}_2$  seems the preferential route (Scheme 3).

A Cu(II)  $\mu$ -peroxo complex  $[(\text{Tpm}^*)_2\text{Cu}_2(\mu\text{-O})_2](\text{PF}_6)_2$  can be prepared from  $[\text{Tpm}^*\text{Cu}(\text{NCMe})]\text{PF}_6$  and dioxygen.<sup>24</sup> This compound undergoes thermal decomposition to afford the di- $\mu$ -hydroxo complex  $[(\text{Tpm}^*)_2\text{Cu}_2(\mu\text{-OH})_2](\text{PF}_6)_2$ . In addition, the reaction of the similar dinuclear complex  $[(\text{Tpm}^{\text{iPr}_2})_2\text{Cu}_2(\mu\text{-OH})_2]$  ( $\text{Tpm}^{\text{iPr}_2} = \text{HC}(3,5\text{-iPr}_2\text{-pz})_3$ ) with hydrazine yields the  $[(\text{Tpm}^{\text{iPr}_2})_2\text{Cu}_2(\mu\text{-RN=NR})]$  complex.<sup>25</sup>

Pombeiro have also reported Cu(II) complexes with tris(pyrazolyl)methanesulfonate ligands.<sup>20b</sup> The reaction of the lithium salt  $\text{Li}[\text{Tpm}^{\text{sPh}}]$  with  $\text{CuCl}_2$  yields the complex  $[\text{Cu}(\text{Tpm}^{\text{sPh}})(\text{H}_2\text{O})]$ , which exhibit the  $\kappa^3\text{-N,N,O}$  coordination mode.

## 2.2. Silver complexes

The coordination chemistry of silver with tris(pyrazolyl)methane ligands started with the pioneer work of Lobbia in 1989.<sup>26</sup> The subsequent work of Reger and co-workers described the synthesis and structure of series of cationic tris(pyrazolyl)methane silver(I) complexes.<sup>27</sup> The fine-tuning of steric properties of  $\text{Tpm}^x$  ligands allows the preparation of complexes with different structure around the silver center. Thus, they obtained a six-coordinated  $[(\text{Tpm}^*)_2\text{Ag}]\text{O}_3\text{SCF}_3$  complex with the ligand  $\text{HC}(3,5\text{-Me}_2\text{pz})_3$ , whereas the bulkier  $\text{HC}(3\text{-}^t\text{Bupz})_3$  gives rise to the formation of the three-coordinated  $[\text{Tpm}^{\text{tBu}}\text{Ag}]\text{O}_3\text{SCF}_3$  complex. The reaction of the latter with  $^t\text{BuNC}$  or  $\text{CO}$  affords the complexes  $[\text{Tpm}^{\text{tBu}}\text{Ag}(\text{CN}^t\text{Bu})]\text{O}_3\text{SCF}_3$  and  $[\text{Tpm}^{\text{tBu}}\text{Ag}(\text{CO})]\text{O}_3\text{SCF}_3$ , respectively, although the carbonyl adduct could not be isolated (Fig. 3). A few years later, Pettinari reported the preparation of a variety of  $[\text{Tpm}^x\text{Ag}(\text{I})]$  complexes by the reaction of  $\text{AgX}$  salts ( $\text{X} = \text{ClO}_4, \text{NO}_3$  or  $\text{SO}_3\text{CH}_3$ ) with  $\text{Tpm}^x$  ligands  $\text{L}$  ( $\text{Tpm}^x = \text{HC}(\text{pz})_3, \text{HC}(4\text{-Me-pz})_3, \text{HC}(3,5\text{-Me}_2\text{-pz})_3, \text{HC}(3,4,5\text{-Me}_3\text{-pz})_3$  or  $\text{HC}(3\text{-Me-pz})_2(5\text{-Me-pz})$ ). They found that the nuclearity depended not only on the steric hindrance of the neutral ligand but also on the counterion  $\text{X}$ .<sup>28</sup>

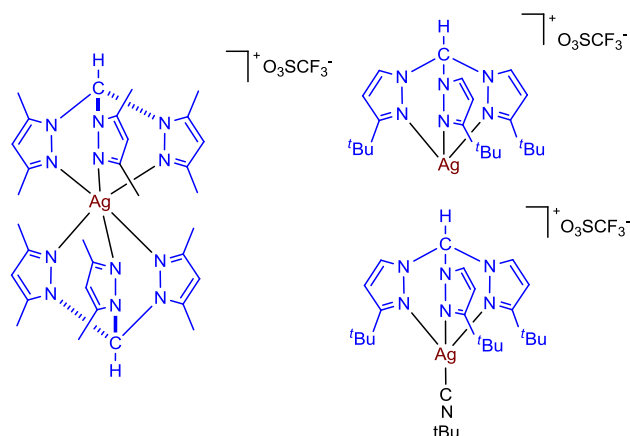


Fig. 3. Structures of six-, four-, and three-coordinated tris(pyrazolyl)methane silver(I) complexes.

The singular coordination chemistry of silver with tris(pyrazolyl)methane is not limited to the  $\kappa^3$  (tripodal) coordination fashion. The  $\kappa^2\text{-}\kappa^0$  mode, with only two pyrazolyl rings bonded to silver center, and the  $\kappa^2\text{-}\kappa^1$  mode, in which the ligand

acts as a bridge between two metals, are also observed by  $\text{Tpm}^x$ -

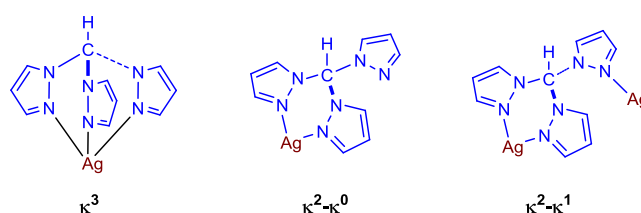


Fig. 4. Coordination modes of silver tris(pyrazolyl)methane complexes.

silver complexes (Fig. 4).

An extensive work in this field has been done as well as recently reviewed by Reger and Semeniuc.<sup>29</sup> They have synthesized several polynuclear silver complexes in which the  $\text{Tpm}^x$  ligands are connected via the apical carbon atom through linkers of variable size in both,  $\kappa^2\text{-}\kappa^0$  or  $\kappa^2\text{-}\kappa^1$  coordination modes.<sup>30,31</sup> Following this methodology, a wide variety of supramolecular structures have been synthesized including coordination polymers with interest as functional materials. The coordination environment around the metallic centers is determined by the nature of the ligand, the counterion, and the solvent. For example, the  $\kappa^2\text{-}\kappa^1$  bonding mode is adopted in the coordination polymer shown in Fig. 5a, whilst the  $\kappa^2\text{-}\kappa^0$  coordination fashion is preferred when a more hindered linker is used to connect both  $\text{Tpm}$  units (Fig. 5b).

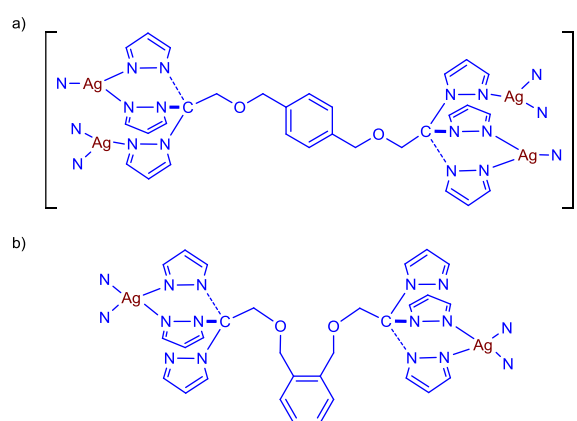
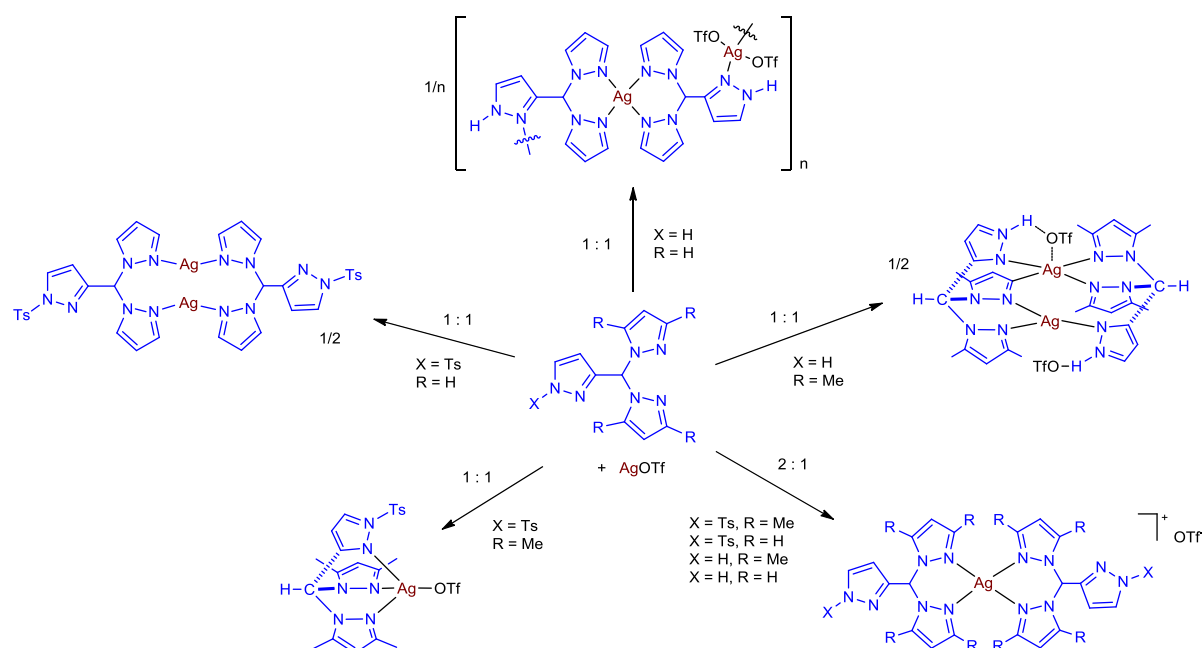


Fig. 5. (a)  $\kappa^2\text{-}\kappa^1$  and (b)  $\kappa^2\text{-}\kappa^0$  coordination modes of polynuclear tris(pyrazolyl)methane silver(I) complexes.

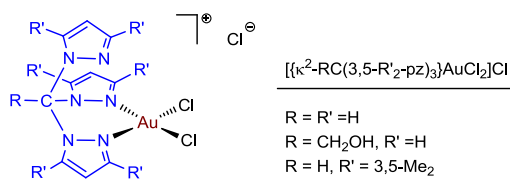
Finally, the group of Gardinier has recently reported the synthesis of a new family of silver(I) complexes bearing “nitrogen-confused” C-scorpionate ligands ( $^x\text{L}$ ).<sup>32</sup> This class of ligands contains one pyrazolyl ring bounded to the apical carbon atom through a carbon atom rather than a nitrogen atom (Scheme 4). The electronic and steric influence of the ligand on the metal center can be tuned by pyrazolyl substituents  $\text{R}$  and  $\text{X}$ . The latter facilitate supramolecular aggregation processes, crystallization, and reactions. A variety of 1:1 and 2:1 ligand to silver ratio complexes has been synthesized, with four different  $^x\text{L}$  ligands ( $^{\text{H}}\text{L}, ^{\text{Ts}}\text{L}, ^{\text{H}}\text{L}^*, ^{\text{Ts}}\text{L}^*$ ). The solid structure of those complexes shows different coordination modes ( $\kappa^3, \kappa^2\text{-}\kappa^0, \kappa^2\text{-}\kappa^1$ ) depending of the nature of the  $\text{X}$  and  $\text{R}$  substituents, as well as the ligand to metal ratio.



Scheme 4. Solid state structures of 1:1 and 2:1  $\text{L}/\text{Ag}(\text{OTf})$  complexes.

### 2.3. Gold complexes

The scarcity of gold complexes bearing  $\text{Tpm}^x$  ligands is even more pronounced than the case of  $\text{Tp}^x$  counterparts.<sup>2</sup> In 1982, Cauty *et al.* described<sup>33</sup> the synthesis of the complex  $[(\kappa^2\text{-Tpm})\text{AuMe}_2]\text{NO}_3$ , which has been the only reported example of this family of compounds until recently. Thus, Martins and coworkers have prepared functionalized  $\text{Tpm}^x$  ligands, which led to the formation of analogous gold(III) complexes of formula  $[(\kappa^2\text{-RC}(3,5\text{-R}'_2\text{-pz})_3)\text{AuCl}_2]\text{Cl}$  ( $\text{R} = \text{R}' = \text{H}$ ;  $\text{R} = \text{CH}_2\text{OH}$ ,  $\text{R}' = \text{H}$ ; and  $\text{R} = \text{H}$ ,  $\text{R}' = 3,5\text{-Me}_2$ ).<sup>34</sup> All these complexes exhibit a square-planar geometry, with a  $\kappa^2\text{-}\kappa^0$  coordination mode (Scheme 5). These complexes were used for the oxidation of cyclohexane under homogeneous and heterogeneous conditions, as will be commented in section 3.3.



Scheme 5.  $\text{Tpm}^x$ -gold(III) complexes.

## 3. Group 11 Tris(pyrazolyl)methane Complexes in Catalytic Transformations

### 3.1. Carbene and nitrene transfer reactions

Cationic  $[\text{Tpm}^x\text{CuL}]\text{X}$  complexes are very efficient catalysts for the insertion of the  $:\text{CHCO}_2\text{Et}$  unit from  $\text{N}_2\text{CHCO}_2\text{Et}$  (EDA) into N-H, O-H, and C-H bonds,<sup>35</sup> as well as olefin cyclopropanation and alkyne cyclopropanation.<sup>36</sup> They are also highly active for the nitrene

transfer from chloramine-T to alkenes and cyclic ethers.<sup>37</sup> However, a comparison between the catalytic activity of complexes  $[\text{Tpm}^x\text{Cu}]$  and  $[\text{Tp}^x\text{Cu}]$  in the functionalization of C-H bonds shows a better performance in the case of neutral counterparts.<sup>2</sup> This difference is attributed to a higher electrophilic character at the metal center coordinated to anionic  $\text{Tp}^x$  ligands, resulting in a more active catalyst.

The electronic factors at the metal center can be modified by installing substituent of different nature in the pyrazol rings. Our group described the synthesis of new mesityl-substituted  $\text{Tpm}^{\text{Ms}}$  and  $\text{Tpm}^{\text{Ms}*}$  ( $\text{HC}(3\text{-Ms-pz})_2(5\text{-Ms-pz})$ ) ligands and the corresponding copper complexes  $[\text{Tpm}^{\text{Ms}}\text{Cu}(\text{NCMe})]\text{PF}_6$  or

Table 2. Carbene transfer reaction from ethyl diazoacetate (EDA) to C-H bonds with  $[\text{Tpm}^x\text{Cu}(\text{NCMe})]\text{PF}_6$  complexes as catalyst.

Entry	Complex	Substrate	Product	Yield (%)
1	$[\text{Tpm}^*\text{Cu}(\text{MeCN})]\text{PF}_6$			30
2	$[\text{Tpm}^{\text{Ms}}\text{Cu}(\text{MeCN})]\text{PF}_6$			77
3	$[\text{Tpm}^{\text{Ms}*}\text{Cu}(\text{MeCN})]\text{PF}_6$			73
4	$[\text{Tpm}^{\text{Ms}}\text{Cu}(\text{MeCN})]\text{PF}_6$			10
5	$[\text{Tpm}^{\text{Ms}*}\text{Cu}(\text{MeCN})]\text{PF}_6$			40

$[\text{Tpm}^{\text{Ms}*}\text{Cu}(\text{NCMe})]\text{PF}_6$ ,<sup>35</sup> which displayed catalytic activity toward the conversion of cyclohexane into ethyl cyclohexylacetate superior to that of the  $\text{Tpm}^*$  derivative (Table 2, entries 1-3).<sup>36</sup> Steric factors exert a certain influence in the catalytic reaction. Thus, a subtle difference in structure of the  $\text{Tpm}^x$  ligand facilitated a better performance for the carbene transfer into hindered C-H bonds.

Thus, the catalyst containing the ligand  $\text{Tpm}^{\text{Ms}^*}$  shows higher catalytic activity (40%) than that with  $\text{Tpm}^{\text{Ms}}$  (10%) for the conversion of 2,3-dimethylbutane into ethyl 3,3,4-trimethylpentanoate (Table 2, entries 4-5). This result is attributed to a wider catalytic pocket in the case of the complex  $[\text{Tpm}^{\text{Ms}^*}\text{Cu}(\text{MeCN})]\text{PF}_6$ , that tolerates the approach of sterically demanding substrates to the metal center. On the other hand, the cationic nature of  $[\text{Tpm}^x\text{Cu}(\text{I})]$  complexes allows performing these transformations in either homogeneous or biphasic conditions. The ionic liquid  $[\text{bmim}]\text{PF}_6$  ( $\text{bmim} = 1$ -*n*-butyl-3-methylimidazolium) together with hexane constitute the biphasic reaction medium. The results obtained thereby in the reaction of EDA with styrene, 1-phenyl-1-propyne, aniline, ethanol, or cyclohexane, using  $[\text{Tpm}^x\text{Cu}(\text{NCMe})]\text{PF}_6$  as catalyst, compare well with those performed in homogeneous conditions (Table 3).<sup>36</sup>

**Table 3.** Carbene transfer reaction from ethyl diazoacetate (EDA) with  $[\text{Tpm}^x\text{Cu}(\text{NCMe})]\text{PF}_6$  as the catalyst under homogeneous or biphasic conditions

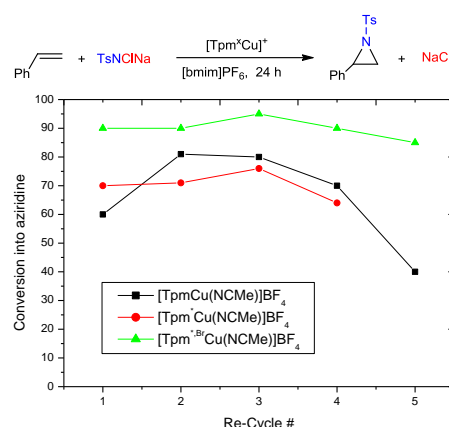
$$\text{Nuc} + \text{N}_2 \begin{array}{c} \text{CO}_2\text{Et} \\ \diagup \\ \text{C} \\ \diagdown \\ \text{H} \end{array} \xrightarrow[\text{Homog.: CH}_2\text{Cl}_2]{\text{Biphasic: [bmim]PF}_6 / \text{hexane}} [\text{Tpm}^x\text{Cu}(\text{NCMe})]\text{PF}_6 \xrightarrow{\text{r.t.}} \text{Nuc}-\text{CH}_2-\text{CO}_2\text{Et} + \text{N}_2$$

Entry	Substrate	Product	Homog., yield (%)	Biphasic, yield (%)
1			96	95
2			80	77
3			99	96
4			99	98
5			30	35

The biphasic methodology facilitates the separation of products and the recycle of the catalyst several times without substantial loss of the catalytic activity. Thus, the conversion of the reactions indicated in Table 3 (entries 1,3-4) were maintained over five consecutive cycles (93-98%). Interestingly, the recovered ionic liquids-catalyst phase can be stored under nitrogen at 0 °C for several weeks and then employed for these transformations with the same outcome. Moreover, the recycling efficiency, as well as the catalytic activity, can be optimized by fine-tuning the structure of the  $\text{Tpm}^x$  ligand. For example, the best result for the aziridination of styrene (Scheme 6) using different  $[\text{Tpm}^x\text{Cu}]$ -based catalysts under biphasic conditions was obtained with the complex  $[\text{Tpm}^{*,\text{Br}}\text{Cu}(\text{NCMe})]\text{BF}_4$  ( $\text{Tpm}^{*,\text{Br}} = \text{HC}(3,5\text{-Me}_2\text{-4-Br-pz})_3$ ).<sup>37</sup>

A different approach to recover the catalyst and reuse it after each cycle is catalyst heterogenization. Thus, tris(pyrazolyl)borate ligands have been supported on a variety of materials.<sup>38</sup> For example,  $\text{Tp}^x\text{Cu}$ -containing complexes were installed on silica gel<sup>39</sup> and polymers;<sup>40</sup> and used as heterogeneous catalysts for carbene and nitrene transfer reactions. However, the heterogenization of group 11  $\text{Tpm}^x$  complexes remains relatively unexplored to date; only  $\text{Tpm}^x\text{Cu}^{\text{II}}$ - and  $\text{Tpm}^x\text{Au}^{\text{III}}$ - complexes have been supported in

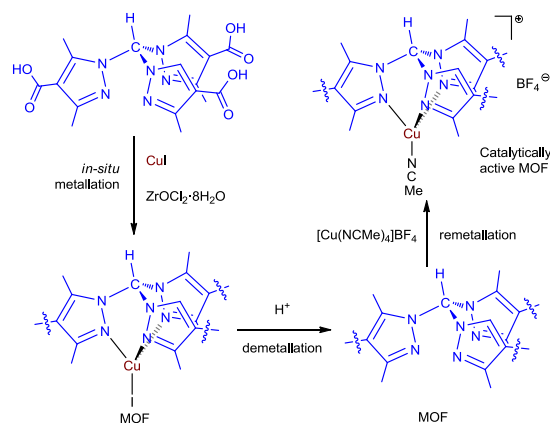
silica nanoparticles<sup>41</sup> and carbon materials,<sup>34</sup> respectively. These materials have been used as heterogeneous catalysts for the



**Scheme 6.** Plot of the conversion vs. number of cycles for the aziridination of styrene with chloramine-T catalyzed by  $[\text{Tpm}^x\text{Cu}(\text{NCMe})]\text{BF}_4$  complexes.

oxidation of cyclohexane see section 3.3).

Very recently, Dincă has reported the first example of the installation of a  $[\text{Tpm}^x\text{Cu}]$  moiety in metal-organic frameworks (MOFs).<sup>42</sup> This methodology provides well-defined materials with site-isolated metal centers; and overcomes the difficult control of the active sites of heterogeneous materials mentioned before. The reaction of  $\text{TpmC}^*$  ligand ( $\text{TpmC}^* = \text{HC}(3,5\text{-Me}_2\text{-4-CO}_2\text{H-pz})_3$ ),  $\text{ZrOCl}_2$ , and  $\text{CuI}$  gives a new MOF containing  $[\text{TpmC}^*\text{Cu}]$  sites. Further processes of demetalation and remetalation yields a catalytically active MOF with retention of crystallinity and porosity (Scheme 7).



**Scheme 7.** Synthesis of MOF with  $\text{TpmC}^*$  and subsequent demetalation/metalation process.

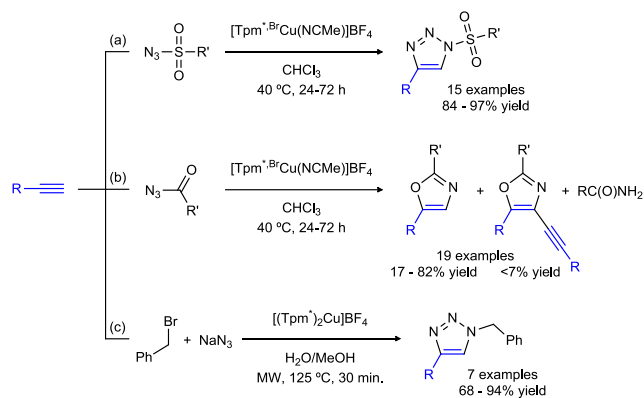
This MOF with a cationic  $\text{Tpm}^x\text{Cu}$ -like environment demonstrated a remarkable catalytic activity. Thus, the cyclopropanation of styrene proceeded in 95%; a result comparable to homogeneous  $[\text{Tpm}^x\text{Cu}]$  complexes; and moreover, the carbene insertion into C-H bonds in cyclohexane produced ethyl cyclohexylacetate in 67% yield, surpassing the 30% yield reported for the molecular counterpart under similar conditions.<sup>36</sup>

The use of silver complexes with  $\text{Tpm}^x$  ligands as catalysts is very reduced: the reaction of styrene with *N*-tosylamine and

PhI(OAc)<sub>2</sub> has been reported very recently with such compounds as catalysts with a “nitrogen-confused” C-scorpionate ligands (\*L) as catalyst.<sup>32</sup> The complexes [(<sup>Ts</sup>L)<sub>2</sub>Ag]OTf and [(<sup>Ts</sup>L\*)Ag]OTf induced the expected aziridination reaction, albeit with modest yields (27% and 18%, respectively).

### 3.2. Cycloadditions of azides and alkynes

The [3+2] cycloadditions reactions between alkynes and azides can be efficiently catalyzed by cationic [Tpm<sup>x</sup>Cu(I)] complexes. Our group has reported the reaction of terminal alkynes with *N*-sulfonylazides catalyzed by this family of complexes under mild conditions.<sup>43</sup> The versatility of Tpm<sup>x</sup> ligands within copper complexes allowed the synthesis of 4-substituted *N*-1-sulfonyl-1,2,3-triazoles; the complex [Tpm<sup>x</sup>,BrCu(NCMe)]BF<sub>4</sub> was found as the most active of the array tested (Scheme 8a). In this context, a novel transformation was discovered while studying the reaction of 1-alkynes with acyl azides, resulting in the formation of 2,5-disubstituted oxazoles as the major product, along with 2,4,5-trisubstituted oxazoles and RC(O)NH<sub>2</sub> as minor products (Scheme 8b).<sup>44</sup> The subsequent mechanistic studies suggested that the reaction proceeds via coordination of the carbonyl azide to the metal, followed by nitrogen extrusion and the formation of copper-nitrene intermediates as the turnover-limiting step.<sup>45</sup> In a related procedure, Pombeiro has recently developed a methodology for the three-component reaction of terminal alkynes, benzyl bromide and sodium azide. Both the reaction medium (MeOH/H<sub>2</sub>O) as well as the [(Tpm<sup>x</sup>)<sub>2</sub>Cu]BF<sub>4</sub> catalyst played an important role to achieve the synthesis 4-substituted *N*-1-benzyl-1,2,3-triazoles in high yields (Scheme 8c).<sup>46</sup>

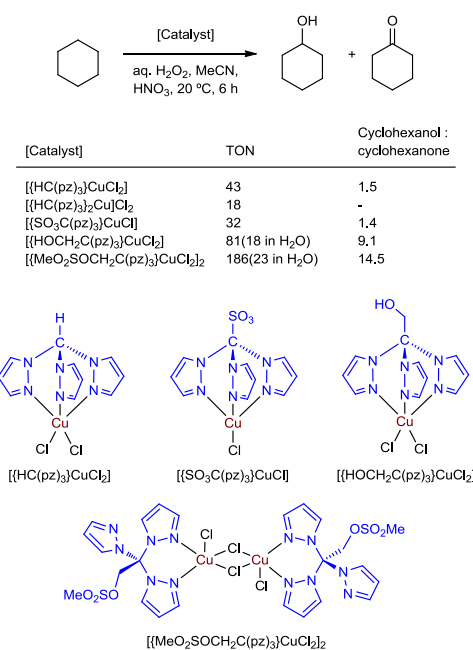


**Scheme 8.** Cycloaddition reactions of 1-alkynes with (a) sulfonyl azides; (b) acyl azides; (c) benzyl bromide and sodium azide catalyzed by Tpm-copper complexes.

### 3.3. Oxidation reactions

In the context of C<sub>sp3</sub>-H oxidation processes, which occur in copper metalloenzymes, several derivatives of tris(pyrazolyl)methane copper complexes have been designed to mimic the active sites of such compounds, and to achieve efficient and highly selective oxidation of alkanes.<sup>47</sup> The first example was reported in 1999 by Lobet and Costas.<sup>48</sup> The complex [TpmCu(py)]ClO<sub>4</sub> (5 mol%), *t*-BuOOH, and molecular oxygen (1 atm) oxidizes ethylbenzene to acetophenone in 32% yield at room temperature. The oxidation of

cyclohexane to cyclohexanol and cyclohexanone, which is a process of high interest in the industrial production of nylon-6 and nylon-6,6', was investigated by Pombeiro and co-workers. This group evaluated the catalytic performance of several

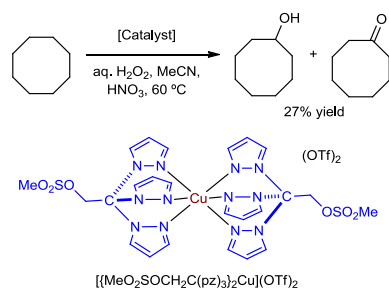


**Scheme 9.** Catalytic activity of tris(pyrazolyl)methane copper(II) complexes in the oxidation of cyclohexane.

tris(pyrazolyl)methane copper(II) complexes in this reaction (Scheme 9). First, the [TpmCuCl<sub>2</sub>] complex displayed a modest turnover number (TON, mol products/mol catalyst) of 43 under mild conditions (at 20 °C and using an aqueous solution of H<sub>2</sub>O<sub>2</sub>).<sup>49</sup> As expected, the catalytic activity was even lower for the complex [(Tpm)<sub>2</sub>Cu]Cl<sub>2</sub> (TON of 18), demonstrating the importance of labile monodentate ligands to promote coordination vacancies in the metal center. The [Tpm<sup>SO3</sup>CuCl] complex was also employed as catalyst and did not improve the previous results, with a TON of 32.

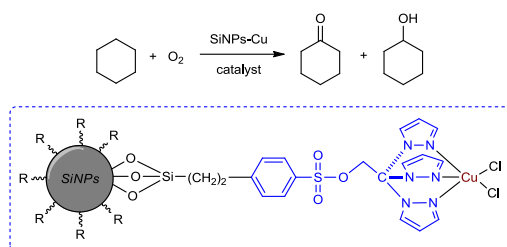
The same group described two functionalized tris(pyrazolyl)methane copper(II) complexes by introducing a methoxy or methyl methanesulfonic ester group in the ligand backbone.<sup>50</sup> The water-soluble complexes [[HOCH<sub>2</sub>C(pz)<sub>3</sub>]CuCl<sub>2</sub>] and [[MeO<sub>2</sub>SOCH<sub>2</sub>C(pz)<sub>3</sub>]CuCl<sub>2</sub>]<sub>2</sub> were also tested as catalyst for the oxidation of cyclohexane (Scheme 9). The latter showed the higher activity (in MeCN/H<sub>2</sub>O) with a TON of 186 and a remarkable alcohol to ketone ratio of 14.5. The hydrophilicity of those complexes allows operating in pure aqueous media, which is desirable towards greener oxidation process, although TONs dropped to 18 and 23, respectively.

The same authors reported a six-coordinated cationic copper(II) complex as catalyst for the oxidation of cyclooctane (Scheme 10).<sup>51</sup> In this full-sandwich complex the ligands are sufficiently labile, and the reaction proceeds efficiently in water/acetonitrile at 60 °C with yields up to 27%. Moreover, the authors found a beneficial effect of additives, such as HNO<sub>3</sub>, on the yield; probably related with ligand protonation leading to vacant coordination sites at the metal center and proton-transfer processes over the catalytic cycle.



**Scheme 10.** Peroxidative oxidation of cyclooctane catalyzed by full-sandwich copper(II) homoscorpionate complex.

As previously commented, the oxidation of cyclohexane has been accomplished using supported tris(pyrazolyl)methane complexes as heterogeneous catalysts. Mishra prepared functionalized silica nanoparticles with  $[\{\text{HOCH}_2\text{C}(\text{pz})_3\text{CuCl}_2\}]$  complex anchored (Scheme 11).<sup>41</sup> This compound catalyzed the



**Scheme 11.** Oxidation of cyclohexane with molecular oxygen catalyzed by tris(1-pyrazolyl)ethanol Cu(II) complex anchored in silica nanoparticles (SiNPs).

oxidation of cyclohexane to cyclohexanol and cyclohexanone with molecular oxygen with a remarkable activity (TON of 1216 with overall yield of 13.7%). They also observed 85% selectivity toward cyclohexanol. Interestingly, the catalytic system is thermally stable under operating reaction temperature (150 °C) and reusable up to five more cycles.

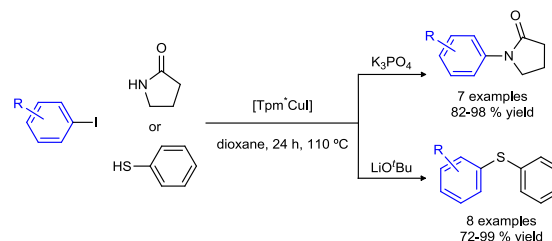
Martins and co-workers synthesized a series of gold(III) complexes, commented in section 2.3. These compounds were used as catalyst for the oxidation of cyclohexane to cyclohexanol and cyclohexanone, with aqueous  $\text{H}_2\text{O}_2$ , under homogeneous and heterogeneous conditions.<sup>34</sup> In the latter case, the  $[\{\kappa^2\text{-Tpm}^x\}\text{Au(III)}]$  complexes were supported on different carbon materials (carbon xerogel, activated carbon or multi-walled carbon nanotubes). The most efficient catalyst was the complex  $[\{\kappa^2\text{-HOCH}_2\text{C}(\text{pz})_3\text{AuCl}_2\}]\text{Cl}$ , which in homogeneous conditions achieved 10% yield with a TON of 300, and 16% yield with a TON of 800 for the heterogeneous homogeneous process.

### 3.4. Other reactions

The  $[\text{Tpm}^x\text{Cu(I)}]$  complexes can be used as efficient catalyst for C-N and C-S bond formation cross-couplings reactions. Our group reported that N- and S-arylation reactions can be achieved using the complex  $[\text{Tpm}^x\text{CuI}]$  as catalyst.<sup>11</sup> First, the coupling of substituted aryl iodides with 2-pyrrolidinone was investigated, the protocol being also extended to the coupling of substituted aryl iodides with thiophenol (Scheme 12). A variety of C-N and C-S

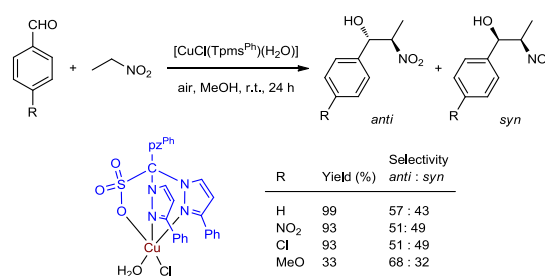
coupling products were obtained with efficiencies similar to those described for mixtures of CuI and tridentate ligands.

Pombeiro reported that tris(pyrazolyl)methanesulfonate copper complexes can be used as catalyst for the Henry reaction,<sup>52</sup> testing the reaction of benzaldehyde with nitroethane in the presence of



**Scheme 12.** Arylation of 2-pyrrolidinone and thiophenol in the presence of the complex  $[\text{Tpm}^x\text{CuI}]$  as catalyst.

the complex  $[\text{CuCl}(\text{Tpms}^{\text{Ph}})(\text{H}_2\text{O})]$  as catalyst. The nitroaldol reaction yields a mixture of the corresponding  $\beta$ -nitroalcohol diastereoisomers, and the Cu(II) complex exhibit a good catalytic activity with yields up to 99%, although with a modest diastereoselectivity (Scheme 13).



**Scheme 13.** Catalytic activity of  $[\text{CuCl}(\text{Tpms}^{\text{Ph}})(\text{H}_2\text{O})]$  in the Henry reaction.

## Conclusions

The coordination chemistry of tris(pyrazolyl)methane ligands with Group 11 metals have been substantially developed in the last two decades. These versatile N-donor ligands stabilize the metal center and control the steric and electronic properties depending of the nature of substituents. Their flexibility allows the formation of a wide range of complexes with different coordination modes.

A key feature of  $\text{Tpm}^x$  ligands is the possibility of backbone modification. It is shown that the solubility in water can be improved by attaching polar substituents in the apical carbon. Additional donor groups can be also installed in order to further extend the coordination ability of the ligand; as is the case of tris(pyrazolyl)methanesulfonates ( $\text{Tpms}^x$ ), with an oxygen atom also available as a donor group. Moreover, backbone modification or decoration of pyrazol rings with the suitable substituents can be harnessed for catalyst heterogenization or installation of a  $\text{Tpm}^x$ -metal moiety into metal-organic frameworks, respectively.

The cationic nature of  $Tpm^x$  complexes allows performing catalytic organic transformations in biphasic reaction medium of an ionic liquid and hydrocarbon. Separation of the products can be easily performed, as well as the catalyst-recycling process that can be achieved several times without any loss of the catalytic activity.

Overall, the versatile design of  $Tpm^x$  ligands, and their metal complexes, offers the possibility to explore a variety of interesting catalytic applications, which, in some cases, cannot be addressed by the homologous tris(pyrazolyl)borates. Thus, further progress is needed in terms of synthetic procedures and novel catalytic transformations of these family of ligands.

## Conflicts of interest

There are no conflicts to declare.

## Acknowledgements

We thank MINECO for support with Grant CTQ2017-82893-C2-1-R.

## Notes and references

- (a) S. Trofimenko, *Scorpionates: The Coordination of Poly(pyrazolyl)borate Ligands*, Imperial College Press, London, 1999; (b) C. Pettinari, *Scorpionates II: Chelating Borate Ligands*, Imperial College Press, London, 2008; (c) C. Pettinari, R. Pettinari and F. Marchetti, *Adv. Organomet. Chem.* 2016, **65**, 175-260.
- J. M. Muñoz-Molina, T. R. Belderrain and P. J. Pérez, *Coord. Chem. Rev.*, 2019, **390**, 171-189.
- (a) C. Pettinari and R. Pettinari, *Coord. Chem. Rev.*, 2005, **249**, 663-691; (b) H. R. Bigmore, S. C. Lawrence, P. Mountford and C. S. Tredget, *Dalton Trans.*, 2005, 635-651.
- S. Trofimenko, *J. Am. Chem. Soc.*, 1970, **70**, 5118-5126.
- (a) S. Julia, P. Sala, J. Del Mazo, M. Sancho, C. Ochoa, J. Elguero, J.P. Fayet and M.C. Vertut, *J. Heterocyclic Chem.*, 1982, **19**, 1141-1145; (b) R. M. Claramunt, H. Hernandez, J. Elguero and S. Julia, *Bull. Chem. Soc. Fr.*, 1983, **2**, 5-10; (c) S. Julia, J. M. Del Mazo, L. Avila and J. Elguero, *Org. Prep. Proced. Int.*, 1984, **16**, 299-307. (d) I. Alkorta, R. M. Claramunt, E. Díez-Barra, J. Elguero, A. de la Hoz and C. López, *Coord. Chem. Rev.* 2017, **339**, 153-182.
- (a) D. L. Jameson and R. K. Castellano, *Inorg. Synth.* 1998, **32**, 51-63; (b) D. L. Reger, J. E. Collins, D. L. Jameson and R. K. Castellano, *Inorg. Synth.* 1998, **32**, 63-65. (c) C. Titze, J. Hermann, H. Vahrenkamp, *Chem. Ber.* 1995, **128**, 1095-1103.
- D. L. Reger, T. C. Grattan, K. J. Brown, C. A. Little and J. J. S. Lamba, A. L. Rheingold, and R. D. Sommer, *J. Organomet. Chem.* 2000, **607**, 120-128.
- D. L. Reger, J. E. Collins, A. L. Rheingold and L. M. Liable-Sands, *Organometallics*, 1996, **15**, 2029-2032.
- (a) C. Mealli, C. S. Arcus, J. L. Wilkinson, T. J. Marks and J. A. Ibers, *J. Am. Chem. Soc.*, 1976, **98**, 711-718; (b) K. Fujisawa, T. Ono, Y. Ishikawa, N. Amir, Y. Miyashita, K. I. Okamoto and N. Lehnert, *Inorg. Chem.*, 2006, **45**, 1698-1713; (c) N. Kitajima, K. Fujisawa, C. Fujimoto, Y. Moro-oka, S. Hashimoto, T. Kitagawa, K. Toriumi, K. Tatsumi and A. Nakamura, *J. Am. Chem. Soc.*, 1992, **114**, 1277-1291; (d) S. M. Carrier, C. E. Ruggiero, W. B. Tolman and G. B. Jameson, *J. Am. Chem. Soc.*, 1992, **114**, 4407-4408.
- (a) J. L. Schneider, S. M. Carrier, C. E. Ruggiero, V. G. Young and W. B. Tolman, *J. Am. Chem. Soc.*, 1998, **120**, 11408-11418; (b) S. M. Carrier, C. E. Ruggiero, R. P. Houser and W. B. Tolman, *Inorg. Chem.*, 1993, **32**, 4889-4899; (c) J. M. Muñoz-Molina, W. M. C. Sameera, E. Álvarez, F. Maseras, T. R. Belderrain and P. J. Pérez, *Inorg. Chem.*, 2011, **50**, 2458-2467.
- E. Haldón, E. Álvarez, M. C. Nicasio and P. J. Pérez, *Inorg. Chem.*, 2012, **51**, 8298-8306.
- M. M. Kimani, J. L. Brumaghim and D. Vanderveer, *Inorg. Chem.*, 2010, **49**, 9200-9211.
- M. Porchia, A. Dolmella, V. Gandin, C. Marzano, M. Pellei, V. Peruzzo, F. Refosco, C. Santini and F. Tisato, *Eur. J. Med. Chem.*, 2013, **59**, 218-226.
- A. A. Melekhova, A. S. Novikov, N. A. Bokach, M. S. Avdonceva, V. Y. Kukushkin, *Inorg. Chim. Acta*, 2016, **450**, 140-145.
- K. Fujisawa, A. Tateda, Y. Miyashita, K. I. Okamoto, F. Paulat, V. K. K. Praneeth, A. Merkle and N. Lehnert, *J. Am. Chem. Soc.*, 2008, **130**, 1205-1213.
- M. Kujime, C. Izumi, M. Tomura, M. Hada and H. Fujii, *J. Am. Chem. Soc.*, 2008, **130**, 6088-6098.
- A. A. Melekhova, A. S. Novikov, A. Y. Dubovtsev, A. A. Zolotarev and N. A. Bokach, *Inorg. Chim. Acta*, 2019, **484**, 69-74.
- C. Santini, M. Pellei, G. G. Lobbia, A. Cingolani, R. Spagna and M. Camalli, *Inorg. Chem. Commun.*, 2002, **5**, 430-433.
- W. Kläui, M. Berghahn, W. Frank, G. J. Reiß, T. Seöhnherr, G. Rheinwald and H. Lang, *Eur. J. Inorg. Chem.*, 2003, 2059-2070.
- (a) R. Wanke, P. Smoleński, M. F. C. Guedes Da Silvan, L. M. D. R. S. Martins and A. J. L. Pombeiro, *Inorg. Chem.*, 2008, **47**, 10158-10168; (b) B. G. M. Rocha, R. Wanke, M. F. C. Guedes Da Silva, K. V. Luzyanin, L. M. D. R. S. Martins, P. Smolénski and A. J. L. Pombeiro, *J. Organomet. Chem.*, 2012, **714**, 47-52.
- M. A. Mesubi and F. O. Anumba, *Transit. Met. Chem.*, 1985, **10**, 5-8.
- (a) W.-Z. Shen, C.-Z. Xie, P. Cheng, J.-T. Chen, S.-P. Yan, D.-Z. Liao and Z.-H. Jiang, *J. Chem. Research (S)*, 2003, 307-309; (b) E. R. Humphrey, K. L. V. Mann, Z. R. Reeves, A. Behrendt, J. C. Jeffery, J. P. Maher, J. A. McCleverty and M. D. Ward, *New J. Chem.*, 1999, **23**, 417-424; (c) K. Fujisawa, T. Ono, H. Aoki, Y. Ishikawa, Y. Miyashita, K. I. Okamoto, H. Nakazawa and H. Higashimura, *Inorg. Chem. Commun.*, 2004, **7**, 330-332; (d) K. Fujisawa, H. Iwamoto, K. Tobita, Y. Miyashita and K. I. Okamoto, *Inorg. Chim. Acta*, 2009, **362**, 4500-4509; (e) D. L. Reger, E. Sirianni, J. J. Horger, M. D. Smith and R. F. Semeniuc, *Cryst. Growth Des.*, 2010, **10**, 386-393; (f) K. Fujisawa, K. Tobita, S. Sakuma, D. Savard and D. B. Leznoff, *Inorg. Chim. Acta*, 2019, **486**, 582-588.
- D. Martini, M. Pellei, C. Pettinari, B. W. Skelton and A. H. White, *Inorg. Chim. Acta*, 2002, **333**, 72-82.

- 24 M. Cvetkovic, S. R. Batten, B. Moubaraki, K. S. Murray and L. Spiccia, *Inorg. Chim. Acta*, 2001, **324**, 131–140.
- 25 F. Paulat, N. Lehnert, Y. Ishikawa, K. I. Okamoto and K. Fujisawa, *Inorg. Chim. Acta*, 2008, **361**, 901–915.
- 26 G. G. Lobbia, F. Bonati, A. Cingolani and D. Leonesi, *Synth. React. Inorg. Met. Chem.*, 1989, **19**, 827–839.
- 27 D. L. Reger, J. E. Collins, A. L. Rheingold, L. M. Liable-Sands and G. P. A. Yap, *Organometallics*, 1997, **16**, 349–353.
- 28 A. Cingolani, Effendy, D. Martini, M. Pellei, C. Pettinari, B. W. Skelton and A. H. White, *Inorg. Chim. Acta*, 2002, **328**, 87–95.
- 29 R. F. Semeniuc and D. L. Reger, *Eur. J. Inorg. Chem.*, 2016, 2253–2271.
- 30 (a) D. L. Reger, R. F. Semeniuc and M. D. Smith, *J. Chem. Soc. Dalton Trans.*, 2008, **2**, 2253–2260; (b) D. L. Reger, R. F. Semeniuc, I. Silaghi-Dumitrescu and M. D. Smith, *Inorg. Chem.*, 2003, **42**, 3751–3764; (c) D. L. Reger, R. F. Semeniuc, V. Rassolov and M. D. Smith, *Inorg. Chem.*, 2004, **43**, 537–554; (d) D. L. Reger, R. F. Semeniuc and M. D. Smith, *Inorg. Chem.*, 2003, **42**, 8137–8139; (e) D. L. Reger, R. F. Semeniuc and M. D. Smith, *Inorg. Chem.*, 2001, **40**, 6545–6546; (f) D. L. Reger, R. F. Semeniuc and M. D. Smith, *Inorg. Chem. Commun.*, 2002, **5**, 278–282; (g) R. F. Semeniuc, D. L. Reger and M. D. Smith, *Acta Crystallogr. Sect. C Struct. Chem.*, 2016, **72**, 826–831.
- 31 (a) D. L. Reger, R. F. Semeniuc and M. D. Smith, *Eur. J. Inorg. Chem.*, 2002, 543–546; (b) D. L. Reger, R. F. Semeniuc and M. D. Smith, *Dalton Trans.*, 2003, **2**, 285–286; (c) D. L. Reger, R. F. Semeniuc, C. A. Little and M. D. Smith, *Inorg. Chem.*, 2006, **45**, 7758–7769; (d) D. L. Reger, R. F. Semeniuc, B. Captain and M. D. Smith, *Inorg. Chem.*, 2005, **44**, 2995–2997; (e) D. L. Reger, R. F. Semeniuc and M. D. Smith, *Eur. J. Inorg. Chem.*, 2003, 3480–3494.
- 32 J. R. Gardinier, K. J. Meise, F. Jahan and S. V. Lindeman, *Inorg. Chem.*, 2018, **57**, 1572–1589.
- 33 A. J. Canty, N. J. Minchin, P. C. Healy and A. H. White, *J. Chem. Soc. Dalton Trans.*, 1982, 1795–1802.
- 34 M. P. De Almeida, L. M. D. R. S. Martins, S. A. C. Carabineiro, T. Lauterbach, F. Rominger, A. S. K. Hashmi, A. J. L. Pombeiro and J. L. Figueiredo, *Catal. Sci. Technol.*, 2013, **3**, 3056–3069.
- 35 P. Rodríguez, E. Álvarez, M. C. Nicasio and P. J. Pérez, *Organometallics*, 2007, **26**, 6661–6668.
- 36 P. Rodríguez, A. Caballero, M. M. Díaz-Requejo, M. C. Nicasio and P. J. Pérez, *Org. Lett.*, 2006, **8**, 557–560.
- 37 I. Cano, M. C. Nicasio and P. J. Pérez, *J. Chem. Soc. Dalton Trans.*, 2009, 730–734.
- 38 (a) P. J. Desrochers, A. J. Pearce, T. R. Rogers and J. S. Rodman, *Eur. J. Inorg. Chem.*, 2016, 2465–2473; (b) P. J. Desrochers, B. M. Besel, A. L. Corken, J. R. Evanov, A. L. Hamilton, D. L. Nutt and R. M. Tarkka, *Inorg. Chem.*, 2011, **50**, 1931–1941; (c) C. Cui, F. Jäkle and Y. Qin, *Macromolecules*, 2008, **41**, 2972–2974; (d) J. A. Camerano, M. A. Casado, M. A. Ciriano and L. A. Oro, *J. Chem. Soc. Dalton Trans.*, 2006, 5287–5293; (e) P. J. Desrochers, A. L. Corken, R. M. Tarkka, B. M. Besel, E. E. Mangum and T. N. Linz, *Inorg. Chem.*, 2009, **48**, 3535–3541; (f) M. C. Kuchta, A. Gross, A. Pinto and N. Metzler-Nolte, *Inorg. Chem.*, 2007, **46**, 9400–9404; (g) Y. Qin, P. O. Shipman and F. Jäkle, *Macromol. Rapid Commun.*, 2012, **33**, 562–567.
- 39 M. M. Díaz-Requejo, T. R. Belderrain, M. C. Nicasio and P. J. Pérez, *Organometallics*, 2000, **19**, 285–289.
- 40 A. C. Albéniz, J. Á. Molina de la Torre, I. Pérez-Ortega, A. Beltrán, M. R. Rodríguez, M. Díaz-Requejo and P. J. Pérez, *Chem. Eur. J.*, 2019, **25**, 556–563.
- 41 K. Machado, S. Mukhopadhyay and G. S. Mishra, *J. Mol. Catal. A Chem.*, 2015, **400**, 139–146.
- 42 C. Sun, G. Skorupskii, J.-H. Dou, A. M. Wright and M. Dincă, *J. Am. Chem. Soc.*, 2018, **140**, 17394–17398.
- 43 I. Cano, M. C. Nicasio and P. J. Pérez, *Org. Biomol. Chem.*, 2010, **8**, 536–538.
- 44 I. Cano, E. Álvarez, M. C. Nicasio and P. J. Pérez, *J. Am. Chem. Soc.*, 2011, **133**, 191–193.
- 45 E. Haldon, M. Besora, I. Cano, X. C. Cambeiro, M. A. Pericas, F. Maseras, M. C. Nicasio and P. J. Perez, *Chem. Eur. J.*, 2014, **20**, 3463–3474.
- 46 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.
- 47 (a) U. Schuchardt, D. Cardoso, R. Sercheli, R. Pereira, S. Rosenira, M. C. Guerreiro, D. Mandelli, E. V. Spinacé and E. L. Pires, *Appl. Catal. A Gen.*, 2001, **211**, 1–17; (b) L. M. D. R. S. Martins and A. J. L. Pombeiro, *Advances in Organometallic Chemistry and Catalysis*, Wiley & Sons: Hoboken, 2014, 285.
- 48 M. Costas and A. Llobet, *J. Mol. Catal. A Chem.*, 1999, **142**, 113–124.
- 49 T. F. S. Silva, E. C. B. A. Alegria, L. M. D. R. S. Martins and A. J. L. Pombeiro, *Adv. Synth. Catal.*, 2008, **350**, 706–716.
- 50 T. F. S. Silva, G. S. Mishra, M. F. Guedes Da Silva, R. Wanke, L. M. D. R. S. Martins and A. J. L. Pombeiro, *Dalton Trans.*, 2009, 9207–9215.
- 51 T. F. S. Silva, B. G. M. Rocha, M. F. C. Guedes Da Silva, L. M. D. R. S. Martins and A. J. L. Pombeiro, *New J. Chem.*, 2016, **40**, 528–537.
- 52 B. G. M. Rocha, T. C. O. Mac Leod, M. F. C. Guedes Da Silva, K. V. Luzyanin, L. M. D. R. S. Martins and A. J. L. Pombeiro, *Dalton Trans.*, 2014, **43**, 15192–15200.