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A Copper-Benzotriazole-Based Coordination Polymer Catalyzes the Efficient One-Pot Synthesis of (*N*′-Substituted)-hydrazo-4-aryl-1,4-dihydropyridines from Azines

Michael Kallitsakis,[+a] Edward Loukopoulos,[+b] Alaa Abdul-Sada,[b] Graham J. Tizzard,[c] Simon J. Coles,[c] George E. Kostakis,[b,*] and Ioannis N. Lykakis[a,*]

[a] Department of Chemistry, Aristotle University of Thessaloniki, Thessaloniki 54124, Greece
Fax: (+30)-231-099-7871; phone: (+30)-231-099-7871; e-mail: lykakis@chem.auth.gr
[b] Department of Chemistry, School of Life Sciences, University of Sussex, Brighton BN1 9QJ, U.K.
E-mail: G.Kostakis@sussex.ac.uk
[c] UK National Crystallography Service, Chemistry, University of Southampton SO1 71BJ, U.K.
[+] These authors contributed equally to this work

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Abstract: A series of new (*N*′-substituted)-hydrazo-4-aryl-1,4-dihydropyridines was successfully synthesized *via* a facile one-pot catalytic pathway utilizing azines and propiolate esters as starting materials and a one-dimensional copper benzotriazole-based coordination polymer as catalyst. In the absence of catalyst, the corresponding 5-substituted 4,5-dihydropyrazoles were formed in moderate to high yields. Fine-tuning of the catalysts allowed us to gain more insights regarding the plausible reaction mechanism.

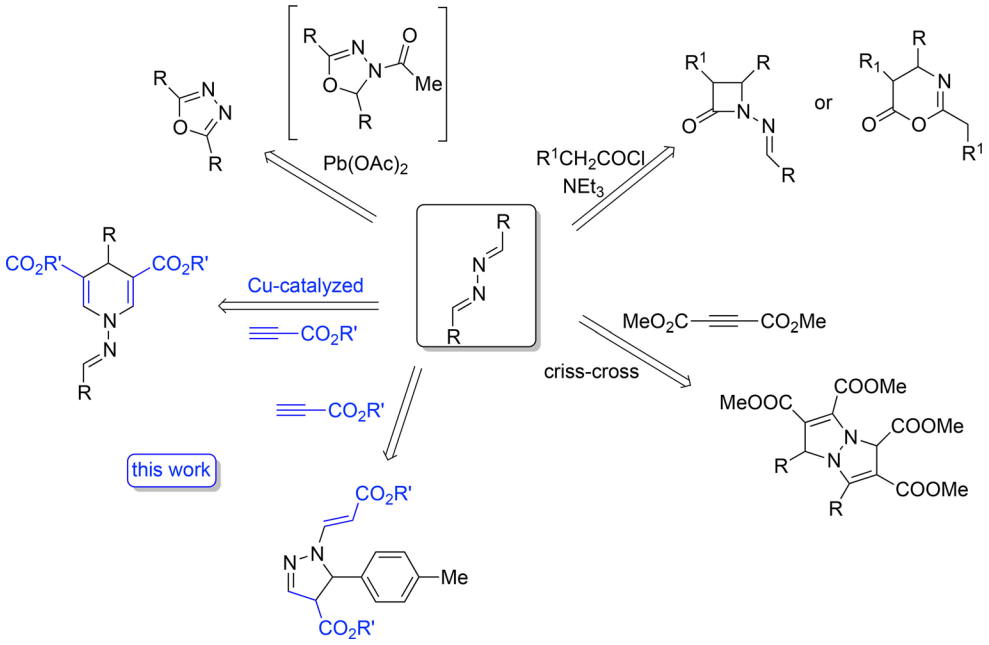
Keywords: 1,4-dihydropyridines; azines; catalysis; coordination polymers; copper

Introduction

Azines (aldazines and ketazines)[1] are a class of compounds with interesting chemical properties that undergo a wide variety of chemical processes (i.e., redox, cycloadditions, criss-cross reactions)[2–4] to yield hydrazones, pyrazoles, purines or pyrimidines (Scheme 1). Aldazines, as conjugated dienes undergo [1,3]-cycloadditions with electron-poor unsaturated molecules, providing an efficient route towards 1,5-diazabicyclooctanes through the known criss-cross reaction.[2] In view of the importance of the synthesis of 1,4-dihydropyridines (1,4-DHPs), the metal-catalyzed process has received considerable attention.[5,6] 1,4-DHPs and their derivatives, are an important class of biologically active organic compound, e.g., the calcium channel blocker, amlodipine.[7–9] Moreover, symmetrical *N*′-substituted-hydrazo-4-aryl-1,4-DHPs (HA-1,4-DHPs) are new heterocycles in nature with probably wide-ranging biological activity.[10,11] Methodologies including Hantzsch,[12] multicomponent,[5,6,13] cycloaddition,[14–16] or C–C coupling reactions,[17] are used for the synthesis of 1,4-DHP derivatives (see the Supporting Information, Scheme S1). A series of organocatalytic procedures has been used for such reactions,[18–21] these, however, exhibit major drawbacks such as the high cost of the reagents, the high temperature and tedious work-up.

Coordination polymers (CPs) are a class of compounds containing repeating coordination entities extending in 1, 2 or 3 dimensions.[22] that have received considerable attention due to their applications in gas adsorption, catalysis, drug delivery, separation, and imaging.[23] Especially in catalysis, in contrast to the porous well-structured three-dimensional CPs (known as metal organic frameworks – MOFs), that retain their structural integrity during a catalytic reaction, one dimensional (1D) CPs have been far less studied.[24–26] However, their easy synthesis and the possibility for tuning make them very promising candidates for catalysis.

Combining our research interests on the synthesis of simple biologically active compounds,[27–29] and the coordination chemistry of benzotriazole-based organic



Scheme 1. Synthetic scheme for known reactions that aldazines undergo. Retrosynthetic methodology towards HA-1,4-DHP derivatives *vs.* 5-arylpyrazoles (highlighted in blue).

ligands,[30,31] we report herein a new one-pot synthesis, under mild conditions, of a series of HA-1,4-DHPs based on Cu-catalyzed reactions between symmetrical electron-rich aldazines and alkyl propiolates (Scheme 1). To the best of our knowledge, the synthesis of substituted symmetrical HA-1,4-DHPs using arylaldazines and propiolates as starting materials, is an unknown chemical transformation.

Results and Discussion

The present catalytic protocol arose during the study of the title reaction using 1,2-bis [(*E*)-4-methylbenzylidene]hydrazine (**1**) and ethyl propiolate, in the presence of different copper salts – $Cu(ClO_4)_2$, $Cu(NO_3)_2$, $Cu(OAc)_2$, $CuCl_2$, $CuSO_4$, $[Cu(PPh_3)_2(MeCN)_2]ClO_4$ (see the Supporting Information for synthesis) and the following $[Cu(II)(L)_2(MeCN)_2]\cdot 2(ClO_4)\cdot 2MeCN$ (**2**), $[Cu(II)(L)_2(NO_3)_2]$ (**3**) and $[Zn(II)(L)_2(H_2O)_2]\cdot 2(ClO_4)\cdot 2MeCN$ (**4**) CPs, where L is 1-{2-[(1*H*-benzo[*d*][1,2,3]triazol-1-yl)methyl]benzyl}-1*H*-benzo[*d*][1,2,3]triazole. Metal salts were used with no further purification, whereas compounds **2**–**4** were characterized with IR, NMR, UV/Vis, ESI-MS, TGA (see the Supporting Information) and single crystal X-ray diffraction. Compound **2** consists of a Cu(II) center, possessing a slightly distorted octahedral geometry, coordinated to four nitrogen atoms belonging to four different organic ligands (equatorial positions) and two acetonitrile solvent molecules (axial positions). The structure extends to one dimension along the *a* axis, forming a 1D CP (Figure 1). Compound **4** is isostructural to **2**; the two coordinating acetonitrile moieties are replaced by H_2O molecules (see the Supporting Information, Figure S2). In compound **3**, the asymmetric unit consists of a Cu(II) center, one organic ligand molecule, two nitrate anions and one acetonitrile solvent molecule (see the Supporting Information, Figure S3). The Cu(II) center has a coordination environment of $\{N_2O_5\}$ and possesses a pseudo octahedral geometry. A dimeric $Cu(II)_2$ unit is formed *via* the chelating and bridging nitrate moieties and the structure extends in two dimensions along the *b* plane. The relevant N–Cu–O bond angles range from 85.32(4)° to 95.66(4)°. As for the relevant bond lengths, the mean Cu–N distances are 1.9849(6) and

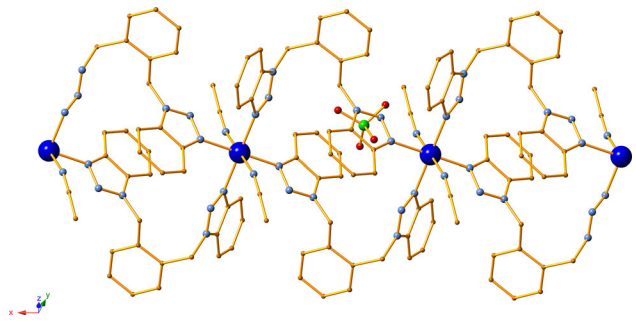
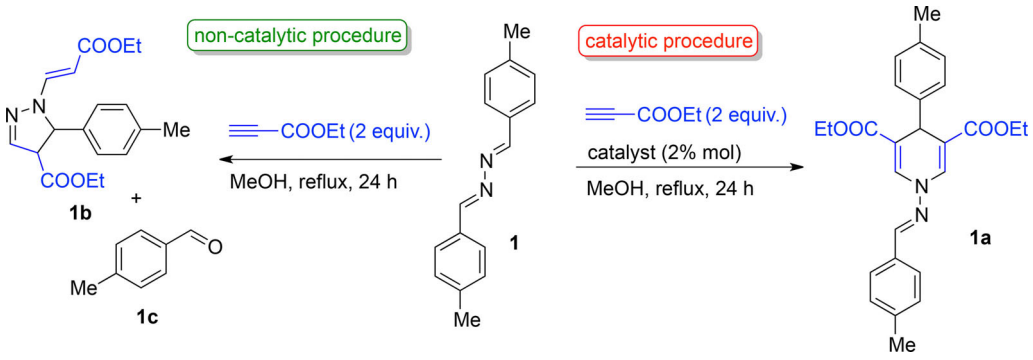


Figure 1. Molecular structure of **2**. Color code: Cu, blue; C, black; N, light blue; O, red, Cl, green. H-atoms are omitted for clarity.

Table 1. Transformation of aldazine (**1**) in HA-1,4-DHP derivative (**1a**) using various catalysts.



Entry	Catalyst[a]	Conversion[b]	**1a**[c]	**1b**[c]	**1c**[c]
1[d]	$Cu(ClO_4)_2$	98%	–	–	–
2[d]	$Cu(NO_3)_2$	54%	–	–	31%
3[d]	$Cu(OAc)_2$	42%	–	–	32%
4	$CuCl_2$	>99%	–	–	>99%
5	$CuSO_4$	>99%	–	–	>99%
6	$Cu(PPh_3)_2(MeCN)_2]ClO_4$	n.r.[f]	–	–	–
7[d]	$Cu(ClO_4)_2$[e]	99%	14%	–	–
8	no catalyst	65%	–	30%	35%
9	L	25%	–	12%	13%
10	**2**	>99%	65%	13%	22%
11	**3**	n.r.[f]	–	–	–
12	**4**	52%	–	25%	27%

[a] **1** (0.1 mmol), ethyl propiolate (0.2 mmol) and 3 mg (2 mol%) of the solid catalysts.
[b] Based on the consumption of **1** determined by ^{1}H NMR.
[c] Relative yields based on ^{1}H NMR analysis from the integration of the corresponding proton shifts.
[d] A mixture of unidentified products was observed by ^{1}H NMR.
[e] Five equivalents of benzotriazole (3 mg) was added into the reaction mixture.
[f] No reaction.

1.9916(6) Å, while the Cu–O distances range from 1.9813(6) to 2.6587(6) Å.

The initial experiments with copper salts, 0.1 mmol of **1**, ethyl propiolate (2 equiv. based on the amount of **1**) in MeOH under reflux for 24 h (Table 1, entries 1–6), show almost quantitative consumption of **1** with the corresponding 4-methylbenzaldehyde (**1c**) produced as the major or only product, along with a mixture of unidentified products. Aldehyde is the product formed through a hydrolysis pathway or an oxidation reaction between the starting aldazine with molecular oxygen. Indeed, aldehyde **1c** was formed as the only product when an oxygen-saturated methanolic solution of **1** was used under the same catalytic conditions (result not shown). In the absence of catalyst, except aldehyde **1c** that was formed in 35% relative yield, a significant amount (30%) of the 5-(*p*-tolyl)-4,5-dihydro-1*H*-pyrazole-4-carboxylate derivative (**1b**) was isolated (Table 1, entry 8). To the best of our knowledge, this transformation has never been reported before under the present reaction conditions, however, the average relative pyrazole yields are in the range of 5–30% (see the Supporting Information, Table S1). When we employed L as catalyst, formation of **1b** with lower conversion and yield was observed (Table 1, entry 9). Astonishingly, on incorporating **2** (2 mol%) as the catalyst under similar conditions, the corresponding **1a** was formed in 65% yield, as determined by ^{1}H NMR (Table 1, entry 10). On the contrary, the use of **3** gives no conversion (Table 1, entry 11), whereas the use of **4** yields **1b** (Table 1, entry 12). These results clearly indicate that a clean and selective transformation of **1** to **1a** takes place only in the presence of **2**. For comparison, a mixture of $Cu(ClO_4)_2$ (2 mol%) and L (10 mol%) was found to catalyze the formation of **1a** in a lower yield of 14% (Table 1, entry 7), however, in the absence of L no formation of **1a** was observed (Table 1, entry 1). The latter indicates a significant ligand effect that probably plays a crucial role in the catalytic reaction mechanism (see below in the mechanistic part).

Among the solvents studied, a high conversion of **1** was observed using methanol and lower convcersion in EtOH, however, in non-protic polar solvents, such as DMF, CH_3CN, acetone, DCE or THF, only the C–C coupling product, diethyl hexa-2,4-diynedioate, was observed (see the Supporting Information, Table S2). In contrast, on using H_2O as reaction solvent or co-

solvent, no formation of **1a** was observed. However, in dry methanolic solution (over 3 Å molecular sieves) no significant increase of the relative yield of **1a** was observed (see the Supporting Information, Table S2). In addition, when using higher loadings of **2** or the ethyl propiolate, the corresponding hydroalkoxylation product, ethyl (*Z*)-3-methoxyacrylate, was observed as the major product (see the Supporting Information, Table S3). When a similar reaction is performed at room temperature, then **1** remains intact, however under microwave irradiation the formation of the ethyl (*Z*)-3-methoxyacrylate is only observed (see the Supporting Information, Table S3). Finally, in the presence of several other alkyl- or arylalkynes (i.e., DMAD, phenylacetylene, propargyl bromide, propargyl alcohol and crotyl ester), no formation of the corresponding HA-1,4-DHP derivative was observed (see the Supporting Information, Table S4).

To study the limitations of the above catalytic procedure, a series of substituted azines (**1** and **5**–**13**) were examined. Figure 2 summarizes the results obtained using catalyst **2**. In all cases the corresponding

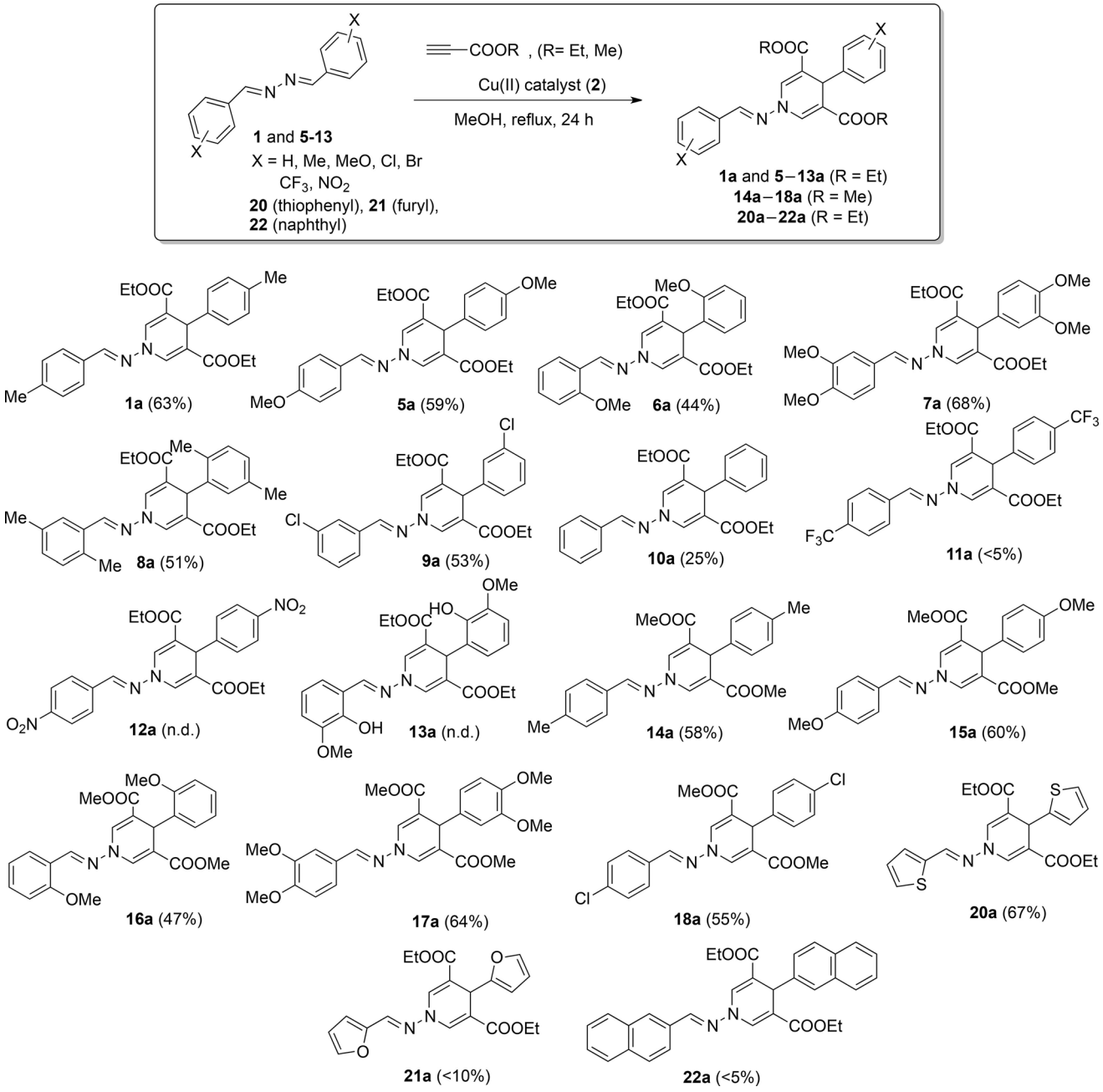


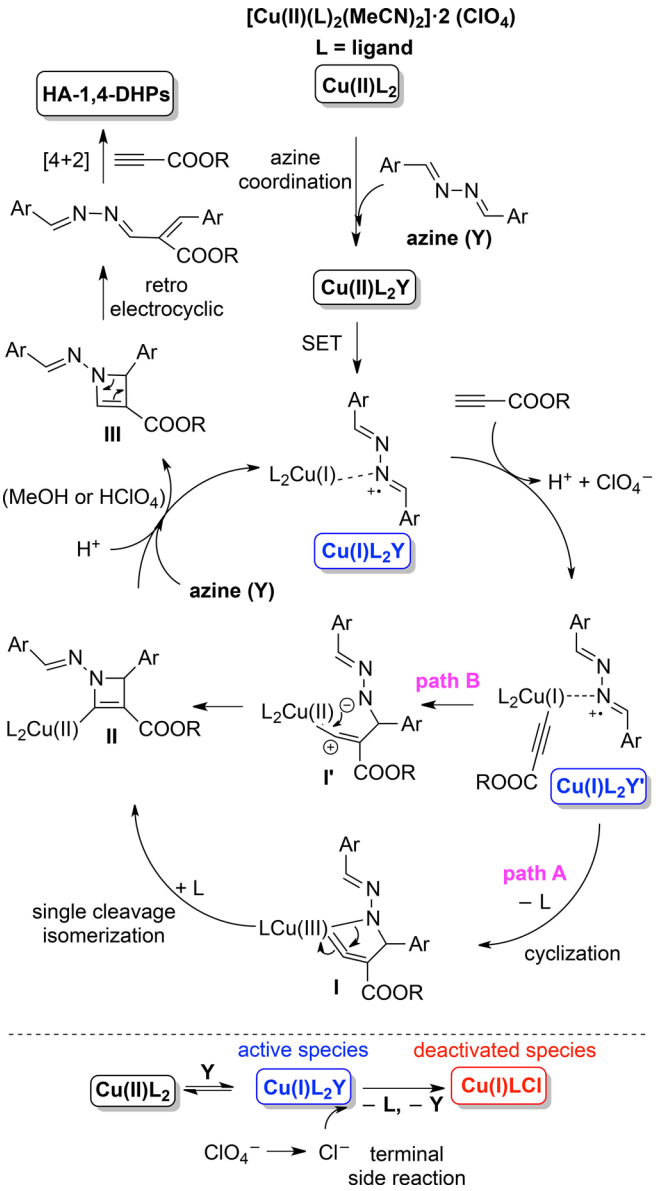
Figure 2. Various (*N*′-substituted)-hydrazo-4-aryl-1,4-dihydropyridines synthesized by Cu-catalyzed reaction. The percentages correspond to the yields of isolated products. n.d. = not detected.

HA-1,4-DHPs derivatives (**1a** and **5a–13a** (R = Et) and **14a–18a** (R = Me)) were formed with good isolated yields (*ca.* 44–68%). It is worth noting that electron-rich aromatic azines (**1** and **5–8**) are transformed to the corresponding HA-1,4-DHPs derivatives (**1a** and **5a–8a**), with higher yields (44–68%) within 24 h, compared to the electron-deficient azine (**11**, X = CF_3) with which a negligible yield (< 5%) was observed within 48 h. Remarkably, no reaction was observed when *para*-nitro-substituted azine **12** was used as substrate. In addition, the use of methyl propiolate instead of ethyl propiolate gave similar conversions and isolated yields of the corresponding HA-1,4-DHPs derivatives compared to the corresponding ethyl propiolate (Figure 2, **14a–18a**). It is worth noting that heterocyclic substituted azines **20** (2-thiophenyl) and **21** (2-furyl), under the present catalytic conditions give the corresponding dihydropyridines **20a** and **21a** in *ca.* 10% and 67% isolated yields, respectively. Subsequently, naphthyl-subtituted azine **22a** shows lower activity, with the corresponding product being formed in negligible yield (< 5%), see Figure 2. All the products were determined by NMR spectroscopy, whereas **7a**, **8a**, **9a** and **16a** were additionally characterized with single X-ray diffraction (see the Supporting Information, Figure S11).

Regarding the mechanism of the title reaction, we observed the following:

a) For azines bearing electron-donating groups such as **1** (4-Me), **5** (4-MeO), **6** (3-MeO), **7** (3,4-diMeO) and **8** (2,5-diMe) a five times faster reaction was observed than the corresponding reaction of azine **10** (4-H). On the other hand, azines **11** (4-CF_3) bearing an electron-withdrawing substituent in the *para* position reacted with a slower rate, however **12** (4-NO_2) remain intact. This first observation implies that an initial complex between the azine and the Cu(II) catalyst is formed, followed by a single electron transfer (SET)[32] process forming the active species Cu(I)L_2Y (Scheme 2). In the same context, addition of a small amount (10 mol%, based on **1**) of an electron donor molecule (e.g., trimethoxybenzene, TMB) with an oxidation potential less than that of the azines ($E_{1/2}$ox *vs.* SCE 1.12 V),[33] retards the reaction process (see the Supporting Information, Table S3).

b) Based on the ability of the azines to donate electrons *via* the lone pairs of the N atoms or the C=N *p*-orbital electrons,[1] it is know that they show versatile properties of coordination in binding to metal centers, such as Cu(II) or Fe(II), especially when the aromatic ring of the azine contains a hydroxy group in the *ortho* position.[34] Indeed, under our catalytic conditions, azine **13** (2-OH, 3-MeO), shows no reactivity towards the synthesis of **13a**, probably through the *in-situ* azine-Cu(II)-catalyst coordination effect (see Figure 2 and Figure S12 in the Supporting Information).



Scheme 2. Plausible mechanism for the synthesis of the (*N*′-substituted)-hydrazo-4-aryl-1,4-dihydropyridines through the hydrazine and propiolate Cu-catalyzed coupling.

c) The reaction of 4-methylbenzaldehyde (**1c**), ethyl propiolate and **2** in methanol yielded a mixture of unidentified products as confirmed by ^{1}H NMR (see the Supporting Information, Figure S13). In the case of the hetero-azine **19**, which bears two different substituent's in the *para*-positions of the aromatic rings (MeO and Cl), both HA-1,4-DHP derivatives **19a** and **19a"** were formed in a ratio of 2/1, as determined by ^{1}H NMR and LC-MS (see the Supporting Information, Figures S14–S16). These results indicate that the azine does not dissociate during our catalytic reactions. Therefore,

our catalytic procedure follows probably a different mechanistic pathway compared to the common proposed multicomponent reaction (MCR) or Lewis acid-catalyzed processes.[5,6] In addition, using the (*Z*)-3-methoxyacrylate (a common starting material of the above literature studies) instead of the propiolate ester, and under the same catalytic conditions, the desired 1,4-dihydropyridine product was not observed (see the Supporting Information, Table S4).

d) In our attempts to recover the catalyst we isolated and characterized *via* single crystal X-ray crystallography a yellow solid material formulated [Cu(I)LCl] (**2i**) corresponding to a 1D CP (see the Supporting Information, Figure S4). This indicates that ClO_4^- converts to Cl^- and Cu(II) to Cu(I).[35] Therefore, we envisage that, at a certain point, transformation of perchlorate to chlorine occurs, which in turn starts to coordinate to Cu(I) centers, transforming the catalyst to **2i** (Scheme 2). In addition, under the new catalytic cyclic **2i** was found to be inactive. This result indicates a low value of turnover number (TON) of the present catalytic system **2**, with a maximum number of *ca.* 55.

Based on the above experimental results we propose a possible reaction mechanism (Scheme 2). Azine (**Y**) initially coordinates to the catalyst **Cu(II)L$_2$** forming a new catalytic intermediate **Cu(II)L$_2$Y** (Scheme 2). ESI-MS and UV/Vis studies in methanolic solutions indicate that Cu(II) in **2** retains the octahedral geometry and coordinates to four N atoms of four different L ligands; a similar pattern was observed for the isostructural Zn analogue **4**. In addition, Cu(II), in the catalytically inactive compound **3**, retains its geometry but coordinates to two N atoms belonging to two ligands L.[36] In sequence, a single electron transfer (SET) occurs from the electron-rich azine to the **Cu(II)L$_2$Y**, yielding the active reduced form: **Cu(I)L$_2$Y**. This active species is responsible for the first catalytic pathway which contains the simultaneously formed propiolate complexes and the proton release by the presence of the perchlorate anion forming the corresponding Cu(I) acetylide intermediate (**Cu(I)L$_2$Y′**). Then, **Cu(I)L$_2$Y′** undergoes a cyclization process, forming the unusual five-membered Cu(III) metallacycle intermediate **I** (**path A**, Scheme 2). A similar intermediate has been supported by a previous theoretical study on the copper-catalyzed synthesis of azoles.[37] This hypothesis found support from related literature on Cu-benzotriazole-catalyzed electrophilic cyclization of *N*-arylamines,[38] as well as Cu-catalyzed synthesis of isoquinoline derivatives or other heteroarenes.[39–41]

Subsequently, a reductive single cleavage (ring contraction)[42] leads to the common intermediate **II**, which after proteolysis releases the cyclic compound dihydroazete **III**, followed by simultaneous conrotatory ring opening, yielding the corresponding diene which in turn reacts *in situ* with a second molecule of propiolate *via* a [4+2], giving the desired product, the dihydopyridine derivative (**HA-1,4-DHPs**). Pathway A requires a ligand (L) replacement by the azine material that coordinates to a Cu center (Scheme 2).[37] In contrast, pathway B that contains the cyclization process without any ligand replacement or azine binding effect cannot be excluded (**path B**, Scheme 2). It is worth noting that during the catalytic process a white powder was formed, that was found to be ligand L (confirmed by IR and NMR). In addition, a possible reductive elimination pathway from intermediate **I**, leads to the Cu(I)L which reacts with Cl^- to form the inactive species Cu(I)LCl (Scheme 2).

In parallel and under non-catalytic conditions, only pyrazole products were formed, through a stepwise mechanism containing a known criss-cross reaction ([3+2] cycloaddition) between the azine and the triple bond of propiolate, at a first step.[1,2] After that, a nucleophilic addition and hydrolysis take place simultaneously (or with the opposite turn) forming the corresponding 5-substituted-4,5-dihydropyrazoles, as shown in Figure S17 of the Supporting Information, accompanied with an equimolar amount of the corresponding X-substituted benzaldehydes as the product from the hydrolysis pathway. It is worth noting that X-substituted benzyl aldehydes were also formed through an oxidative pathway from the initial azine (result not shown). Indeed, using a molecular oxygen (O_2)-saturated methanolic solution and under the present catalytic conditions (**1**, ethyl propiolate and **2** as catalyst) the corresponding aldehyde **1c** was observed as the only product (see the Supporting Information, Table S3).

Conclusions

In conclusion, the current work exemplifies the unique nature of the Cu-benzotriazole one-dimensional coordination polymer as a catalyst in the efficient synthesis of (*N′*-substituted)-hydrazo-4-aryl-1,4-dihydropyridines (HA-1,4-DHPs). A series of substituted HA-1,4-DHPs was formed in good isolated yields; however, by fine tuning of the catalyst we were able to obtain useful information about the mechanism. From the mechanistic point of view, a hydrazine coordination initial step is followed by an SET pathway and a cyclization process which constitute the basic catalytic procedures in the title reaction. The herein described Cu-catalyzed process is advantageous because of its possible wide use towards the synthesis of different heterocyclic organic molecules and because of its unique mechanistic understanding. Future efforts of our groups will concentrate

on improving the catalytic behaviour of **2** and its application towards other chemical transformations.

Experimental Section

General

The aromatic aldehydes used as starting materials for the synthesis of arylhydrazines were of high purity and commercially available from Aldrich. Arylhydrazines were synthesized *via* the reaction between the corresponding aldehydes and hydrazine. $Cu(ClO_4)_2$, $Cu(NO_3)_2$, $Cu(OAc)_2$, $CuCl_2$, $CuSO_4$ and all the solvents were purchased from Sigma–Aldrich.

Cu Catalyst (2) Preparation

Synthetic Protocol: 0.24 mmol (0.082 g) of L were dissolved in 10 mL MeCN while stirring to produce a colourless solution. A solution containing 0.48 mmol (0.178 g) of $Cu(ClO_4)_2{\cdot}6H_2O$ in MeCN (7.5 mL) was slowly added. The resulting green solution was filtered, then stored at room temperature. High quality green crystals were obtained after 3 days. Yield: 49% (based on Cu). For $C_{46}H_{41}Cl_2CuN_{14.5}O_8$ ($M = 1059.37\ g\,mol^{-1}$) crystal data, see the Supporting Information.

General Cu-Catalyzed Reactions

Into a sealed tube containing the azine (0.2 mmol) and methanol (1 mL), 0.4 mmol of ethyl propiolate and 3 mg of the corresponding catalyst (2 mol% Cu) were added. The reaction mixture was vigorously stirred at 70 °C for selected time and then reaction process was monitored by thin layer chromatography (TLC). After completion, the slurry was filtered and the filtrate was then evaporated under vacuum to give a mixture containing the corresponding HA-1,4-DHPs. Further purification with column chromatography afforded the HA-1,4-DHPs in pure form (see the Supporting Information). Product analysis was conducted by ^{1}H NMR and ^{13}C NMR spectroscopy (Bruker AM 300 and Agilent AM 500). Identification of the products was realized by comparing the NMR spectra data with those of the commercially available pure substances. Mass spectra were determined on an LCMS-2010 EV Instrument (Shimadzu) under electrospray ionization (ESI) conditions.

CCDC 1482180, CCDC 1482181, CCDC 1482182, CCDC 1482183, CCDC 1482184, CCDC 1482185, CCDC 1482186, and CCDC 1482276 contain the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre *via* www.ccdc.cam.ac.uk/data_request/cif.

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References

[1] J. Safari, S. Gandomi-Ravandi, *RSC Adv.* **2014**, *4*, 46224–46249.
[2] S. Rádl, *Aldrichimica Acta* **1997**, *30*, 97–100.
[3] J. Verner, M. Potacek, *Molecules* **2006**, *11*, 34–42.
[4] A. El-Alali, A. S. Al-Kamali, *Can. J. Chem.* **2002**, *80*, 1293–1301.
[5] J.-P. Wan, Y. Liu, *RSC Adv.* **2012**, *2*, 9763–9777.
[6] D. M. Stout, A. I. Meyers, *Chem. Rev.* **1982**, *82*, 223–243.
[7] C. O. Kappe, *Eur. J. Med. Chem.* **2000**, *35*, 1043–1052.
[8] C. Safak, R. Simsek, *Mini-Reviews Med. Chem.* **2006**, *6*, 747–755.
[9] P. Ioan, E. Carosati, M. Micucci, G. Cruciani, F. Broccatelli, B. S. Zhorov, A. Chiarini, R. Budriesi, *Curr. Med. Chem.* **2011**, *18*, 4901–4922.
[10] G. Verma, A. Marella, M. Shaquiquzzaman, M. Akhtar, M. R. Ali, M. M. Alam, *J. Pharm. Bioallied Sci.* **2014**, *6*, 69–80.
[11] A. Cukurovali, E. Yilmaz, *J. Mol. Struct.* **2014**, *1075*, 566–578.
[12] A. Hantzsch, *Justus Liebigs Ann. Chem.* **1882**, *215*, 1–82.
[13] S. Sueki, R. Takei, Y. Zaitsu, J. Abe, A. Fukuda, K. Seto, Y. Furukawa, I. Shimizu, *Eur. J. Org. Chem.* **2014**, *2014*, 5281–5301.
[14] Y. Deng, L. Liu, R. G. Sarkisian, K. Wheeler, H. Wang, Z. Xu, *Angew. Chem.* **2013**, *125*, 3751–3755; *Angew. Chem. Int. Ed.* **2013**, *52*, 3663–3667.
[15] P. R. Girling, A. S. Batsanov, H. C. Shen, A. Whiting, *Chem. Commun.* **2012**, *48*, 4893–4895.
[16] S. Sueki, R. Takei, J. Abe, I. Shimizu, *Tetrahedron Lett.* **2011**, *52*, 4473–4477.
[17] W. Gati, M. M. Rammah, M. B. Rammah, F. Couty, G. Evano, *J. Am. Chem. Soc.* **2012**, *134*, 9078–9081.
[18] O. Quinonero, M. Jean, N. Vanthuyne, C. Roussel, D. Bonne, T. Constantieux, C. Bressy, X. Bugaut, J. Rodriguez, *Angew. Chem.* **2016**, *128*, 1423–1427; *Angew. Chem. Int. Ed.* **2016**, *55*, 1401–1405.
[19] D. Hu, Y. Liu, J.-P. Wan, *Tetrahedron* **2015**, *71*, 6094–6098.
[20] H. Jiang, R. Mai, H. Cao, Q. Zhu, X. Liu, *Org. Biomol. Chem.* **2009**, *7*, 4943–4953.
[21] J. Jiang, J. Yu, X.-X. Sun, Q.-Q. Rao, L.-Z. Gong, *Angew. Chem.* **2008**, *120*, 2492–2496; *Angew. Chem. Int. Ed.* **2008**, *47*, 2458–2462.
[22] S. R. Batten, N. R. Champness, X.-M. Chen, J. Garcia-Martinez, S. Kitagawa, L. Öhrström, M. O'Keeffe, M. Paik Suh, J. Reedijk, *Pure Appl. Chem.* **2013**, *85*, 1715–1724.
[23] H.-C. J. Zhou, S. Kitagawa, *Chem. Soc. Rev.* **2014**, *43*, 5415–5418.
[24] W. L. Leong, J. J. Vittal, *Chem. Rev.* **2011**, *111*, 688–764.
[25] A. Karmakar, G. M. D. M Rúbio, M. F. C. Guedes da Silva, S. Hazra, A. J. L. Pombeiro, *Cryst. Growth Des.* **2015**, *15*, 4185–4197.

[26] R. F. Mendes, P. Silva, M. M. Antunes, A. A. Valente, F. A. Almeida Paz, *Chem. Commun.* **2015**, *51*, 10807–10810.
[27] C. Efe, I. N. Lykakis, M. Stratakis, *Chem. Commun.* **2011**, *47*, 803–805.
[28] S. Fountoulaki, V. Daikopoulou, P. L. Gkizis, I. Tamiolakis, G. S. Armatas, I. N. Lykakis, *ACS Catal.* **2014**, *4*, 3504–3511.
[29] S. Fountoulaki, P. L. Gkizis, T. S. Symeonidis, E. Kaminioti, A. Karina, I. Tamiolakis, G. S. Armatas, I. N. Lykakis, *Adv. Synth. Catal.* **2016**, *358*, 1500–1508.
[30] G. E. Kostakis, P. Xydias, E. Nordlander, J. C. Plakatouras, *Inorg. Chim. Acta* **2012**, *383*, 327–331.
[31] E. Loukopoulos, N. Chilton, G. E. Kostakis, unpublished results.
[32] G. O. Jones, P. Liu, K. N. Houk, S. L. Buchwald, *J. Am. Chem. Soc.* **2010**, *132*, 6205–6213.
[33] J. Eriksen, C. S. Foote, *J. Phys. Chem.* **1978**, *82*, 2659–2662.
[34] N. Narayanaswamy, T. Govindaraju, *Sensors Actuators B Chem.* **2012**, *161*, 304–310.
[35] The redox potential of Cu(II) to Cu(I) is +0.15 eV, and for ClO_4^- to Cl^- is +0.65 eV.
[36] Efforts to record CV of **2** in MeOH were not succesful due to ist low solubility. Preliminary experiments performed in DMF showed a quasi-reversible behaviour, but **2** does remain intact as confirmed by UV/Vis and ESI-MS (see the Supporting Information).
[37] F. Himo, T. Lovell, R. Hilgraf, V. V. Rostovtsev, L. Noodleman, K. B. Sharpless, V. V. Fokin, *J. Am. Chem. Soc.* **2005**, *127*, 210–216.
[38] S. Battula, R. A. Vishwakarma, Q. N. Ahmed, *RSC Adv.* **2014**, *4*, 38375–38378.
[39] X. Zhao, Y. Zhang, J. Wang, *Chem. Commun.* **2012**, *48*, 10162–10173.
[40] T. Patra, S. Nandi, S. K. Sahoo, D. Maiti, *Chem. Commun.* **2016**, *52*, 1432–1435.
[41] A. K. Verma, T. Kesharwani, J. Singh, V. Tandon, R. C. Larock, *Angew. Chem.* **2009**, *121*, 1158–1163; *Angew. Chem. Int. Ed.* **2009**, *48*, 1138–1143.
[42] C. Gryparis, C. Efe, C. Raptis, I. N. Lykakis, M. Stratakis, *Org. Lett.* **2012**, *14*, 2956–2959.
[43] S. J. Coles, P. A. Gale, *Chem. Sci.* **2012**, *3*, 683–689.

A Copper-Benzotriazole-Based Coordination Polymer Catalyzes the Efficient One-Pot Synthesis of (*N*′-Substituted)-hydrazo-4-aryl-1,4-dihydropyridines from Azines

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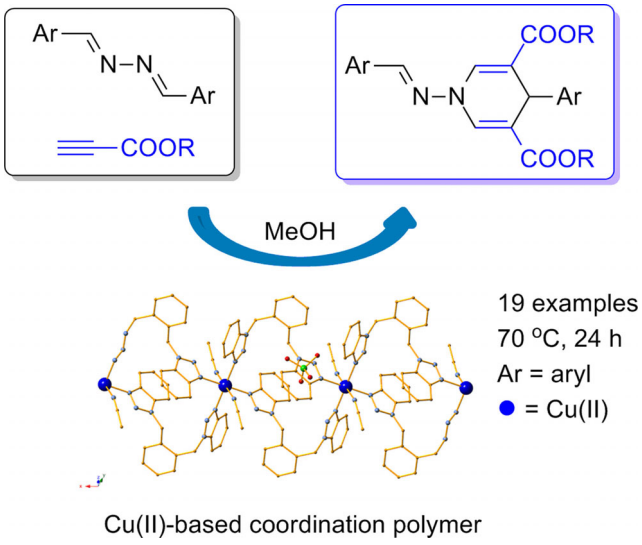
Michael Kallitsakis, Edward Loukopoulos, Alaa Abdul-Sada, Graham J. Tizzard, Simon J. Coles, George E. Kostakis,* Ioannis N. Lykakis*



Cu(II)-based coordination polymer

