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Copper(II) NHC pincer complexes containing 1,2,3-triazole units: Synthesis, structure and catalysis for C—N bond forming reactions☆

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ABSTRACT

Two new tridentate copper(II) *N*-heterocyclic carbene (NHC) pincer complexes with triazolyl donor groups, L2, [TrzmPymBI][PF_6] and L3, [bTrzmBI][PF_6], were synthesized and characterized by X-ray single crystal analysis and elemental analysis. The 5-coordinate τ value shows distorted square pyramidal geometry for both complexes. These copper(II)-NHC complexes exhibited excellent catalytic activity (95–100 % conversion) for N—H insertion reactions toward the formation of new N—C bonds between aniline and methyl phenyldiazoacetate. Under optimized conditions, the catalyst was screened against 22 different aniline derivatives and achieved high conversion (65–100 %) toward both electron-donating and electron-withdrawing functional groups on the amine substrates, while limiting self-coupling of activated diazo compounds. The substrate scope study revealed that steric hindrance and basicity are key factors influencing reactivity. Secondary and aliphatic amines showed weak reactivity. Moreover, the utility of this catalyst was demonstrated through a gram-scale synthesis of a diarylhydantoin, a class of compound known to act as a COX-2 inhibitor. These results highlight the versatility and efficiency of copper(II)-NHC complexes in facilitating selective carbene insertions and provide a promising approach for the synthesis of valuable nitrogen-containing compounds.

Introduction

Light transition metal-catalyzed organic transformations have gained significant attention over the past decades due to their versatility, efficiency, and low cost [1]. Among these transformations, the copper-catalyzed insertion of carbenes into X–H bonds (where X can be C, N, O, Si, S) [1–4] have proved to be useful methodologies that maintain performance under mild conditions and ambient temperature. Similar reactions have been widely explored with various metal catalysts, but copper stands out for its low cost, environmental friendliness, and unique reactivity profile [5–8].

Copper-activated carbenes, especially those derived from diazo compounds, have been demonstrated as useful precursors for amino acid synthesis and other C—N bond forming reactions. However, the challenges to these reactions lie in controlling the selectivity of the carbene insertion, particularly in the presence of competing reactive sites. This short report focuses on carbene insertion into N—H bonds of aniline catalyzed by copper complexes. Functionalized aniline derivatives are key building blocks in both industrial and pharmaceutical fields. The activation of diazo compounds to carbenes for the insertion into amine N—H bonds play a crucial role in the synthesis of unnatural amino acids such as α-phenylglycines [9], which can serve as starting materials for a range of pharmaceutically active compounds.

Developing effective transition metal-based catalysts for diazo activation and N—H insertion reactions require careful selection of both the metal ion and supporting ligand, where the ligand plays a distinctive role in both tuning the electronics of the metal ion for efficient chemical processes and defining the structure of the complex. 1,2,3-Triazole has gained significant attention in recent years due to its versatile chemical hydrogen bonding (acceptor, donor) and metal coordination, which is driven from its large dipole moment (~5 D). The nitrogen atoms at positions N2 and N3, along with the C5 carbon, play a crucial role in coordinating with metal ions, enabling 1,2,3-triazole to serve as a ligand in various coordination complexes [10,11]. In 2011, Guha *et al.* reported the coordination of 1,2,3-triazolyl-containing ligands featuring pyridyl and azido functionalities. Structural analysis of copper(II) complexes

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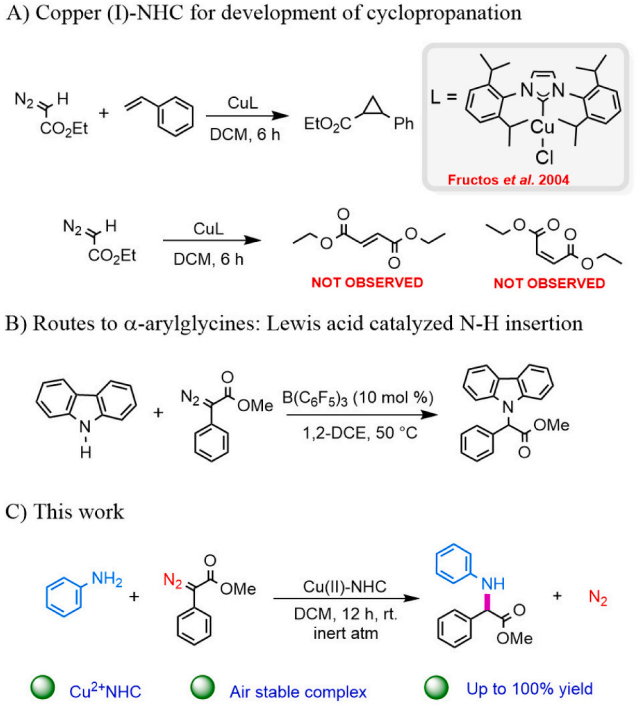
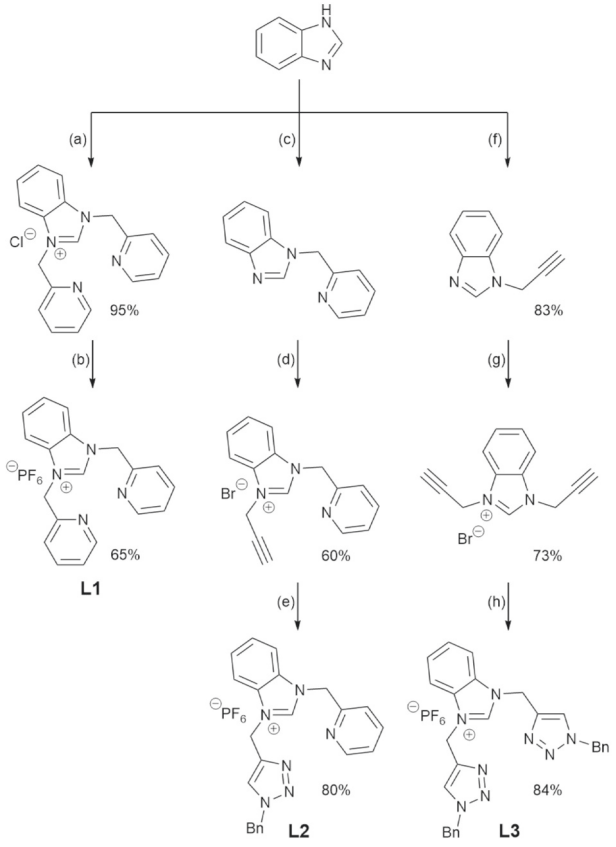
revealed that the counter anion influences the coordination mode of 1,2,3-triazole molecules and favors the formation of a planar chelation pocket involving the pyridyl nitrogen and the Nγ atom of the 1,2,3-triazolyl moiety over a six-membered coordination environment [12]. Despite numerous studies on NHC complexes containing 1,2,3-triazoles, including those with Ni [13], Pd [13–15], Ru [16,17], Rh, and Ir [18], where either the N3 of the triazolyl ring acts as a neutral electron donor or the C5 carbon serves as a negatively charged donor. In contrast, to the best of our knowledge there is only one reported example of a copper complex containing a neutral *N*-donor 1,2,3-triazolyl ligand [19]. The family of pincer ligands bearing *N*-heterocyclic carbenes (NHCs) have tunable σ-donor and π-acceptor character resulting in highly stable and reactive metal complexes [20,21]. The electronic character of metal ions in *N*-heterocyclic carbene complexes have been demonstrated to drastically impact the chemo- and regioselectivity of reactions [22]. However unlike other popular ligands (*e.g.* phosphine containing ligands), NHC ligands are not overly oxophilic providing some resilience under aerobic conditions. There has been an abundance of research focused on transition metals NHC complexes focusing on Ru, Rh, Pd, and copper(I) chemistry [23–25]. The pioneering copper(I)-NHC complexes, first developed by Arduengo and co-workers in 1993, were later utilized for diazo activation for cyclopropanation reactions, as studied by the laboratories of Díaz-Requejo and Pérez in 2004 (Scheme 1A) [26,27]. Even main group elements, like boron, has garnered significant attention where boranes have the ability to generate carbene intermediates *in situ* similar to transition metals (Scheme 1B) [28]. While triarylboranes show promise as alternative catalysts for transition metal-mediated insertion reactions, their preferential binding to oxygen limits their applicability with oxygen-containing substrates like benzamide and 4-aminophenol. Examples of copper(II) NHC pincer complexes are more limited in the literature [29–34]. That being noted, the copper(II) complexes by Meyer and colleagues in 2003 established a critical foundation in the field [35]. Following these landmark contributions, metal complexes bearing NHCs with pendant picolyl donors have gained attention due to their straightforward synthesis. However the pendant *N*-donors can be other Lewis bases where triazolyl moieties have shown relatively weak σ-donor character compared to their pyridyl cousins yet introduce structural aspects that impact the flexibility of the complex [36,37]. In 2022, Hartinger and co-workers reported a wide array of NHCs scaffold incorporating picolyl and triazolyl in bi- and tridentate chelation modes in the presence of Os, Rh, and Ru [38]. Interestingly, the triazolyl donors provided faster ligand exchange behavior in DMSO, which correlated to higher reactivity [38]. Building on these studies, we report the diazo activation and N—H insertion reactions catalyzed by a series of copper(II) NHC pincer complexes. In this report, we aim to design and utilize copper(II) NHC complexes with modified flanking groups including triazole to support N—H insertion reactions. Understanding how ligand structure and donor properties, like bite angle, impact catalytic efficiency and selectivity is key to developing new platforms for catalyzing the formation of new nitrogen-containing compounds.



Scheme 1. Example of N—H insertion, previous reports and our strategy.

Results and discussions

The ligands 3-bis(pyridin-2-ylmethyl)-1*H*-benzo[*d*]imidazol-3-ium (**L1**, [bPymBI][PF_6]), 3-((1-benzyl-1*H*-1,2,3-triazol-4-yl)methyl)-1-(pyridin-2-ylmethyl)-1*H*-benzo[*d*]imidazol-3-ium (**L2**, [TrzmPymBI][PF_6]) and 1,3-bis((1-benzyl-1*H*-1,2,3-triazol-4-yl)methyl)-1*H*-benzo[*d*]imidazol-3-ium (**L3**, [bTrzmBI][PF_6]) were synthesized according to a general procedure outlined in Scheme 2. The ligand precursor [bPymBI][PF_6] was fully characterize by our group and used with copper(II) to



L1, [bPymBI][PF6]: (a) 2-picolyl chloride hydrochloride, $CHCl_3$, K_2CO_3, 140 °C, reflux, 3 days; (b) NH_4PF_6, H_2O, 1 h, rt.

L2, [TrzmPymBI][PF6]: (c) 2-picolyl chloride hydrochloride, CH_3CN, K_2CO_3, 120 °C, reflux, 36 h; (d) propargyl bromide, DMF, 80 °C, 16 h; (e) benzyl azide, H_2O:t-BuOH, Na ascorbate, $CuSO_4$, 60 °C, 24 h; then NH_4PF_6, H_2O

L3, [bTrzmBI][PF6]: (f) NaOH, THF, 50 °C, 3h, propargyl bromide, rt., 24 h; (g) propargyl bromide, DMF, 80 °C, 16 h; (h) benzyl azide, H_2O:t-BuOH, Na ascorbate, $CuSO_4$, 60 °C, 24 h; then NH_4PF_6, H_2O

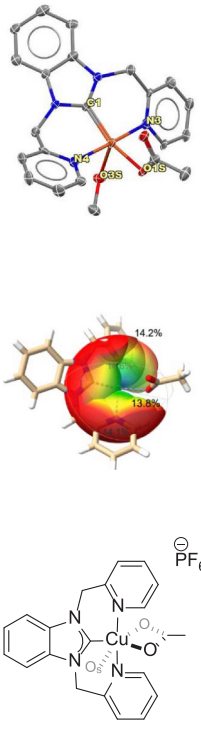
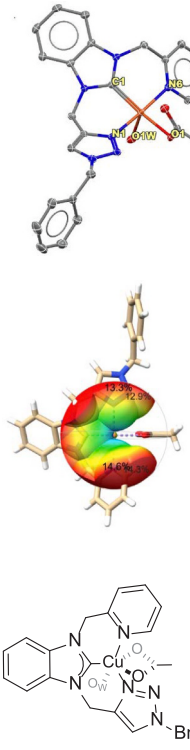
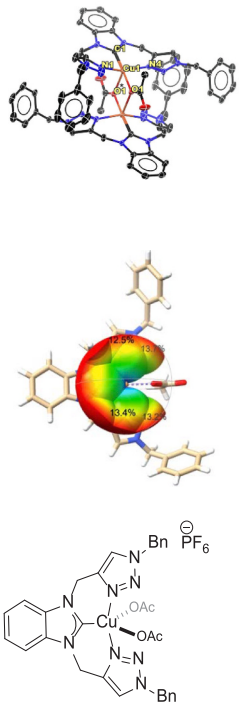
Scheme 2. Ligand syntheses.

catalyze the Chan–Evans-Lam (CEL) cross-coupling reaction of imidazole and other *N*-heterocyclic nucleophiles with arylboronic acid [33,39]. The ligand precursors [TrzmPymBI][PF_6] and [bTrzmBI][PF_6] were characterized by ^{1}H NMR, ^{13}C NMR, and ^{19}F NMR. The formation of 1,2,3-traizolyl moiety was confirmed by a characteristic peak at 8.48 ppm for [TrzmPymBI][PF_6] and 8.36 ppm for [bTrzmBI][PF_6] observed in ^{1}H NMR. These σ-donor properties of the NHC ligand were estimated through measuring the $^1J_{CH}$-coupling value of the carbene carbon precursor. Our ligand precursors (**L2** and **L3**) exhibited $^1J_{CH}$-coupling values of 225 Hz, indicating relatively weak σ-donor characteristics [40]. The higher s-character of carbene center has been correlated to σ-donating properties of NHC ligands, as indicated by the measured *J*-coupling values of the carbene carbon precursor. The related Cu^{2+}-NHCs complexes were synthesized through a straightforward method involving stoichiometric reaction of $Cu(OAc)_2$ in methanol at 40 °C for 12 h, without the need for additional base and under the ambient atmosphere, resulting in formation of purple precipitate corresponding to complexes [Cu(TrzmPymBI)(OAc)][PF_6] and [Cu(bTrzmBI)(OAc)][PF_6], with yields ranging from 60 to 84 %. When DCM was used as the solvent, a soluble green complex was obtained with a similar yield. This approach did not require the removal of moisture or oxygen, and any excess copper salt was easily separated by filtration. These complexes were characterized by mass spectroscopy, elemental analysis, and X-ray crystallography. Analysis of the complexes by NMR spectroscopy is precluded due to the paramagnetic nature of the complexes. ESI-chromatogram obtained in the positive mode for the [Cu(bTrzmBI)(OAc)][PF_6] complex shows a characteristic peak for corresponding to $[Cu(bTrzmBI)(OAc)]^+$ without any fragmentation of 1,2,3-traizolyl rings on the ligand. The peaks at 582.1558, 583.1589, 584.1547 and 585.1561 *m/z* indicated the presence of the $[Cu(bTrzmBI)(OAc)]^+$ ion with corresponding copper isotopic patterns. Likewise, peaks at 443.1040, 444.1069, 445.1027, and 446.1052 m/z show the isotopic pattern for the $[Cu(TrzmPymBI)(OAc)]^+$.

The [Cu(bPymBI)(OAc)][PF_6] complex was structurally characterized and reported previously [33]. Data related to this complex is reported in Table 1 for comparison. A single crystal of [Cu(bTrzmBI)(OAc)][PF_6] was obtained by vapor diffusion where diethyl ether was allowed to dissolve slowly into a saturated solution of [Cu(bTrzmBI)(OAc)][PF_6] in methanol, resulting in crystal formation at room temperature. [Cu(TrzmPymBI)(OAc)][PF_6] was grown via slow evaporation in a DCM solution of the complex. Significant efforts were made to crystallize this complex under vapor diffusion methods without success.

Table 1 shows the ORTEP diffraction data for these coordination complexes. The asymmetric cation $[Cu(TrzmPymBI)(OAc)]^+$ is a 5-

Table 1
Copper(II) NHC pincers structures (shown with 50 % probability thermal ellipsoids), selected bond lengths and angles, and calculated buried volume.

Catalyst	[Cu(bPymBI)(OAc)] [PF_6] [a]	[Cu(TrzmPymBI)(OAc)] [PF_6]	[Cu(bTrzmBI)(OAc)] [PF_6]
Complex structure			
CCDC entry	2170331	2405899	2405900
Cu—C1 (Å)	1.935(8)	1.951(2)	1.967(3)
Cu—O (Å)	Cu—O1s = 1.975(5) Cu—O3s = 2.287(6)	Cu—O1w = 2.3572(17) Cu—O1 = 1.9706(15)	Cu—O1 = 1.958(2) Cu—O* = 2.177(2)
Cu—N (Å)	Cu—N3 = 2.066(7) Cu—N4 = 2.112(7)	Cu—N1 = 2.0572(18) Cu—N6 = 2.0474(19)	Cu—N1 = 2.004(3) Cu—N4 = 2.014(3)
Bond angles (°) C1—Cu—N	C1—Cu—N3 = 87.7(3) C1—Cu—N4 = 90.3(3)	C1—Cu—N1 = 87.67(8) C1—Cu—N6 = 89.38(8)	C1—Cu—N1 = 90.42(13) C1—Cu—N4 = 90.45(13)
C_1—Cu—O	C1—Cu—O1 = 162.1(3) C1—Cu—O3 = 106.6(3)	C1—Cu—O1 = 167.59(8) C1—Cu—O1w = 98.44(7)	C1—Cu—O1 = 176.71(12) C1—Cu—O1* = 95.98(11)
5-coord τ values [50]	0.25	0.15	0.37
$\%V_{Bur}$	56.7	55.2	52.7

[a] [Cu(bPymBI)(OAc)][PF_6] has been reported in Ref. 33.

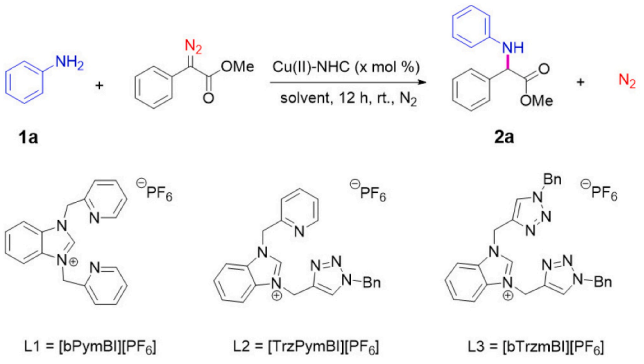
coordinate copper(II) complex with two nitrogen atoms and one carbon atom donating from the NHC pincer ligand. The additional coordination sites are occupied by an acetate ion and a water molecule. The acetate ion appears to have some bidentate character, however the long distance between this second Cu—O interaction (2.607 Å) suggests it is not a formal coordinating group in this distorted square pyramidal geometry. The geometry of [Cu(TrzmPymBI)(OAc)][PF_6] likely arises from steric interactions between picolyl and triazolyl groups and the inherent flexibility of the methylene (CH_2) linkages with sp^3 hybridization between the heterocyclic rings, which allow the ligand to adopt conformations that minimize steric hindrance or angle strain. The Cu—$C_{carbene}$ bond distances agree with a Cu—C bond length of 1.96 Å [30,41,42].

On the other hand, symmetrical cation [Cu(bTrzBI)(OAc)]$^+$ demonstrated a bimetallic crystallization mode in the unit cell. This structure exhibits two 5-coordinate copper(II) complexes bridged by two acetate groups. Interestingly, the [Cu(bTrzmBI)(OAc)][PF_6] lacks labile or solvent-derived species, leaving an open axial position at each copper center, which may be due to crystallization conditions. The Cu—$C_{carbene}$ bond in this complex is slightly longer than similar bonds in other Cu-complexes in this family. There seems to be a measurable impact of the 5-membered v. 6-membered *N*-donor groups in these complexes, where pyridyl donors demonstrate a slightly shorter and presumably stronger interaction than their triazolyl counterparts. The donor ring size appears to have an impact on the sterics of the chelate ring that it forms within the pincer complex. The pyridyl groups provide slightly increased flexibility to the chelate ring allowing for a puckered conformation, where the triazolyl donors yield a more planar chelate structure. In solution, [Cu(bTrzmBI)(OAc)][PF_6] has magnetic moment (μ_β) equal to 1.7 (measured using the Evans method in DMSO-d_6 solution) [43–45], which is consistent with a mononuclear copper(II) center in solution. This data supports that in solution these complexes are likely mononuclear copper complexes, where there are no strong antiferromagnetic or ferromagnetic interactions as expected for a dimeric copper complex in solution [32–34]. The stability of the [Cu(bTrzmBI)(OAc)][PF_6] complex after 16 h of reaction was evaluated using HRMS (Fig. S3). Identifying transition metal catalysts in condensed-phase reactions can be quite challenging; however, the obtained data confirm that the copper complex remains intact, showing the copper(I) NHC ligand complex associated with product, an acetate ion, a protonated aniline molecule, and a water.

The 5-coordinate τ values of 0.15 and 0.37 for [Cu(TrzmPymBI)(OAc)]$^+$ and [Cu(bTrzmBI)(OAc)]$^+$, respectively. Both complexes demonstrate a distorted square pyramidal geometry. To visually depict the steric bulk of the NHC ligands and their distribution in space around the copper center, topographic steric maps and volume cutout were created using crystallographic data processed through the ChimeraX software and its SEWCROW plugin [46–48]. A comparison between % V_{bur} around the catalytic pocket and conversion reveals that as the overall %V_{bur} increased, the conversion observed in N—H insertion reactions decreased (c.f. Table 2 entry 5–7). The red regions of the volume cutout and strict map (see Supporting Information), represents areas with highest group ligand density while the green areas reflect less steric hindrance. The steric demands of the pincer architecture have some correlation to the nature of the *N*-donor moiety, where the chelate rings formed from the pyridyl units are more structurally demanding than the triazolyl chelates. The bite angles of the pyridyl units are slightly smaller (~87°) compared to the chelates with the triazole donors (~90°), which can have an impact to the structure and the overall reactivity [49].

The catalytic activity of the copper(II) NHC complexes were screened for the N—H insertion reactions with aniline (**1a**) and methyl phenyldiazoacetate, similar to previously reported efforts catalyzing diazo activation and N—H insertion by an aminoquinoline-based tridentate *(NNN)*-copper(II) catalyst [51]. The reactivity of this model reaction was optimized as shown in Table 2. In the first trial (Table 2, entry 1) using $Cu(OAc)_2$ as a catalyst, no conversion was observed in dichloromethane (DCM). However, Cu^+ supported catalysis was observed using

Table 2
Optimization of reaction conditions.



Entry	Metal salt	Ligand	Solvent	Conv % (**2a**)
1	$Cu(OAc)_2$	–	DCM	ND
2	CuOAc	–	DCM	60
3	$Cu(OAc)_2$	Phen	DCM	ND
4	$Cu(OAc)_2$	Bipy	DCM	45
5	$Cu(OAc)_2$	L1	DCM	67
6	$Cu(OAc)_2$	L2	DCM	90
7	$Cu(OAc)_2$	L3	DCM	100
8	$Cu(OAc)_2$	L3	CB	10
9	$Cu(OAc)_2$	L3	H_2O	ND
10	$Cu(OAc)_2$	L3	THF	ND
11	$Cu(OAc)_2$	L3	ACN	57
12	$Co(OAc)_2$	L3	DCM	ND
13	$Zn(OAc)_2$	L3	DCM	ND
14[a]	$Cu(OAc)_2$	L3	DCM	81
15[b]	$Cu(OAc)_2$	L3	DCM	68
16[c]	[Cu(bTrzmBI)(OAc)][PF_6]		DCM	95

Reaction condition: **1a** (0.25 mmol), methyl phenyldiazoacetate (0.5 mmol), $Cu(OAc)_2$ (10 mol%), ligand (15 mol%), DCM (2 mL), rt., 16 h, N_2 atmosphere. Methyl phenyldiazoacetate was added over 2 h *via* syringe pump. Conversions were determined by ^{1}H NMR and mesitylene as an internal standard.
[a] 5 mol % $Cu(OAc)_2$.
[b] 2 mol % $Cu(OAc)_2$.
[c] Trial conducted with isolated [Cu(bTrzmBI)(OAc)][PF_6] added at 10 mol % in DCM with 1a (0.25 mmol), methyl phenyldiazoacetate (0.5 mmol).

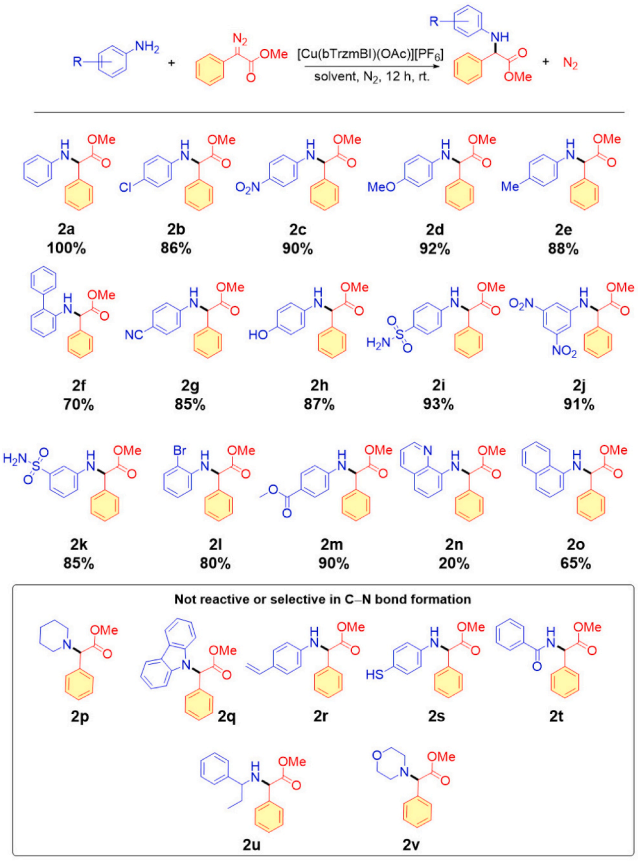
CuOAc (Table 2, entry 2), where a 60 % conversion of the desired product (**2a**). While copper(I) improved the conversion, the reaction required deoxygenation with N_2 prior to substrate addition. The addition of supporting bidentate ligands (phen or bipy) were also tested (Table 2, entries 3–4). These ligands have supported copper-catalyzed transformations including aziridination of olefins, reduction of ketones, and Chan-Evans-Lam (CEL) coupling reaction [31,52,53]. The N—H insertion reaction proceeded in the presence of bipy ligand to afford **2a** with 45 % conversion (Table 2, entry 4). When $Cu(OAc)_2$ was mixed with NHC precursor ligands (**L1**, **L2**, and **L3**) aerobically for 1 h in DCM, a major color change was observed, which eventually developed into a green solution similar to the color normally associated the with Cu-NHC complexes [Cu(bPymBI)]$^{2+}$, [Cu(TrzmPymBI)]$^{2+}$, and [Cu(bTrzmBI)]$^{2+}$ in DCM. It is our contention that the Cu-NHC complexes were generated *in situ*. Under a nitrogen atmosphere, aniline was added to these mixtures, and solutions of methyl phenyldiazoacetate were slowly introduced using a syringe pump infusion over 3 h at a rate of 0.3 mL/min. These reactions resulted in 67 %, 90 %, and 100 % conversion to product **2a**, respectively (Table 2, entry 5–7). Other solvents for N—H insertion reactions were screened, where it was established that N—H insertion achieves the best result in non-polar, non-coordinating solvents such as DCM and DCE (Table 2, entries 8–11) [54–56]. The investigation of the catalyst demonstrated that other metal salts such as cobalt and zinc were not effective under this condition (Table 2, entry 12–13). Reducing catalyst loading from 10 mol% to 2 and 5 mol% in the presence of **L3** showed moderate to high conversion, indicating the reaction could be carried out at low catalyst loading for industrial purposes (entry 14–15).

Finally, a trial with the isolated Cu^{2+}-NHC complex ([Cu(bTrzmBI)(OAc)][PF_6]) was performed (Table 2, entry 16) to compare to the *in situ* formed catalyst in trial 7. The isolated copper(II) complex performed indistinguishably from the *in situ* generated system, supporting our earlier contention that the NHC complexes form *in situ*.

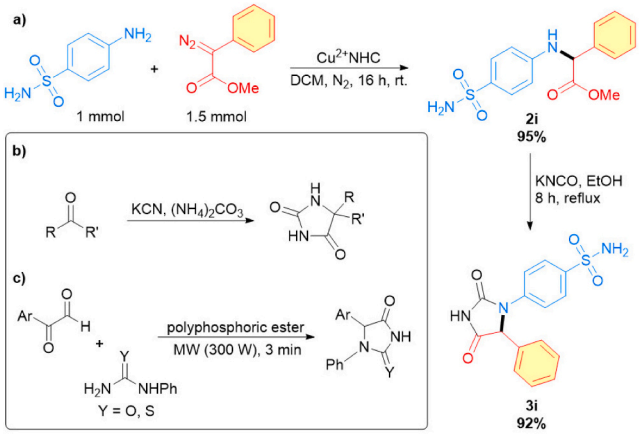
Building on the optimized conditions, the scope and limitations of substrates with various functional groups were screened (Scheme 3). In general, the reactivity is impacted primarily by steric hindrance and the Lewis basicity of the substrates rather than the electron donating or withdrawing substituents associated with the substrates. For example, anilines with both electron-withdrawing and electron-donating groups supported high conversion to products (**2a-2m**). The comparable yields observed for substrates with both electron-donating and electron-withdrawing groups can be explained by overactivation of the N—H unit leading to non-targeted byproducts. Analysis by chromatography revealed more side-product formation for substrates with electron-donating groups compared to those with electron-withdrawing groups, which are likely a result of further alkylation of the substrate. Products were not observed for a range of amine substrates (**2p–2v**). Secondary and aliphatic amines showed limited reactivity (**2p**, **2q**, **2u**, and **2v**), and carbazole was challenged by its low solubility in DCM, resulting in complete recovery of carbazole after the reaction (**2q**). Notably, the reaction with the substrate containing a vinyl group (**2r**) and with alternative attack sites (**2s**) showed complex reaction products which are likely a complex mixture of products with insertions, including X—H insertions where X = N or S, and cyclopropanation [57].

Finally, to directly demonstrate the potential application of this methodology, this insertion reaction was applied to the synthesis of a 1,5-substituted diarylhydantoin (Scheme 4). Diarylhydantoins are COX-2 inhibitors, which have frameworks similar to those found in drugs such as celecoxib and rofecoxib [58]. The pharmaceutical interest in imidazolidine-2,4-diones, also known as hydantoins, has seen significant advancements over the last two decades. The Bucherer-Bergs reaction is a widely used multicomponent reaction involving aldehydes or ketones to synthesize hydantoins. Alternative approaches to this reaction, utilizing microwave irradiation or polyphosphoric ester as catalysts, have also been reported (Scheme 3b & c) [59,60]. Using a 1 mmol scale of substrate **2i**, we obtained product **3i** with a 92 % yield. This gram-scale, straightforward method for the synthesis of hydantoins offers a promising approach for the generation of a library of hydantoin derivatives to facilitate structure-activity relationship (SAR) studies.

In summary, copper(II) NHC complexes like [Cu(bTrzmBI)(OAc)][PF_6] can be generated and isolated providing a unique copper(II) binding domain that relies upon triazolyl coordination. The triazolyl provides a subtle, yet impactful difference in the bite angle of the pincer architecture that has an impact on the copper-based coordination chemistry and electronic structure. These complexes can also be generated *in situ*, where both options efficiently catalyze carbene insertion into the N—H bond of aromatic amines using methyl phenyldiazoacetate. Notably, this complex demonstrates strong reactivity in the presence of electron withdrawing and donating groups on aniline derivatives and effectively prevents the self-coupling of diazo compounds even when an excess of diazoacetate is present. This new method shows direct applicability toward the synthesis of diarylhydrantoins, which have shown COX-2 inhibition activity. Adapting this method toward synthetic efforts to functionalized bioactive molecules holds significant potential for use in therapeutic discovery efforts.



Scheme 3. Investigation of the amine substrate scope and related reaction conversions.



Scheme 4. Gram-scale synthesis of diarylhydantoin

CRediT authorship contribution statement

Mohsen Teimouri: Writing – original draft, Investigation, Conceptualization. **Mahshid Attarroshan:** Writing – original draft, Investigation. **Bruno Donnadieu:** Investigation, Formal analysis, Conceptualization. **Sean L. Stokes:** Writing – review & editing, Formal analysis, Conceptualization. **Joseph P. Emerson:** Writing – review & editing, Funding acquisition, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.tetlet.2025.155588.

Data availability

Data will be made available on request.

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