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A copper(II)-catalyzed annulative formylation of *o*-alkynylanilines with DMF: a single-step strategy for 3-formyl indoles†

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In this paper, a copper(II)-catalyzed reaction of *o*-alkynylanilines with dimethylformamide (DMF) in the presence of oxygen has been developed for synthesizing multisubstituted 3-formyl indole scaffolds. This one-pot reaction proceeds through a cascade 5-*endo*-dig cyclization followed by formylation to construct 1,2-disubstituted 3-formyl indoles. The key aspects of this synthesis method are the broad substrate scope (with 38 examples), and well tolerating various functional groups. In addition, a detailed mechanism has been proposed, where DMF may serve as a carbon source for the *in situ* C3 formylation of the obtained indole derivatives.

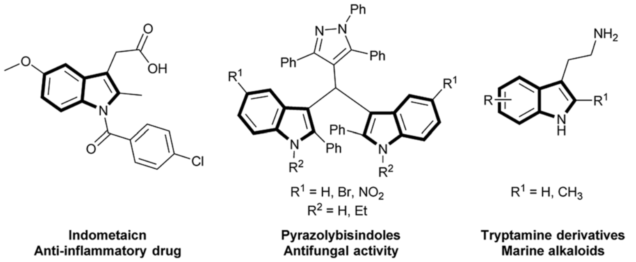
Introduction

2,3-Disubstituted and 1,2,3-multi-substituted indoles are widely available in various alkaloids and natural products possessing potential biological activities. Several essential examples include indometacin, pyrazolybisindoles and substituted tryptamine derivatives, which exhibit significant anticancer activities (Scheme 1).[1] Among these crucial molecules, intermediates with a formyl functional group at the C3 position can serve as a primary building block to construct substituted indoles through their broad and specific reactivity for various chemical transformations. Therefore, 1,2,3-tri-substituted indole preparation has received considerable interest in previous decades.

According to a literature survey, several pioneering methods have been reported for the construction of 1,2 di-substituted 3-formyl indoles through two-step reactions. The first step involves the use of the easily accessible starting materials of *o*-alknylaniline derivatives and is mediated by transition metals (Pt,[2] Pd,[3] Ag,[4] Au,[5] Ir,[6] In,[7] Fe,[8] and Cu[9]), the molecular halogen[10] catalyzed annulation of *o*-alkynylaniline derivatives, or free radical assisted indole construction through either C–C or C–N bond-forming reactions.[11] The second step involves direct formylation by an existing indole using the Vilsmeier–Haack reaction,[12] or other methods[13] (Scheme 2, eqn (1)). Tsui and coworkers[14] recently reported an elegant method for synthesizing 2-(trifluoromethyl)indoles from *N*-mesylated-2-alkynylanilines through domino cyclization and formylation by using TMEDA as a carbon synthon (Scheme 2, eqn (2)).[14] Although these methods are potentially useful, some have certain limitations, such as desulfonylation, post-functionalization is necessary for the *N*-substitution of the indole derivatives, expensive metal-catalysts[2–5] and strong acidic conditions.[12] Herein, we wish to report a complementary approach by employing *o*-phenylethynyl *N*-substituted aniline (**1**, **3**, and **5**) as a starting material for the one-pot domino synthesis of multisubstituted-3-formyl indole (**2**, **4**, and **6**) using DMF in the presence of oxygen (Scheme 2, eqn (3)). Moreover, detailed mechanistic studies of the Cu(II) and O_2-mediated formylation were conducted.

Results and discussion

To optimize reaction parameters, preliminary screening was conducted using *o*-phenylethynyl aniline **1a** as a model substrate (Table 1). The reaction was initially carried out using



Scheme 1 Biological importance of indole derivatives.

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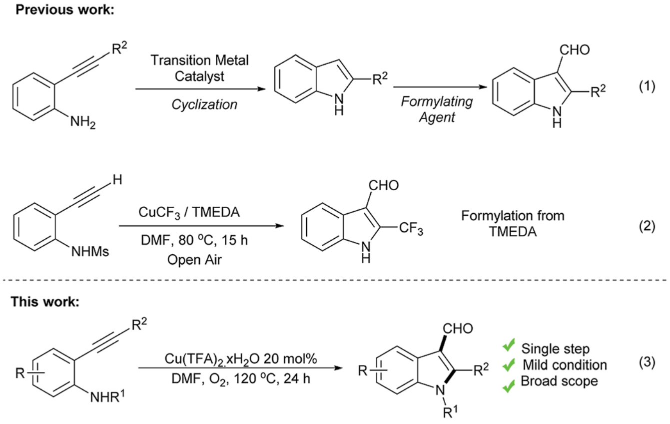
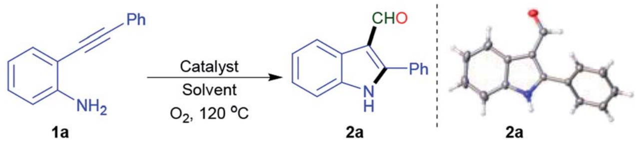


Scheme 2 Previous and this work on 3-formyl indoles.

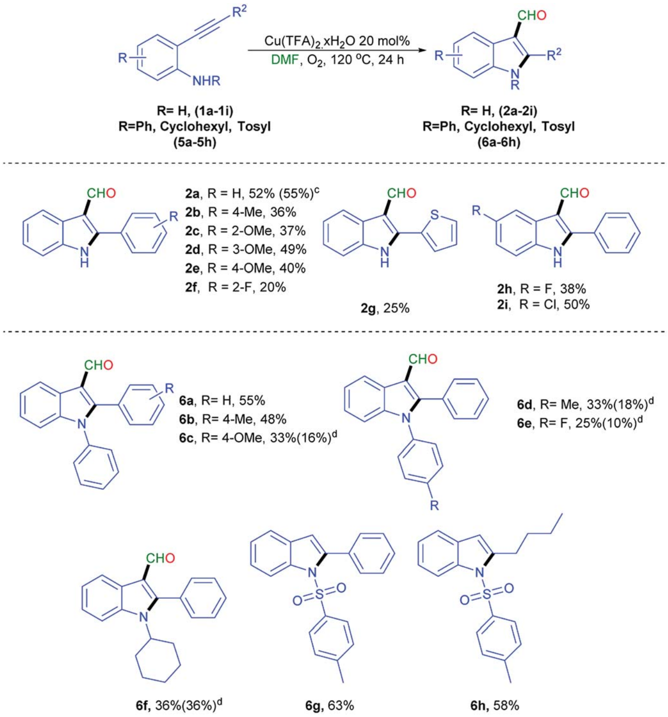
1a in DMF (0.25 M) with 20 mol% of $Cu(OAc)_2 \cdot H_2O$ as a catalyst, and TFA as an additive (2.0 equiv.) under an O_2 atmosphere at 120 °C for 24 h. The desired product **2a** was obtained in 31% yield (Table 1, entry 1). To optimize the catalyst, TFA was added as an additive with various copper catalysts such as anhyd. $Cu(OAc)_2$, $Cu(OTf)_2$, $CuSO_4 \cdot H_2O$, Cu(I), and Cu. The desired product **2a** was obtained in 45% yield when Cu powder was used as a catalyst (Table 1, entries 2–6). The reaction yield did not improve when different Brønsted acids were used, including TfOH and $TsOH \cdot H_2O$ additives (Table 1, entries 7–8). **2a** was not obtained, when only Cu was added as a catalyst (Table 1, entry 9). To our delighted, $Cu(TFA)_2 \cdot xH_2O$ was used as a catalyst instead of Cu/TFA, and the reaction yield increased to 52% (Table 1, entry 10). The reaction yield was reduced to 32% when the reaction was performed in air (Table 1, entry 11). Furthermore, no product was formed under a N_2 atmosphere (Table 1, entry 12). Other oxidants such as DDQ, and AgOAc under the N_2 atmosphere, resulted in low yield (Table 1, entries 13–14). These

Table 1 Optimization of the reaction conditions[a]



Entry	Catalyst (20 mol%)	Additive (2.0 equiv.)	Oxidant	Solvent/time (h)	Yield[b] (%)
1	$Cu(OAc)_2 \cdot H_2O$	TFA	O_2	DMF/20	31
2	$Cu(OAc)_2$	TFA	O_2	DMF/14	37
3	$Cu(OTf)_2$	TFA	O_2	DMF/28	20
4	$CuSO_4 \cdot H_2O$	TFA	O_2	DMF/25	27
5	CuI	TFA	O_2	DMF/22	27
6	Cu	TFA	O_2	DMF/20	45
7	Cu	TfOH	O_2	DMF/24	15
8	Cu	$TsOH \cdot H_2O$	O_2	DMF/24	18
9	Cu	—	O_2	DMF/20	N.R
10	$Cu(TFA)_2 \cdot xH_2O$	—	O_2	DMF/24	52
11[c]	$Cu(TFA)_2 \cdot xH_2O$	—	Open air	DMF/24	32
12[d]	$Cu(TFA)_2 \cdot xH_2O$	—	—	DMF/24	N.R
13	$Cu(TFA)_2 \cdot xH_2O$	—	DDQ	DMF/24	16
14	$Cu(TFA)_2 \cdot xH_2O$	—	AgOAc	DMF/24	11
15	$Cu(TFA)_2 \cdot xH_2O$	—	O_2	Dioxane/24	Trace
16	$Cu(TFA)_2 \cdot xH_2O$	—	O_2	DMSO/24	Trace
17	$Cu(TFA)_2 \cdot xH_2O$	—	O_2	THF/DMF (1/1)/24	Trace
18[e]	$Cu(TFA)_2 \cdot xH_2O$	—	O_2	DMF/24	12
19[f]	$Cu(TFA)_2 \cdot xH_2O$	—	O_2	DMF/24	30
20[g]	$Cu(TFA)_2 \cdot xH_2O$	—	O_2	DMF/24	54

[a] Reaction conditions **1a** (1.0 equiv.), catalyst (20 mol%), solvent (3.0 mL), O_2 balloon, 120 °C, 24 h at indicated time unless otherwise noted. [b] Isolated yield. [c] Reaction was performed under open air. [d] Reaction was performed under nitrogen atmosphere. [e] 5 mol% of $Cu(TFA)_2 \cdot xH_2O$ was used. [f] 10 mol% of $Cu(TFA)_2 \cdot xH_2O$ was used. [g] Another 20 mol% of $Cu(TFA)_2 \cdot xH_2O$ was added after 12 h.

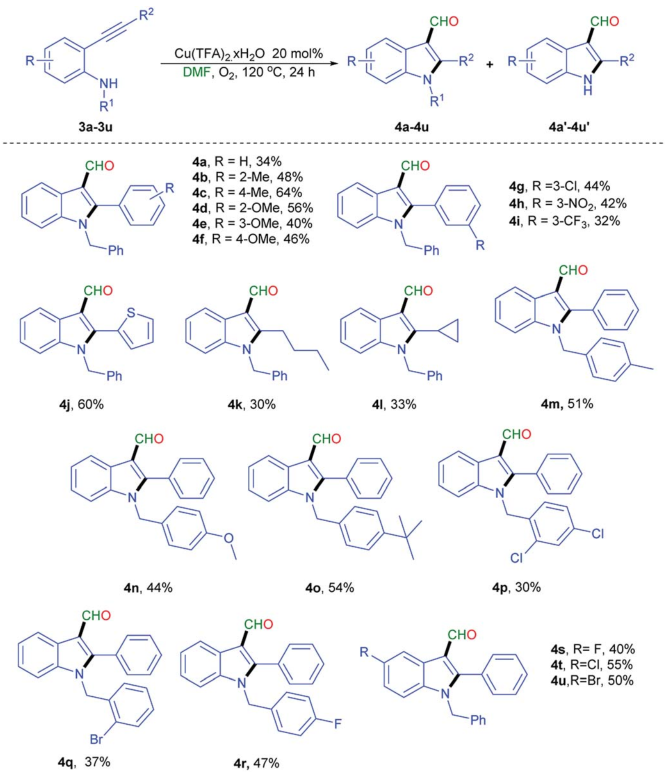


Scheme 3 Scope of 2-phenylethynyl aniline derivatives[a,b]. [a]Reaction conditions: **1a** (0.3 mmol), Cu(TFA)$_2$·xH$_2$O (20 mol%), DMF (3 mL), 120 °C, 24 h, O$_2$. [b]Isolated yield. [c]3.0 mmol scale. [d]Recovered yield of starting material.

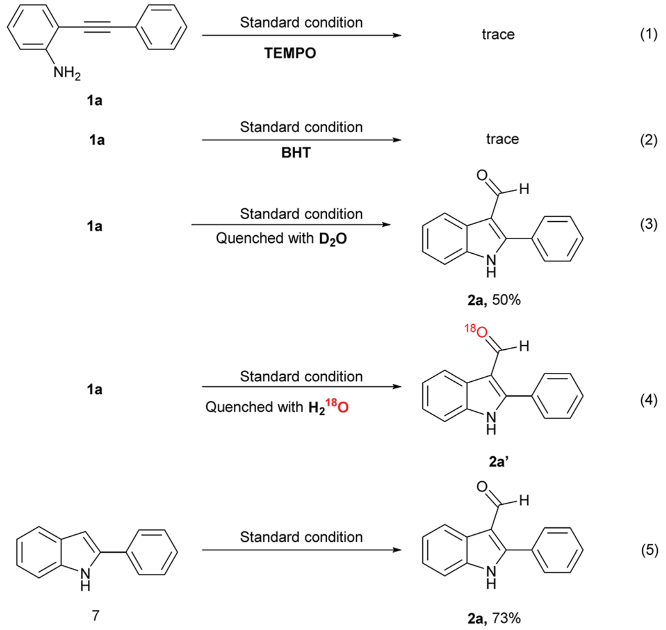
results indicate that the oxygen supply is crucial for the reaction. The use of alternative solvents such as, dioxane, DMSO, and a binary solvent system (THF/DMF 1 : 1) generated trace yield (Table 1, entries 15–17). When the catalyst was reduced to 5 mol% or 10 mol%, the reaction yield was reduced (Table 1, entries 18–19). The addition of another 20 mol% of Cu(TFA)$_2$·xH$_2$O catalyst after 12 h, did not substantially improve the reaction yield (Table 1, entry 20).

With the optimized conditions (Table 1, entry 10), the scope of this reaction was studied using *o*-phenylethynyl aniline derivatives [(**1a–1i**) and (**5a–5h**)], and the reaction results are summarized in Scheme 3. To evaluate the reaction scope and probable substituent effects of R^2, various functional groups including substituted phenyls, and the heterocyclic group were studied (Scheme 3, **1a–1g**). Compared with **1a**, substrates with electron-donating groups on the phenyl ring, such as 2-Me and 2 or 4-OMe were suitable for this reaction, generating the corresponding products **2b**, **2c** and **2e** in moderate yield. A substrate with electron-withdrawing groups, such as 2-F (**1f**) gave **2f** in lower yield. When the substituent group was thiophene (**1g**), the desired was obtained in a low yield of 25% (**2g**). The substituent on the aryl ring (R) was subsequently studied (Scheme 3, **1h–1i**). Electron-withdrawing groups, including 4-F (**1l**), and 4-Cl (**1m**) generated the corresponding products **2l** and **2m** in 38% and 50% yield, respectively. A scale up experiment could be performed in a 3 mmol scale of **1a**, to obtain **2a** in 55% yield, indicating the efficacy and scalability of the reaction. The structure of **2a** was validated through X-ray crystallography analysis, and the data was presented in ESI.†[18] The scope of the *N*-phenyl-2-phenylethynyl aniline derivatives (**5a–5h**) were explored and the resulting data are shown in Scheme 3. Electron-donating groups at the alkynyl position, exhibiting the desired product (**6a–6c**) in 33–55% yields. 4-Me (**5d**), and 4-F (**5e**) groups on the *N*-phenyl were formed smoothly, with 10–18% recovery of starting materials. A cyclohexyl group (**5f**) present on a nitrogen atom gave the desired product (**6f**). Surprisingly, when *N*-tosylate-2-phenylethynyl aniline derivatives (**5g** and **5h**) used as substrates, only led to the formation of indole[14] (Scheme 5, **6g**, **6h**).

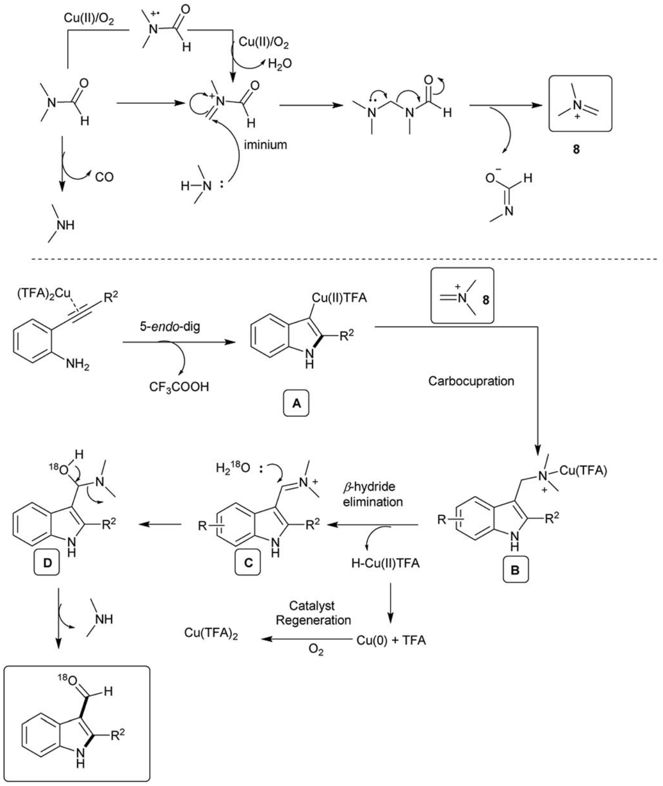
With the successful outcome of 2,3 di-substituted indole derivatives, this method was extended to synthesize of 1,2,3 tri-substituted indole derivatives by using the *N*-benzylated 2-phenylethynyl aniline derivatives (**3a–3u**) under the optimized conditions (Scheme 4). When **3a** was tested, the desired product **4a** was obtained in 34% yield. Substituents at the R^2 position with a phenyl ring having electron-donating groups, such as 2-Me (**3b**), 4-Me (**3c**), 2-OMe (**3d**), and 4-OMe (**3f**) had appropriate reactivity. By contrast, the electron-withdrawing groups, including 3-Cl (**3g**), 3-NO$_2$ (**3h**), and 3-CF$_3$ (**3i**), produced the corresponding products in moderate yields (32–44%). Thiophene group (**3j**) smoothly proceeded in 60% yield. Aliphatic groups, such as hexyl (**3k**) and cyclopropane (**3l**), were examined, the desired products were obtained in 30% and 33% yields, respectively. The substitution of a phenyl ring bearing an



Scheme 4 Scope *N*-benzylated-2-phenylethynyl aniline derivatives[a,b,c]. [a]Reaction conditions: **3a–3v** (0.3 mmol), Cu(TFA)$_2$·xH$_2$O (20 mol%), DMF (3 mL), 120 °C, 24 h, O$_2$. [b]Isolated yield. [c]Please see Table S1 in ESI† for isolated yield of **4a′–4u′**.



Scheme 5 Control experiments.



Scheme 6 Proposed mechanism.

electron donating groups such as 4-Me (**3m**), 4-OMe (**3n**), and *t*-Bu (**3o**), on R^1 provided moderate yield (44–54%). The presence of electron withdrawing groups (**3p**–**3r**) on a benzyl ring generated a similar moderate yield. An indole phenyl ring bearing with electron withdrawing groups such as F (**3s**), Cl (**3t**), and Br (**3u**) provided in good yield. During this reaction, the formation of debenzylation products was observed (ESI†). This formation might be a side reaction of substrate with molecular oxygen under high temperature.[14,15]

To understand the formation of the 3-formyl indoles derivatives, several control experiments were performed (Scheme 5). Table 1 (*vide supra*) indicates that when oxygen was replaced by air or nitrogen, the reaction yield was reduced to 32% and 0%, respectively (Table 1, entries 11 and 12). These results revealed that sufficient supply of oxygen is necessary for this reaction. When a 2.5 equivalent of common radical scavengers, including TEMPO or BHT was added, a trace amount (<5%) of **2a** was detected through GC-MS and the starting material remained. The results suggested that this reaction may occur through a radical process (Scheme 5, eqn (1) and (2)). The addition of D_2O after the completion of the reaction could not afford the deuterium-labeled aldehyde in 50% yield (Scheme 5, eqn (3)). The addition of ^{18}O-labeled water to the reaction mixture under a standard condition afforded 100% of ^{18}O-labeling product **2a′** (Scheme 5, eqn (4), and ESI†), where the oxygen atom of the formyl group is originated from water. The reaction with the 3-*H*-indole substrate **7** generated **2a** in good yield (73%) under the standard condition (Scheme 5, eqn (5)). These results indicate that the product formation was through a pathway involving radical intermediates that utilized molecular oxygen as an oxidant.

The proposed mechanism is based on the control experiments and previous reports[13e,14,16,17] (Scheme 6). DMF was activated by Cu(II) and oxygen to generate the iminium ion **8**.[13e,14,16] The simultaneous electrophilic activation of alkyne by Cu(II) and intramolecular 5-*endo*-dig cyclization generated the vinyl Cu(II) intermediate **A**.[14] The carbocupration of the intermediate **A** and the reaction with an iminium ion led to formation of the *N*–Cu(II) intermediate **B**.[13e,14,16,17] The β-hydride elimination of the **B** gave the primary iminium species **C** along with the catalytic regeneration of Cu(0) in the presence of oxygen. The nucleophilic addition of ^{18}O-labeled water to the **C** generated the hemiketal intermediate **D**. Finally, the elimination of dimethylamine from the **D** generated the desired 3-formyl indoles derivatives.

Experimental

Experimental procedure,[11a] crystallographic data and spectroscopic data of new starting materials and final products were given in ESI.†[18]

In sealed tube, *o*-alkynylaniline derivatives (**1a**–**1i**, **5a**–**5h** & **3a**–**3u**) (0.3 mmol) was taken in DMF (3 mL). To the stirred solution, $Cu(TFA)_2 \cdot xH_2O$ (20 mol%) was added and allowed to stir under O_2 source at 120 °C, until the completion of starting material (∼24 h). The reaction mixture was quenched with ice cold water and extracted with ethyl acetate. Combined organic layer washed with brine, dried over $MgSO_4$ and concentrated in vacuum. Then the crude material was purified by column chromatography using 20% ethyl acetate in hexane as eluent to afford the desired product (**2a**–**2i**, **6a**–**6h** & **4a**–**4u**).

Conclusions

In summary, in this paper, a new synthetic method was developed for the direct synthesis of 1,2-disubstituted 3-formyl indole or 2-substituted 3-formyl indole from the common starting materials of *o*-alkynylaniline through 5-*endo*-dig cyclization followed by an iminium ion attack at the C3 position. Compared with other methods, this one-pot reaction was using the inexpensive Cu-catalyst and DMF as a formyl carbon source, without any additives. This method can be used with a wide range of functional groups and the desired products can be obtain up to moderate yield. In the near future, this method can be adapted as a potential route for the direct synthesis of 3-formyl indole. Further investigation of this reaction in continuous flow system are currently ongoing in our laboratories.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

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18 CCDC number 1876301 (**2a**)† contains the supplementary crystallographic data for this paper.