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N-Heterocyclic carbene (NHC)-catalyzed oxidation of unactivated aldimines to amides *via* imine umpolung under aerobic conditions†

Jakkula Ramarao,‡[ab] Sanjay Yadav,‡[ab] Killari Satyam[ab] and Surisetti Suresh *[ab]

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Herein, we disclose an NHC-catalyzed aerobic oxidation of unactivated aldimines for the synthesis of amides *via* umpolung of imines proceeding through an aza-Breslow intermediate. We have developed an eco-friendly method for the conversion of imines to amides by using molecular oxygen in air as the sole oxidant and dimethyl carbonate (DMC) as a green solvent under mild reaction conditions. Broad substrate scope, high yields and gram scale syntheses expand the practicality of the developed method.

NHCs have emerged as an important class of organocatalysts for unconventional organic transformations due to their unique property of umpolung *i.e.* essentially reversing the polarity of electrophilic carbon centers. NHC-catalyzed umpolung reactivity has been extensively exploited over the past two decades for the construction of carbon–carbon and carbon–heteroatom bonds.[1] NHC-catalytic transformations proceeding through umpolung reactivity, *via* Breslow intermediate, have been well established using aldehydes.[1,2] Despite imines being considered to be potentially important building blocks, the obvious use of imines as reactants for the same is still an under developed area, probably due their lower reactivity. The umpolung of imine came into existence after the isolation of a nitrogen containing Breslow intermediate (known as aza-Breslow intermediate) by the Douthwaite and Rovis groups from the reaction of stoichiometric amounts of NHC and imine or iminium salt, respectively.[3] For the first time, our group[4] and the Biju group,[5] independently, reported the NHC-catalyzed imine umpolung transformations. Recently, a few other groups including our group,[6] the Wei–Fu–Huang,[7] Biju,[8] Lupton[9] and Tian–Zhang–Chi[10] groups reported NHC-catalyzed imine C–H functionalization or oxidation of imines. In continuation of our ongoing research on NHC-catalyzed umpolung transformations,[4,6,11] herein, we present the development of NHC-catalyzed aerobic oxidation of aldimines to amides, *via* imine umpolung without using any additive. We became interested to access the amide functionality because amide is a very crucial functional group due its ubiquitous presence in life-processes in the form of peptide bond in protein molecules as well as its appearance in several of the drug molecules.[12] For example, imatinib[13a] and ponatinib[13a] are used in the chemotherapy treatment of chronic myelogenous leukemia (CML) in cancer disease (Fig. 1). Betrixaban containing two amide functional groups is an oral anticoagulant drug (Fig. 1).[13b]

The scientific community has been showing great interest to develop new and efficient methods for the construction of amide bond. Coupling of carboxylic acid with amine is one of the most common methods used for the construction of amide molecule.[14] However, this method requires stoichiometric amounts of peptide coupling reagents such as carbodiimides and 1-hydroxy benzotriazoles or activated carboxylic acid derivatives.[15] The Schmidt reaction[16] and Beckmann rearrangement[17] are classical examples for the synthesis of amides. However, there are considerably a few reports available for the oxidation of imine to amide. Palladium-catalyzed oxidation of imines to amides was reported by using excess *tert*-butyl hydroperoxide (TBHP) as an oxidant.[18] Methods for the oxidation of imines to amides were reported by using peroxy acids in the presence of strong Lewis acid and Brønsted acid, which generate stoichiometric amount of by-products.[19] Cheon and co-workers reported the oxidation of imines to amides by using sodium cyanide (NaCN) in stoichiometric amounts. High toxic nature of NaCN is the limitation of this methodology (Scheme 1a).[20a] Recently, Fu and Huang group reported the oxidation of imines, limited to the imines derived from heteroaryl amines, to

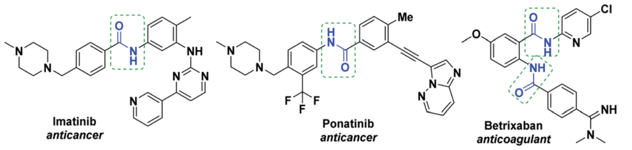

Fig. 1 Selected amide containing therapeutic molecules.

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[a] *Department of Organic Synthesis and Process Chemistry, CSIR-Indian Institute of Chemical Technology (CSIR-IICT), Hyderabad 500 007, India. E-mail: surisetti@iict.res.in; suresh.surisetti@yahoo.in*

[b] *Academy of Scientific and Innovative Research (AcSIR), Ghaziabad 201 002, India*

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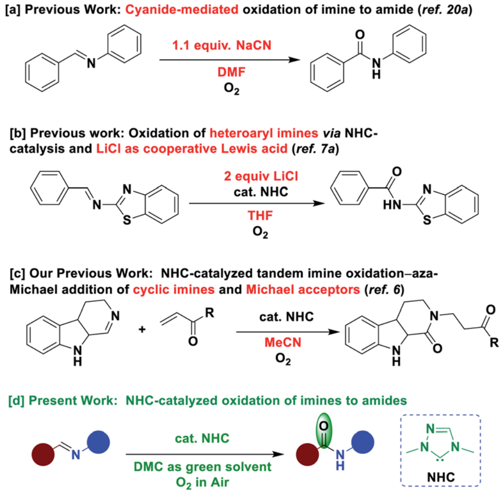
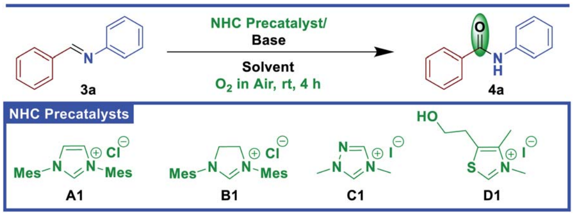
‡ Equal contribution.



Scheme 1 Prior work and this work.

Table 1 Optimization study



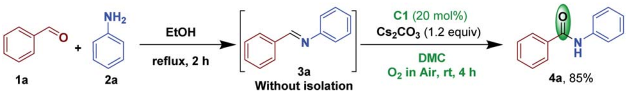
Entry[a]	NHC precatalyst	Base	Solvent	Yield of **4a**[b]
1	**A1**	Cs_2CO_3	DMC	53
2	**B1**	Cs_2CO_3	DMC	—
3	***C1***	$\boldsymbol{Cs_2CO_3}$	***DMC***	***87***
4	**D1**	Cs_2CO_3	DMC	—
5	**C1**	DBU	DMC	71
6	**C1**	DABCO	DMC	65
7	**C1**	NaH	DMC	72
8	**C1**	K_2CO_3	DMC	55
9	**C1**	Cs_2CO_3	THF	75
10	**C1**	Cs_2CO_3	EtOAc	65
11	**C1**	Cs_2CO_3	DMSO	63
12	**C1**	Cs_2CO_3	EtOH	—
13	**C1**	Cs_2CO_3	DMC	70[c]
14	**C1**	Cs_2CO_3	DMC	72[d]
15	—	Cs_2CO_3	DMC	—
16	**C1**	—	DMC	—

[a] Reaction conditions: **3a** (0.5 mmol), NHC precatalyst (0.1 mmol), base (0.6 mmol), solvent (4 mL). [b] Yields are of pure compounds after crystallization. [c] With 0.075 mmol of **C1**. [d] With 0.5 mmol of Cs_2CO_3; Mes: 2,4,6-trimethylphenyl; DBU: 1,8-diazabicyclo[5.4.0]undec-7-ene; DABCO: 1,4-diazabicyclo[2.2.2]octane; DMSO = dimethyl sulfoxide.

amides by using NHC catalysis with the assistance of excess lithium chloride as Lewis acid (Scheme 1b).[7a] Recently, we reported an NHC-catalyzed tandem aza-Michael oxidation of β-carboline cyclic imines in the presence of external Michael acceptors (Scheme 1c).[6] Besides the limitations associated with the above transformations, those were performed in non-green solvent media. However, to the best of our knowledge, there are no reports for the conversion of imines to amides under NHC-catalysis without using an external additive/assistance.[21] On the other hand, the development of new methods to access amide functionality inclusive of green chemistry principles such as organocatalysis, air as the sole oxidant and use of green solvent medium under ambient conditions is highly desirable. Herein, we report an NHC-catalyzed conversion of aldimines to amides, proceeding through imine umpolung–oxidation, in the presence of air in a green solvent such as DMC[22] under mild conditions.

Initially, we began our investigation with the reaction of aldimine **3a**, derived from benzaldehyde **1a** and aniline **2a**, in the presence of NHC **A1** catalyst under open air conditions at room temperature in a green solvent such as DMC. Gratifyingly, we observed the formation of the corresponding amide **4a** in 53% yield (Table 1, entry 1). Motivated by this initial result, we assayed different NHCs. As shown in Table 1, the imidazolinium NHC **B1** was ineffective in this transformation (Table 1, entry 2). Delightfully, with triazolium NHC **C1** the amide **4a** was isolated in 87% yield (Table 1, entry 3). It was found that thiazolium NHC **D1** was not effective for this transformation (Table 1, entry 4). We then moved to the screening of bases with NHC **C1** and it was observed that Cs_2CO_3 proved to be the most effective choice for this transformation (Table 1, entry 3), while bases such as DBU, DABCO, NaH and K_2CO_3 also provided the desired amide **4a** in moderate to good yields (Table 1, entries 5–8). Furthermore, we examined the effect of solvent for this protocol and observed the best yields in DMC (Table 1, entry 3), while other solvents such as THF, EtOAc and DMSO are tolerated and gave moderate to good yields of **4a** (Table 1, entry 9–11). However, this reaction did not work in ethanol (Table 1, entry 12). After successfully identifying the optimal NHC/base/solvent, we investigated the loading of the NHC catalyst in this transformation. Accordingly, the catalyst loading of NHC **C1** was reduced from 20 mol% to 15 mol% to observe 70% yield of **4a**. Similarly, when the base loading was decreased from 120 mol% to 100 mol% the yield of **4a** was reduced to 72% (Table 1, entry 13-14). Subsequently, we performed a couple of reactions to know the necessity of NHC and base for this transformation. Accordingly, two experiments were performed in the presence of NHC or base alone, and neither of these reactions gave the product **4a** (Table 1, entry 15-16) (see ESI† for an extensive optimization survey). We conducted an experiment in presence of LiCl (1.2 equiv.), and it did not help to improve the yield of the product.

By choosing the acceptable optimized conditions from Table 1 (entry 3), we next conducted NHC-catalyzed conversion of imine to amide in a sequential manner-starting from benzaldehyde **1a** and aniline **2a**. Accordingly, **1a** and **2a** were reacted to give the corresponding aldimine **3a**. Subsequently, without further purification, the crude aldimine **3a** was subjected to NHC catalyzed imine umpolung–oxidation to furnish the corresponding benzanilide **4a** in a comparable yield of 85% (Scheme 2).



Scheme 2 Sequential imine formation–NHC-catalyzed aerobic oxidation to access amide **4a**.

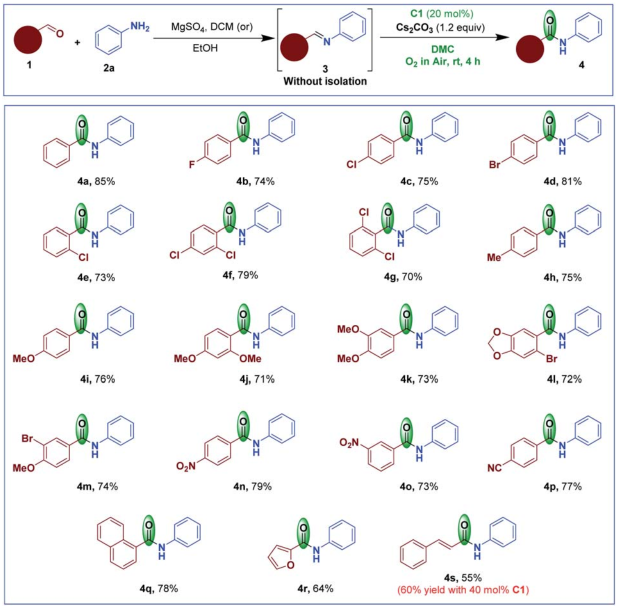
We then examined the scope of the NHC-catalyzed imine umpolung–oxidation to access amides under aerobic conditions in DMC at room temperature. Firstly, the reaction of variously substituted aromatic, heteroaromatic and vinyl aldehydes **1** were converted to the corresponding aldimines **3** with aniline **2a**. Subsequently the aldimine **3**, without further purification, was subjected to optimized NHC catalysis conditions (Scheme 3). Imines derived from aromatic aldehydes bearing either electron-withdrawing or electron-donating groups smoothly afforded the corresponding substituted amides **4** in high yields. The imines derived from *ortho-*/*para*-halo-substituted benzaldehydes provided the amides **4b–f** in high yields. It was interesting to note that sterically hindered 2,6-dichlorobenzaldehyde derived imine also provided the corresponding amide **4g** in 70% yield. Aldimines bearing mono-/di-substituted electron-donating groups provided the respective amides **4h–k** in good yields. The aldimines containing both electron-donating and halogen substituents furnished the corresponding amides **4l** and **4m** in 72% and 74%, yields, respectively. Imines having electron-withdrawing functional groups such as NO_2 or CN also shown tolerance to afford their amides **4n–p** in 73–79% yields. The naphthaldehyde imine provided its amide **4q** in 78% yield. We also tested the imines derived from heterocyclic aldehyde such as 2-furaldehyde and α,β-unsaturated aldehyde such as cinnamaldehyde in this transformation to produce the corresponding amides **4r** and **4s** in 64% and 55%, yields, respectively. The yield of **4s** was only slightly increased with 40 mol% NHC **C1**.

To further study the substrate scope of the NHC-catalyzed imines to amides, benzaldehyde imines derived from variously substituted aromatic/heteroaromatic amines were tested in this transformation (Scheme 4). The imines bearing mono-/di-substituted halogen groups on the aniline side gave the corresponding amides **4t–y** in high yields. The imines containing electron-donating and electron-withdrawing groups on the aniline side were also smoothly converted to their respective amides **4z-4ab** in good yields. Imines derived from heteroaromatic amines such as 3-aminoquinoline and 2-aminobenzothiazole furnished the corresponding amides **4ac** and **4ad** in 77% and 80% yields, respectively.

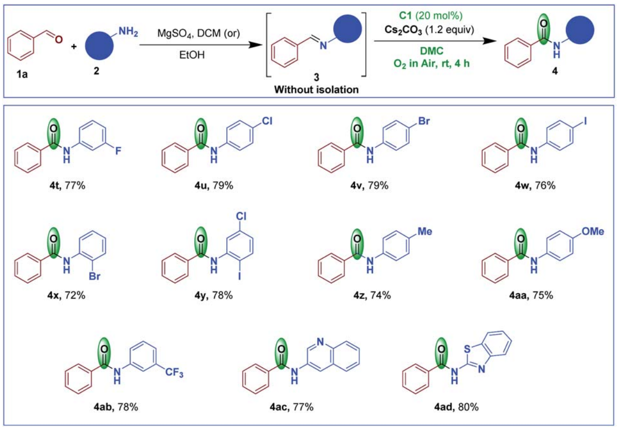
We also tested the imines derived from substituted benzaldehyde and substituted aniline to give the desired amide **4ae** in 72% yield (Scheme 5). Later, an imine derived from heteroaromatic aldehyde and heteroaromatic amine was subjected to NHC-catalyzed oxidation to afford the respective amide **4af** in 70% yield (Scheme 5). We also conducted the reactions with imines derived from aliphatic aldehyde/aliphatic amine, however, the corresponding amide formation was not observed. The reason may be attributed to the less reactivity of these imines.

The practicality of this transformation was tested by gram-scale syntheses on 10 mmol scales; the NHC-catalyzed aerobic oxidation of imines **3a**, **3n**, **3v** proceeded smoothly to afford the corresponding amides **4a**, **4n**, **4v** in 70%, 65%, 66% yields, respectively (Scheme 6).

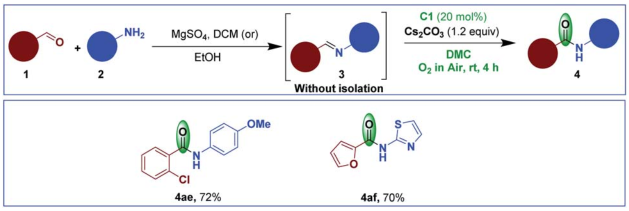
We have performed a few control experiments to know the requirement of molecular oxygen for the NHC-catalyzed oxidation of imine to amide. Accordingly, we conducted a reaction under inert conditions and observed a drastic decrease in the yield of the product (Scheme 7a).[6] This result indicate that molecular oxygen in air is responsible and acting as the sole oxidant in this transformation. We also conducted the NHC-catalyzed imine **3a** oxidation in the presence of pure oxygen to give the desired amide **4a** in 84% yield (Scheme 7b). We further conducted a direct reaction of **1a** and **2a** under optimized NHC-



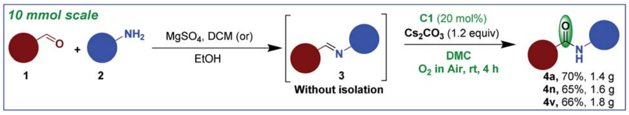
Scheme 3 Scope of the reaction starting with different aldehydes.



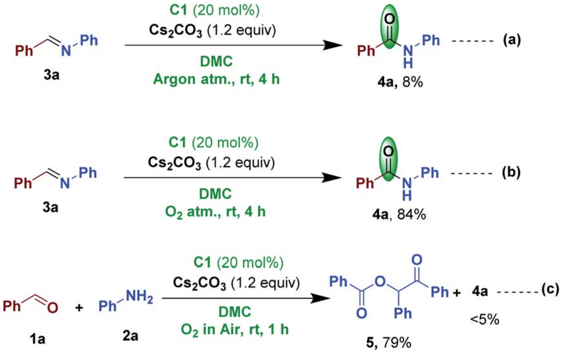
Scheme 4 Scope of the reaction starting with different amines.



Scheme 5 Additional scope of the reaction.



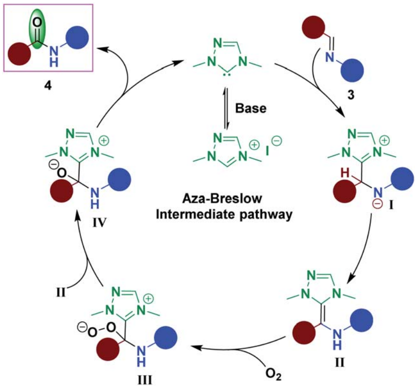
Scheme 6 Gram-scale syntheses of **4a**, **4n** and **4v**.



Scheme 7 Control experiments.

catalyzed conditions to know whether oxidation of **1a** provide NHC-azolium intermediate and add to the amine, akin to the NHC-catalyzed ester formation from the reaction of aldehydes and alcohols.[23] However, in this reaction we did not observed the formation of amide but obtained the compound **5** [20b] resulted from the benzoin condensation-acylation (Scheme 7c).

Based on the previous literature reports,[6,7,24] a possible mechanism for the NHC-catalyzed aerobic oxidation of imine to amide is depicted in Scheme 8. Initially, the free NHC would add to the imine **3** to form intermediate I. Aza-Breslow intermediate II would generate from intermediate I upon proton shift. The intermediate II would react with molecular oxygen and undergo single electron transfer of the intermediate II with dioxygen followed by radical recombination to give intermediate III.[7,24] Thereafter one more molecule of aza-Breslow intermediate II would react with intermediate III to produce two molecules of intermediate IV. Then from intermediate IV NHC would regenerate and produce the amide **4.** This mechanism suggests that one molecule of oxygen is sufficient to produce two molecules of the amide **4.**



Scheme 8 Plausible mechanism.

Conclusions

In conclusion, we have developed an efficient and environmentally friendly approach for the conversion of imines to amides with NHC-catalyzed aerobic oxidation of imines proceeding through imine umpolung involving aza-Breslow intermediate. In this protocol, we have used a green solvent such as dimethyl carbonate and molecular oxygen in air acts as the sole oxidant under mild conditions without using any additive. Further research work is in progress in our laboratory towards the investigation and application of the NHC-catalyzed imine umpolung for its potential in organic transformations and will be communicated in due course.

Conflicts of interest

There are no conflicts to declare.

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