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Acid-promoted iron-catalysed dehydrogenative [4 + 2] cycloaddition for the synthesis of quinolines under air†

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An acid-promoted iron-catalysed dehydrogenative [4 + 2] cycloaddition reaction was developed for the synthesis of quinolines using air as a terminal oxidant. Acetic acid was the best cocatalyst for the cycloaddition of *N*-alkyl anilines with alkenes or alkynes under air. Various quinoline derivatives were obtained in satisfactory-to-excellent yields, and no other byproducts besides water were produced in the reaction. The zebrafish model has become an important vertebrate model for evaluating drug effects. We tested the activity of **3n** in zebrafish. The test results showed that 1 µg mL⁻¹ **3n** treatments resulted in morphological malformation, and 0.01–0.1 µg mL⁻¹ **3n** treatments led to potent angiogenic defects in zebrafish embryos. The results of this study will be of great significance for promoting drug research in cardiovascular and cerebrovascular diseases.

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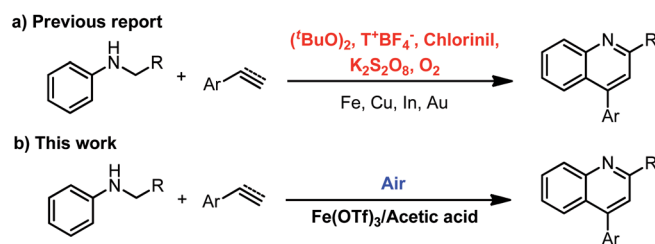
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The construction of quinoline motifs has received intensive attention owing to their potential application in photovoltaic devices¹ and pharmaceuticals,² such as anticancer, antiviral, anti-fungal, antiplatelet aggregation, antimalarial, antibacterial, anti-leishmanial and anti-inflammatory medicine.³ Because of their importance, many methods have been reported for the synthesis of quinolines.⁴ Among them, the most attractive strategy for the synthesis of these compounds is the dehydrogenative [4 + 2] cycloaddition through transition-metal catalysis and Lewis/Bronsted acid catalysis. In its most general and classical form, dehydrogenative [4 + 2] cycloaddition catalysed by transition metals such as Fe,⁵ Cu,⁶ Pd,⁷ and others,⁸ has been used as a potent tool for the synthesis of quinolone derivatives (Scheme 1a). However, these methods require the presence of excess peroxides, chloranil, potassium persulfate or other oxidants to promote the cycloaddition reaction and to obtain good product yields. Furthermore, in these processes, the formation of stoichiometric amounts of acid or tetrachlorohydroquinone waste as byproducts is a substantial problem that has limited their use. To overcome these drawbacks, several methods that utilise oxygen as a terminal oxidant have been reported.⁹ However, in many cases, the industrial use of these methods is problematic owing to operational difficulty. Therefore, the development of more efficient and economical synthetic methods is still necessary. Undoubtedly, the use of air as a terminal oxidant is the best choice. In addition, in the field of transition-metal catalysis, iron is one of the most

commonly used base metals and has been widely applied in various coupling reactions.¹⁰ Therefore, it is desirable to develop an iron-catalysed dehydrogenative cycloaddition for the synthesis of quinoline under air.

Herein, we report the first acid-promoted iron-catalysed dehydrogenative [4 + 2] cycloaddition of *N*-alkyl anilines with alkenes or alkynes using air as a terminal oxidant (Scheme 1b). Iron-catalysed cycloaddition reaction for the synthesis of quinolines under air has always been a challenge because of metal deactivation after the end of the catalytic cycle. We commenced our studies by treating *N*-benzylaniline (**1a**) and styrene (**2a**) with 5 mol% iron as a catalyst. Initially, we tried to use a variety of iron catalysts to catalyse the cycloaddition of *N*-alkyl anilines and olefins under air (Table 1, entries 1–6). Trace amounts of the desired product (**3a**) were obtained with FeCl₂, Fe(OTf)₂, Fe₂(SO₄)₃ and Fe₂O₃, as detected by GC analysis, and a 28% or 33% yield was observed when FeCl₃ or Fe(OTf)₃ was used as a catalyst. To improve the reaction efficiency, different solvents



■ Air as a terminal oxidant ■ Up to 96% yield ■ Gram Scale ■ Zebrafish experiment

Scheme 1 Different strategies for [4 + 2] cycloaddition of *N*-alkyl anilines and alkenes or alkynes by transition-metal catalysis.

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Table 1 Solvent effect and acid effect. *N*-benzylaniline (0.2 mmol), styrene (0.4 mmol), Fe(OTf)₃ (10 μmol), acid (0.3 mmol), toluene (1.0 mL), at 140 °C under air for 24 h

Entry	Catalyst (5 mol%)	Acid (0.3 mmol)	Solvent	<i>T</i> (°C)	Yield ^a (%)
1	Fe(OTf) ₂	No	Toluene	120	Trace
2	FeCl ₂	No	Toluene	120	Trace
3	FeCl ₃	No	Toluene	120	28
4	Fe ₂ O ₃	No	Toluene	120	Trace
5	Fe ₂ (SO ₄) ₃	No	Toluene	120	Trace
6	Fe(OTf) ₃	No	Toluene	120	33
7	Fe(OTf) ₃	No	Ethanol	120	0
8	Fe(OTf) ₃	No	Mesitylene	120	26
9	Fe(OTf) ₃	No	Dioxane	120	0
10	Fe(OTf) ₃	No	Nitrobenzene	120	28
11	Fe(OTf) ₃	No	Acetonitrile	120	23
12	Fe(OTf) ₃	No	Toluene	150	42
13	Fe(OTf) ₃	No	Toluene	140	49
14	Fe(OTf) ₃	No	Toluene	100	16
15	Fe(OTf) ₃	No	Toluene	80	8
16	Fe(OTf) ₃	No	Toluene	60	Trace
17	Fe(OTf) ₃	No	Toluene	40	0
18	Fe(OTf) ₃	H ₂ SO ₄	Toluene	140	0
19	Fe(OTf) ₃	TfOH	Toluene	140	0
20	Fe(OTf) ₃	TFA	Toluene	140	65
21	Fe(OTf) ₃	PTSA	Toluene	140	61
22 ^b	Fe(OTf) ₃	BNPA	Toluene	140	57
23	Fe(OTf) ₃	HCOOH	Toluene	140	42
24	Fe(OTf) ₃	BzOH	Toluene	140	50
25	Fe(OTf)₃	AcOH	Toluene	140	82
26	Fe(OTf) ₃	PhB(OH) ₂	Toluene	140	35
27	Fe(OTf) ₃	B(OH) ₃	Toluene	140	15
28	Fe(OTf) ₃	Phenol	Toluene	140	54
29 ^c	Fe(OTf) ₃	AMSA	Toluene	140	51
30	No	AcOH	Toluene	140	Trace

^a Isolated yields. ^b BNPA = 1,1'-binaphthyl-2,2'-diylhydrogen-phosphate. ^c AMSA = aminomethanesulfonic acid.

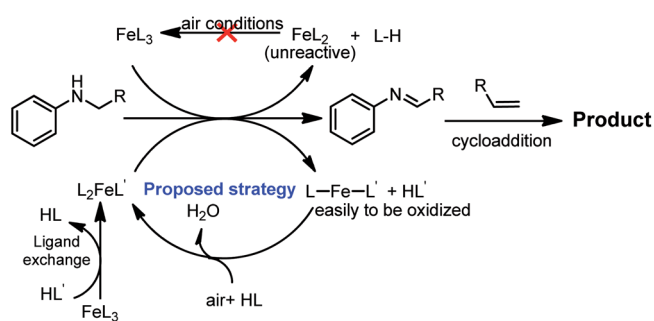
such as ethanol, mesitylene, 1,4-dioxane, nitrobenzene, acetonitrile and toluene were tested (Table 1, entries 6–11).

The optimal solvent for the reaction was toluene (Table 1, entry 6). Encouraged by this result, we examined a wide range of reaction temperatures (Table 1, entries 12–17); the best yield was obtained at 140 °C, but it did not meet our expectations.

We reasoned that an unreactive catalytic species, FeL₂ (Scheme 2), could be formed in the reaction from the interaction of the imine intermediate and FeL₃, which could not catalyse the conversion of imines to quinoline. Critically, the FeL₂ species was difficult to oxidize to FeL₃ under air conditions. Inspired by Birk's work,¹¹ we envisaged that the addition of an acid may promote the oxidation of Fe(II) to Fe(III) under air. Based on this assumption, we proposed that FeL₃ can undergo ligand exchange with HL' to generate the active catalytic species L₂FeL'. A subsequent oxidation reaction provided LFeL', which was easier to oxidize to L₂FeL' than FeL₂ under air, enabling the next catalytic cycle.

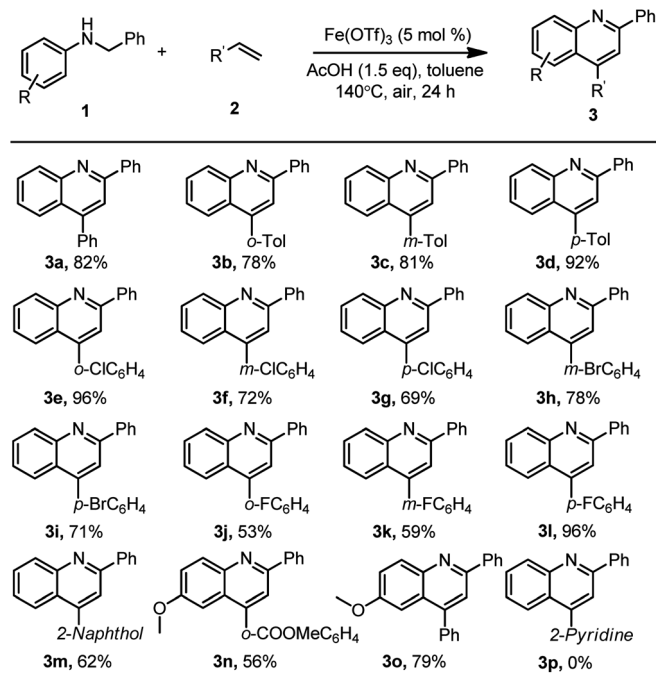
Based on this hypothesis, we investigated some strong acids and moderate acids. Trifluoroacetic acid (TFA) was a cocatalyst

that promoted the Fe-catalysed [4 + 2] cycloaddition of *N*-alkyl anilines and alkenes to deliver 2,4-diphenylquinoline in 65% yield (Table 1, entries 18–20). If 1,1'-binaphthyl-2,2'-diylhydrogen phosphate or *p*-toluenesulfonic acid (PTSA) were used instead of TFA, the yield was significantly reduced (Scheme 3, entries 21–22). For further improvement of the reaction, other



Scheme 2 Proposed strategy.





Scheme 3 Reaction conditions: substrate **1** (0.2 mmol), aryl olefin (0.4 mmol), $\text{Fe}(\text{OTf})_3$ (10 μmol), AcOH (0.3 mmol), toluene (1.0 mL), at 140°C under air for 24 h, and isolated yields of the products.

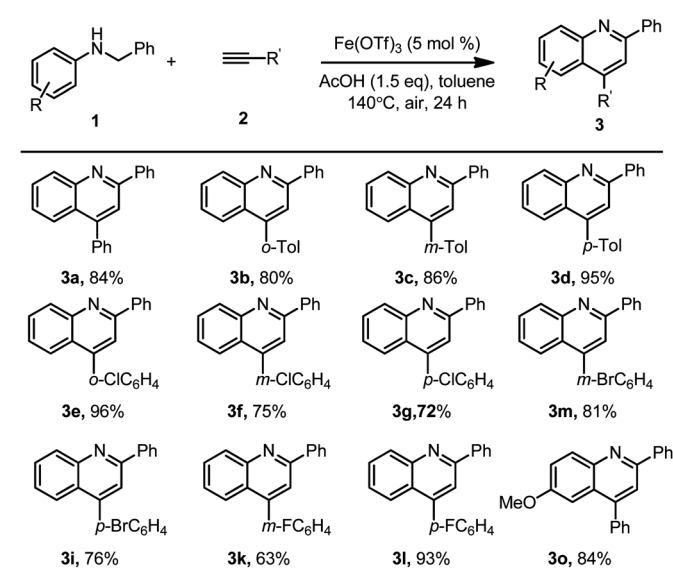
acid such as formic acid (HCOOH), benzoic acid (BzOH), acetic acid (AcOH), phenylboronic acid, boric acid, phenol and carbamic acid were tested (Table 1, entries 23–29). The results showed that the addition of 1.5 equivalents of acetic acid was the best choice, furnishing the corresponding 2,4-diphenylquinoline in 82% yield (Table 1, entry 25). Under the acidic conditions, a strong acid was completely inefficient (Table 1, entry 18), which suggested that the strength of the acid was critical to the reaction. Other acids did not give better results. Therefore, we performed the subsequent reactions between the *N*-alkyl anilines with alkenes or alkynes in the presence of $\text{Fe}(\text{OTf})_3/\text{AcOH}$ at 140°C under air conditions for 24 h.

With the optimized reaction conditions in hand, a series of aryl ethylenes were investigated for extending the substrate scope (Scheme 3). This acid-promoted iron-catalysed dehydrogenative $[4 + 2]$ cycloaddition reaction displayed good functional group tolerance. Aryl ethylenes with electron-neutral or electron-donating groups on the aryl rings, such as alkyl, phenyl and naphthyl, all gave the corresponding 2,4-diarylquinoline with high selectivity in good yields. Aryls containing an electron-withdrawing group such as fluoro, chloro, bromo and ester were also tolerated and afforded the corresponding 2,4-diarylquinolines **3e–3n** in moderate to good yields. Moreover, the reaction of *N*-benzylaniline **1b** containing a substituent (MeO) at the *para*-position of the aniline ring also produced the corresponding quinoline products **3o** in 79% yield. These results indicated that different groups, such as methyl, phenyl, fluoro, chloro, bromo and methoxyl on benzene rings, were tolerated under the optimized reaction conditions. Notably, the retention of the F, Cl and Br atoms in the structures of the products should make the products considerably useful in organic

transformations. Unfortunately, the current method could not be applied to olefins containing N heteroatoms, which was likely because of the strong coordination of N atoms with iron.

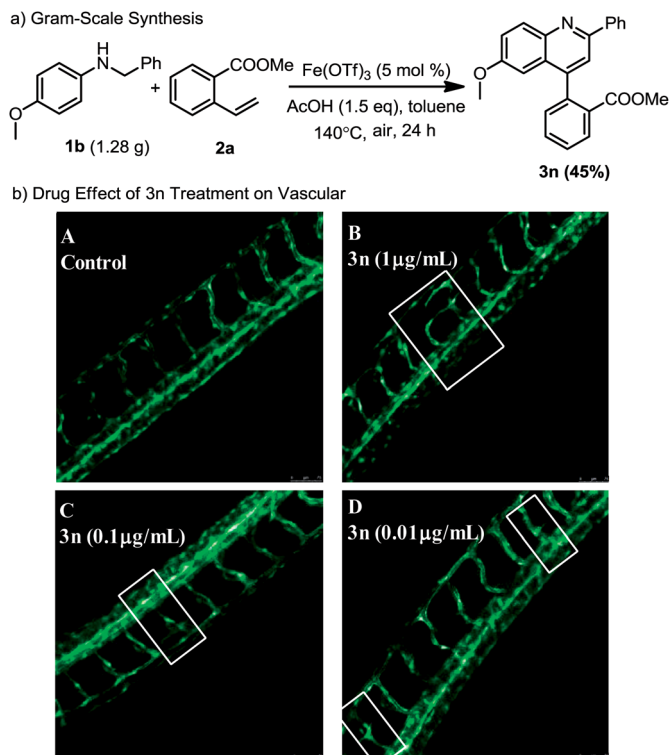
Next, the scope of arylacetylenes was also investigated, and the results are summarized in Scheme 4. Arylacetylenes could be used instead of arylethylenes for the synthesis of 2,4-diarylquinoline under the optimized reaction conditions. Similar good results were obtained, as shown in Scheme 4. Quinoline derivatives **3a–3g**, **3i**, **3k–3m** and **3o** were obtained in satisfactory to good yields (63–96%).

To test the synthetic utility of the current method, a gram scale dehydrogenative $[4 + 2]$ cycloaddition reaction of *N*-benzyl-4-methoxyaniline with methyl-2-vinylbenzoate was conducted under the optimal conditions, providing the target **3n** in 45% yield. To demonstrate the potential of our approach, we conducted molecular docking studies of human phenylethanolamine *N*-methyltransferase (hPNMT) and the quinoline derivatives. The studies were performed to help visualize possible interactions between hPNMT and the quinoline derivatives. The results showed that methyl-2-(6-methoxy-2-phenylquinolin-4-yl)benzoate **3n** may have π - π interactions with ARG 90, and π -cation interactions with TYR 27 in hPNMT. Based on this docking result, **3n** is highly likely to be a potent inhibitor of hPNMT. The results of the docked poses of hPNMT and **3n** are shown in the ESI.† The zebrafish model has become an important vertebrate model for evaluating drug effects.¹² To demonstrate the drug effect of **3n** on the vascular system in the trunk of zebrafish embryos, we tested the activity of **3n** in zebrafish. The test results showed treatment of zebrafish embryos with $1\ \mu\text{g mL}^{-1}$ **3n** resulted in morphological malformation, and treatment with 0.01 – $0.1\ \mu\text{g mL}^{-1}$ **3n** led to potent angiogenic defects (Scheme 5b). The results of this study will be of great significance for promoting drug research in cardiovascular and cerebrovascular diseases.



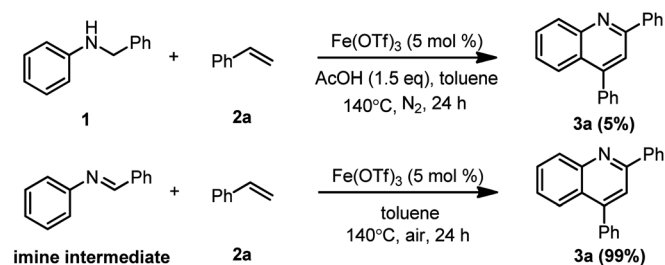
Scheme 4 Reaction conditions: substrate **1** (0.2 mmol), aryl alkyne (0.4 mmol), $\text{Fe}(\text{OTf})_3$ (10 μmol), AcOH (0.3 mmol), toluene (1.0 mL), at 140°C under air for 24 h, and isolated yields of the products.





Scheme 5 Gram-scale synthesis and the drug effect of **3n** treatment on vascular in the trunk of Tg(kdrl:EGFP) zebrafish embryos at 48 hpf. (A–D) control group and 1, 0.1, 0.01 $\mu\text{g mL}^{-1}$ **3n** treated groups. Scale bar, 75 μm .

To gain a better understanding of the role of the acid, air and iron in the current cycloaddition reaction, additional experiments were conducted. First, control experiments showed that the absence of any of the three components, air, AcOH and $\text{Fe}(\text{OTf})_3$, significantly reduced the reaction yield, implying that each of the components was essential to this reaction. To clarify that the reaction was undergoing the production of an imine intermediate, we employed *N*-benzylideneaniline as a substrate to test if 2,4-diphenylquinoline could be obtained (Scheme 6). To our great surprise, **3a** was obtained in 99% yield. The results showed that a cycloaddition reaction occurred after *N*-benzylideneaniline was oxidized to an imine. Based on these results, we proposed the following catalytic cycle: FeL_3 first underwent ligand exchange with AcOH to generate an active catalytic species L_2FeOAc , leading to subsequent oxidative dehydrogenation to provide the imine intermediate and intermediate LFeOAc while releasing HL. The imine intermediate can then



Scheme 6 Mechanistic experiments.

undergo a $[4 + 2]$ cycloaddition with an alkyne or alkene, forming the desired 2,4-diarylquinoline or dihydroquinoline. A subsequent dehydrogenation reaction of dihydroquinoline provided the target product. The intermediate LFeOAc underwent an oxidation reaction in the presence of air to regenerate the catalytic species L_2FeOAc .

Conclusions

In summary, we successfully developed a highly efficient acid-promoted iron-catalysed dehydrogenative $[4 + 2]$ cycloaddition for the synthesis of quinoline under air conditions. The new method is compatible with alkenes and alkynes, and we performed molecular docking experiments with **3n**, which indicated that this compound might be an inhibitor of hPNMT. Moreover, we used the zebrafish model as an important way to demonstrate the drug effect of **3n** treatment on the vascular system in the trunk of zebrafish embryos. The test results showed that **3n** had a significant effect on angiogenesis. The results of this study will be of great significance for promoting drug research in cardiovascular and cerebrovascular diseases. Further investigation of cell experiments, animal experiments and other reaction types are under way in our laboratory.

Ethics statement

All animal procedures were performed in accordance with the Guidelines for Care and Use of Laboratory Animals of Nantong University and Experiments were approved by the Animal Ethics Committee of SYXK(SU) 2007–0021.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

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