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Sustainable synthesis of N-heterocycles in water using alcohols following the double dehydrogenation strategy

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ABSTRACT

The present study describes the first example of synthesis of pharmaceutically relevant N-heterocycles like substituted quinolines, acridines and 1,8-naphthyridines in water under air using alcohols in presence of a new water soluble Ir-complex. The viability and efficiency of this approach was demonstrated by the efficient synthesis of biologically active natural product (±)-galipinine and gram scale synthesis of various N-heteroaromatics. Several kinetic experiments and DFT calculations were carried out to support the plausible reaction mechanism which disclosed that this system followed a concerted outer sphere mechanism for the dehydrogenation of alcohols.

1. Introduction

As fossil feedstocks as well as the crude oil reserve are decreasing rapidly, the search for alternative pathways for the production of fine chemicals and fuels has become inevitably significant [1]. Alcohols are inexpensive precursors and easily accessible by conversion of biomass or fermentation process [2,3]. Hence, development of efficient and sustainable methodologies for the transformation of alcohols to fine chemicals is highly desirable.

Among various nitrogen containing heteroaromatics, quinolines, acridines and naphthyridines have substantial importance, owing to their higher abundance in various natural products and pharmacologically important drugs [4–6]. Commonly quinoline and naphthyridine scaffolds were synthesized following the Friedländer synthesis, but owing to its high susceptibility towards self-condensation, later on several metal/base catalyzed oxidative cyclization reactions were developed using 2-aminobenzyl alcohol [7–10]. However, most of these procedures required either large excess of ketones/alcohols or sacrificial hydrogen acceptors [11–14]. In recent years, transition metal catalyzed acceptorless dehydrogenative condensation approach has received much attention for environmentally benign C—N bond formation reactions [15–20]. Following this protocol, Milstein, Beller, Kempe and others reported formation of various N-heterocyclic compounds [21–24]. Similar transformations using the dehydrogenative aldol condensation strategy were also well known in literature for the sustainable C—C bond formation [25–32]. The catalytic synthesis of quinolines and naphthyridines via cyclization of 2-aminobenzyl alcohol with either ketones or alcohols was achieved using Ru, Ir, Pd and other metals [23,33–36]. Notably, most of these methodologies inevitably required organic solvents. Although, organic solvents have many advantages, they are toxic, flammable and relatively expensive [37]. On the other hand, water as a solvent has many potential benefits over organic solvents as it is environmentally friendly, safe, cheap, and easy to separate from organic products.

In the last few decades, there has been a growing interest in utilization of water as a solvent [38]. For that purpose numerous water soluble metal complexes were synthesized and their catalytic activity explored [39–43]. Lately, based on the alcohol dehydrogenation strategy, C—C and C—N bond formation reactions in water were reported by Williams, Fujita, Yamaguchi, Li, and others [44–55]. For the synthesis of nitrogen containing heteroaromatics, the coupling reaction of 2-aminoaryl alcohol with sustainable and readily available alcohols following the double dehydrogenation strategy is challenging in aqueous medium and to the best of our knowledge has not yet been reported.

For the designing of an efficient catalytic system, metal-ligand cooperativity emerged as a powerful tool which received much attention in last few decades [56–58]. In this regard, 2-hydroxypyridine containing ligands represent an important class of cooperative ligands. Various transition metal complexes bearing 2-hydroxypyridine fragment containing ligands were synthesized

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and successfully explored in several transformations such as transfer hydrogenation, CO_2 hydrogenation, dehydrogenation of alcohols, dehydrogenation and hydrogenation of heterocycles, water oxidation, etc. [41,59–63].

Herein, we report the synthesis and catalytic activity of a new phosphine-free water soluble Ir-complex bearing 2-(2-benzimidazolyl)-6-hydroxypyridine ligand. Remarkably, a variety of quinolines, acridines and naphthyridines were synthesized in water under air utilizing this Ir-complex (Scheme 1). To the best of our knowledge, this is the first report for oxidative cyclization of 2-aminoaryl alcohols or 2-nitroaryl alcohols with alcohols in water.

2. Results and discussion

Inspired by the high catalytic activities of bidentate N-containing Ir-complexes [40,41,64], several substituted 2-(2-benzimidazolyl) pyridine ligand containing Ir(III) complexes were synthesized in good yields and complex **1** was characterized by X-ray diffraction (Fig. 1). The catalytic activity of the newly synthesized complexes was investigated for the dehydrogenative coupling between 2-aminobenzyl alcohol and 1-phenylethanol in water (Table 1).

Preliminary results showed that the reaction was facilitated in air compared to argon (Table 1, entry **2**) [65]. Several Ir-catalysts were screened and among them cat. **1** displayed superior activity (Table 1). Notably, cat. **1** and cat. **6** containing the easily deprotonated hydroxyl-pyridine group, showed significantly higher reactivity compared to their —OMe (cat. **2** and **7**) and —Me (cat. **3** and **8**) analogue respectively. Optimization of catalyst amount, base and amino alcohol/alcohol ratio suggested that 1.5 mol% of catalyst **1** was sufficient to achieve the 97% yield of 2-phenylquinoline (**2a**) within 24 h in presence of 1.5 equiv. of KOH (Table 1, entries **3**–**19**). In contrast, using acetophenone, this catalytic system delivered quantitative yield of **2a** within 6 h (Table 1, entry **22**) [13]. This result demonstrated that, compared to ketones, the dehydrogenative coupling of 2-aminobenzyl alcohol was more challenging with easily accessible alcohols.

Using the optimized reaction conditions, this protocol was applied for the coupling of various secondary alcohols with 2-aminobenzyl alcohol and the results are summarized in Table 2. Different substituted secondary alcohols bearing both electron donating and withdrawing groups in *para* and *meta* position afforded good to excellent yields (78–98%) of quinoline derivatives (**2a-2g**). Substitution in the *ortho* position of secondary alcohol delivered poor yield and considerable amount of dehalogenated quinoline was observed as by-product (**2h**). Moreover, 1-(2-naphthalenyl)ethanol and heteroatom substituted alcohols were converted successfully (77–92%) under the reaction conditions (**2i-2k**). Acyclic aliphatic alcohols also reacted well and delivered the desired products (**2l-2n**). The scope of the reaction was further explored towards the coupling of substituted 2-aminobenzyl alcohols with various alcohols (Table 3). Reaction of electron

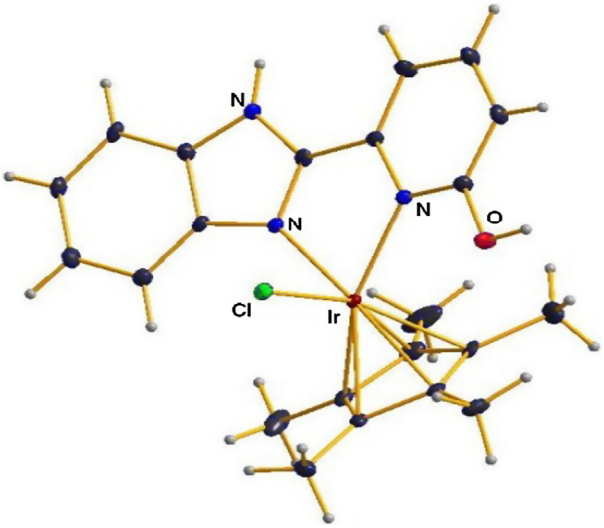


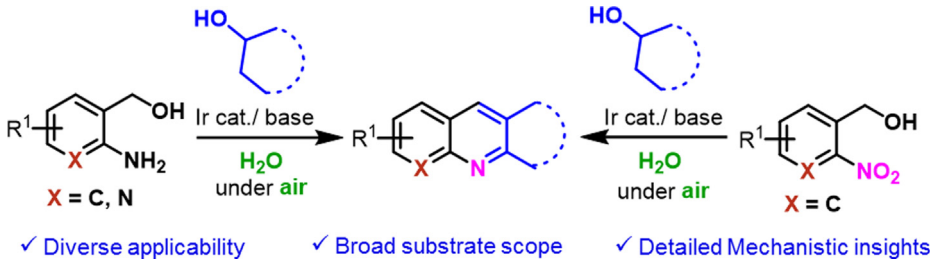
Fig. 1. Solid state structures of complex **1** (30% thermal ellipsoids).

withdrawing as well as electron donating group substituted 2-aminobenzyl alcohols afforded the corresponding products in good to excellent yields (**3a**-**3g**). Notably, naphthyl substituted 2-aminobenzyl alcohol also delivered good yield (**3h**).

In the acceptorless dehydrogenative coupling reaction using alcohols, the liberated hydrogen could be used in transfer hydrogenation of nitro functionality in situ without using any external reducing agents [66,67]. As 2-aminoaryl alcohols can be easily accessed from 2-nitroaryl alcohols, we were interested to explore this strategy for the synthesis of quinolines directly from 2-nitroaryl alcohols. Using this protocol various substituted aryl alcohols, heteronuclei containing alcohols and aliphatic alcohols furnished the desired products in good to excellent yields ((Table 4; **4a-4g**; 74–94%).

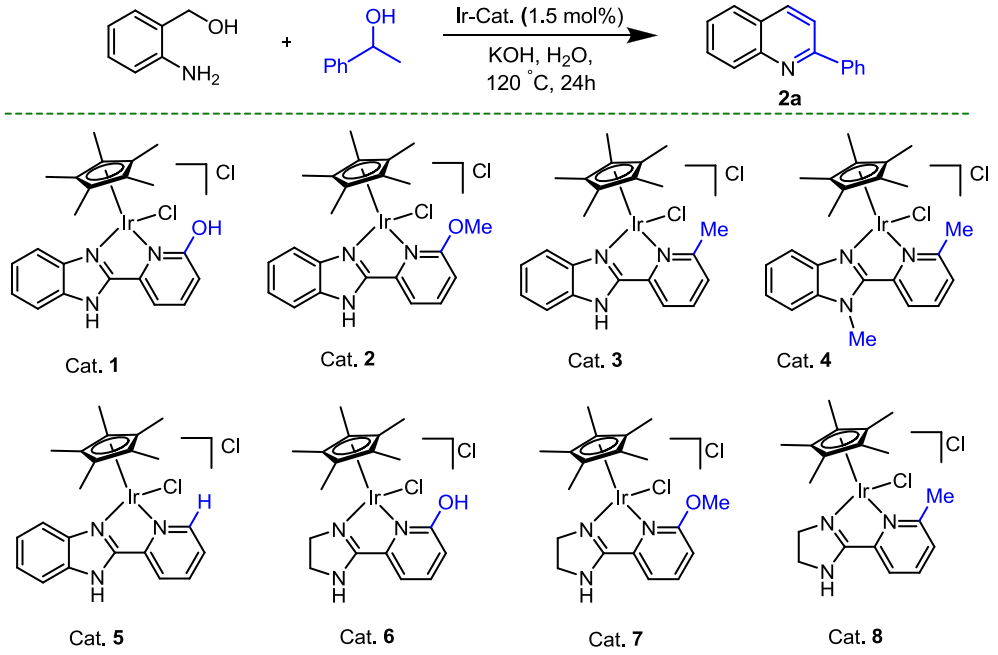
Acridine derivatives are highly important N-heterocyclic moiety which has potential applications as antiparasitic drugs [5,68]. Owing to the widespread applicability of the acridine derivatives, we were fascinated to synthesize them by using the dehydrogenative condensation strategy. Several fused quinolines and acridines were smoothly synthesized from 2-aminobenzyl alcohols and cyclic alcohols employing the standard reaction conditions (Table 5; **5a**-**5h**). Interestingly, with decreasing ring size of the cyclic alcohols, the yield of fused quinoline derivatives increases (**5a-5c**) [5].

1,8-Naphthyridine derivatives have significant importance in medicinal chemistry and materials science. Inspired by their multidirectional biological properties we next explored viable synthesis of 1,8-naphthyridines in water. Notably, this protocol efficiently delivered a variety of 1,8-naphthyridine derivatives (Table 6, **6a**–**6g**). Notably, 1-(2-pyridinyl) ethanol with strong chelation site



Scheme 1. Synthesis of N-heteroaromatics following the double dehydrogenation strategy.

Table 1
Optimization for the synthesis of 2-phenylquinoline from 2-aminobenzyl alcohol.[a]



Entry	Ir-complex (x mol%)	Base (y equiv.)	Amino alcohol/alcohol	Yield (%)[b]
1[c]	Cat. **1** (2.0)	KOH (0.75)	1:1.2	68
2	Cat. **1** (2.0)	KOH (0.75)	1:1.2	79
3	Cat. **1** (2.0)	KOH (1.0)	1:1.2	84
4	Cat. **1** (2.0)	KOH (1.5)	1:1.2	90
5	Cat. **1** (2.0)	KOH (1.5)	1:1.5	98
6	Cat. **2** (2.0)	KOH (1.5)	1:1.5	49
7	Cat. **3** (2.0)	KOH (1.5)	1:1.5	31
8	Cat. **4** (2.0)	KOH (1.5)	1:1.5	27
9	Cat. **5** (2.0)	KOH (1.5)	1:1.5	43
10	Cat. **6** (2.0)	KOH (1.5)	1:1.5	73
11	Cat. **7** (2.0)	KOH (1.5)	1:1.5	21
12	Cat. **8** (2.0)	KOH (1.5)	1:1.5	37
13	Cat. **1** (2.0)	NaOH (1.5)	1:1.5	87
14	Cat. **1** (2.0)	K_2CO_3 (1.5)	1:1.5	65
15	Cat. **1** (2.0)	Cs_2CO_3 (1.5)	1:1.5	69
16	**Cat. 1 (1.5)**	**KOH (1.5)**	**1:1.5**	**97**
17	Cat. 1 (1.5)	KOH (0.25)	1:1.5	<10
18	Cat. 1 (1.5)	KOH (0.5)	1:1.5	31
19	Cat. 1 (1.5)	KOH (0.75)	1:1.5	53
20	–	KOH (1.5)	1:1.5	–
21	$[Cp^*IrCl_2]_2$ (1.5)	KOH (1.5)	1:1.5	19
22[d]	Cat. **1** (1.0)	KOH (1.5)	1:1.5	>99

[a] Reaction conditions: 2-aminobenzyl alcohol (0.25 mmol), Ir-complex (x mol%), KOH (y equiv.), water (1.5 mL) at 120 °C for 24 h under air.
[b] Yield determined by GC analysis using *n*-dodecane as an internal standard.
[c] Under argon atmosphere.
[d] Reaction with 2-aminobenzyl alcohol (0.25 mmol) and acetophenone (0.375 mmol) for 6 h.

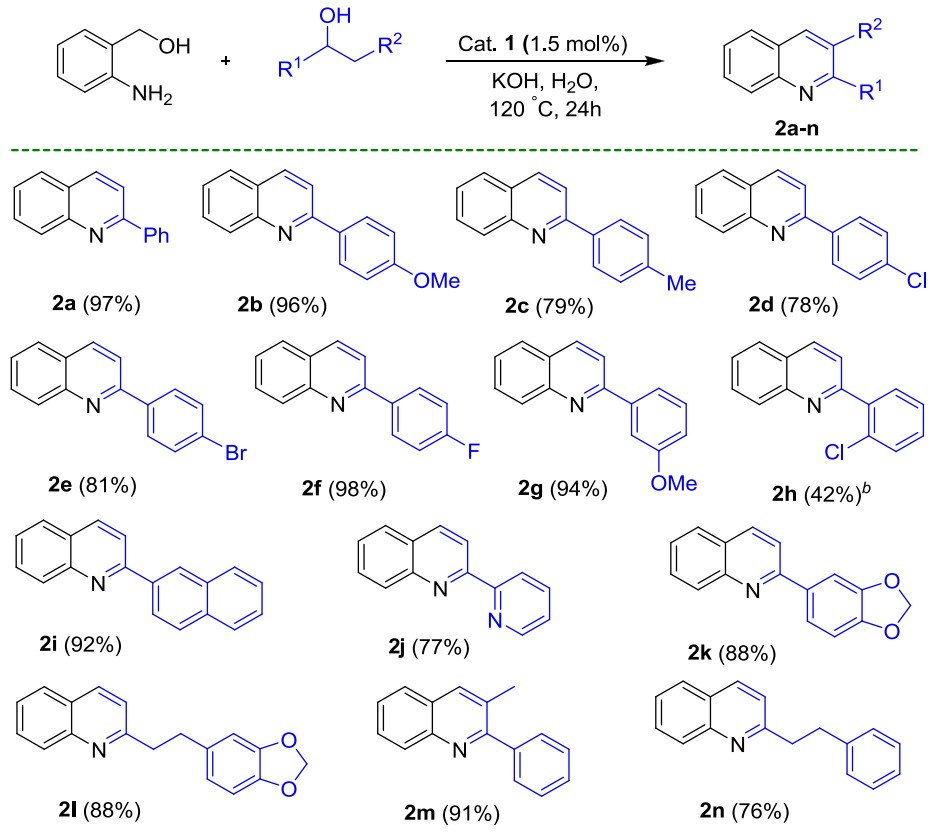
and also heteroatom containing 1-(3,4-methylenedioxyphenyl) ethanol were efficiently converted to the expected products (**6d-6e**). Additionally, aliphatic cyclic and acyclic alcohols like cyclopentanol and 1-phenyl-1-propanol were found to be efficient coupling partners for the synthesis of 1,8-naphthyridine derivatives (Table 6, entries **6f-6g**).

3. Practical applicability of the methodology

Next, we checked the reusability of this catalytic system for the synthesis of 2-phenylquinoline in water by simple phase separation technique. The recovered aqueous solution containing the catalyst could be utilized for the synthesis of 2-phenylquinoline up to the fourth run although yields reduced significantly after the second run (Table S2). To demonstrate the synthetic applicability of this methodology, biologically active natural product (±)-galipinine was synthesized [69,70]. Following the optimized conditions, **2l** was smoothly prepared from 2-aminobenzyl alcohol. Applying the same catalytic system, hydrogenation of **2l** in water followed by methylation using HCHO yielded (±)-galipinine (**2lb**) in excellent yield (Scheme 2).

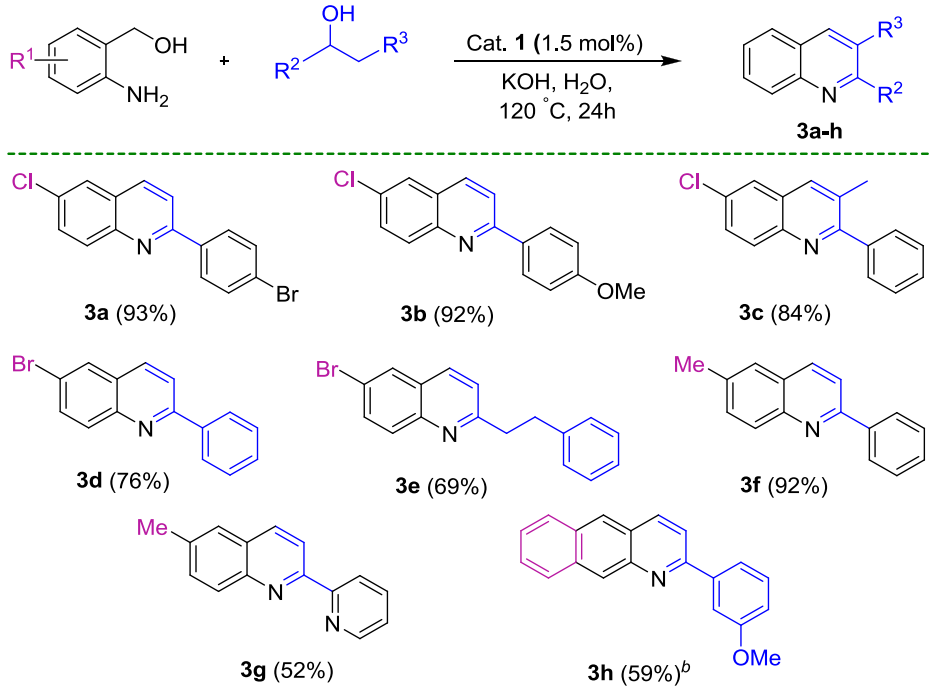
This protocol was extended towards the gram scale synthesis of a variety of quinolines, acridines and naphthyridines in water under air (Table 7). The green chemistry metrics [71] for the synthesis of 2-(2-(benzo[d][1,3]dioxol-5-yl)ethyl)quinoline (**2l**) was

Table 2
Synthesis of quinolines from 2-aminobenzyl alcohol and various alcohols.[a]



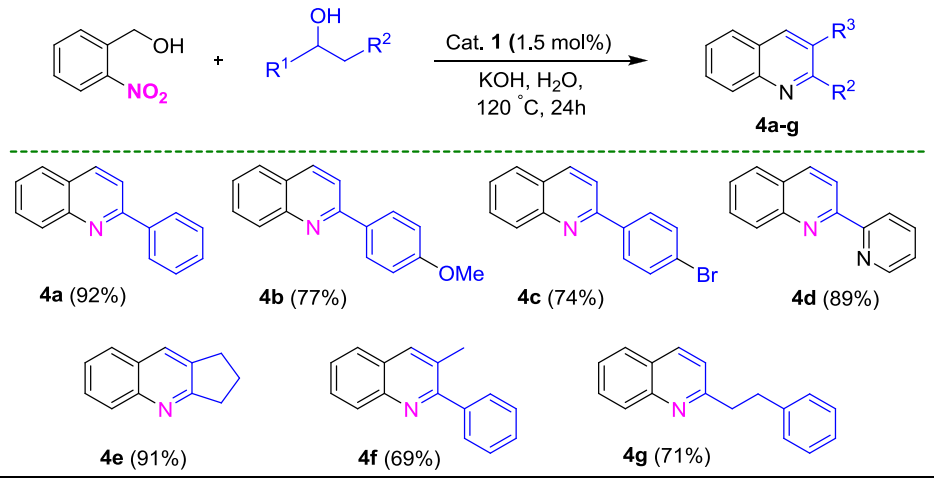
[a] Reaction Conditions: 2-aminoaryl alcohol (0.5 mmol), alcohol (0.75 mmol), KOH (0.75 mmol), water (3.0 mL), isolated yields.
[b] Cat. **1** (2.0 mol%) for 36 h.

Table 3
Synthesis of quinolines from various 2-aminobenzyl alcohols in water.[a]



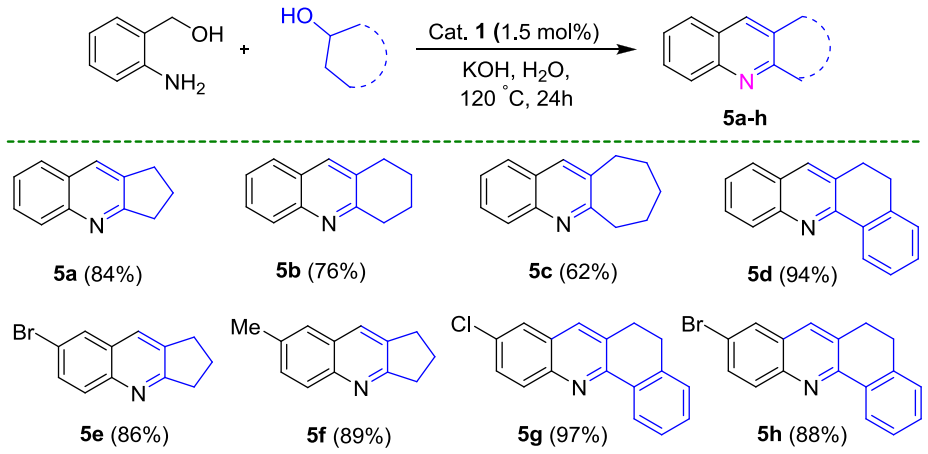
[a] Reaction Conditions: 2-aminoaryl alcohol (0.5 mmol), alcohol (0.75 mmol), KOH (0.75 mmol), water (3.0 mL), isolated yields.
[b] 2.0 mol% of Cat. **1** was used.

Table 4
Synthesis of quinolines from 2-nitrobenzyl alcohols.[a]



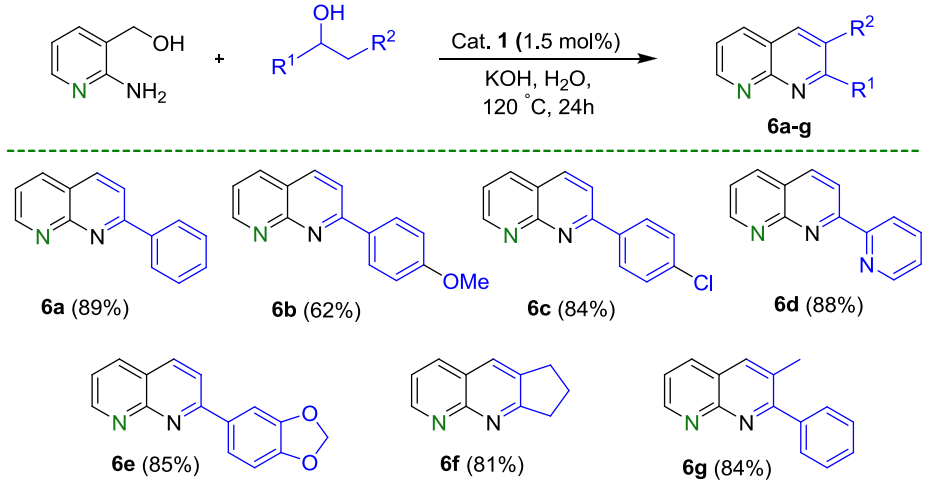
[a] Reaction Conditions: 2-nitrobenzyl alcohol (0.5 mmol), alcohol (1.5 mmol), KOH (0.75 mmol), water (3.0 mL), isolated yields.

Table 5
Dehydrogenative synthesis of fused quinoline derivatives.[a]

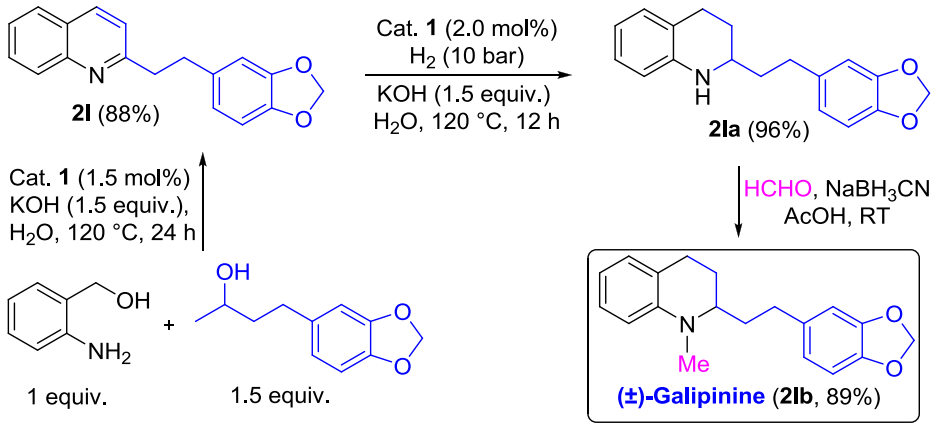


[a] Reaction Conditions: 2-aminoaryl/2-nitrobenzyl alcohol (0.5 mmol), alcohol (0.75 mmol), KOH (0.75 mmol), water (3.0 mL), isolated yields.

Table 6
Dehydrogenative synthesis of 1,8-naphthyridine derivatives.[a]



[a] Reaction Conditions: 2-aminoaryl alcohol (0.5 mmol), alcohol (0.75 mmol), KOH (0.75 mmol), water (3.0 mL), isolated yields.



Scheme 2. Synthesis of bio-active natural product: (±)-galipinine.

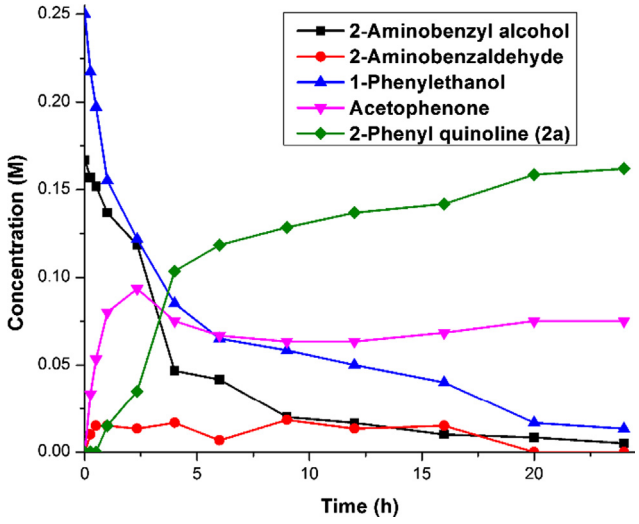


Fig. 2. Time course of the reaction for the synthesis of 2-phenylquinoline.

estimated on a preparative scale with an E factor of 2.1, 87% atom economy, 94% atom efficiency, 100% carbon efficiency, and 55% reaction mass efficiency (Table 8), which provides a clear overview of technical and environmental benefits and also indicates that this methodology is highly sustainable.

4. Mechanistic insights

To understand the mechanism of this dehydrogenative coupling reaction, several kinetic experiments and theoretical calculations were carried out. The progress of the catalytic cyclization of 2-aminobenzyl alcohol and 1-phenylethanol was monitored by GC-analysis. From the plot it is evident that several intermediates were involved in the course of the reaction (Fig. 2). Also it is noteworthy that the concentration of in situ generated 2-aminobenzaldehyde is much smaller than acetophenone, thus retarding the self-condensation of 2-aminobenzaldehyde. Synthesis of **2a** from 2-aminobenzyl alcohol and acetophenone in presence of cat. **1** required only 4 h, while in absence of cat. **1**, from 2-amino benzaldehyde and acetophenone it took only 30 min (Scheme 3A–B). Additionally, formation of quinoline was not detected from both coupling of alcohol-alcohol or alcohol-ketone in the absence of cat. **1** (Scheme 3C–D). These results suggested that cat. **1** facilitated the dehydrogenation of the alcohols, and 2-amino benzaldehyde and acetophenone were intermediates in this process.

As Ir-H species is considered as one of the intermediates in this catalytic cycle [48], we independently synthesized the corresponding Ir-H species by treating cat. **1** with 10 equiv. of KO^{t}Bu in ^{i}PrOH

Table 7
Gram scale synthesis of N-heterocycles.

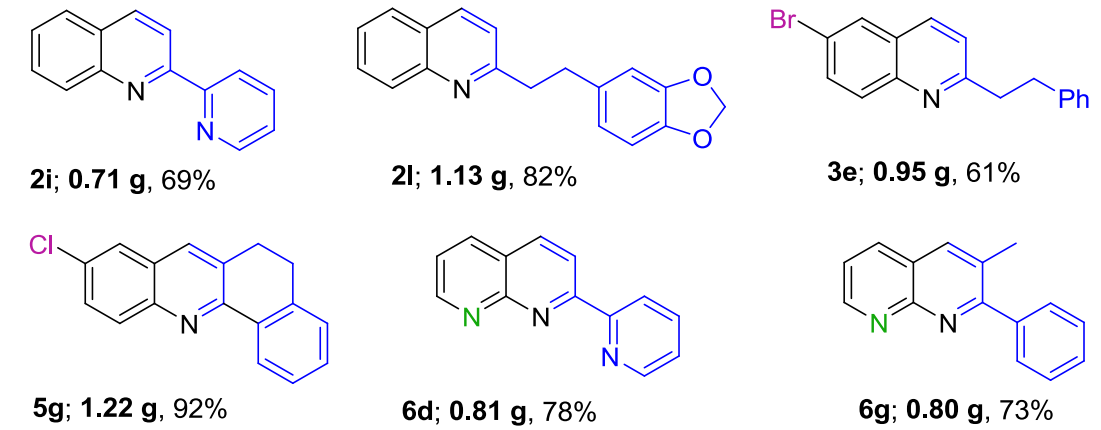
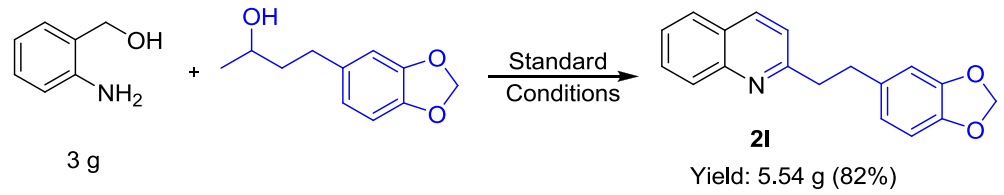
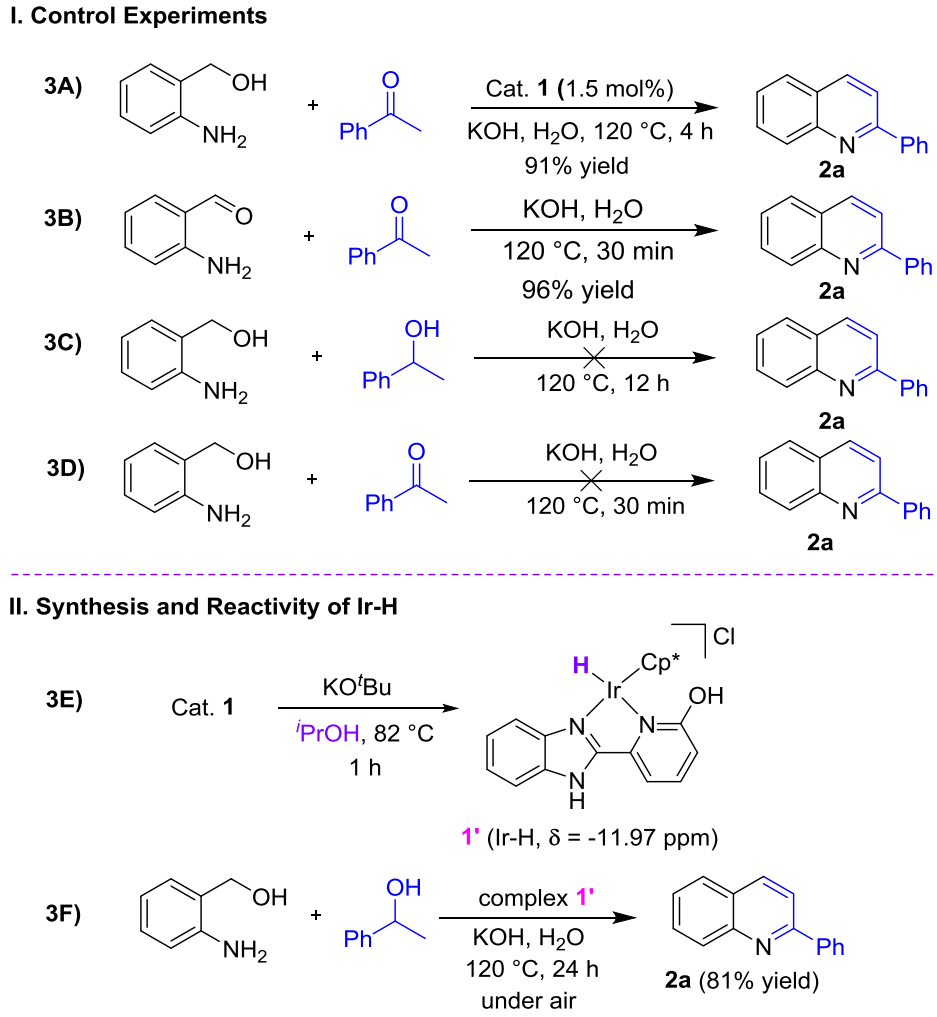


Table 8
Evaluation of green metrics for the current methodology.



E-factor:	2.1	**Carbon Efficiency:**	100%
Atom Economy:	87%	**Reaction Mass Efficiency:**	55%
Atom Efficiency:	94%		



Scheme 3. (I) Control experiments (II) Synthesis and reactivity of Ir-hydride.

at 82 °C for 1 h (Scheme 3E). A sharp singlet at δ = −11.97 ppm in ^{1}H NMR spectra confirmed the formation of Ir-H species [40]. This complex under the standard reaction conditions yielded 81% of **2a** (Scheme 3F), which suggested that the proposed Ir-H complex was the active intermediate in this reaction.

To understand the reaction mechanism more clearly, DFT calculations for the dehydrogenation of 2-aminobenzyl alcohol were performed (Fig. 3). In the DFT study we focused on two major steps: (a) dehydrogenation of 2-aminobenzyl alcohol and (b) ligand assisted hydrogen liberation. Initially, in presence of base the precatalyst **1** would be converted to species **I1** having pyridonate ligand fragment [41,72]. Now, **I1** could follow two pathways for the alcohol dehydrogenation (i) outer sphere pathway or (ii) inner sphere pathway (**I2**) [73]. In the concerted outer sphere pathway, 2-aminobenzyl alcohol was dehydrogenated through an eight membered transition state **TS1$_{out}$** ($\Delta G^{\ddagger}$ = 18.5 kcal/mol) where the hydroxyl hydrogen of the 2-aminobenzyl alcohol was transferred to the pyridonate oxygen and C—H was transferred to the Ir center, resulting in the formation of Ir-H intermediate **I3** [74,75]. However, for the dehydrogenation of alcohol the stepwise outer-sphere

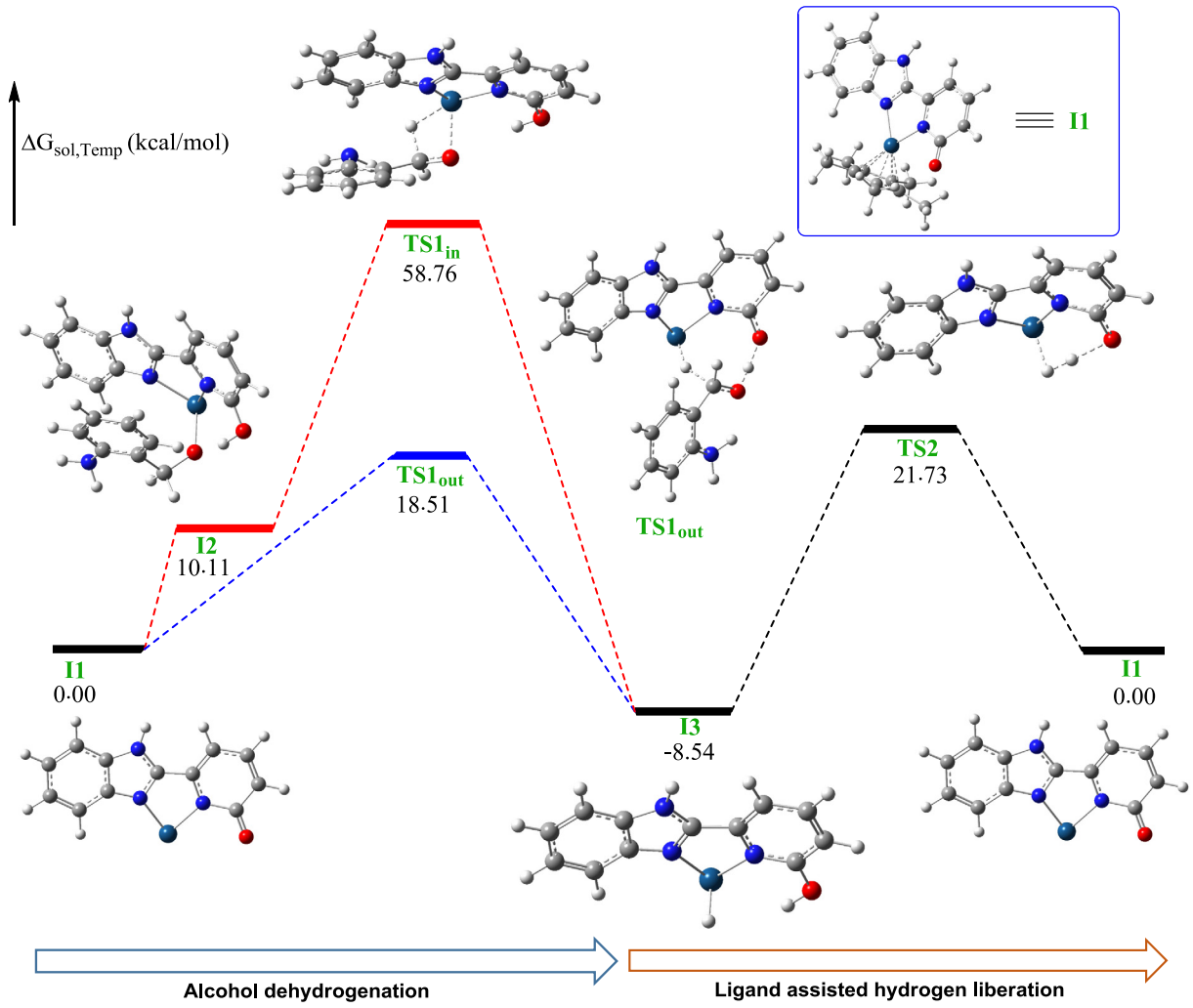


Fig. 3. DFT study: free energy profile for dehydrogenation of 2-aminobenzyl alcohol (Hybrid functional, M062X was used with the LANL2DZ basis set for Ir and 6-31G** basis set for nonmetal elements). Cp* rings in the pictorial representations were omitted for clarity.

pathway could not be ruled out [76]. Afterwards, hydrogen molecule was eliminated from the metal hydride and ligand pendent hydroxyl proton with an activation barrier of 30.3 kcal/mol, generating the active species (**I1**) [41]. On the other hand, in the inner sphere route, first the metal-alkoxy complex (**I2**) was generated from **I1**. Afterward, this alkoxy-complex underwent β-hydride elimination through a four-membered transition-state (**TS1$_{in}$**) with an activation barrier of 48.6 kcal/mol and formed Ir-H species **I3** [74]. Finally, hydrogen elimination from **I3** regenerated the active species **I1**. Catalyst **2**–**4** may follow inner sphere pathway for the dehydrogenation of alcohol, as there is no hydroxyl group present in the ligand. The activation energy for the dehydrogenation of 2-aminobenzyl alcohol via the concerted pathway was much lower ($\Delta G^{\ddagger}$ = 21.7 kcal/mol) compared to the inner sphere route ($\Delta G^{\ddagger}$ = 48.6 kcal/mol). This clearly indicates that the outer sphere pathway is more favoured over the inner sphere route (Fig. 2 and SI, Fig. S3).

5. Conclusions

In conclusion, a new class of water soluble Ir-complexes was synthesized and characterized. Among them 2-hydroxypyridine based cat. **1** presented excellent catalytic activity and offered a greener methodology for the synthesis of quinoline, 1,8-naphthyridine and acridine derivatives from 2-aminoaryl alcohols and substituted secondary alcohols in water under air. Interestingly, combination of transfer hydrogenation and acceptorless dehydrogenative coupling was demonstrated in a single process for synthesis of quinolines starting from 2-nitrobenzyl alcohols. This sustainable protocol was successfully applied for the synthesis of biologically active natural product (±)-galipinine and gram scale synthesis of important N-heterocycles. The green chemistry metrics were evaluated for the synthesis of 2-(2-(benzo[d][1,3]dioxol-5-yl)ethyl)quinoline, which showed the technical benefits and sustainability of the present methodology. The proposed reaction mechanism was supported by several control experiments, kinetic studies and DFT calculations. To the best of our knowledge, this is the first example for the synthesis of quinolines, acridines and 1,8-naphthyridines in water using 2-aminobenzyl alcohol and substituted secondary alcohols.

Conflicts of interest

There are no conflicts to declare.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jcat.2019.03.028.

References

[1] G.A. Olah, Beyond oil and gas: the methanol economy, Angew. Chem., Int. Ed. 44 (2005) 2636–2639.
[2] T.P. Vispute, H. Zhang, A. Sanna, R. Xiao, G.W. Huber, Renewable chemical commodity feedstocks from integrated catalytic processing of pyrolysis oils, Science 330 (2010) 1222–1227.
[3] S. Michlik, R. Kempe, A sustainable catalytic pyrrole synthesis, Nat. Chem. 5 (2013) 140.
[4] J.P. Michael, Quinoline, quinazoline and acridone alkaloids, Nat. Prod. Rep. 19 (2002) 742–760.
[5] G.C. Muscia, G.Y. Buldain, S.E. Asís, Design, synthesis and evaluation of acridine and fused-quinoline derivatives as potential anti-tuberculosis agents, Eur. J. Med. Chem. 73 (2014) 243–249.
[6] W.W.P., R.M. Sheets, Advances in Heterocyclic Chemistry, Academic Press, New York, 1983.
[7] J. Marco-Contelles, E. Pérez-Mayoral, A. Samadi, M.d.C. Carreiras, E. Soriano, Recent advances in the Friedländer reaction, Chem. Rev. 109 (2009) 2652–2671.
[8] H. Vander Mierde, P. Van Der Voort, D. De Vos, F. Verpoort, A ruthenium-catalyzed approach to the Friedländer quinoline synthesis, Eur. J. Org. Chem. (2008, 2008,) 1625–1631.
[9] W.Y.X. Yu, W. Hu, D. Wang, Iridium-catalyzed synthesis of quinolines from 2-aminobenzyl alcohols with secondary alcohols, Russ. J. Gen. Chem. 86 (2016) 376–379.
[10] H.V. Mierde, P.V.D. Voort, F. Verpoort, Base-mediated synthesis of quinolines: an unexpected cyclization reaction between 2-aminobenzylalcohol and ketones, Tetrahedron Lett. 49 (2008) 6893–6895.
[11] R. Martínez, D.J. Ramón, M. Yus, Transition-metal-free indirect Friedländer synthesis of quinolines from alcohols, J. Org. Chem. 73 (2008) 9778–9780.
[12] Y. Zhu, C. Cai, An N-heterocyclic carbene-catalyzed approach to the indirect Friedländer quinoline synthesis, RSC Adv. 4 (2014) 52911–52914.
[13] N. Anand, S. Koley, B.J. Ramulu, M.S. Singh, Metal-free aerobic one-pot synthesis of substituted/annulated quinolines from alcohols via indirect Friedländer annulation, Org. Biomol. Chem. 13 (2015) 9570–9574.
[14] H.V. Mierde, P.V.D. Voort, F. Verpoort, Fast and convenient base-mediated synthesis of 3-substituted quinolines, Tetrahedron Lett. 50 (2009) 201–203.
[15] P. Daw, S. Chakraborty, J.A. Garg, Y. Ben-David, D. Milstein, Direct synthesis of pyrroles by dehydrogenative coupling of diols and amines catalyzed by cobalt pincer complexes, Angew. Chem., Int. Ed. 55 (2016) 14373–14377.
[16] S.P. Midya, V.G. Landge, M.K. Sahoo, J. Rana, E. Balaraman, Cobalt-catalyzed acceptorless dehydrogenative coupling of aminoalcohols with alcohols: direct access to pyrrole, pyridine and pyrazine derivatives, Chem. Commun. 54 (2018) 90–93.
[17] W. Zhao, P. Liu, F. Li, Quinazolinones from o-aminobenzonitriles by one-pot sequential selective hydration/condensation/acceptorless dehydrogenation catalyzed by an iridium complex, ChemCatChem 8 (2016) 1523–1530.
[18] R.H. Crabtree, Homogeneous transition metal catalysis of acceptorless dehydrogenative alcohol oxidation: applications in hydrogen storage and to heterocycle synthesis, Chem. Rev. 117 (2017) 9228–9246.
[19] S. Elangovan, J.-B. Sortais, M. Beller, C. Darcel, Iron-catalyzed α-alkylation of ketones with alcohols, Angew. Chem., Int. Ed. 54 (2015) 14483–14486.
[20] M. Maji, K. Chakrabarti, B. Paul, B.C. Roy, S. Kundu, Ruthenium(II)-NNN-pincer-complex-catalyzed reactions between various alcohols and amines for sustainable C−N and C−C bond formation, Adv. Synth. Catal. 360 (2018) 722–729.
[21] D. Srimani, Y. Ben-David, D. Milstein, Direct synthesis of pyrroles by dehydrogenative coupling of β-aminoalcohols with secondary alcohols catalyzed by ruthenium pincer complexes, Angew. Chem., Int. Ed. 52 (2013) 4012–4015.
[22] M. Zhang, H. Neumann, M. Beller, Selective ruthenium-catalyzed three-component synthesis of pyrroles, Angew. Chem., Int. Ed. 52 (2013) 597–601.
[23] S. Ruch, T. Irrgang, R. Kempe, New iridium catalysts for the selective alkylation of amines by alcohols under mild conditions and for the synthesis of quinolines by acceptor-less dehydrogenative condensation, Chem. Eur. J. 20 (2014) 13279–13285.
[24] M. Mastalir, M. Glatz, E. Pittenauer, G. Allmaier, K. Kirchner, Sustainable synthesis of quinolines and pyrimidines catalyzed by manganese PNP pincer complexes, J. Am. Chem. Soc. 138 (2016) 15543–15546.
[25] C.S. Cho, B.T. Kim, H.-S. Kim, T.-J. Kim, S.C. Shim, Ruthenium-catalyzed one-pot β-alkylation of secondary alcohols with primary alcohols, Organometallics 22 (2003) 3608–3610.
[26] S. Michlik, R. Kempe, Regioselectively functionalized pyridines from sustainable resources, Angew. Chem., Int. Ed. 52 (2013) 6326–6329.
[27] Y. Obora, Recent advances in α-alkylation reactions using alcohols with hydrogen borrowing methodologies, ACS Catal. 4 (2014) 3972–3981.
[28] K. Chakrabarti, M. Maji, D. Panja, B. Paul, S. Shee, G.K. Das, S. Kundu, Utilization of MeOH as a C1 building block in tandem three-component coupling reaction, Org. Lett. 19 (2017) 4750–4753.
[29] K. Chakrabarti, B. Paul, M. Maji, B.C. Roy, S. Shee, S. Kundu, Bifunctional Ru(ii) complex catalysed carbon–carbon bond formation: an eco-friendly hydrogen borrowing strategy, Org. Biomol. Chem. 14 (2016) 10988–10997.
[30] N. Deibl, K. Ament, R. Kempe, A sustainable multicomponent pyrimidine synthesis, J. Am. Chem. Soc. 137 (2015) 12804–12807.
[31] S. Musa, L. Ackermann, D. Gelman, Dehydrogenative cross-coupling of primary and secondary alcohols, Adv. Synth. Catal. 355 (2013) 3077–3080.
[32] M.V. Jiménez, J. Fernández-Tornos, F.J. Modrego, J.J. Pérez-Torrente, L.A. Oro, Oxidation and β-alkylation of alcohols catalysed by iridium(i) complexes with functionalised N-heterocyclic carbene ligands, Chem. Eur. J. 21 (2015) 17877–17889.
[33] D. Srimani, Y. Ben-David, D. Milstein, Direct synthesis of pyridines and quinolines by coupling of γ-amino-alcohols with secondary alcohols liberating H2 catalyzed by ruthenium pincer complexes, Chem. Commun. 49 (2013) 6632–6634.
[34] C.S. Cho, B.T. Kim, T.-J. Kim, S.C. Shim, Ruthenium-catalysed oxidative cyclisation of 2-aminobenzyl alcohol with ketones: modified Friedlaender quinoline synthesis, Chem. Commun. 2576–2577 (2001).
[35] K. Taguchi, S. Sakaguchi, Y. Ishii, Synthesis of quinolines from amino alcohol and ketones catalyzed by [IrCl(cod)]2 or IrCl3 under solvent-free conditions, Tetrahedron Lett. 46 (2005) 4539–4542.
[36] B.W.J. Chen, L.L. Chng, J. Yang, Y. Wei, J. Yang, J.Y. Ying, Palladium-Based Nanocatalyst for One-Pot Synthesis of Polysubstituted Quinolines, ChemCatChem 5 (2013) 277–283.
[37] T. Welton, Solvents and sustainable chemistry, Proc. Roy. Soc. A: Math. Phys. Eng. Sci. 471 (2015).
[38] B. Li, P.H. Dixneuf, sp2 C-H bond activation in water and catalytic cross-coupling reactions, Chem. Soc. Rev. 42 (2013) 5744–5767.
[39] P.H. Dixneuf, V. Cadierno, Metal-Catalyzed Reactions in Water, 1st ed., Wiley-VCH, 2013.
[40] L. Wang, N. Onishi, K. Murata, T. Hirose, J.T. Muckerman, E. Fujita, Y. Himeda, Efficient hydrogen storage and production using a catalyst with an imidazoline-based, proton-responsive ligand, ChemSusChem 10 (2017) 1071–1075.
[41] R. Kawahara, K.-I. Fujita, R. Yamaguchi, Dehydrogenative oxidation of alcohols in aqueous media using water-soluble and reusable Cp*Ir catalysts bearing a functional bipyridine ligand, J. Am. Chem. Soc. 134 (2012) 3643–3646.
[42] T. Kitanosono, K. Masuda, P. Xu, S. Kobayashi, Catalytic organic reactions in water toward sustainable society, Chem. Rev. 118 (2018) 679–746.
[43] Z. Yang, Z. Zhu, R. Luo, X. Qiu, J.-T. Liu, J.-K. Yang, W. Tang, Iridium-catalyzed highly efficient chemoselective reduction of aldehydes in water using formic acid as the hydrogen source, Green Chem. 19 (2017) 3296–3301.
[44] P. Qu, C. Sun, J. Ma, F. Li, The N-alkylation of sulfonamides with alcohols in water catalyzed by the water-soluble iridium complex {Cp*Ir[6,6′-(OH)2bpy](H2O)}[OTf]2, Adv. Synth. Catal. 356 (2014) 447–459.
[45] R. Kawahara, K.-I. Fujita, R. Yamaguchi, N-alkylation of amines with alcohols catalyzed by a water-soluble Cp*iridium complex: an efficient method for the synthesis of amines in aqueous media, Adv. Synth. Catal. 353 (2011) 1161–1168.
[46] R. Kawahara, K.-I. Fujita, R. Yamaguchi, Multialkylation of aqueous ammonia with alcohols catalyzed by water-soluble Cp*Ir−ammine complexes, J. Am. Chem. Soc. 132 (2010) 15108–15111.
[47] H. Hikawa, Y. Ino, H. Suzuki, Y. Yokoyama, Pd-catalyzed benzylic C-H amidation with benzyl alcohols in water: a strategy to construct quinazolinones, J. Org. Chem. 77 (2012) 7046–7051.
[48] R. Wang, H. Fan, W. Zhao, F. Li, Acceptorless dehydrogenative cyclization of o-aminobenzyl alcohols with ketones to quinolines in water catalyzed by water-soluble metal-ligand bifunctional catalyst [Cp*(6,6′-(OH)2bpy)(H2O)][OTf]2, Org. Lett. 18 (2016) 3558–3561.
[49] A. Wetzel, S. Wöckel, M. Schelwies, M.K. Brinks, F. Rominger, P. Hofmann, M. Limbach, Selective alkylation of amines with alcohols by Cp*–Iridium(III) half-sandwich complexes, Org. Lett. 15 (2013) 266–269.
[50] A. Fernandes, B. Royo, Water-soluble iridium N-heterocyclic carbene complexes for the alkylation of amines with alcohols, ChemCatChem 9 (2017) 3912–3917.
[51] C. Ge, X. Sang, W. Yao, L. Zhang, D. Wang, Unsymmetrical indazolyl-pyridinyl-triazole ligand-promoted highly active iridium complexes supported on hydrotalcite and its catalytic application in water, Green Chem. 20 (2018) 1805–1812.
[52] Z. Xu, X. Yu, X. Sang, D. Wang, BINAP-copper supported by hydrotalcite as an efficient catalyst for the borrowing hydrogen reaction and dehydrogenation cyclization under water or solvent-free conditions, Green Chem. 20 (2018) 2571–2577.
[53] G. Xu, Q. Li, J. Feng, Q. Liu, Z. Zhang, X. Wang, X. Zhang, X. Mu, Direct α-alkylation of ketones with alcohols in water, ChemSusChem 7 (2014) 105–109.
[54] H. Hikawa, T. Koike, K. Izumi, S. Kikkawa, I. Azumaya, Borrowing hydrogen methodology for N-benzylation using a π-benzylpalladium system in water, Adv. Synth. Catal. 358 (2016) 784–791.
[55] L. Rakers, F. Schäfers, F. Glorius, In water and under mild conditions: α-alkylation of ketones with alcohols by phase-transfer-assisted borrowing hydrogen catalysis, Chem. Eur. J. 24 (2018) 15529–15532.

[56] J. Frank, A.R. Katritzky, Tautomeric pyridines. Part XV. Pyridone–hydroxypyridine equilibria in solvents of differing polarity, J. Chem. Soc., Perkin Trans. 2 (1976) 1428–1431.
[57] J.R. Khusnutdinova, D. Milstein, Metal-ligand cooperation, Angew. Chem., Int. Ed. 54 (2015) 12236–12273.
[58] R. Kawahara, K.-I. Fujita, R. Yamaguchi, Cooperative catalysis by iridium complexes with a bipyridonate ligand: versatile dehydrogenative oxidation of alcohols and reversible dehydrogenation-hydrogenation between 2-propanol and acetone, Angew. Chem., Int. Ed. 51 (2012) 12790–12794.
[59] K.-I. Fujita, Y. Tanaka, M. Kobayashi, R. Yamaguchi, Homogeneous perdehydrogenation and perhydrogenation of fused bicyclic N-heterocycles catalyzed by iridium complexes bearing a functional bipyridonate ligand, J. Am. Chem. Soc. 136 (2014) 4829–4832.
[60] K.-I. Fujita, W. Ito, R. Yamaguchi, Dehydrogenative lactonization of diols in aqueous media catalyzed by a water-soluble iridium complex bearing a functional bipyridine ligand, ChemCatChem 6 (2014) 109–112.
[61] C.M. Moore, B. Bark, N.K. Szymczak, Simple ligand modifications with pendent oh groups dramatically impact the activity and selectivity of ruthenium catalysts for transfer hydrogenation: the importance of alkali metals, ACS Catal. 6 (2016) 1981–1990.
[62] J. DePasquale, I. Nieto, L.E. Reuther, C.J. Herbst-Gervasoni, J.J. Paul, V. Mochalin, M. Zeller, C.M. Thomas, A.W. Addison, E.T. Papish, Iridium dihydroxybipyridine complexes show that ligand deprotonation dramatically speeds rates of catalytic water oxidation, Inorg. Chem. 52 (2013) 9175–9183.
[63] N. Onishi, S. Xu, Y. Manaka, Y. Suna, W.-H. Wang, J.T. Muckerman, E. Fujita, Y. Himeda, CO_2 Hydrogenation catalyzed by iridium complexes with a proton-responsive ligand, Inorg. Chem. 54 (2015) 5114–5123.
[64] W.-H. Wang, M.Z. Ertem, S. Xu, N. Onishi, Y. Manaka, Y. Suna, H. Kambayashi, J. T. Muckerman, E. Fujita, Y. Himeda, Highly robust hydrogen generation by bioinspired Ir complexes for dehydrogenation of formic acid in water: experimental and theoretical mechanistic investigations at different pH, ACS Catal. 5 (2015) 5496–5504.
[65] X. Wang, C. Wang, Y. Liu, J. Xiao, Acceptorless dehydrogenation and aerobic oxidation of alcohols with a reusable binuclear rhodium(ii) catalyst in water, Green Chem. 18 (2016) 4605–4610.
[66] S. Shee, K. Ganguli, K. Jana, S. Kundu, Cobalt complex catalyzed atom-economical synthesis of quinoxaline, quinoline and 2-alkylaminoquinoline derivatives, Chem. Commun. 54 (2018) 6883–6886.
[67] F. Xie, M. Zhang, M. Chen, W. Lv, H. Jiang, Convenient synthesis of quinolines from α-2-nitroaryl alcohols and alcohols via a ruthenium-catalyzed hydrogen transfer strategy, ChemCatChem 7 (2015) 349–353.
[68] G.C. Muscia, M. Bollini, J.P. Carnevale, A.M. Bruno, S.E. Asís, Microwave-assisted Friedländer synthesis of quinolines derivatives as potential antiparasitic agents, Tetrahedron Lett. 47 (2006) 8811–8815.
[69] P.J. Houghton, T.Z. Woldemariam, Y. Watanabe, M. Yates, Activity against mycobacterium tuberculosis of alkaloid constituents of angostura bark, Galipea officinalis, Planta Med. 65 (1999) 250–254.
[70] R. Adam, J.R. Cabrero-Antonino, A. Spannenberg, K. Junge, R. Jackstell, M. Beller, A general and highly selective cobalt-catalyzed hydrogenation of N-heteroarenes under mild reaction conditions, Angew. Chem., Int. Ed. 56 (2017) 3216–3220.
[71] N.S. Upadhyay, V.H. Thorat, R. Sato, P. Annamalai, S.-C. Chuang, C.-H. Cheng, Synthesis of isoquinolones via Rh-catalyzed C-H activation of substituted benzamides using air as the sole oxidant in water, Green Chem. 19 (2017) 3219–3224.
[72] A.M. Royer, T.B. Rauchfuss, D.L. Gray, Organoiridium pyridonates and their role in the dehydrogenation of alcohols, Organometallics 29 (2010) 6763–6768.
[73] G. Zeng, S. Sakaki, K.-I. Fujita, H. Sano, R. Yamaguchi, Efficient catalyst for acceptorless alcohol dehydrogenation: interplay of theoretical and experimental studies, ACS Catal. 4 (2014) 1010–1020.
[74] H. Li, G. Lu, J. Jiang, F. Huang, Z.-X. Wang, Computational mechanistic study on Cp^*Ir complex-mediated acceptorless alcohol dehydrogenation: bifunctional hydrogen transfer vs β-H elimination, Organometallics 30 (2011) 2349–2363.
[75] K.-I. Fujita, R. Tamura, Y. Tanaka, M. Yoshida, M. Onoda, R. Yamaguchi, Dehydrogenative oxidation of alcohols in aqueous media catalyzed by a water-soluble dicationic iridium complex bearing a functional N-heterocyclic carbene ligand without using base, ACS Catal. 7 (2017) 7226–7230.
[76] P.A. Dub, J.C. Gordon, Metal-ligand bifunctional catalysis: the "Accepted" mechanism, the issue of concertedness, and the function of the ligand in catalytic cycles involving hydrogen atoms, ACS Catal. 7 (2017) 6635–6655.