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# Tetraalkylammonium-Based Ionic Liquids for a RuCl<sub>3</sub> Catalysed C-H-Activated Homocoupling

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# Tetraalkylammonium-Based Ionic Liquids for a RuCl<sub>3</sub> Catalyzed C-H Activated Homocoupling

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### ARTICLE INFO

ABSTRACT

[BuEt<sub>3</sub>N][NTf<sub>2</sub>] can be a superior ionic liquid in a RuCl<sub>3</sub> catalyzed oxidative C-H activation reaction compared to standard imidazolium-based ionic liquids. The tetraalkylammonium-based ionic liquid resulted in higher yields. This could be due to the absence of a possible C-H activation on the tetraalkylammonium-based ionic liquid itself. This side reaction could occur with imidazolium-based ionic liquids. The ionic liquid could be recycled and different oxidation agents could be used in the reaction. The best results were obtained with FeCl<sub>3</sub>  $\cdot$  6 H<sub>2</sub>O and with a combination of LiCl under an oxygen atmosphere. Up to 83% yield were obtained in the homocoupling of 2-arylpyridines.

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#### Tetrahedron

# 1. Introduction

The application of ionic liquids (ILs) in catalytic reactions has grown continuously over the years due to their unique features.<sup>1</sup> Ionic liquids have been used as solvents in a variety of reactions such as Diels-Alder,<sup>2</sup> Friedel-Crafts,<sup>3</sup> Suzuki coupling,<sup>5</sup> hydroformylation<sup>6</sup> Heck,<sup>4</sup> and hydrogenation reactions.7 Also many electrolytes based on ionic liquids have been developed.<sup>1</sup> Their application as electrolytes shows their potential in electrochemical reactions and solvents for oxidative reactions. Examples for the latter are the Ni(acac)2-catalysed aerobic oxidation of aromatic aldehydes,<sup>8</sup> the TEMPO catalyzed aerobic oxidation of alcohols,<sup>9</sup> the palladium-catalyzed oxidation of stvrene<sup>10</sup> alcohol<sup>11</sup> and benzyl and the Nhydroxyphthalimide-catalyzed oxidative production of phthalic acids from xylenes.<sup>12</sup> The application as solvents in these reactions is beneficial, since problematic and harmful molecular solvents can be exchanged with the ionic liquids. In comparison to many conventional used solvents many ionic liquids have a low vapor pressure, excellent solvation properties for salts, are not flammable or explosive, can be easily handled and recycled.<sup>13</sup>

Although ionic liquids can be used as solvents for many reactions, there can be limits to their application due to their own reactivity with some reagents under certain reaction conditions.<sup>14</sup> Especially the most common used ILs based on 1,3-dialkylimidazolium ions can be deprotonated under basic conditions<sup>14a-c</sup> or oxidized via C-H bond activation to give carbene species and carbene complexes in the presence of a metal.<sup>14d,14e</sup> Hence, ionic liquids are rarely applied as solvents in oxidative C-H functionalizations.<sup>15</sup> Yet, with Cp\*-Rhodium complexes C-H bond activations in [BMIM][NTf<sub>2</sub>] are possible.<sup>16</sup> In addition, a manganese complex in [HMIM][OTf] could be applied as a catalyst in amidation.17 C-H For an oxime-directed tetraalkylammonium salts dealkylations have been reported for harsh conditions, which can be of thermal or chemical nature.<sup>18</sup> In the catalytic hydrodimerization of butadiene, Pd-(II) species are used as catalysts, which are immobilized in ILs. In this case, dealkylations of imidazolium-based ILs could be observed at higher temperatures.<sup>19</sup> In case of the base-catalyzed Baylis-Hillman reaction the ionic liquids cations based on 1-butyl-3-methylimidazolium are deprotonated to their corresponding carbenes, which react with benzaldehyde resulting in the inhibition of the desired reaction and make the recycling of the ILs impossible.<sup>20</sup>

Yet, the base-initiated deprotonation of the C-2 position for the generation of N-heterocyclic carbenes is desired, if the latter are used as ligands in transition-metal-catalyzed reactions.<sup>21</sup> E.g. Pd-catalyzed cross-couplings in ILs are improved via this process.<sup>22</sup> However, under these condition the recycling of the ILs is compromised, and in some cases the carbene complexes may also hinder the reaction.

As part of our effort on ionic liquids<sup>14c,23</sup> we recently reported the application of an iron-based IL as catalyst and oxidant in a dehydrogenation reaction.<sup>24</sup> In the presented work a transition metal catalyzed C-H bond activation followed by a C-C bond formation for the resource saving

synthesis of biaryl moieties was used,<sup>25</sup> to evaluate different ionic liquids in an oxidative C-H activation reaction for a C-C bond formation. The best oxidants for oxidative C-C bond formations are environmental friendly compounds like oxygen or salts based on iron which are non-toxic, cheap, easy to handle and readily available.<sup>26</sup> In comparison to other techniques no additional steps are needed to introduce reacting functional groups in C-H activations. This way time and materials can be saved and waste is avoided.<sup>27</sup> The biaryl moiety is an essential part for a variety of natural products, agrochemicals, ligands or pharmaceuticals.<sup>28</sup> Hence, environmental friendly and resource saving methods for the synthesis of these moieties are highly desirable.

#### 2. Results and discussion

The oxidative homocoupling reaction was investigated with 2-phenylpyridine (1), a ruthenium catalyst and iron(III) chloride as oxidant which gives the product 2,2'-di(pyridin-2-yl)-1,1'-biphenyl (2) (Scheme 1). An improved reaction protocol towards 2 would be desirable since so far chlorobenzene and a sensitive ruthenium complex catalyst were reported as optimal conditions for this reaction.<sup>29</sup>



Scheme 1

First, the impact of different ionic liquids (Scheme 2) on the homocoupling of 1 was examined. The results are summarized in Table 1. In order to obtain a baseline for the study, a literature known procedure was repeated with 5 mol%  $RuCl_3$  as catalyst and  $FeCl_3$  as oxidant in chlorobenzene as solvent. A yield of 6% was obtained (Table 1, Entry 2) which is slightly lower compared to a reported 27% in the literature for these conditions (Table 1, Entry 1).<sup>29</sup> With the established reference point initially the oxidizing agent FeCl<sub>3</sub> was replaced with different iron-based ionic liquids, since the later were catalyzing an oxidation in work.<sup>24</sup> а preceding [BMIM][FeCl<sub>4</sub>] (3) and [THTDP][FeCl<sub>4</sub>] (4) were applied as oxidants in the reaction. Both ILs increased the yields of the reaction to 24% with 3 and 42% with 4 (Table 1, Entries 3-4).  $[BMIM][Fe_2Cl_7]$  (5) with a higher FeCl<sub>3</sub> content resulted in a yield of 33 % (Table 1, Entry 6). After exploring the ironbased ILs as oxidants, the influence of water on the reaction had to be considered. By changing from anhydrous FeCl<sub>3</sub> to its hexahydrate analogue a yield of 78% was isolated (Table 1, Entry 6), which makes the latter system more efficient for the oxidation than the applied metallic ionic liquids. Hence, for further reactions FeCl<sub>3</sub> 6 H<sub>2</sub>O was the oxidant of choice. In order to start the examination of different ionic liquids in the oxidative C-C bond formation via C-H activation the problematic<sup>30</sup> and volatile chlorobenzene was replaced with various ionic liquids. While [BMIM][Cl] (6), [BMIM][PF<sub>6</sub>]<sup>P</sup>re-pro

(7), and [BMIM][OAc] (8) did not support the reaction (Table 1, Entries 7-9) and no conversion was observed. [BMIM][BF<sub>4</sub>] (9) gave a yield of 60% (Table 1, Entry 10) and [BMIM][NTf<sub>2</sub>] (10) a yield of 66% with a reaction time of 48 h (Table 1, Entries 10,11).

Bu∽N N~Me <sup>A</sup>	[BMIM][FeCl <sub>4</sub> ] <b>3</b> [BMIM][Fe <sub>2</sub> Cl <sub>7</sub> ] <b>5</b> [BMIM][Cl] <b>6</b> [BMIM][PF <sub>6</sub> ] <b>7</b> [BMIM][OAc] <b>8</b> [BMIM][BF <sub>4</sub> ] <b>9</b> [BMIM][NTf <sub>2</sub> ] <b>10</b>			
$\begin{array}{c} \oplus R^1 & A^{}\\ R^2 \cdot P - R^1 \\ K^1 \end{array}$	[THTDP][FeCl <sub>4</sub> ] <b>4</b> [THTDP][NTf <sub>2</sub> ] <b>13</b> [THTDP][Cl] <b>14</b>			
$\sim \stackrel{\oplus}{\underset{NH_3}} A^{\ominus}$	EAN 11			
Bu Cl Bu−P−Bu Bu	[TBP][Cl] <b>12</b>			
$ \begin{array}{c} \overset{(+)}{\underset{L}{E}} A^{\bigcirc} \\ \overset{(+)}{\underset{L}{B}} A^{\bigcirc} \\ \overset{(+)}{\underset{L}{E}} A^{\ominus} \\ \overset{(+)}{\underset{L}{E}} A^{\bullet} \\ \overset{(+)}{\underset{L}{}} A^{\bullet} \\ \overset{(+)}{\underset{L}{}} A^{\bullet} \\ \overset{(+)}$	[BuEt <sub>3</sub> N][NTf <sub>2</sub> ] <b>15</b> [BuEt <sub>3</sub> N][PF <sub>6</sub> ] <b>16</b> [BuEt <sub>3</sub> N][HSO <sub>4</sub> ] <b>17</b>			
$\begin{array}{c} & & \\ & Et & \\ Pr - \begin{array}{c} & \\ N - Et \\ & \\ Et \end{array} \end{array} A^{\bigcirc}$	[PrEt <sub>3</sub> N][NTf <sub>2</sub> ] 18			
R <sup>1</sup> = hexyl, R <sup>2</sup> = tetradecyl				
Scheme 2				

Since imidazolium-based ionic liquids are known for their capability to form carbene species via deprotonation or C-H activation, 31,14d,19 which could decrease the yield for the reaction, the influence of non-imidazolium-based ionic liquids as solvents was explored. The protic IL EAN (11) did not support the reaction (Table 1, Entry 12) and neither did [TBP][Cl] (12) or [THTDP][NTf<sub>2</sub>] (13) (Table 1, Entries 13-14). Only starting material could be recovered. Interestingly, [THTDP][Cl] (14) gave a yield of 17 % (Table 1, Entry 15). A significant increase of the yield to 45% after 16 h was found with [BuEt<sub>3</sub>N][NTf<sub>2</sub>] (15). The extension of the reaction time to 48 h gave a maximum yield of 83%. A longer reaction time of 72 h decreased the yield to 66% due to decomposition and possible subsequent side reactions (Table 1, Entries 17-19). Applying [BuEt<sub>3</sub>N][PF<sub>6</sub>] (16) gave a yield of 12% with a reaction time of 48 h, while the reaction with [BuEt<sub>3</sub>N][HSO<sub>4</sub>] (17) failed to give the desired product (Table 1, Entries 20-21), showing a tendency that lipophilic anions support the reaction. Finally,  $[ProEt_3N][NTf_2]$  (18) with a slightly smaller cation compared to 15 gave a lower yield of 63% after 48 h (Table 1, Entry 22).



Table 1. Homocoupling reaction of 2-phenylpyridine 1.

		0	1	17
Entry <sup>a</sup>	Oxidant	Solvent	t [h]	Yield [%] <sup>b</sup>
$1^{c}$	FeCl <sub>3</sub>	C <sub>6</sub> H <sub>5</sub> Cl	16	27
2	FeCl <sub>3</sub>	C <sub>6</sub> H <sub>5</sub> Cl	16	6
3	3	C <sub>6</sub> H <sub>5</sub> Cl	16	24
4	4	C <sub>6</sub> H <sub>5</sub> Cl	16	42
5	5	C <sub>6</sub> H <sub>5</sub> Cl	16	33
6	$FeCl_3\cdot \ 6\ H_2O$	C <sub>6</sub> H <sub>5</sub> Cl	16	78
7	$FeCl_3 \cdot 6 H_2O$	[BMIM][Cl] 6	16	-
8	$FeCl_3 \cdot 6 H_2O$	[BMIM][PF <sub>6</sub> ] 7	16	-
9	$FeCl_3\cdot \ 6\ H_2O$	[BMIM][OAc] 8	16	-
10	$FeCl_3 \cdot 6 H_2O$	[BMIM][BF <sub>4</sub> ] 9	48	60
11	$FeCl_3 \cdot 6 H_2O$	[BMIM][NTf2] 10	48	66
12	FeCl <sub>3</sub> · 6 H <sub>2</sub> O	EAN 11	16	-
13	$FeCl_3 \cdot 6 H_2O$	[TBP][Cl] 12	16	-
14	$FeCl_3 \cdot 6 H_2O$	[THTDP][NTf <sub>2</sub> ] 13	16	-
15	$FeCl_3 \cdot 6 H_2O$	[THTDP][Cl] 14	16	17
16	$FeCl_3 \cdot 6 H_2O$	[BuEt <sub>3</sub> N][NTf <sub>2</sub> ] 15	16	45
17	$FeCl_3 \cdot 6 H_2O$	[BuEt <sub>3</sub> N][NTf <sub>2</sub> ] 15	24	60
18	FeCl <sub>3</sub> · 6 H <sub>2</sub> O	[BuEt <sub>3</sub> N][NTf <sub>2</sub> ] 15	48	83
19	$FeCl_3 \cdot 6 H_2O$	[BuEt <sub>3</sub> N][NTf <sub>2</sub> ] 15	72	66
20	$FeCl_3 \cdot \ 6 \ H_2O$	[BuEt <sub>3</sub> N][PF <sub>6</sub> ] 16	48	12
21	$FeCl_3\cdot \ 6\ H_2O$	[BuEt <sub>3</sub> N][HSO <sub>4</sub> ] 17	16	-
22	$FeCl_3 \cdot 6 H_2O$	[PrEt <sub>3</sub> N][NTf <sub>2</sub> ] 18	48	63

<sup>a</sup> reaction was performed with 0.5 mmol 2-phenylpyridine **1**, 0.4 mmol oxidant, 5 mol% RuCl<sub>3</sub> and 1 mL chlorobenzene or 0.5 mL ionic liquid; <sup>b</sup> isolated yields; <sup>c</sup> result from Li et al.<sup>29</sup>

Taking into account that  $[BuEt_3N][NTf_2]$  (15) resulted in the highest yield, further studies were conducted with this ionic liquid and are summarized in Table 2. To gain a better inside on the influence of water, once pure water and once a mixture of  $[BuEt_3N][NTf_2]$  (15) and water was applied as solvent. In both cases no product was found with a reaction temperature of 100 °C (Table 2, Entries 1-2). Hence, a small amount of moisture is beneficial for the reaction yet an excess of water has the opposite effect. For optimization of the temperature one reaction was carried out at 80 °C and another at 130 °C. In the first case a strong decrease of the yield to 17% was found and in the second a small decrease to 71% was observed compared to the optimum yield at 110 °C (Table 2, Entries 3-4). The decrease was due to the formation of by-products via decomposition.

**Table 2.** Variation of reaction conditions for thehomocoupling of 2-phenylpyridine 1.

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Entry <sup>a</sup>	Catalyst	Oxidant	Solvent JOLYield P	
				[%] <sup>b</sup>
1	RuCl <sub>3</sub>	$FeCl_3 \cdot 6 H_2O$	$H_2O$	-
2	RuCl <sub>3</sub>	$FeCl_3 \cdot 6 H_2O$	15/H <sub>2</sub> O	-
3°	RuCl <sub>3</sub>	$FeCl_3 \cdot 6 H_2O$	15	13
4 <sup>d</sup>	RuCl <sub>3</sub>	$FeCl_3 \cdot 6 H_2O$	15	71
5	RuCl <sub>3</sub>	$FeNO_3\cdot 9\ H_2O$	15	-
6	RuCl <sub>3</sub>	K <sub>3</sub> [Fe(CN) <sub>6</sub> ]	15	-
7	RuCl <sub>3</sub>	$Fe(OAc)_2 \cdot 4 H_2O$	15	6
8	RuCl <sub>3</sub>	$H_2O_2$	15	36
9	RuCl <sub>3</sub>	$FeCl_3\cdot6~H_2O/$	15	43
		$H_2O_2$		
10	RuCl <sub>3</sub>	-	15	-
11 <sup>e</sup>	RuCl <sub>3</sub>	$FeCl_3 \cdot 6 H_2O$	15	56
12	RuCl <sub>3</sub>	$FeCl_3 \cdot \ 6 \ H_2O \ / \ O_2$	15	80
13	RuCl <sub>3</sub>	$O_2$	15	33
14	RuCl <sub>3</sub>	LiCl	15	19
15	RuCl <sub>3</sub>	LiCl / H <sub>2</sub> O	15	-
16	RuCl <sub>3</sub>	LiCl / O <sub>2</sub>	15	76
17	RuCl <sub>3</sub>	$LiNTf_2$	15	-
18	RuCl <sub>3</sub>	NaCl	15	21
19	RuCl <sub>3</sub>	KCl	15	-
$20^{\rm f}$	RuCl <sub>3</sub>	$FeCl_3 \cdot \ 6 \ H_2O$	15	75
21 <sup>g</sup>	RuCl <sub>3</sub>	$FeCl_3 \cdot \ 6 \ H_2O$	15	41
22	CoCl <sub>2</sub>	$FeCl_3 \cdot \ 6 \ H_2O$	15	-
23	CuCl	$FeCl_3 \cdot \ 6 \ H_2O$	15	-
24	CuCl <sub>2</sub>	$FeCl_3 \cdot 6 H_2O$	15	-
25	$RhCl_3 \cdot 3$	$FeCl_3\cdot6H_2O$	15	-
	$H_2O$			
26	Ir (I) <b>19</b> <sup>i</sup>	$FeCl_3 \cdot 6 H_2O$	15	-
27	PtCl <sub>2</sub>	$FeCl_3 \cdot \ 6 \ H_2O$	15	-
28	PdCl <sub>2</sub>	$FeCl_3 \cdot \ 6 \ H_2O$	15	13
29 <sup>h</sup>	RuCl <sub>3</sub>	$FeCl_3 \cdot \ 6 \ H_2O$	15	81
30 <sup>j</sup>	RuCl <sub>3</sub>	$FeCl_3 \cdot \ 6 \ H_2O$	15	77
31 <sup>k</sup>	RuCl <sub>3</sub>	$FeCl_3 \cdot 6 H_2O$	15	71

<sup>a</sup> reaction was performed with 0.5 mmol 2-phenylpyridine **1**, 0.4 mmol oxidant, 5 mol% catalyst and 0.5 mL ionic liquid at a temperature of 110 °C for 48 h; <sup>b</sup> isolated yield; <sup>c</sup> reaction temperature 80 °C; <sup>d</sup> reaction temperature 130 °C; <sup>e</sup> under N<sub>2</sub>; <sup>f</sup> 0.5 eq FeCl<sub>3</sub>  $\cdot$  6 H<sub>2</sub>O; <sup>g</sup> 0.25 eq FeCl<sub>3</sub>  $\cdot$  6 H<sub>2</sub>O; <sup>h</sup> recycled ionic liquid was used; <sup>i</sup> bis(1,5-cyclooctadiene)diiridium(I) dichloride; <sup>j</sup> a scale up reaction with 5 mmol **1** was carried out; <sup>k</sup> reaction with 5 mmol **1** and recycled ionic liquid

Next, different oxidation agents were evaluated. Different iron salts as well as H<sub>2</sub>O<sub>2</sub> and also the absence of an oxidation agent resulted always in lower or no yields compared to FeCl<sub>3</sub> <sup>6</sup> H<sub>2</sub>O (Table 2, Entries 5-10). The application of deoxygenated ionic liquid under a nitrogen atmosphere with FeCl<sub>3</sub> <sup>6</sup> H<sub>2</sub>O decreased the yield to 56 % (Table 2, Entry 11). When the reaction was conducted with FeCl<sub>3</sub> <sup>6</sup> H<sub>2</sub>O under an atmosphere of oxygen, a yield of 80 % was obtained comparable to the result with air (Table 2, Entry 12). A reaction under oxygen but in the absence of any other oxidant furnished a yield of 33% (Table 2, Entry 13). Hence, the presence of oxygen is beneficial for the reaction as is an iron salt with a chloride counter anion. The conversion of 33% without an oxidant besides oxygen, showed that a substoichiometric use of FeCl<sub>3</sub> in further experiments was sufficient.

The importance of chloride can be attributed to the proposed mechanism with  $RuCl_3$  as catalyst (Scheme 3). In this mechanism the chloride anion is necessary for the recycling

of the catalytic ruthenium species. To determine the influence of chloride further, different chloride salts were explored in the reaction under air or oxygen. Under air and 2 eq lithium chloride as substitute for the oxidant a yield of 19% was obtained (Table 2, Entry 14). The amount of lithium chloride was chosen in order to maintain a chloride level close to FeCl<sub>3</sub>. This is a significant improvement to the absence of a chloride salt under air which gave no product (Table 2, Entry 10). Additional water in the reaction with LiCl gave no product, while a run under an atmosphere of oxygen with LiCl improved the yield to 76 % (Table 2, Entries 15-16). The absence of product with lithium bis(trifluoromethylsulfonyl)amide as a replacement for LiCl supported the importance of chloride anions further (Table 2, Entry 17). Other chloride salts like sodium chloride or potassium chloride were decreasing the yield (Table 2, Entries 18-19). Further optimization studies were conducted with  $FeCl_3$  6 H<sub>2</sub>O as oxidation agent. Reducing  $FeCl_3$  6  $H_2O$  from 0.8 eq to 0.5 eq decreased the yield to 75 % and 0.25 eq to 41 % (Table 2, Entries 20-21).

Finally, other possible catalysts were also explored as substitutes for RuCl<sub>3</sub>. No product was formed with CoCl<sub>2</sub>, CuCl, CuCl<sub>2</sub>, RhCl<sub>3</sub>  $\cdot$  3 H<sub>2</sub>O, iridium(I) chloride-1,5-cyclooctadiene complex (**19**) and PtCl<sub>2</sub> (Table 2, Entries 24-27). PdCl<sub>2</sub> gave a low yield of 13 % (Table 2, Entry 28).

Hence, the optimum conditions for the reaction with 2phenylpyridine (1) and [BuEt<sub>3</sub>N][NTf<sub>2</sub>] (15) as solvent were 5 mol% RuCl<sub>3</sub> as catalyst, 0.8 eq FeCl<sub>3</sub>  $\cdot$  6 H<sub>2</sub>O as oxidant at 110 °C for 48 h under air. Simple recycling of the ionic liquid was possible during the purification of the product via column chromatography. Alternatively, the reaction mixture was added directly to ethyl acetate and the organic phase was washed with an aqueous solution of potassium hydrogencarbonate to remove ruthenium and iron salts as well as remains of HCl. After the removal of ethyl acetate, the product was extracted from the ionic liquid with diethyl ether. The ionic liquid was dried and obtained in pure form and could be reused (Table 2, Entry 29).

In Scheme 3 a possible reaction mechanism is depicted as it has been suggested by several groups.<sup>29</sup> Initially, RuCl<sub>3</sub> reacts with 2-phenylpyridine 1 via a C-H activation to complex A. Next, intermediate A loses HCl in a reductiveelimination to form complex **B**. A second 2-phenylpyridine 1 undergoes the same process and the intermediate C is formed after the release of HCl. Finally, the oxidative coupling product 2 is formed via reductive elimination. The ruthenium catalyst is regenerated by the oxidant FeCl<sub>3</sub>. The formation of HCl can be observed by the decrease of the pH value. The reaction mixture becomes gradually more and more acidic. Obviously, the product is being protonated by the HCl. In its protonated ionic form, the product cannot be extracted from the ionic liquid. This causes the necessity to use a base like triethylamine or KHCO3 in the work up procedure in order to obtain the non-protonated product. For the regeneration of the catalytic active RuCl<sub>3</sub> are next to the oxidation the presence of two chloride anions necessary. In general, these could come from the released HCl and the

formed pyridinium salts, however, it appears that a chloride source from  $\text{FeCl}_3$  or LiCl is more efficient, since some HCl could be lost as gas. Furthermore, it is possible that the iron is reoxidized by oxygen or maybe it functions especially as a source for chloride anions and the oxidation to the product is mainly performed by oxygen. The oxidation of iron(II) could be also promoted by presence of water in the reaction.





<sup>a</sup> reaction was performed with 0.5 mmol 2-phenylpyridine **1**, 0.4 mmol oxidant, 5 mol% catalyst and 0.5 mL ionic liquid at a temperature of 110 °C for 48 h; <sup>b</sup> isolated yield; <sup>c</sup> 72 h reaction time.

3. Conclusions

It was possible to demonstrate that  $[BuEt_3N][NTf_2]$  (15) is an efficient ionic liquid in an oxidative C-H activation reaction. The ionic liquid resulted in higher yields compared to imidazolium-based ionic liquids. This could be due to the fact that a C-H activation on the ionic liquid 15 is not possible compared to imidazolium-based systems. In addition, also lithium chloride in combination with an oxygen atmosphere was found as a suitable oxidation system for the RuCl<sub>3</sub> catalyst. Up to 83% yield were obtained in the homocoupling of 2-arylpyridine and the ionic liquid could be recycled. This finding will lead to further applications of tetraalkylammonium-based ionic liquids in these kinds of reactions.

After the studies on the influence of various parameter on the reaction were completed, different 2-aryl-pyridines were coupled under the optimized conditions as shown in Table 3. In general, different analogues with electron withdrawing and donating groups can be applied in the reaction. However, the yields decreased more when electron withdrawing substituents were present in the aryl rings. An explanation for this could be a less stable intermediate due to the absence of ligands for the ruthenium complexes.

**Table 3.** Application of 2-arylpyridines under optimizedconditions.

# Tetrahedron

#### 4. Experimental section

General methods: [BuEt<sub>3</sub>N][NTf<sub>2</sub>] (15), [BuEt<sub>3</sub>N][PF<sub>6</sub>] (16) and  $[BuEt_3N][HSO_4]$  (17) and  $[ProEt_3N][NTf_2]$  (18) were prepared according to the literature from triethylamine, bromobutane or bromopropane.<sup>32</sup> [BMIM][FeCl<sub>4</sub>] (3), [BMIM][Fe<sub>2</sub>Cl<sub>7</sub>] (5) and [THTDP][FeCl<sub>4</sub>] (4) were prepared according to the literature.<sup>24</sup> The 2-arylpyrdines **20-26** were prepared according to literature procedures.<sup>33</sup> All other reagents were commercially available and used as supplied without further purification. IR spectra were recorded on a Bruker VERTEX 70 FT-IR spectrometer. The <sup>1</sup>H-NMR and <sup>13</sup>C-NMR spectra were recorded at 500 MHz or 125 MHz on a Bruker Avance 500 spectrometer using the deuterated solvent as the lock and the residual solvent or TMS as the internal reference. Mass spectra were obtained on a Bruker Esquire 3000 plus mass spectrometer (Bruker-Franzen Analytik GmbH, Bremen, Germany) equipped with an ESI interface and an ion trap analyzer. High-resolution mass spectra (ESI) were recorded on a Waters Quadrupole-ToF Synapt 2G. The reactions were followed by thin layer chromatography on silica gel.

General experimental for the preparation of 2,2'-di(2pyridinyl)-1,1'-biphenyl 2. 2-Phenylpyridine (77.5 mg, 0.5 mmol, 1 eq), RuCl<sub>3</sub> (2.6 mg, 0.0125 mmol, 5 mol%), FeCl<sub>3</sub><sup>-</sup> 6 H<sub>2</sub>O (108 mg, 0.4 mmol) and [BuEt<sub>3</sub>N][NTf<sub>2</sub>] (15) (0.5 mL) were added under an atmosphere of air to a 10 mL round bottom flask. The reaction was stirred for 48 h at 110 °C. After completion of the reaction it was cooled to room temperature and then ethyl acetate (1 mL) and triethylamine (1 mL) were added and the mixture was allowed to stir for 30 min. The purification was performed by flash chromatography (diethylether/ n-hexane = 1:1) to afford 5 (64 mg, 21 mmol, 83 %). <sup>1</sup>H NMR (500 MHz, CDCl<sub>3</sub>) δ: 8.34 (ddd, J=5 Hz, 2 Hz, 1Hz, 2H), 7.54 - 7.57 (m, 2H), 7.37-7.43 (m, 6H), 7.33 (ddd, J=7.5 Hz, 7.5 Hz, 2 Hz, 2H), 7.01 (ddd, J=7.5 Hz, 5 Hz, 1 Hz, 2H), 6.80 (ddd, J=7.5 Hz, 1 Hz, 1 Hz, 2H) ppm; <sup>13</sup>C NMR (125 MHz, CDCl<sub>3</sub>) δ: 157.1, 148.9, 139.9, 139.8, 135.1, 131.3, 130.0, 128.4, 127.7, 124.4, 121.1 ppm. The spectral data of the product was consistent with literature values.<sup>29</sup>

#### **Supplementary Material**

Supplementary material as a pdf file with NMR spectra are available online.

#### Notes and references

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# Highlights

- Tetraalkylammonium based ionic liquids as green reaction medium.
- Ionic Liquids for C-H bond activation reactions.
- Robust simple RuCl<sub>3</sub> as catalyst for a C-H Activated Homocoupling.

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#### **Declaration of interests**

 $\boxtimes$  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.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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