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Ruthenium(η⁶,η¹-arene-CH₂-NHC) Catalysts for Direct Arylation of 2-Phenylpyridine with (Hetero)Aryl Chlorides in Water

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Abstract: A series of new benzimidazolium halides were synthesized in good yields as unsymmetrical N-heterocyclic carbene (NHC) precursors containing the N–CH₂–arene group. The benzimidazolium halides were readily converted into ruthenium(II)–NHC complexes with the general formula [RuCl₂(η⁶,η¹–arene–CH₂–NHC)]. The structures of all new compounds were characterized by ¹H NMR (Nuclear Magnetic Resonance), ¹³C NMR, FT-IR (Fourier Transform Infrared) spectroscopy and elemental analysis techniques. The single crystal structure of one benzimidazole ruthenium complex, 2b, was determined. The complex is best thought of as containing an octahedrally coordinated Ru center with the arene residue occupying three sites, the remaining sites being occupied by a (carbene)C–Ru bond and two Ru–Cl bonds. The catalytic activity of [RuCl₂(η⁶,η¹–arene–CH₂–NHC)] complexes was evaluated in the direct (hetero)arylation of 2-phenylpyridine with (hetero)aryl chlorides in water as the nontoxic reaction medium. These results show that catalysts 2a and 2b were the best for monoarylation with simple phenyl and tolyl chlorides. For functional aryl chlorides, 2d, 2e, and 2c appeared to be the most efficient.

Keywords: homogeneous catalysis; ruthenium; N-heterocyclic carbene; 2-phenylpyridine; direct arylation; single crystal structure

1. Introduction

The prevalence and importance of biaryl compounds in natural products, advanced materials, and pharmaceuticals have made the preparation of C(sp²)–C(sp²) bond among the core interests of organic synthesis [1]. Transition metal-catalyzed cross-coupling reactions of aromatic compounds are useful synthetic routes to biaryl compounds [2–7]. By far, traditional transition metal-catalyzed biaryl cross-coupling reactions, which generally employ aryl halides and organometallics as coupling partners, have served as the most common methods for constructing biaryl unions (Figure 1a) [8,9]. Despite the large scope of reactions and opportunities opened by these traditional methodologies, the starting organometallic reagents are often not commercially available. Moreover, the amount of byproducts produced, whether in the synthesis of the organometallic reagent or during the coupling step itself, remains significant. Recently, there has been much interest in transition metal-catalyzed direct cross-coupling C–C bond formation of aromatic compounds with aryl halides as electrophilic...
partners involving the activation of normally unreactive aromatic C–H bond, in terms of synthesis efficiency and minimization of reaction steps waste (Figure 1b) [10–12]. Therefore, direct arylation reactions through cleavage of C–H bonds represent an environmentally and economically more attractive strategy.

The direct C–C bond formation reactions generally involve directing-group-assisted activation of sp² C–H bonds of ortho aromatic C–H bonds. Many directing groups, such as acetyl, acetamino, carboxylic acid, oxazolyl, pyridyl, hydroxyl, imino, and cyano moieties, have been used for C–H bond activation [13–24]. The first example of a functional group assisted ruthenium-catalyzed C–H bond functionalization was reported by Lewis in 1986 [25]. Further pioneering work by Murai, Kakiuchi and Chatani on ruthenium-catalyzed hydroarylations showed the ability of ruthenium catalysts to activate C–H bonds selectively, via assistance of a coordinating functional group [26]. In 2001, the first ruthenium(II)-catalyzed chelation-assisted direct arylation with aryl bromides was performed by Oi, Inoue and co-workers [27]. In addition, Prades and Peris also reported the acetate-assisted arylation of 2-phenylpyridine using N-heterocyclic carbene-ruthenium complexes [28].

Recently, different direct arylation reactions catalysed by ruthenium-based complexes have been described by the groups of Ackermann [29–31], Dixneuf [32], Davies [33] and others [34–38]. Several ruthenium-catalyzed direct arylation reactions were also reported by our group [39–41]. Most of these reported direct arylation were performed either in NMP (N-methyl-2-pyrrolidone) or toluene as solvent. However, the demand for a more environmentally friendly chemistry opens a new horizon for the extended application of “green solvents” in direct C–H bond functionalizations as well [42]. In this connection, several ruthenium-catalyzed direct arylation in water or diethylcarbonate (DEC) as green solvent using an additive were reported by Dixneuf’s group [43–49].

We now described the synthesis and characterization of new unsymmetrical benzimidazolium halides (1a–e) and five new ruthenium(II) complexes of the general formula [RuCl2(η5-C5H4N1–1-arylmethyl–3–butylbenzimidazol–2–ylidene)] (2a–e). All new compounds were characterized by ¹H NMR, ¹³C NMR, FT-IR spectroscopy and elemental analysis techniques. The single crystal structure of the benzimidazole ruthenium complex 2b was also determined. These new complexes with KOAc partner were evaluated as catalyst precursors for the direct mono orthoarylation of 2-phenylpyridine with (hetero)aryl chlorides in water, without the need of surfactant.

2. Results and Discussion

2.1. Preparation of Benzimidazolium Halides

Benzimidazolium halides 1a, 1b, 1d and 1e were synthesized by reacting N-(alkyl)benzimidazole with alkyl halide in dimethylformamide (DMF) at 80 °C for 24 h. The benzimidazolium chloride 1c was obtained as we previously described [40]. These products were isolated as crystalline solids in high yields (78–87%). The benzimidazolium halides 1a–e are air- and moisture-stable both in the solid state and in solution and are soluble in chlorinated solvents, ethyl alcohol and water (Scheme 1). The benzimidazolium halides were characterized using ¹H NMR, ¹³C NMR, and FT-IR spectroscopy and gave satisfactory elemental analysis. The FT-IR data clearly indicated that the benzimidazolium halides 1a–e exhibit a characteristic ν(NCN) band typically between 1553–1560 cm⁻¹. In the ¹³C NMR
spectra of compounds 1a–e, the characteristic peak of the imino carbon (NCHN) resonance was detected in the area $\delta$ 143.2–143.6 ppm. The $^1$H NMR spectra of compounds 1a, 1b, 1d and 1e further supported the assigned structures. The resonances for C(2)–H were observed as sharp singlets at $\delta$ 10.53–11.53 ppm and consistent with NMR values of other benzimidazolium halides [50].

2.2. Preparation of Ruthenium(II)-NHC Complexes Containing the $\eta^6$,$\eta^1$-NHC Mixed Chelating Ligand

The carbene ligands formed by deprotonation of benzimidazolium salts 1a–e using Cs$_2$CO$_3$ were reacted with [RuCl$_2$(p-cymene)]$_2$ in toluene at 110 °C for 5 h to give good yield of [RuCl$_2$(η$^6$,$\eta^1$-1-arylmethyl-3–butylbenzimidazol-2-ylidene)] (Scheme 2). Selective crystallization by solvent diffusion technique (CH$_2$Cl$_2$/Hexane) allowed the formation of suitable orange-brown crystalline solids in yields of 70–82%. The air- and moisture-stable complexes 2a–e are soluble in solvents such as dichloromethane, chloroform, toluene, and tetrahydrofuran. The ruthenium(II)–NHC complexes 2a–e were characterized using $^1$H NMR, $^{13}$C NMR, and FT-IR spectroscopy and gave satisfactory elemental analysis. The FT-IR data clearly indicated that the exhibit a characteristic $\nu$(CN) band typically within 1400–1407 cm$^{-1}$. NMR analysis confirmed the loss of the p-cymene ligand and the coordination of the (arene-CH$_2$-NHC)arene. $^{13}$C NMR chemical shifts provide a useful diagnostic tool for this type of metal carbene complex. The chemical shifts for the carbene carbon atom are located in $\delta$ 181.3–185.2 ppm range and are similar to those found in other ruthenium(II)–NHC complexes [51]. The analytical data are in good agreement with the compositions proposed for all the compounds we prepared, and are summarized in Table 1.

Table 1. Physical and spectroscopic properties of new compounds 1 and 2.

| Compound | Formula          | Isolated Yield (%) | M.p. (Melting Point) (°C) | $\nu$(CN) (Frequency) (cm$^{-1}$) | $^1$H NMR H(2) (ppm) | $^{13}$C NMR C(2) (ppm) |
|----------|------------------|--------------------|--------------------------|----------------------------------|-----------------------|------------------------|
| 1a       | C$_{19}$H$_{23}$ClN$_2$ | 78                 | 198–199                  | 1558                             | 11.49                 | 143.2                  |
| 1b       | C$_{22}$H$_{29}$ClN$_2$ | 83                 | 176–177                  | 1553                             | 10.86                 | 142.9                  |
| 1d       | C$_{22}$H$_{29}$BrN$_2$ | 80                 | 184–185                  | 1560                             | 11.45                 | 142.6                  |
| 1e       | C$_{26}$H$_{29}$ClN$_2$O | 87                 | 191–192                  | 1557                             | 11.53                 | 143.6                  |
| 2a       | C$_{19}$H$_{23}$ClN$_2$Ru | 87                | 231–232                  | 1401                             | -                     | 181.3                  |
| 2b       | C$_{22}$H$_{29}$ClN$_2$Ru | 80                 | 311–312                  | 1400                             | -                     | 184.9                  |
| 2c       | C$_{23}$H$_{30}$ClN$_2$Ru | 82                 | 319–320                  | 1406                             | -                     | 186.0                  |
| 2d       | C$_{23}$H$_{30}$ClN$_2$Ru | 71                 | 298–299                  | 1403                             | -                     | 186.1                  |
| 2e       | C$_{26}$H$_{28}$ClN$_2$ORu | 76                | 310–311                  | 1407                             | -                     | 185.2                  |
The Ru(1)–Cl(1) and Ru(1)–Cl(2) single bond lengths are 2.4267(9) and 2.4222(8) Å. The values of the geometrical parameters of compound 2b group are almost co-planar with maximum deviations of 0.010(2) Å for N1 and 0.010(2) Å for Cl5, respectively. The dihedral angle between benzimidazolylidine and tetramethylbenzyl rings is 84.49 (16)°. The Ru-carbene distance, Ru(1)–C(1), of 2.040(3) Å, matches the literature data. The C(1)–Ru(1)–Cl(1) and C(1)–Ru(1)–Cl(2) angles of 78.59(12), 92.94(9) and 89.64(8)°, respectively, a result that reflects the situation we found in related Ru complexes (Table 2) [52–55]. The atoms comprising the tetramethylbenzyl ring are coplanar, the mean deviation from their least squares plane being 0.017(2) Å.

The small steric demand of the benzimidazolylidene ligand is reflected in the C(1)–Ru(1)–C(13), C(1)–Ru(1)–Cl(1) and C(1)–Ru(1)–Cl(2) angles of 78.59(12), 92.94(9) and 89.64(8)°, respectively, a result that reflects the situation we found in related Ru complexes (Table 2) [52–55]. The atoms comprising the arene residue occupying three sites, the remaining sites being occupied by an Ru–C(carbene) bond, derived from the benzimidazole ring, and two Ru–Cl bonds. The small steric demand of the benzimidazolylidene ligand is reflected in the C(1)–Ru(1)–C(13), C(1)–Ru(1)–Cl(1) and C(1)–Ru(1)–Cl(2) angles of 78.59(12), 92.94(9) and 89.64(8)°, respectively, a result that reflects the situation we found in related Ru complexes (Table 2) [52–55]. The atoms comprising the tetramethylbenzyl ring are coplanar, the mean deviation from their least squares plane being 0.017(2) Å. The five- and six-membered rings (N1/C1/N2/C7/C2) and (C2–C7) of the benzimidazolylidene group are almost co-planar with maximum deviations of 0.010(2) Å for N1 and 0.010(2) Å for C5, respectively. The dihedral angle between benzimidazolylidine and tetramethylbenzyl rings is 84.49 (16)°. The Ru-carbene distance, Ru(1)–C(1), of 2.040(3) Å, matches the literature data [52–54]. The Ru(1)–Cl(1) and Ru(1)–Cl(2) single bond lengths are 2.4267(9) and 2.4222(8) Å. The values of the geometrical parameters of compound 2b agree with those reported for similar compounds [52–54].

Scheme 2. Synthesis of [Ru-Cl2(η-C-p-cymene)] complexes, 2a–e.

2.3. Single Crystal X-ray Diffraction and Structure Analysis of Complex 2b

The ligand in compound 2b has both benzimidazolylidene and arene rings, which are connected chelating via a CH2 bridge (Figure 2). Further details concerning data collection and refinements are given in the Supplementary Materials. This configuration leads to a system with very little apparent strain on coordinating the ruthenium atom. The complex is best described as containing an octahedrally coordinated Ru center with the arene residue occupying three sites, the remaining sites being occupied by an Ru–C(carbene) bond, derived from the benzimidazole ring, and two Ru–Cl bonds. The small steric demand of the benzimidazolylidene ligand is reflected in the C(1)–Ru(1)–C(13), C(1)–Ru(1)–Cl(1) and C(1)–Ru(1)–Cl(2) angles of 78.59(12), 92.94(9) and 89.64(8)°, respectively, a result that reflects the situation we found in related Ru complexes (Table 2) [52–55]. The atoms comprising the tetramethylbenzyl ring are coplanar, the mean deviation from their least squares plane being 0.017(2) Å.

The five- and six-membered rings (N1/C1/N2/C7/C2) and (C2–C7) of the benzimidazolylidene group are almost co-planar with maximum deviations of 0.010(2) Å for N1 and 0.010(2) Å for C5, respectively. The dihedral angle between benzimidazolylidine and tetramethylbenzyl rings is 84.49 (16)°. The Ru-carbene distance, Ru(1)–C(1), of 2.040(3) Å, matches the literature data [52–54]. The Ru(1)–Cl(1) and Ru(1)–Cl(2) single bond lengths are 2.4267(9) and 2.4222(8) Å. The values of the geometrical parameters of compound 2b agree with those reported for similar compounds [52–54].

Figure 2. The molecular structure of compound 2b. Displacement ellipsoids are drawn at the 50% probability level.
Table 2. Selected bond lengths (Å), angles (°) and torsion angles (°) for compound 2b.

| Bond Lengths | Bond Angles | Torsion Angle |
|--------------|-------------|---------------|
| C(1)–N(2)    | 1.360(4)    | N(2)–C(1)–N(1) 105.2(3) |
| C(1)–N(1)    | 1.361(4)    | N(2)–C(1)–Ru(1) 138.3(2) |
| C(1)–Ru(1)   | 2.040(3)    | N(2)–C(1)–Ru(1)–Cl(2) 129.7(2) |
| C(2)–N(1)    | 1.386(4)    | N(1)–C(1)–N(1)–C(12) 176.2(3) |
| C(2)–C(7)    | 1.394(5)    | N(1)–C(1)–Ru(1)–Cl(1) 129.7(2) |
| C(7)–C(12)   | 1.393(4)    | N(2)–C(1)–Ru(1)–Cl(1)–C(13) 141.1(2) |
| C(14)–C(13)  | 1.466(4)    | C(1)–N(1)–C(12) 111.6(3) |
| C(12)–N(1)   | 1.466(4)    | C(1)–N(1)–C(2) 111.6(3) |
| C(12)–C(13)  | 1.517(4)    | C(1)–N(1)–C(12) 121.5(3) |
| C(13)–Ru(1)  | 2.109(3)    | C(2)–N(1)–C(12) 126.7(3) |
| C(14)–Ru(1)  | 2.190(3)    | C(1)–N(2)–C(7) 111.1(3) |
| C(15)–C(16)  | 1.426(5)    | C(1)–N(2)–C(7) 111.1(3) |
| C(15)–C(20)  | 1.513(4)    | C(1)–N(2)–C(8) 124.5(3) |
| Cl(1)–Ru(1)  | 2.4267(9)   | Cl(1)–N(2)–C(8) 124.3(3) |
| Cl(2)–Ru(1)  | 2.4222(8)   | Cl(1)–N(2)–C(8) 124.3(3) |

2.4. Optimization Conditions of Direct Arylation of 2-Phenylpyridine with (hetero)Aryl Chlorides with Catalysts 2

The catalytic activity of the [RuCl₂(η⁶,H₃=n¹–1–arylmethyl–3-butylbenzimidazole–2–ylidene)] complexes 2a–e for the activation of phenylpyridine towards (hetero)arylation of sp² C–H bonds was investigated by the reaction of (hetero)aryl chloride and 2-phenylpyridine as a standard reaction. The reaction was carried out using 2-phenylpyridine, (hetero)aryl chloride and Cs₂CO₃ in the presence of complex 2c as the catalyst in water with Cs₂CO₃ as a base and a carboxylate RCO₂K as additive. The results of varying the reaction parameters, including base, additive and reaction time are given in Table 3.

It has been shown by Dixneuf’s group [43–49] that carboxylates were efficient partners for ruthenium(II) C–H bond activation at room temperature, especially in water [44]. The mechanism of the catalytic cycle showed that a carboxylate was crucial to deprotonate the C–H bond of aromatic systems [48,49]. Thus, pivalate and acetate additives were evaluated. When KOPOiv was used as additive, the reaction gave low conversion of only 9% with Cs₂CO₃ after 5 h at 100 °C, and 100% (Table 3, entry 1). However, when K₂CO₃ and Na₂CO₃ were used as bases under similar conditions, no reaction took place (Table 3, entries 2 and 3). In the presence of KOAc as additive, the conversion was increased to 15% with Cs₂CO₃ after 5 h at 100 °C, to give mono-alkylated product, A, was also observed (Table 3, entry 4). When the reaction time was increased from 5 h to 10 h, the conversion was improved to 47% and 100% yield (Table 3, entry 5). Similarly, when the reaction time was increased from 10 to 20 h, the conversion was improved to 95% and 100% yield of product A was also observed (Table 2, entry 6). However, when the reaction time was increased from 20 to 24 h, no significant difference was observed in the conversion (Table 3, entry 7). These conditions (Table 3, entry 6) were selected for mono ortho-heteroarylation of phenylpyridine. As a result, the scope of the direct arylation of 2-phenylpyridine was investigated with 2-chlorothiophene applying our best experimental conditions (Table 3, entry 6). When 4-chlorotoluene was used as model coupling partner, the reaction gave full conversion (100% yield of mono-alkylated product A, was observed) with Cs₂CO₃ as base at different durations (5–20 h) at 100 °C (Table 3, entries 8–10). Eventually, the scope of the direct arylation of 2-phenylpyridine was investigated with 4-chlorotoluene applying our best experimental conditions (Table 3, entry 10). This shows that ortho-arylation is much easier than heteroarylation.
When the reaction of 2-phenylpyridine with 4-chlorotoluene was performed by compounds 2a with six aryl chloride and thiophenyl chloride. In all of the reactions between different (hetero)aryl (Table 4, entries 20 and 30). Heteroaryl derivative such as 2-chlorothiophene was also applicable to this product was observed in conversion of 95% (selectivity of A 100%), (Table 4, entry 33). These results show that catalysts 2a–2e were the best for monoarylation with simple phenyl and tolyl chlorides. For functional aryl chlorides ClC₆H₄Y, 2d (Y = CHO), 2e (Y = COMe and Y = CN), 2e (thiophenyl chloride) appeared the most efficient.

### 2.5. Direct Arylation of 2-Phenylpyridine with (Hetero)Aryl Chlorides

Based on this preliminary study, the scope of the direct arylation of 2-phenylpyridine was investigated with various (hetero)aryl chlorides applying our best experimental conditions to produce new potential bidentate ligands. With KOAc as additive, Cs₂CO₃ as base in water at 100 °C for different durations, ruthenium complexes 2a–e were examined in the direct arylation of 2-phenylpyridine with six aryl chloride and thiophenyl chloride. In all of the reactions between different (hetero)aryl chlorides and 2-phenylpyridine, mono ortho-arylated product (A) was formed selectively. In addition, high conversion of ortho-arylated products was observed, and the selectivity was in high ratio towards to A. Although the other aryl chlorides showed good conversion in 5 h, chlorobenzene showed full conversion after 1 h. For example, when 2a and 2b complexes were used as catalyst, ortho-arylated product observed full conversion (selectivity of A 100%), (Table 4, entries 1 and 2). When the reaction of 2-phenylpyridine with 4-chlorotoluene was performed by compounds 2a, 2b and 2c, ortho-arylated products (A and B) obtained full conversion (selectivity of A 100%), (Table 4, entries 6–8). When the reaction of 2-phenylpyridine with 4-chlorobenzaldehyde was performed by compounds 2a–e, ortho-arylated products (A and B) obtained full conversion (Table 4, entries 11–15). When compound 2e was used as catalyst, high conversion (>80%) was observed (selectivity of A >85%) (Table 4, entries 20 and 30). Heteroaryl derivative such as 2-chlorothiophene was also applicable to this direct arylation system (Table 4, entries 31–35). When compound 2e was used as catalyst, ortho-arylated product was observed in conversion of 95% (selectivity of A 100%), (Table 4, entry 33). These results show that catalysts 2a–2b were the best for monoarylation with simple phenyl and tolyl chlorides. For functional aryl chlorides ClC₆H₄Y, 2d (Y = CHO), 2e (Y = COMe and Y = CN), 2e (thiophenyl chloride) appeared the most efficient.

### Table 3. Arylation of 2-phenylpyridine with (hetero)aryl chlorides: A search for optimal catalytic conditions

| Entry | (Het)ArCl | Additive | Base   | Time (h) | Conversion (%) | Yield (%) A | Yield (%) B |
|-------|-----------|----------|--------|----------|---------------|-------------|-------------|
| 1     | 2-Chlorothiophene | KOPiv | Cs₂CO₃  | 5        | 9             | 100         | -           |
| 2     | 2-Chlorothiophene | KOPiv | K₂CO₃   | 5        | -             | -           | -           |
| 3     | 2-Chlorothiophene | KOPiv | Na₂CO₃  | 5        | -             | -           | -           |
| 4     | 2-Chlorothiophene | KOAc  | Cs₂CO₃  | 5        | 15            | 100         | -           |
| 5     | 2-Chlorothiophene | KOAc  | Cs₂CO₃  | 10       | 47            | 100         | -           |
| 6     | 2-Chlorothiophene | KOAc  | Cs₂CO₃  | 20       | 95            | 100         | -           |
| 7     | 2-Chlorothiophene | KOAc  | Cs₂CO₃  | 24       | 97            | 100         | -           |
| 8     | 4-Chlorotoluene   | KOAc  | Cs₂CO₃  | 20       | 100           | 100         | -           |
| 9     | 4-Chlorotoluene   | KOAc  | Cs₂CO₃  | 10       | 100           | 100         | -           |
| 10    | 4-Chlorotoluene   | KOAc  | Cs₂CO₃  | 5        | 100           | 100         | -           |

*a Reaction conditions: Additive (0.05 mmol), ruthenium(II)-NHC complex, 2c (0.025 mmol), H₂O as solvent (2 mL), r.t. for 1 h, then 2-phenylpyridine (0.5 mmol), (hetero)aryl chloride (1.25 mmol), base (1.5 mmol). The conversions were based on the 2-phenylpyridine by GC (Gas chromatography) and GC-MS (Gas chromatography-Mass Spectrometry).
Table 4. Direct arylation of 2-phenylpyridine with (hetero)aryl chlorides catalyzed by ruthenium(II)-NHC complexes 2a–e. 

\[
\text{Ru-NHC} + (\text{Het})\text{ArCl} \xrightarrow{\delta} \text{Ar(Het)}
\]

| Entry | Ru-NHC | (Het)ArCl | Time (h) | Conversion (%) | Yield (%) |
|-------|--------|-----------|---------|---------------|-----------|
| A     | B      |           |         |               |           |
| 1     | 2a     |           | 1       | 100           | 100       |
| 2     | 2b     |           | 1       | 100           | 100       |
| 3     | 2c     |           | 1       | 80            | 80        |
| 4     | 2d     |           | 1       | 90            | 90        |
| 5     | 2e     |           | 1       | 85            | 87        |
| 6     | 2a     |           | 5       | 100           | 100       |
| 7     | 2b     |           | 5       | 100           | 100       |
| 8     | 2c     |           | 5       | 100           | 100       |
| 9     | 2d     |           | 5       | 100           | 88        |
| 10    | 2e     |           | 5       | 90            | 95        |
| 11    | 2a     |           | 5       | 100           | 70        |
| 12    | 2b     |           | 5       | 100           | 80        |
| 13    | 2c     |           | 5       | 100           | 72        |
| 14    | 2d     |           | 5       | 100           | 92        |
| 15    | 2e     |           | 5       | 100           | 86        |
| 16    | 2a     |           | 5       | 76            | 76        |
| 17    | 2b     |           | 5       | 72            | 72        |
| 18    | 2c     |           | 5       | 71            | 71        |
| 19    | 2d     |           | 5       | 70            | 70        |
| 20    | 2e     |           | 5       | 80            | 85        |
| 21    | 2a     |           | 5       | 72            | 72        |
| 22    | 2b     |           | 5       | 77            | 77        |
| 23    | 2c     |           | 5       | 70            | 70        |
| 24    | 2d     |           | 5       | 79            | 79        |
| 25    | 2e     |           | 5       | 74            | 75        |
| 26    | 2a     |           | 5       | 76            | 76        |
| 27    | 2b     |           | 5       | 71            | 71        |
| 28    | 2c     |           | 5       | 88            | 88        |
| 29    | 2d     |           | 5       | 85            | 85        |
| 30    | 2e     |           | 5       | 89            | 90        |
| 31    | 2a     |           | 20      | 90            | 90        |
| 32    | 2b     |           | 20      | 88            | 95        |
| 33    | 2c     |           | 20      | 95            | 100       |
| 34    | 2d     |           | 20      | 89            | 97        |
| 35    | 2e     |           | 20      | 83            | 85        |

\(^a\) Reaction conditions: KOAc (0.05 mmol), ruthenium(II)-NHC complexes 2a–e (0.025 mmol), H₂O as solvent (2 mL), r.t. for 1 h, then 2-phenylpyridine (0.5 mmol), (Het)ArCl (1.25 mmol), Cs₂CO₃ (1.5 mmol).
3. Materials and Methods

3.1. General

All reactions for the preparation benzimidazolium halides (1a–e) and (arene)ruthenium(II)-(NHC)(Cl)_2 complexes (2a–e) were carried out under argon in flame-dried glassware using standard Schlenk techniques. Chemicals and solvents were purchased from Sigma-Aldrich (Istanbul, Turkey) and Merck (Istanbul, Turkey). The solvents used were purified by distillation over the drying agents indicated and were transferred under Argon, Et_2O (Na/K alloy), CH_2Cl_2 (P_4O_10), hexane, and toluene (Na). Microanalyses were performed by İnönü University Scientific and Technological Research Center (Malatya, Turkey). Melting points were determined in glass capillaries under air with an Electrothermal-9200 melting point apparatus (Cole-Parmer, Istanbul, Turkey). FT-IR spectra were recorded on ATR (Attenuated Total Reflection) unit in the range of 400–4000 cm\(^{-1}\) with Perkin Elmer Spectrum 100 Spectrophotometer (Istanbul, Turkey). Routine \(^1\)H NMR and \(^{13}\)C NMR spectra were recorded using a Bruker Avance AMX spectrometer (Ankara, Turkey) operating at 300 and 400 MHz for \(^1\)H NMR, and at 75 and 100 MHz for \(^{13}\)C NMR in CDCl_3 with tetramethylsilane as an internal reference. Chemical shifts (\(\delta\)) and coupling constants (\(J\)) are reported in ppm and in Hz, respectively. \(^1\)H NMR spectra are referenced to CDCl_3 (\(\delta = 7.26\) ppm for CDCl_3), \(^{13}\)C chemical shifts are reported relative to deuterated solvent (\(\delta = 77.16\) ppm for CDCl_3). All catalytic reactions were monitored on an Agilent 6890N Gas Chromatography (Ankara, Turkey) and Schimadzu 2010 Plus GC-MS system (Ankara, Turkey) by GC-FID (Flame Ionization Dedector) with a HP-5 column of 30 m length, 0.32 mm diameter and 0.25 µm film thickness. Column chromatography was performed using silica gel 60 (70–230 mesh).

3.2. General Procedure for the Preparation of Benzimidazolium Halides 1a–e

To a solution of 1-(n-butyl)benzimidazole (5.0 mmol) in DMF (5 mL) was added benzyl halide (5.0 mmol) and the resulting mixture was stirred at 80 °C for 5 h. After completion of the reaction, the solid was removed by vacuum and diethylether (15 mL) was added to obtain a white crystalline solid, which was filtered off. The solid was washed with diethyl ether (3 × 10 mL) and dried under vacuum. The crude product was recrystallized from EtOH/Et_2O mixture (1:2, v/v) and dried under vacuum. The \(^1\)H NMR and \(^{13}\)C NMR spectra of new benzimidazolium halides (1a, 1b, 1d and 1e) are available supporting information (Figures S1–S4).

1-(3-Methylbenzyl)-3-(n-Butyl)Benzimidazolium Chloride, 1a: (1.228 g, yield 78%) \(^1\)H NMR (400 MHz, CDCl_3, 25 °C): \(\delta = 0.90\) (t, \(3J = 7.4\) Hz, 3H, CH_2CH_2CH_2CH_3); 1.38 (hex, \(3J = 7.5\) Hz, 2H, CH_2CH_2CH_2CH_3); 1.97 (pent, \(3J = 7.5\) Hz, 2H, CH_2CH_2CH_2CH_3); 2.22 (s, 3H, CH_2C_6H_4(CH_3)-3; 4.57 (t, \(2J = 7.4\) Hz, 2H, CH_2CH_2CH_2CH_3); 5.79 (s, 2H, CH_2C_6H_4(CH_3)-3); 7.04 (d, \(3J = 7.5\) Hz, 1H, arom. CH, NC_6H_4N and CH_2C_6H_4(CH_3)-3); 7.13–7.21 (m, 3H, arom. CH, NC_6H_4N and CH_2C_6H_4(CH_3)-3); 7.47–7.57 (m, 3H, arom. CH, NC_6H_4N and CH_2C_6H_4(CH_3)-3); 7.67 (d, \(3J = 8.2\) Hz, 1H, arom. CH, NC_6H_4N and CH_2C_6H_4(CH_3)-3); 11.49 (s, 1H, NCHN) ppm. \(^{13}\)C NMR (100 MHz, CDCl_3, 25 °C): \(\delta = 13.5\) (CH_2CH_2CH_2CH_3); 19.8 (CH_2CH_2CH_2CH_3); 21.3 (CH_2C_6H_4(CH_3)-3); 31.3 (CH_2CH_2CH_2CH_3); 47.5 (CH_2CH_2CH_2CH_3); 51.3 (CH_2C_6H_4(CH_3)-3); 113.1, 113.9, 125.3, 127.0, 127.1, 128.8, 129.1, 129.8, 131.2, 131.5, 132.9, 139.1 (arom. C, NC_6H_4N and CH_2C_6H_4(CH_3)-3); 143.2 (NCHN) ppm (Figure S1).

Elemental analysis calcd (%) for C_{19}H_{25}ClN_2 (Molar Mass (Mr) = 314.90): C 72.48, H 7.36, N 8.90; found (%): C 72.54, H 7.38, N 8.93.

1-(2,3,5,6-Tetramethylbenzyl)-3-(n-Butyl)Benzimidazolium Chloride, 1b: (1.481 g, yield 83%) \(^1\)H NMR (300 MHz, CDCl_3, 25 °C): \(\delta = 0.87\) (t, \(3J = 7.0\) Hz, 3H, CH_2CH_2CH_2CH_3); 1.33 (hex, \(3J = 6.9\) Hz, 2H, CH_2CH_2CH_2CH_3); 1.91 (pent, \(3J = 6.5\) Hz, 2H, CH_2CH_2CH_2CH_3); 2.16 (s, 12H, CH_2C_6H_4(CH_3)-3,5,6); 4.61 (t, \(2J = 6.3\) Hz, 2H, CH_2CH_2CH_2CH_3); 5.85 (s, 2H, CH_2C_6H_4(CH_3)-4,2,3,5,6); 6.98 (s, 1H, arom. CH, CHCH_2H(CH_3)-4,2,3,5,6); 7.22 (d, \(3J = 8.2\) Hz, 1H, arom. CH of benzimidazole, NC_6H_4N); 7.40 (t, \(3J = 7.7\) Hz, 1H, arom. CH of benzimidazole, NC_6H_4N); 7.53 (t, \(3J = 7.4\) Hz, 1H, arom. CH...
of benzimidazole, NC6H4(N); 7.69 (d, 3J = 8.0 Hz, 1H, arom. CH of benzimidazole, NC6H4(N); 10.86 (s, 1H, NCH) ppm. 13C NMR (75 MHz, CDCl3, 25 °C): δ = 13.5 (CH2CH2CH2CH3); 16.0 (CH2CH2CH2CH2CH3); 19.7 (CH2CH2CH2CH3); 20.5 (CH2CH2CH2CH2CH3); 31.3 (CH2CH2CH2CH3); 47.5 (CH2CH2CH2CH3); 47.8 (CH2CH2CH2CH3); 113.1, 113.8, 127.0, 127.2, 127.9, 131.4, 131.5, 133.4, 134.0, 134.9 (arom. C, NC6H4(N) and CH2CH2CH2CH3); 142.9 (NCH) ppm (Figure S2). Elemental analysis calc’d (%) for C22H29ClN2 (Mr = 356.90): C 74.03, H 8.19, N 7.85; found (%): C 74.00, H 8.16, N 7.81.

1-(4-tet-Butylbenzyl)-3-(n-Butyl)Benzimidazolium Bromide, 1d: (1.605 g, yield 80%) 1H NMR (400 MHz, CDCl3, 25 °C): δ = 0.99 (t, 3J = 7.4 Hz, 3H, CH3(CH2)4CH2); 1.26 (s, 9H, CH3(CH2)4CH2(N)); 1.48 (hext, 3J = 7.7 Hz, 2H, CH2CH2CH2CH3); 2.07 (pent, 3J = 7.6 Hz, 2H, CH2CH2CH2CH3); 4.64 (t, 3J = 7.4 Hz, 2H, CH2CH2CH2CH3); 5.88 (s, 2H, CH2CH2H4(C(CH3)3)-4); 7.37–7.39 (m, 2H, arom. CH, NC6H4(N) and CH2CH2H4(C(CH3)3)-4); 7.47–7.49 (m, 2H, arom. CH, NC6H4(N) and CH2CH2H4(C(CH3)3)-4); 7.57–7.64 (m, 2H, arom. CH, NC6H4(N) and CH2CH2H4(C(CH3)3)-4); 7.68–7.74 (m, 2H, arom. CH, NC6H4(N) and CH2CH2H4(C(CH3)3)-4); 11.45 (s, 1H, NCHN) ppm. 13C NMR (100 MHz, CDCl3, 25 °C): δ = 13.5 (CH2CH2CH2CH3); 19.9 (CH2CH2CH2CH3); 31.2 (CH2CH2H4(C(CH3)3)-4); 31.3 (CH2CH2CH2CH3); 34.7 (CH2CH2H4(C(CH3)3)-4); 47.6 (CH2CH2CH2CH3); 51.1 (CH2CH2H4(C(CH3)3)-4); 113.1, 113.9, 126.3, 127.1, 127.2, 128.2, 128.9, 131.3, 131.5, 152.4 (arom. C, NC6H4(N) and CH2CH2H4(C(CH3)3)-4); 142.6 (NCH) ppm (Figure S3). Elemental analysis calc’d (%) for C22H29BrN2 (Mr = 401.40): C 65.83, H 7.28, N 6.98; found (%): C 65.75, H 7.29, N 6.95.

1-(2,3,5,6-Tetramethylbenzyl)-3-(3-Methoxybenzyl)Benzimidazolium Chloride, 1e: (1.831 g, yield 87%) 1H NMR (300 MHz, CDCl3, 25 °C): δ = 2.25 and 2.26 (s, 12H, CH2(CH3)4CH2); 3.76 (s, 3H, CH2CH2H4(OCH3)); 5.98 (s, 2H, CH2CH2H4(OCH3)); 5.89 (s, 2H, CH2CH2H4(OCH3)); 6.86 (d, 3J = 8.6 Hz, 2H, arom. CH, NC6H4(N) and CH2CH2H4(OCH3)); 7.08 (s, 1H, arom. CH, CH2CH2H4(OCH3)); 7.20 (d, 3J = 8.1 Hz, 1H, arom. CH, NC6H4(N) and CH2CH2H4(OCH3)); 7.38–7.51 (m, 4H, arom. CH, NC6H4(N) and CH2CH2H4(OCH3)); 11.53 (s, 1H, NCHN) ppm. 13C NMR (75 MHz, CDCl3, 25 °C): δ = 16.2 and 20.6 (CH2H4(CH3)4C(CH2)3); 47.9 (C(CH2)4CH2H4(OCH3)); 55.3 (CH2CH2H4(OCH3)); 113.6, 113.8, 114.4, 114.7, 125.1, 126.9, 127.0, 127.7, 129.9, 131.6, 133.6, 134.1, 135.1, 160.1 (arom. C, NC6H4(N), CH2CH2H4(CH3)4C(CH2)3); 7.47–7.46 (m, 1H, arom. CH of benzimidazole, NC6H4(N)); 7.42–7.46 (m, 1H, arom. CH of benzimidazole, NC6H4(N)) ppm. 13C NMR (75 MHz, CDCl3, 25 °C): δ = 13.9 (CH2CH2CH2CH3); 19.0 (CH2CH2CH2CH3); 20.0 (CH2CH2H4(C(CH3)3)-3); 32.3 (CH2CH2CH2CH3); 48.3 (CH2CH2CH2CH3); 50.8 (CH2CH2H4(C(CH3)3)-3); 87.4, 99.8, 100.6, 109.7, 111.9, 114.4, 123.4, 124.0, 132.8, 134.7 (arom. C, NC6H4(N) and CH2CH2H4(C(CH3)3);
181.3 (Ru-Carbene) ppm (Figure S5). Elemental analysis calcd (%) for C_{19}H_{22}Cl_{2}N_{2}Ru (Mr = 450.40): C 50.67, H 4.92, N 6.22; found (%): C 50.74, H 4.95, N 6.26.

**Dichloro-[1-(2,3,5,6-tetramethylbenzyl)-3-(butyl)benzimidazol-2-yldiene]ruthenium(II), 2b:** (0.393 g, yield 80%) 1H NMR (300 MHz, CDCl3, 25 °C): δ = 0.94 (t, 3J = 7.4 Hz, 3H, CH(CH3)2), 1.44 (hext, 3J = 7.5 Hz, 2H, CH2CH2CH2CH3); 1.85 (pent, 3J = 7.5 Hz, 2H, CH2CH2CH2CH3); 1.99 and 2.13 (s, 12H, CH2CH2CH2CH3); 4.42–4.48 ppm (m, 2H, CH2CH2CH2CH3); 5.06 (s, 2H, CH2CH2CH2CH3); 5.54 (s, 1H, arom. CH, CH2CH2CH2CH3); 7.32–7.38 ppm (m, 2H, arom. CH of benzimidazole, NC6H4(N)).

**Dichloro-[1-(2,3,5,6-tetramethylbenzyl)-3-(4-methoxybenzyl)benzimidazol-2-yldiene]ruthenium(II), 2d:** (0.349 g, yield 71%) 1H NMR (300 MHz, CDCl3, 25 °C): δ = 0.97 (t, 3J = 7.1 Hz, 3H, CH(CH3)2), 1.26 (s, 9H, CH2C6H4(C(CH3)3)-4); 1.46 (hext, 3J = 6.4 Hz, 2H, CH2CH2CH2CH3); 1.93–1.95 (m, 2H, CH2CH2CH2CH3); 4.65 (m, 2H, CH2CH2CH2CH3); 5.40 (dd, J = 52.0, 14.7 Hz, 2H, CH2CH2CH2CH3); 5.44 (s, 1H, arom. CH, CH2C6H4(C(CH3)3)-4); 7.32–7.58 ppm (m, 4H, arom. CH of benzimidazole, NC6H4(N)).

**Dichloro-[1-(2,3,5,6-tetramethylbenzyl)-3-(3-butyl)benzimidazol-2-yldiene]ruthenium(II), 2e:** (0.422 g, yield 76%) 1H NMR (300 MHz, CDCl3, 25 °C): δ = 2.04 and 2.16 (s, 12H, CH2C6H4(C(CH3)3)-4,2,5,6); 3.74 (s, 3H, CH3C6H4(OCH3)-4); 5.12 (s, 2H, CH2C6H4(CH3)2); 5.59 (s, 1H, arom. CH, CH2C6H4(CH3)2); 6.58 (s, 2H, CH2C6H4(OCH3)-4); 6.77 (d, 3J = 8.7 Hz, 2H, arom. CH, NC6H4(N) and CH2C6H4(OCH3)-4); 7.06–7.12 (m, 1H, arom. CH, NC6H4(N) and CH2C6H4(OCH3)-4); 7.20–7.28 ppm (m, 3H, arom. CH, NC6H4(N) and CH2C6H4(OCH3)-4); 7.42 (d, 3J = 8.0 Hz, 1H, arom. CH, NC6H4(N) and CH2C6H4(OCH3)-4).

**Dichloro-[1-(2,3,5,6-tetramethylbenzyl)-3-(4-methoxybenzyl)benzimidazol-2-yldiene]ruthenium(II), 2e:** (0.422 g, yield 76%) 1H NMR (300 MHz, CDCl3, 25 °C): δ = 2.04 and 2.16 (s, 12H, CH2C6H4(C(CH3)3)-4,2,5,6); 3.74 (s, 3H, CH3C6H4(OCH3)-4); 5.12 (s, 2H, CH2C6H4(CH3)2); 5.59 (s, 1H, arom. CH, CH2C6H4(CH3)2); 6.58 (s, 2H, CH2C6H4(OCH3)-4); 6.77 (d, 3J = 8.7 Hz, 2H, arom. CH, NC6H4(N) and CH2C6H4(OCH3)-4); 7.06–7.12 ppm (m, 1H, arom. CH, NC6H4(N) and CH2C6H4(OCH3)-4); 7.20–7.28 ppm (m, 3H, arom. CH, NC6H4(N) and CH2C6H4(OCH3)-4); 7.42 (d, 3J = 8.0 Hz, 1H, arom. CH, NC6H4(N) and CH2C6H4(OCH3)-4).
3.4. General Procedure for the Direct Catalytic Arylation of 2-Phenylpyridine with (Hetero)Aryl Chlorides

Each [RuCl$_2$(η$^6$,η$^1$-arene-CH$_2$-NHC)] complex (2a–e) (0.025 mmol) and KOAc (0.05 mmol) was stirred in water (2 mL) at room temperature for 1 h, and then 2-phenylpyridine (0.5 mmol), (hetero)aryl chloride (1.25 mmol) and Cs$_2$CO$_3$ (1.50 mmol) were added. The resulting mixture was stirred at 100 °C for different durations. After completion of the reaction, the reaction mixture was cooled to room temperature. Dichloromethane was added to this mixture and organic phase was extracted. The extracted organic phase was dried over MgSO$_4$ and concentrated under vacuum. The remaining residue was purified by column chromatography on silica gel (pentane/diethylether mixture, 1:5 v/v). The ortho-arylated products A and B conversion and ratio were determined by GC and GC-MS analyses.

3.5. Single Crystal X-ray Diffraction and Structure Analysis

A crystal of compound 2b with dimensions of 0.31 × 0.13 × 0.07 mm$^3$ was mounted on the tip of a glass fiber using epoxy and placed on a Bruker SMART 1000 CCD (Atlanta, GA, USA) sealed tube diffractometer with graphite monochromated MoKα (0.71073 Å) radiation. Data were measured at 373(2) K using a series of combinations of phi and omega scans. Data collection, indexing and initial cell refinements were all carried out using SMART software [55]. Frame integration and final cell refinements were done using SAINT software [56]. The structure was solved using Direct methods and difference Fourier techniques (SHELXTL, V6.12) [57]. Hydrogen atoms were placed in their expected chemical positions using the HFIX command and were included in the final cycles of least squares with isotropic Uij related to the atoms ridden upon. All non-hydrogen atoms were refined anisotropically. Structure solution, refinement, graphics and generation of publication materials were performed using the software SHELXTL, Version 6.12 [57].

4. Conclusions

The above described reactions demonstrate that water can be used as solvent for direct C–H bond functionalization. It is noteworthy that, in addition to its role as safe, clean, and recoverable solvent, water also plays the role of a positive catalyst partner, as in the direct selective mono(hetero)arylation of 2-phenylpyridine. We have synthesized and characterized new benzimidazolium halides (1a–e) and five new [RuCl$_2$(η$^6$,η$^1$-arene-CH$_2$-NHC)] complexes (2a–e). Complexes 2a–e with KOAc partner showed good catalytic activity for the direct arylation of 2-phenylpyridine with (hetero)aryl chlorides in water. The catalytic activity of [RuCl$_2$(η$^6$,η$^1$-arene-CH$_2$-NHC)] for mono heteroarylation of heterocyclic arene (pyridine arene) has the potential to reach bidentate new ligands in the future. There is no serious doubt that this field of research will increase significantly in the future, hopefully making another step towards more environmentally friendly and energy/resources saving processes.

Supplementary Materials: Supplementary materials are available online. CCDC-1823696 contains the supplementary crystallographic data for this paper. These data can be obtained free of charge via www.ccdc.cam.ac.uk/data_request/cif, or by e-mailing data_request@ccdc.cam.ac.uk, or by contacting The Cambridge Crystallographic Data Centre, 12 Union Road, Cambridge CB2 1EZ, UK; Fax: +44(0)1223-336033.

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**Sample Availability:** Samples of the compounds 1a–e and 2a–e are available from the authors.