(This article was presented to the 28th National Chemistry Congress and submitted to JOTCSA as a full manuscript)

N-Butyl Substituted N-Heterocyclic Carbene-Pd(II)-Pyridine (PEPPSI) Complexes: Synthesis, Characterization, and Catalytic Activity in the Suzuki-Miyaura Reaction

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Abstract: A series of N-butyl substituted imidazolium salts, (**1a-c**) and their pyridine enhanced precatalyst preparation stabilization and initiation (**PEPPSI**) themed palladium *N*-heterocyclic carbene complexes (**2a-c**) were synthesized and characterized. Pd-NHC complexes were fully determined by elemental analysis and spectroscopic methods. The synthesized complexes were tested in Suzuki-Miyaura cross-coupling reaction. These complexes were found to be efficient catalysts for the Suzuki-Miyaura reaction of phenylboronic acid with aryl bromides.

Keywords: Suzuki-Miyaura coupling reaction, *N*-heterocyclic carbene, PEPPSI palladium complexes.

Submitted: July 20, 2016. **Revised:** August 22, 2016. **Accepted:** August 24, 2016.

Cite this: Fırıncı R. N-Butyl Substituted N-Heterocyclic Carbene-Pd(II)-Pyridine (PEPPSI) Complexes: Synthesis, Characterization, and Catalytic Activity in the Suzuki-Miyaura Reaction. Journal of the Turkish Chemical Society, Section A: Chemistry. 2016;3(3):93–104.

DOI: 10.18596/jotcsa.90024.

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INTRODUCTION

N-Heterocyclic carbenes (NHCs) have become a significant class of ligands in organometallic chemistry [1]. Stable *N*-heterocyclic carbenes (NHCs) have attracted much attention, due to being a strong *σ*-donor for transition metals [2, 3]. NHC complexes have some advantages over phosphine complexes such as their stability, being ease-to-handle, and lower toxicity [4]. Many NHC transition metal complexes have been generated in homogeneous catalysis as catalysts [5, 6] after the first isolation of free NHC by Arduengo [7]. Since the electronic and steric features of NHCs are tunable, the bearing NHC ligand metal complexes have become valuable reagents for homogeneous/heterogeneous catalysis [8-12].

Pd-NHC complexes have proved to be efficient catalysts in catalytic formation of carbon-carbon and carbon-heteroatom bonds [13-19]. Since the first example PEPPSI type (PEPPSI= Pyridine-Enhanced Precatalyst Preparation, Stabilization, and Initiation) Pd-NHC complexes were reported by Organ *et al*. in 2006, considerable efforts have been undertaken to develop these type of complexes because they are easy to prepare, air- and moisture-stable [20]. After Organ's work, Doucet and Matt exhibited monoligated NHC-based palladium pyridine complexes [21, 22].

In this context, this study was reported that the synthesis and characterization of three novel PEPPSI type N-butyl functionalized N-heterocyclic carbenes (NHC) complexes. Moreover, the catalytic activity of Pd(II) complexes were examined in Suzuki-Miyaura reaction.

MATERIALS and METHODS

All manipulations for the preparations of (**2a-c**) were performed under a dry argon atmosphere using standard Schlenk techniques. All glassware was flame-dried before use. Solvents were purified by distillation from an appropriate drying agent. Unless otherwise specified, chemicals were used as received without further purification. ^{1}H- and ^{13}C-NMR spectra were recorded on a Varian Mercury AS 400 spectrometer. A HP Agilant-6890N gas chromatograph was used in catalytic studies. Chemical shifts (δ) are referenced to external TMS. An electrothermal-9200 melting point apparatus was used to record the melting points. Elemental analyses were obtained by ODTU Microlab (Ankara, Turkey).

Syntheses of Imidazolium Salts (1a-c): To a solution of *N*-butylimidazole (10.0 mmol) in toluene (10.0 mL) was added aryl halides slowly (10.0 mmol) at 25°C for 24 h. Diethyl ether (15.0 mL) was added to obtain a white precipitate, which was collected on a Gooch crucible and washed with Et_2O (3×15.0 mL), and dried under vacuum. Recrystallization of the crude product from EtOH/Et_2O solution obtained white crystals of the salt (Scheme 1).

1a: Yield: 84%. m.p.: 100 °C. ^{1}H-NMR (δ, 400 MHz, $CDCl_3$): 0.83 [t, *J* = 7.2 Hz, 3H, C*H*$_3$CH$_2$CH$_2$CH$_2$N]; 1.26 [m, 2H, CH$_3$C*H*$_2$CH$_2$CH$_2$N]; 1.81 [m, 2H, CH$_3$CH$_2$C*H*$_2$CH$_2$N]; 2.16 [s, 9H, NCH$_2$-Ar-(CH$_3$)$_3$-*o*,*p*-C*H*$_3$]; 4.27 [t, *J* = 7.2 Hz, 2H, CH$_3$CH$_2$CH$_2$C*H*$_2$N]; 5.49 [s, 2H, NC*H*$_2$-Ar-(CH$_3$)$_3$]; 6.80 [s, 2H, NCH$_2$-Ar*H*$_2$-(CH$_3$)$_3$]; 6.80 [s, 2H, NC*H*CHN]; 7.60 [s, 2H, NCHC*H*N]; 10.26 [s, 1H, NC*H*N]. ^{13}C-NMR (δ, 100 MHz, $CDCl_3$): 13.4 [*C*H$_3$CH$_2$CH$_2$CH$_2$N]; 19.4 [CH$_3$*C*H$_2$CH$_2$CH$_2$N]; 19.8 [NCH$_2$-Ar-(CH$_3$)$_3$-*o*-*C*H$_3$]; 21.0 [NCH$_2$-Ar-(CH$_3$)$_3$-*p*-*C*H$_3$]; 32.1 [CH$_3$CH$_2$*C*H$_2$CH$_2$N]; 47.8 [CH$_3$CH$_2$CH$_2$*C*H$_2$N]; 50.0 [N*C*H$_2$C$_6$H$_2$(CH$_3$)$_3$]; 120.6 [N*C*HCHN]; 122.3 [NCH*C*HN]; 125.3 [NCH$_2$-Ar*C*-(CH$_3$)$_3$]; 130.0 [NCH$_2$-Ar*C*-(CH$_3$)$_3$]; 136.7 [NCH$_2$-Ar*C*-(CH$_3$)$_3$]; 138.0 [NCH$_2$-Ar*C*-(CH$_3$)$_3$]; 139.9 [N*C*HN].

1b: Yield: 81%. m.p.: 110 °C. ^{1}H-NMR (δ, 400 MHz, $CDCl_3$): 0.85 [t, *J* = 7.4 Hz, 3H, C*H*$_3$CH$_2$CH$_2$CH$_2$N]; 1.30 [m, 2H, CH$_3$C*H*$_2$CH$_2$CH$_2$N]; 1.84 [m, 2H, CH$_3$CH$_2$C*H*$_2$CH$_2$N]; 2.09 [s, 6H, NCH$_2$-Ar-(CH$_3$)$_4$-*o*-C*H*$_3$]; 2.14 [s, 6H, NCH$_2$-Ar-(CH$_3$)$_4$-*m*-C*H*$_3$]; 4.29 [t, *J* = 7.4 Hz, 2H, CH$_3$CH$_2$CH$_2$C*H*$_2$N]; 5.57 [s, 2H, NC*H*$_2$-Ar-(CH$_3$)$_4$]; 6.81 [s, 1H, NC*H*CHN]; 6.95 [s, 1H, NCH$_2$-Ar*H*-(CH$_3$)$_4$]; 7.59 [s, 1H, NCHC*H*N]; 10.27 [s, 1H, NC*H*N]. ^{13}C-NMR (δ, 100 MHz, $CDCl_3$): 13.4 [*C*H$_3$CH$_2$CH$_2$CH$_2$N]; 15.8 [CH$_3$*C*H$_2$CH$_2$CH$_2$N]; 19.4 [NCH$_2$-Ar-(CH$_3$)$_4$-*o*-*C*H$_3$]; 20.4 [NCH$_2$-Ar-(CH$_3$)$_4$-*p*-*C*H$_3$]; 32.1 [CH$_3$CH$_2$*C*H$_2$CH$_2$N]; 48.5 [CH$_3$CH$_2$CH$_2$*C*H$_2$N]; 50.0 [N*C*H$_2$-Ar-(CH$_3$)$_4$]; 120.8 [N*C*HCHN]; 122.4 [NCH*C*HN]; 128.0 [NCH$_2$-Ar*C*-(CH$_3$)$_4$]; 129.7 [NCH$_2$-Ar*C*-(CH$_3$)$_4$]; 133.4 [NCH$_2$-Ar*C*-(CH$_3$)$_4$]; 134.0 [NCH$_2$-Ar*C*-(CH$_3$)$_4$]; 135.0 [NCH$_2$-Ar*C*-(CH$_3$)$_4$]; 135.8 [NCH$_2$-Ar*C*-(CH$_3$)$_4$]; 136.4 [N*C*HN].

1c: Yield: 89%. m.p.: 117 °C. ^{1}H-NMR (δ, 400 MHz, $CDCl_3$): 0.86 [t, *J* = 7.4 Hz, 3H, C*H*$_3$CH$_2$CH$_2$CH$_2$N]; 1.29 [m, 2H, CH$_3$C*H*$_2$CH$_2$CH$_2$N]; 1.83 [m, 2H, CH$_3$CH$_2$C*H*$_2$CH$_2$N]; 2.13 [s, 6H, NCH$_2$-Ar-(CH$_3$)$_5$-*o*-C*H*$_3$]; 2.14 [s, 6H, NCH$_2$-Ar-(CH$_3$)$_5$-*m*-C*H*$_3$]; 2.17 [s, 3H, NCH$_2$-Ar-(CH$_3$)$_5$-*p*-C*H*$_3$]; 4.29 [t, *J* = 7.2 Hz, 2H, CH$_3$CH$_2$CH$_2$C*H*$_2$N]; 5.57 [s, 2H, NC*H*$_2$-Ar-(CH$_3$)$_5$]; 6.83 [t, *J* = 1.7 Hz, 1H, NC*H*CHN]; 7.54 [t, *J* = 1.7 Hz, 1H, NCHC*H*N]; 10.14 [s, 1H, NC*H*N]. ^{13}C-NMR (δ, 100 MHz, $CDCl_3$): 13.4 [*C*H$_3$CH$_2$CH$_2$CH$_2$N]; 16.8 [CH$_3$*C*H$_2$CH$_2$CH$_2$N]; 16.9 [NCH$_2$-Ar-(CH$_3$)$_5$-*o*-*C*H$_3$]; 17.2 [NCH$_2$-Ar-(CH$_3$)$_5$-*m*-*C*H$_3$]; 19.4 [NCH$_2$-Ar-(CH$_3$)$_5$-*p*-*C*H$_3$]; 32.1 [CH$_3$CH$_2$*C*H$_2$CH$_2$N]; 49.0 [CH$_3$CH$_2$CH$_2$*C*H$_2$N]; 50.0 [N*C*H$_2$-Ar-(CH$_3$)$_5$]; 120.8 [N*C*HCHN]; 122.2 [N*C*HCHN]; 125.3 [NCH$_2$-Ar*C*-(CH$_3$)$_5$]; 133.5 [NCH$_2$-Ar*C*-(CH$_3$)$_5$]; 133.7 [NCH$_2$-Ar*C*-(CH$_3$)$_5$]; 136.4 [NCH$_2$-Ar*C*-(CH$_3$)$_5$]; 137.2 [N*C*HN].

Syntheses of Pd-NHC Complexes (2a–c): Imidazolium bromide salts (**1a-c**, 1.0 mmol), $PdCl_2$ (1.1 mmol), KBr (5.0 mmol) and K_2CO_3 (5.0 mmol) were mixed in pyridine (5.0 mL). After the mixture was refluxed in for 18h, it was cooled down to room temperature. The mixture was then filtered by cannula and the solution was removed under vacuum. The residue was dissolved with CH_2Cl_2 (20.0 mL) and subsequently treated with saturated aqueous $CuSO_4$ solution (2 x 20.0 mL). After separation of the organic and the aqueous layer, the organic layer was dried over anhydrous $MgSO_4$ and then filtered. The filtrate was concentrated under vacuum to give the product (**2a-c**) as a yellow solid.

2a: Yield: 56%. m.p.: 172 °C. Anal. Calc. for $C_{22}H_{29}Br_2N_3Pd$: C, 43.91; H, 4.86; N, 6.98. Found: C, 44.34; H, 5.11; N, 6.92%. ^{1}H-NMR (δ, 400 MHz, $CDCl_3$): 1.02 [t, *J* = 7.4 Hz, 3H, C*H*$_3$CH$_2$CH$_2$CH$_2$N]; 1.44-1.54 [m, 2H, CH$_3$C*H*$_2$CH$_2$CH$_2$N]; 2.03-2.11 [m, 2H, CH$_3$CH$_2$C*H*$_2$CH$_2$N]; 2.30 [s, 3H, NCH$_2$-Ar-(CH$_3$)$_3$-*p*-C*H*$_3$]; 2.31 [s, 6H, NCH$_2$-Ar-(CH$_3$)$_3$-*o*-C*H*$_3$]; 4.49-4.53 [m, 2H, CH$_3$CH$_2$CH$_2$C*H*$_2$N]; 5.70 [s, 2H, NC*H*$_2$-Ar-(CH$_3$)$_3$]; 6.27 [d, *J* = 2.4 Hz, 1H, NC*H*CHN]; 6.78 [d, *J* = 2.4 Hz, 1H, NCHC*H*N]; 6.92 [s, 2H, NCH$_2$-Ar*H*$_2$-(CH$_3$)$_3$]; 7.32-7.35 [m, 2H, pyridyl-C*H*]; 7.75 [tt, *J* = 7.7 Hz, *J* = 1.8 Hz, *J* = 1.6 Hz, 1H, pyridyl-C*H*]; 9.09 [dt, *J* = 4.8 Hz, *J* = 1.5 Hz, 2H, pyridyl-C*H*]. ^{13}C-NMR (δ, 100 MHz, $CDCl_3$): 13.8 [*C*H$_3$CH$_2$CH$_2$CH$_2$N]; 20.0 [CH$_3$*C*H$_2$CH$_2$CH$_2$N]; 20.1 [NCH$_2$-Ar-(CH$_3$)$_3$-*o*-*C*H$_3$]; 21.0 [NCH$_2$-Ar-(CH$_3$)$_3$-*p*-*C*H$_3$]; 32.2 [CH$_3$CH$_2$*C*H$_2$CH$_2$N]; 49.5 [CH$_3$CH$_2$CH$_2$*C*H$_2$N]; 51.2 [N*C*H$_2$-Ar-(CH$_3$)$_3$]; 119.9 [N*C*HCHN]; 120.8 [NCH$_2$-Ar*C*-(CH$_3$)$_3$]; 124.5 [pyridyl-*C*]; 127.4 [NCH*C*HN]; 129.3 [NCH$_2$-Ar*C*-(CH$_3$)$_3$]; 137.8 [NCH$_2$-Ar*C*-(CH$_3$)$_3$]; 138.7 [pyridyl-*C*]; 138.8 [NCH$_2$-Ar*C*-(CH$_3$)$_3$]; 146.5 [Pd-*C*$_{carbene}$]; 152.6 [pyridyl-*C*].

2b: Yield: 67%. m.p.: 187 °C. Anal. Calc. for $C_{23}H_{31}Br_2N_3Pd$: C, 44.86; H, 5.07; N, 6.82. Found: C, 44.38; H, 5.46; N, 7.59%.^{1}H-NMR (δ, 400 MHz, $CDCl_3$): 1.03 [t, *J* = 7.4 Hz, 3H, C*H*$_3$CH$_2$CH$_2$CH$_2$N]; 1.46-1.52 [m, 2H, CH$_3$C*H*$_2$CH$_2$CH$_2$N]; 2.05-2.10 [m, 2H, CH$_3$CH$_2$C*H*$_2$CH$_2$N]; 2.21 [s, 6H, NCH$_2$-Ar-(CH$_3$)$_4$-*o*-C*H*$_3$]; 2.25 [s, 6H, NCH$_2$-Ar-(CH$_3$)$_4$-*m*-C*H*$_3$]; 4.49-4.53 [m, 2H, CH$_3$CH$_2$CH$_2$C*H*$_2$N]; 5.76 [s, 2H, NC*H*$_2$-Ar-(CH$_3$)$_4$]; 6.27 [d, *J* = 2.4 Hz, 1H, NC*H*CHN]; 6.78 [d, *J* = 2.4 Hz, 1H, NCHC*H*N]; 7.02 [s, 1H, NCH$_2$-Ar*H*-(CH$_3$)$_4$]; 7.32-7.36 [m, 2H, pyridyl-C*H*]; 7.73-7.77 [tt, *J* = 7.7 Hz, *J* = 1.8 Hz, *J* = 1.6 Hz, 1H, pyridyl-C*H*]; 9.08-9.10 [dt, *J* = 4.8 Hz, *J* = 1.5 Hz, 2H, pyridyl-C*H*]. ^{13}C-NMR (δ, 100 MHz, $CDCl_3$): 13.8 [*C*H$_3$CH$_2$CH$_2$CH$_2$N]; 16.0 [CH$_3$*C*H$_2$CH$_2$CH$_2$N]; 20.0 [NCH$_2$C$_6$H(CH$_3$)$_4$-*o*-*C*H$_3$]; 20.4 [NCH$_2$-Ar-(CH$_3$)$_4$-*m*-*C*H$_3$]; 32.2 [CH$_3$CH$_2$*C*H$_2$CH$_2$N]; 50.2 [CH$_3$CH$_2$CH$_2$*C*H$_2$N]; 51.2 [N*C*H$_2$-Ar-(CH$_3$)$_4$]; 120.2 [N*C*HCHN]; 120.7 [NCH$_2$-Ar*C*-(CH$_3$)$_4$]; 124.5 [pyridyl-*C*]; 130.2 [NCH*C*HN]; 132.4 [NCH$_2$-Ar*C*-(CH$_3$)$_4$]; 134.3 [NCH$_2$-Ar*C*-(CH$_3$)$_4$]; 134.8 [pyridyl-*C*]; 137.8 [NCH$_2$-Ar*C*-(CH$_3$)$_4$]; 146.4 [Pd-*C*$_{carbene}$]; 152.6 [pyridyl-*C*].

2c: Yield: 71%. m.p.: 193 °C. Anal. Calc. for $C_{24}H_{33}Br_2N_3Pd$: C, 45.77; H, 5.28; N, 6.67. Found: C, 45.79; H, 5.64; N, 7.78%. ^{1}H-NMR (δ, 400 MHz, $CDCl_3$): 1.03 [t, *J* = 7.2 Hz, 3H, C*H*$_3$CH$_2$CH$_2$CH$_2$N]; 1.44-1.54 [m, 2H, CH$_3$C*H*$_2$CH$_2$CH$_2$N]; 2.04-2.11 [m, 2H, CH$_3$CH$_2$C*H*$_2$CH$_2$N]; 2.24 [s, 6H, NCH$_2$-Ar-(CH$_3$)$_5$-*o*-C*H*$_3$]; 2.25 [s, 6H, NCH$_2$-Ar-(CH$_3$)$_5$-*m*-C*H*$_3$]; 2.27 [s, 3H, NCH$_2$-Ar-(CH$_3$)$_5$-*p*-C*H*$_3$]; 4.49-4.53 [m, 2H, CH$_3$CH$_2$CH$_2$C*H*$_2$N]; 5.77 [m, 2H, NC*H*$_2$-Ar-(CH$_3$)$_5$]; 6.31 [d, *J* = 2.0 Hz, 1H, NC*H*CHN]; 6.77 [d, *J* = 2.0 Hz, 1H, NCHC*H*N]; 7.32-7.35 [m, 2H, pyridyl-C*H*]; 7.73-7.77 [tt, *J* = 7.7 Hz, *J* = 1.8 Hz, *J* = 1.6 Hz, 1H, pyridyl-C*H*]; 9.08-9.10 [dt, *J* = 4.8 Hz, *J* = 1.5 Hz, 2H, pyridyl-C*H*]. ^{13}C-NMR (δ, 100 MHz, $CDCl_3$): 13.8 [*C*H$_3$CH$_2$CH$_2$CH$_2$N]; 16.8 [CH$_3$*C*H$_2$CH$_2$CH$_2$N]; 17.0 [NCH$_2$-Ar-(CH$_3$)$_5$-*o*-*C*H$_3$]; 17.1 [NCH$_2$-Ar-(CH$_3$)$_5$-*m*-*C*H$_3$]; 20.0 [NCH$_2$-Ar-(CH$_3$)$_5$-*p*-*C*H$_3$]; 32.0 [CH$_3$CH$_2$*C*H$_2$CH$_2$N]; 50.7 [CH$_3$CH$_2$CH$_2$*C*H$_2$N]; 51.1 [N*C*H$_2$-Ar-(CH$_3$)$_5$]; 120.3 [N*C*HCHN]; 120.6 [NCH$_2$-Ar*C*-(CH$_3$)$_5$]; 124.4 [pyridyl-*C*]; 127.5 [NCH*C*HN]; 133.1 [NCH$_2$-Ar*C*-(CH$_3$)$_5$]; 134.3 [NCH$_2$-Ar*C*-(CH$_3$)$_5$]; 136.0 [pyridyl-*C*]; 137.7 [NCH$_2$-Ar*C*-(CH$_3$)$_5$]; 146.2 [Pd-*C*$_{carbene}$]; 152.6 [pyridyl-*C*].

General procedure for Suzuki-Miyaura cross-coupling reactions: In a typical procedure, a mixture of aryl halide (0.5 mmol), phenylboronic acid (0.75 mmol), Cs_2CO_3 (1.5 mmol), diethylene glycol di-n-butyl ether (0.3 mmol, as an internal standard) and palladium(II) catalyst (1 mol%) was added to a two-necked 25.0 mL flask containing 3.0 mL of 2-propanol. The flask was placed in a pre-heated oil bath (25 °C and 80 °C) under an argon atmosphere. After completion of the reaction, the mixture was cooled down to room temperature and 2-propanol was added. The mixture was filtered through a pad of silica gel with copious washing. The solution was concentrated and purified by flash chromatography on silica gel. The reactions were followed by GC and the yields were based on aryl bromide.

Table 1: Performance of the **2c** in the Suzuki-Miyaura of 4-bromoacetophenone in the presence of different bases (Temperature = 80 °C).

Entry	Base	Solvent	Time (min.)	Yield (%)[b,c]
1	NaOH	IPA	30	41
2	KOH	IPA	30	47
3	K_2CO_3	IPA	15	73
4	Cs_2CO_3	IPA	15	99

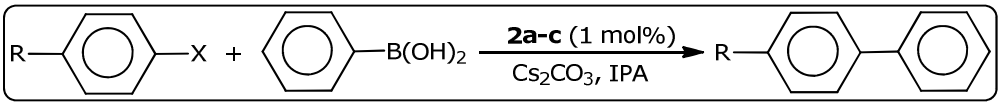
RESULTS and DISCUSSION

Preparation of the imidazolium salts: The asymmetrically substituted imidazolium salts (**1a-c**) were synthesized by reaction of *N*-butylimidazole and benzyl bromide derivative in toluene at room temperature (see the scheme). The imidazolium salts were

obtained as white solids, which have been observed to be air-stable. The imidazolium salts were characterized by ^{1}H- and ^{13}C-NMR spectroscopy. ^{1}H- and ^{13}C-NMR chemical shifts complied with the expected structures. The resonances for NC*H*N protons give as a sharp singlet between at δ 10.14 and 10.27 ppm. According to ^{13}C-NMR spectrum of these salts, the C2 carbon atoms appeared between at δ 136.4 and 137.2 ppm.

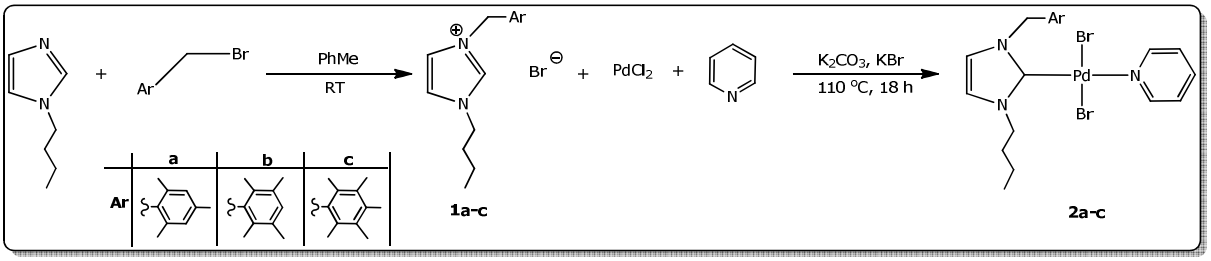
Preparation of NHC-Pd-pyridine complexes: PEPPSI type Pd-NHC complexes (**2a-c**) were synthesized from the reaction of 1,3-dialkylimidazolium salts with $PdCl_2$, KBr and K_2CO_3 as base in pyridine (Scheme 1). The characterization of the NHC-Pd-pyridine complexes were confirmed by ^{1}H- and ^{13}C-NMR spectroscopy and elemental analysis. The chemical shifts for the carbene carbon atom, **2a-c**, fall in the range δ 146.2–146.5 ppm.

Table 2: The Suzuki–Miyaura cross-coupling reaction of aryl bromide with phenylboronic acid catalyzed by Pd-NHC (PEPPSI) complexes (**2a-c**). Optimization of reaction parameters[a].



Entry	[Cat.]	[Pd](%)	Ar-X	T (°C)	t (min)	Yield (%)[b,c]
1	**2a**	1	Ph-Br	25/80	120/15	67/94
2	**2a**	1	Me-C_6H_4-4-Br	25/80	120/15	29/90
3	**2a**	1	$CH_3(O)C$-C_6H_4-4-Br	25/80	30/15	89/99
4	**2b**	1	Ph-Br	25/80	120/15	65/75
5	**2b**	1	Me-C_6H_4-4-Br	25/80	120/15	32/91
6	**2b**	1	$CH_3(O)C$-C_6H_4-4-Br	25/80	30/15	87/99
7	**2c**	1	Ph-Br	25/80	120/15	69/94
8	**2c**	1	Me-C_6H_4-4-Br	25/80	120/15	34/72
9	**2c**	1	$CH_3(O)C$-C_6H_4-4-Br	25/80	30/15	97/99
10	**$PdCl_2$**	1	$CH_3(O)C$-C_6H_4-4-Br	80	240	1
11	**2a**	1	$CH_3(O)C$-C_6H_4-4-Cl	80	240	37
12	**2b**	1	$CH_3(O)C$-C_6H_4-4-Cl	80	240	30
13	**2c**	1	$CH_3(O)C$-C_6H_4-4-Cl	80	240	36

[a] Reagents: an aryl halide (0.50 mmol), $PhB(OH)_2$ (0.75 mmol), Cs_2CO_3 (1.50 mmol), diethylene glycol di-*n*-butyl ether (0.3 mmol, internal standard), Pd-NHC catalyst (1 mol%), and 2-propanol (3.0 mL).
[b] Yields based on the aryl halide and average of two runs.
[c] All reactions were followed by GC.
[d] Referred to the reaction time indicated in column.



Scheme 1: Synthesis of imidazolium salts and PEPPSI type Pd-NHC complexes.

Suzuki-Miyaura Coupling Reaction: A series of studies were performed to determine a suitable base for the catalytic system in Suzuki-Miyaura coupling reaction (Table 1). In the catalytic studies, complexes (**2a-c**) were employed in 2-propanol with 1 mol% catalyst loading, Suzuki-Miyaura coupling reactions (Table 2). The works were initiated with the investigation of coupling of *p*-bromoacetophenone and phenylboronic acid in the presence of Pd-NHC catalyst at 25°C. The results indicated that the complexes (**2a-c**) displayed the best catalytic activity, giving excellent yield for 30 min. Under these conditions, *p*-bromobenzene and *p*-bromotoluene reacted with phenylboronic acid. The three complexes (**2a-c**) showed the lowest coupling yields for *p*-bromotoluene, and moderate yields for *p*-bromobenzene within 2h. In order to examine the influence of temperature on the yields, same reactions were performed for *p*-bromoacetophenone, *p*-bromobenzene, and *p*-bromotoluene reacting with phenylboronic acid at 80 °C instead of 25 °C. The results indicated that the complexes (**2a**-**c**) could also be converted to corresponding desired coupling products in good to excellent yields at 80 °C within 15 min (Table 2). After good results from bromo derivatives, the catalytic activities were investigated for the coupling of *p*-chloroacetophenone and phenylboronic acid, in the presence of **2a-c** at 80 °C. The results are summarized in Table 2. It indicates that the complexes exhibited low activity when *p*-chloroacetophenone was used as substrates within 4 h. Also, the catalytic activity of $PdCl_2$ was studied (Entry 10) which the coupling yield is 1% for *p*-bromoacetophenone as a substrate at 80 °C. The low activity of aryl chloride in Suzuki-Miyaura cross coupling reaction has also been reported in the previous studies [23-24].

In this work, several new air- and moisture-stable, convenient to handle, and easily synthesized PEPPSI-type Pd-NHC complexes have been designed. A series of NHC precursors (**1a-c**) were synthesized by the alkylation reaction of *N*-butylimidazole. The Pd-NHC complexes (**2a-c**) were prepared from their respective imidazolium halide salts by the reaction with KBr and $PdCl_2$ in pyridine in presence of K_2CO_3 as a base. All complexes are stable toward light and air both in the solid state and in solution. The molecular structures of the imidazolium bromide salt (**1a-c**) and the Pd–NHC complexes (**2a-c**) have been characterized by elemental analysis and ^{1}H- and ^{13}C-NMR spectra.

These novel imidazolium based NHC-palladium(II)-pyridine complexes have high catalytic activity in the Suzuki-Miyaura coupling reactions of aryl bromides. Reactions reach completion in short reaction time for *p*-bromoacetophenone as a substrate at 25°C. The catalytic activities of **2a-c** were compared with $PdCl_2$ for *p*-bromoacetophenone as a substrate at 80°C. Synthesized complexes have significantly better activity than $PdCl_2$. Furthermore, the complex **2c** shows the most noticeable activity and a maximum yield of 97% was achieved after 30 min. The complexes (**2a**-**c**) exhibit good catalytic activity at 80°C within 15 min.

ACKNOWLEDGEMENTS

Financial support of "Scientific Research Project Unit (BAP) of Adnan Menderes University" (Project No: FEF-14002) and "The Scientific and Technological Research Council of Turkey" (TUBITAK, Project No: 110T765) are gratefully acknowledged.

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Türkçe Öz ve Anahtar Kelimeler

N-Butyl Substituted N-Heterocyclic Carbene-Pd(II)-Pyridine (PEPPSI) Complexes: Synthesis, Characterization, and Catalytic Activity in the Suzuki-Miyaura Reaction

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Öz: Bir seri N-butil sübstitüe imidazolyum tuzu (**1a-c)** ve piridinle kuvvetlendirilen ön katalizör hazırlama, kararlılaştırma ve başlatma (PEPPSI) yöntemiyle üretilen paladyum *N*-heterosiklik karben kompleksleri (**2a-c**) sentezlenmiş ve karakterizasyonları yapılmıştır. Pd-NHC kompleksleri elementel analiz ve spektroskopik yöntemlerle tam olarak tayin edilmiştir. Sentezlenen kompleksler Suzuki-Miyaura çapraz eşleşme tepkimesinde test edilmiştir. Bu kompleksler Suzuki-Miyaura tepkimesinde kullanılan fenilboronik asit ve aril bromürler için etkili katalizörler olarak bulunmuştur.

Anahtar kelimeler: Suzuki-Miyaura eşleşme tepkimesi, *N*-heterosiklik karben, PEPPSI paladyum kompleksleri.

Gönderme: 20 Temmuz 2016. **Düzeltme:** 22 Ağustos 2016. **Kabul:** 24 Ağustos 2016.