FULL PAPER

Versatile and highly efficient *trans*-[Pd(NHC)Cl_2(DMS/THT)] precatalysts for C-N and C-C coupling reactions in green solvents

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Abstract: *A straightforward synthetic procedure to well-defined, air- and moisture- stable trans-[Pd(NHC)Cl_2(DMS/THT)] (NHC = IPr, SIPr, IMes, IPr^{Cl}, IPr*, IPr$^{\#}$) pre-catalysts is reported. These complexes were obtained by reacting NHC·HCl imidazolium salts with trans-[$PdCl_2$(DMS/THT)$_2$] precursors with the assistance of the weak base K_2CO_3 in green acetone at 40 °C. The scalability of this protocol was demonstrated. The catalytic activity of the synthesized complexes was studied in the Buchwald–Hartwig and Suzuki-Miyaura reactions. Remarkably, most of the synthesized complexes exhibit higher catalytic activity with respect to their PEPPSI congeners in the Buchwald-Hartwig amination in 2-MeTHF. In particular, complex trans-[Pd(IPr$^{\#}$)Cl_2(DMS)] enabled the coupling of various (hetero)aryl chlorides and primary/secondary amines with a 0.2 mol% catalyst loading. In addition, trans-[Pd(IPr)Cl_2(DMS)] showed excellent performance in the room-temperature Suzuki-Miyaura reaction involving various (hetero)aryl chlorides and aryl boronic acids. In summary, the synthesized complexes, especially trans-[Pd(NHC)Cl_2(DMS)], can be considered as greener alternatives to classical PEPPSI type catalysts based on the lower toxicity of the throw-away DMS ligand compared to 3-chloropyridine.*

Introduction

Transition metal-catalysed cross-coupling reactions have revolutionized chemical synthesis. These reactions have enabled the preparation of a wide range of pharmaceuticals, agrochemicals, and fine chemicals.[1] Among the cross-coupling processes, carbon-carbon (C-C) and carbon-nitrogen (C-N) couplings are the most employed in organic synthesis and are usually catalyzed by palladium[2] and nickel[3] complexes. Although nickel is less expensive and more abundant than palladium, in many cases Ni(0)-catalysts suffer from poor stability or low reactivity and require additional steps to ensure complete metal removal.[3b, 4] For these reasons, palladium pre-catalysts are still dominant in cross coupling reactions. Many research groups have focused on the development of palladium complexes bearing phosphine ligands as efficient cross-coupling catalysts.[1b,5] However, some phosphines and their palladium complexes are air- and moisture-sensitive, requiring strictly inert atmosphere handling, thus making their application in industry more difficult.[6] In order to overcome these drawbacks, *N*-heterocyclic carbenes (NHCs) have been employed as an alternative to classical phosphine ligands. The high stability to air- and moisture of palladium-NHC complexes and the stronger σ-donor character of NHCs with respect to phosphine ligands, has favoured the use of Pd-NHC derivatives in catalysis as well as in medicinal chemistry.[7] Regarding their use in catalysis, Suzuki-Miyaura and Buchwald-Hartwig reactions are undoubtedly the most studied C-C and C-N coupling reactions. Particularly used to this end are the Nolan allyl-based systems,[8] Organ PEPPSI complexes [9] and Buchwald palladacycles [1b, 5c, 10] (Figure 1). In all cases the active catalyst is considered to be the putative Pd(0)-L species. Therefore, a “throw-away” ligand is generated during the catalyst activation step. Notably, in Organ’s PEPPSI complexes the throw-away ligand, 3-chloropyridine or its coupling product, is very toxic and difficult to remove from the reaction mixture due to its high boiling point. Considering the above issues, developing environmentally friendly, less-toxic and more efficient Pd(II)-NHC pre-catalysts is of paramount importance in modern chemistry.

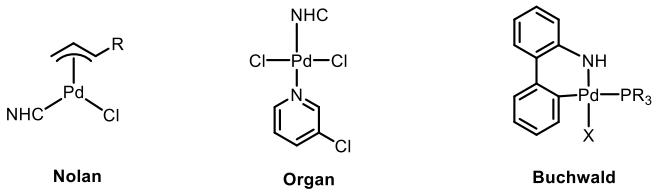


Figure 1. Three widely utilized well-defined palladium pre-catalysts.

In this context, it should be noted that in many cases the Suzuki-Miyaura coupling is conducted under inert atmosphere [1c, 2c, 11] and in the presence of deleterious solvents such as toluene[8c] or 1,4-dioxane.[9b, 12] Similarly, the Buchwald-Hartwig amination also has significant limitations in many cases. The most common are the use of expensive aryl bromides/iodides rather than cheaper aryl chlorides as substrates, high catalyst loading, temperature (>100 °C) and the use of environmentally unfriendly solvents such as 1,2-dimethoxyethane (DME) and toluene.[1e, 3c, 5c, 6a, 13]

Therefore, the development of robust, efficient, versatile and easily accessible Pd(II)–NHC pre-catalysts that operate under air and in the presence of greener solvents remains a key issue in cross-coupling applications.

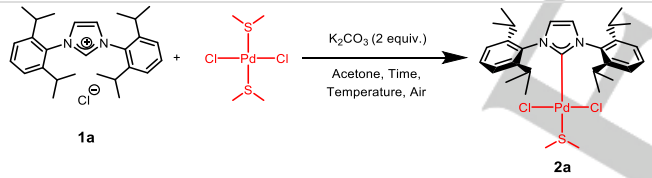
Here, we report a simple synthetic route to a selection of novel air- and moisture-stable *trans*-[Pd(NHC)Cl_2(DMS/THT)] complexes (DMS = dimethyl sulfide; THT = tetrahydrothiophene), with excellent catalytic activity in Buchwald-Hartwig and Suzuki-Miyaura reactions under mild aerobic conditions, and in well-established green solvents. Moreover, the synthesized compounds, especially those bearing the DMS ligand, can be considered greener and less toxic alternatives to classical PEPPSI-type catalysts.[14] In fact, the throw-away DMS ligand is a flavouring agent in the food industry and easier to remove from the catalytic system when compared to 3-chloropyridine or its coupling product.

Results and Discussion

Based on our experience in the synthesis of metal-NHC complexes with the assistance of a weak base (e.g. K_2CO_3, NaOAc, NEt_3),[15] we launched the model reaction between IPr·HCl and *trans*-[$PdCl_2(DMS)_2$] in presence of K_2CO_3 (2.0 equiv.) under aerobic mild conditions (60 °C in green acetone).

Two hours are sufficient for achieving full conversion of the starting materials, affording the desired complex **2a** in high yields (Entries 1-2, Table 1). To our surprise the reaction proceeds even at 40 °C with comparable yields (Entry 3, Table 1). Conversely, at room temperature a 72% conversion was obtained under the same conditions (Entry 4, Table 1).

Table 1. Optimization of reaction conditions[a]



Entry	Time (h)	Temperature (°C)	Conv.[b] (%)	Yield [b] (%)
1	3	60	>99	87
2	2	60	>99	92
3	2	40	>99	94
4	2	rt	72	70

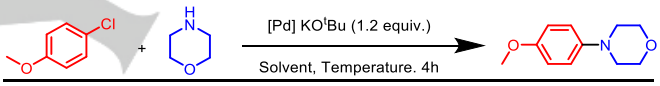
[a] Reaction condition: IPr·HCl (25 mg, 0.059 mmol), trans-[$PdCl_2(DMS)_2$] (18.4 mg, 0.029 mmol); K_2CO_3 (16.3 mg, 0.117 mmol); acetone, 0.5 mL; in air. [b] All conversions and yields were determined by ^{1}H NMR, using 1,3,5-trimethoxybenzene as internal standard.

With the optimal reaction conditions in hand, a selection of *trans*-[Pd(NHC)Cl_2(DMS)] complexes (**2a-e**) bearing different unsaturated and saturated NHCs were synthesized in excellent isolated yields (78-95%, Scheme 1). Encouraged by these excellent results, we successfully prepared also their tetrahydrothiophene (THT) congeners (**2f-i**), using the palladium precursor *trans*-[$PdCl_2(THT)_2$]. In all cases excellent yields and purity were obtained with a simple work-up procedure. Furthermore, *trans*-[Pd(IPr)Cl_2(DMS)] and *trans*-[Pd(IPr)Cl_2(THT)] complexes were synthesized on a multigram-scale with nearly quantitative yields (Scheme 1) highlighting the scalability of the simple procedure.

All synthesized palladium complexes were fully characterized by NMR spectroscopy and elemental analysis. In particular, the disappearance of the imidazolium proton in the ^{1}H NMR spectra and the presence of the carbene carbon signal at ca. 160 ppm in the ^{13}C NMR spectra are clearly indicative of the formation of the complexes of interest. Moreover, crystals of **2a-d**, **2f**, **2h** and **2i** suitable for X-ray diffraction were grown by slow diffusion of hexane (or pentane) into a saturated $CDCl_3$ (or CH_2Cl_2) solution of the complexes and the corresponding molecular structures are showed in Scheme 1.

To test the catalytic activity of the synthesized complexes, we examined the Buchwald–Hartwig amination reaction catalyzed by our new complexes. Also in this case, we opted for the challenging and inexpensive aryl chlorides as substrates. Firstly, the coupling between 4-chloroanisole and morpholine in THF and 2-MeTHF with 0.2 mol% of **2a** at 80 °C was initially examined. The highest yield (92%) can be achieved after 4 hours in 2-MeTHF (Entries 1 and 2, Table 2). 2-MeTHF is a greener version of THF as it can be produced form renewable resources.[16] For all these reasons, we chose 2-MeTHF as reaction solvent in the catalyst screening presented in Table 2.

Table 2. Optimization of reaction conditions between 4-chloroanisole and morpholine.

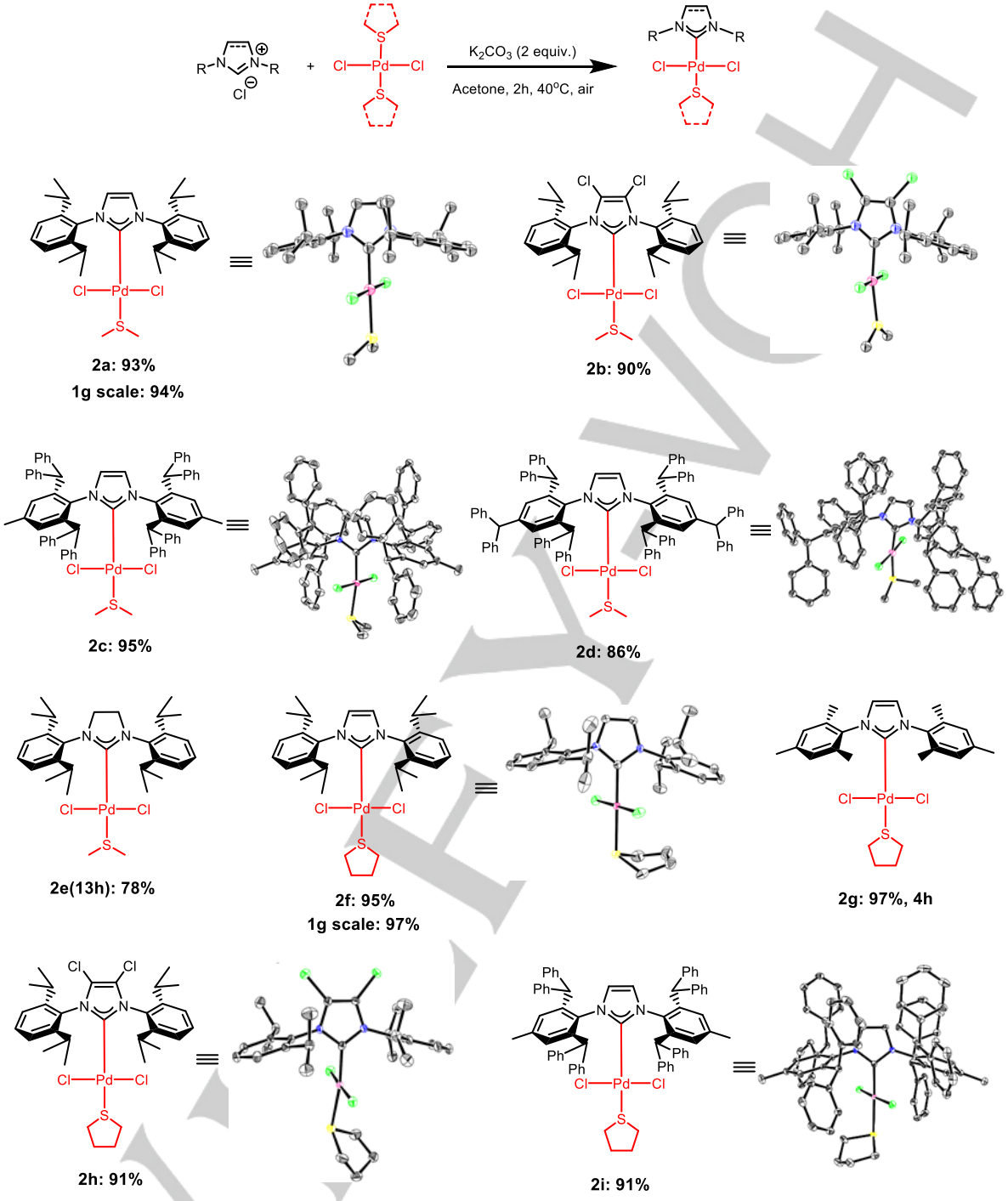


Entry	Catalyst	Loading (mol%)	Temp. (°C)	Solvent	Yield [b] (%)
1	**2a**	0.2	80	THF	88
2	**2a**	0.2	80	2-MeTHF	92
3	**PEPPSI (3)**	0.2	80	2-MeTHF	88
4	**2b**	0.2	80	2-MeTHF	91
5	**2c**	0.2	80	2-MeTHF	94
6	**2d**	0.2	80	2-MeTHF	98
7	**2e**	0.2	80	2-MeTHF	87
8	**2f**	0.2	80	2-MeTHF	86
9	**2g**	0.2	80	2-MeTHF	8
10	**2h**	0.2	80	2-MeTHF	90
11	**2i**	0.2	80	2-MeTHF	84
12	**2d**	0.2	60	2-MeTHF	34
13	**2d**	0.1	80	2-MeTHF	25

[a] Reaction conditions: 4-chloroanisole (1.0 mmol), morpholine (1.2 mmol), KO^{t}Bu (1.2 mmol), Pd(NHC)Cl_2(DMS/THT) **2a-i** or **PEPPSI (3)**, solvent (2.0 mL); [b] GC yield was determined using dodecane as internal standard.

All reactions were conducted in the presence of KO^{t}Bu (1.2 equiv.) and 0.2 mol% catalyst loading. Remarkably, the catalytic activity of most of the synthesized complexes (Entries 2, 4-6 and 10,

Table 2) is higher than that observed for the standard *trans*-[Pd(IPr)Cl_2(3-Cl-Py)] (**PEPPSI**) (Entry 3, Table 2). Interestingly, the bulky IPr* and IPr# derivatives **2c-d** showed best activity among all tested catalysts. We suspect that these bulky ligands can accelerate the rate-determining reductive elimination step.



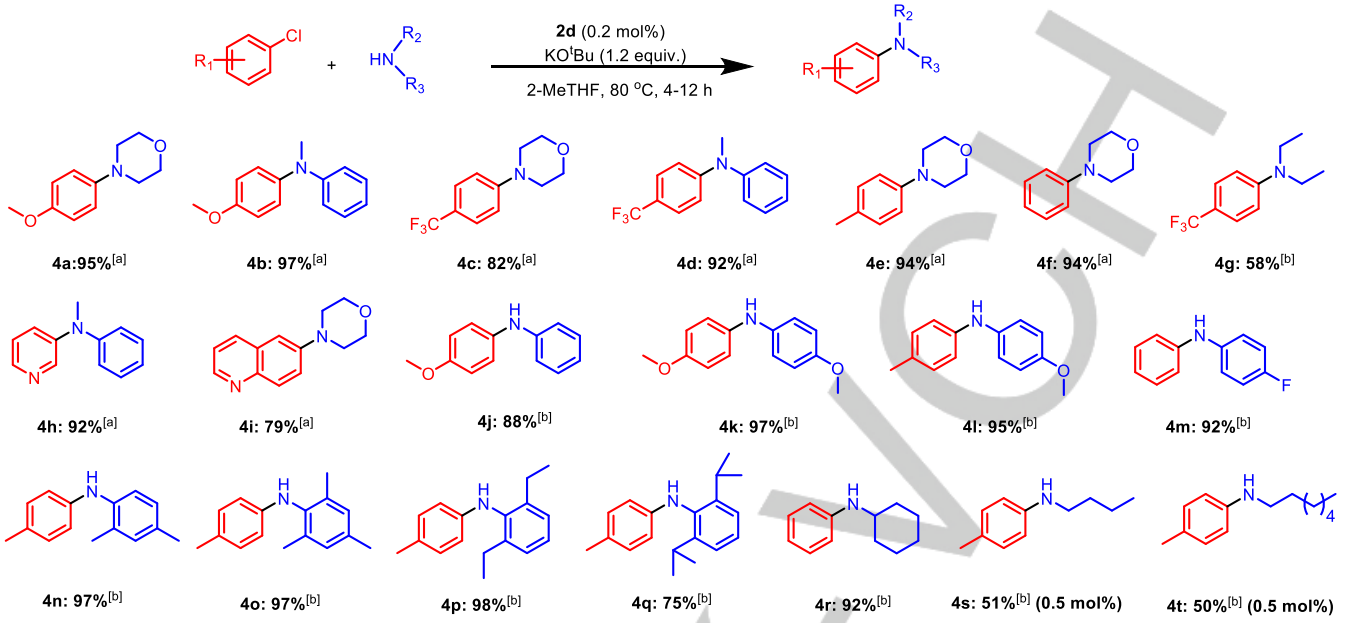
Scheme 1. Straightforward synthetic route to trans-[Pd(NHC)Cl_2(DMS/THT)] complexes **2a-i**. The X-ray molecular structure of complexes **2a-d**, **2f**, **2h** and **2i** are presented, showing thermal displacement ellipsoids at the 50% probability level and hydrogen atoms omitted for clarity (see ESI for more detailed structural information)

Conversely, the activation of the catalyst no longer represents a restriction as the reaction is carried at 80 °C. Again, the dimethyl sulfide complexes **2a-e** exhibited superior catalytic activities compared to their tetrahydrothiophene congeners **2f-i**.

Further variations of reaction conditions with the most efficient pre-catalyst **2d** demonstrated that lower temperatures (60 °C, Entry 12, Table 2) or lower catalyst loadings (0.1 mol%, Entry 13, Table 2) are both deleterious to achieving high yields.

With the optimal reaction conditions in hand (Entry 6, Table 2), Buchwald-Hartwig amination reactions were carried out between various (hetero)aryl chlorides and amines in the presence of

0.2 mol% of **2d** (Scheme 2). Aryl chlorides bearing electron donating and withdrawing functional groups reacted smoothly with secondary alkyl and arylalkyl amines. The desired coupling products (**4a-f**), with the only exception of the less active diethylamine derivative **4g**, were obtained in excellent yields.



Scheme 2. Scope of the room-temperature Buchwald-Hartwig reaction catalyzed by 2d; [a] reaction time was 4 hours; [b] reaction time was 12 hours.

Anilines of various natures including sterically hindered di-*ortho*-substituted examples were well tolerated and typically excellent yields were obtained with these as nucleophiles (**4j-q**).

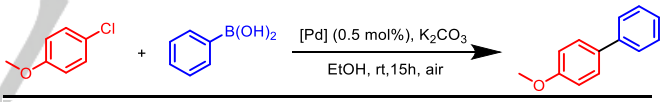
This catalytic system has also proven efficient for more challenging coupling partners such as heteroaryl chlorides and primary amines. Heteroaryl chlorides are known for possible catalyst deactivation and poor solubility that cause significant difficulties for C-N coupling.[17] Nevertheless, 3-chloropyridine and 6-chloroquinoline reacted with secondary amines without the need for increased reaction times (**4h-l**).

In the case of primary amines, the most important challenge is the prevention of diarylation product formation. We observed this product is formed with cyclohexylamine only when the reaction time was prolonged to 12 hours, while *n*-butyl and *n*-pentyl amines required increased catalyst loading to achieve double arylation.

Therefore, our catalytic system proved quite versatile and selective for Buchwald-Hartwig amination of various (hetero)aryl chlorides with secondary alkyl and arylalkyl amines, primary alkyl amines and anilines.

Encouraged by the excellent results in Buchwald-Hartwig reactions, we next explored the Suzuki-Miyaura cross-coupling of aryl chlorides as the benchmark reaction to further explore the activity of our synthesized catalysts. Considering the principles of green chemistry, we carried out the C-C coupling reactions between 4-chloroanisole and phenylboronic acid in the green solvent EtOH with different bases such as K_2CO_3, K_3PO_4 and NaOAc in the presence of 0.5 mol% of **2a** at room temperature. In this manner, the highest yields can be achieved with K_2CO_3 as the base (See Entries 1-3, Table S3). To obtain excellent yields, the model reaction was carried out using **2a** for 15 hours. Interestingly, comparable yields were achieved under air and argon (Entries 1-2, Table 3). Therefore, in view of the robustness and efficacy of the synthesized pre-catalyst, their use does not appear to require the use of inert conditions and anhydrous solvents. However, the use of half of the catalyst loading (0.25 mol%) was insufficient to reach acceptable conversion/time results (See Entry 16, Table S3).

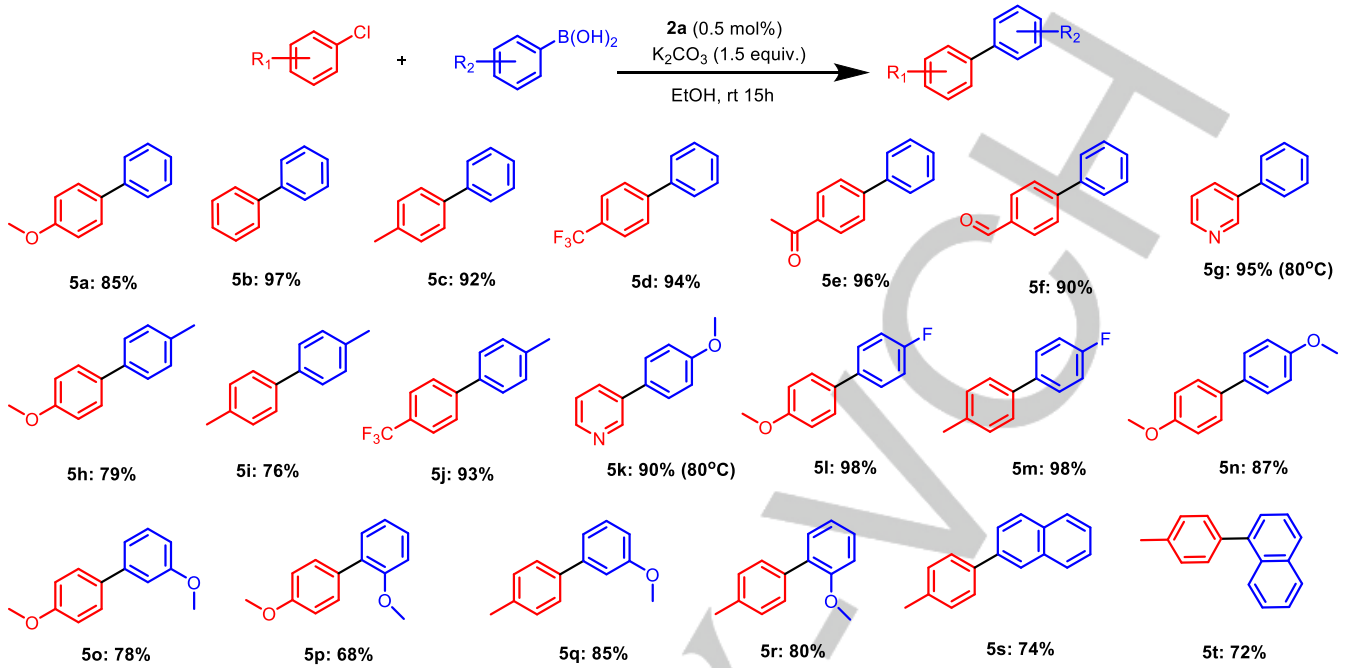
Table 3. Catalyst screening for Suzuki-Miyaura coupling between 4-chloroanisole and phenylboronic acid.



Entry	Catalyst	Yield [b] (%)
1	**2a**	85
2	**2a**	86[c]
3	**PEPPSI (3)**	87
4	**2b**	44
5	**2c**	36
6	**2d**	n.d.
7	**2e**	42
8	**2f**	78
9	**2g**	7
10	**2h**	35
11	**2i**	5

[a] Reaction condition: 4-chloroanisole (0.5 mmol), phenylboronic acid (0.55 mmol), Pd(NHC)Cl_2(DMS/THT) **2a-h** or **PEPPSI** (**3**), K_2CO_3 (0.75 mmol), EtOH (1.0 mL), 15h; [b] GC yield, dodecane was used as internal standard. [c] Reaction under argon

Interestingly, the use of the well-known Organ **PEPPSI** catalyst under the same reaction conditions afforded 87% yield (Entry 3, Table 3). Therefore, **2a** and **PEPPSI** have similar activity for this reaction (See Entries 1 and 4, Table S3). Conversely, the change of NHC ligands lowered the reaction yields significantly (Entries 4-6, Table 3). IPr# and IPr* bearing complexes **2d** and **2i** proved



Scheme 3. Scope of the room-temperature Suzuki-Miyaura reaction catalyzed by 2a.

the least active under the examined conditions (Entries 6 and 11, Table 2). This can be attributed to the higher activation barrier for such bulky NHC-containing Pd catalysts and poor activation at rt under these conditions.[18] When the saturated SIPr ligand was employed, a moderate yield was achieved (Entry 7, Table 3). The superiority of IPr in this catalytic system is also evidenced by the better performance of the tetrahydrothiophene complex **2f** with respect to the IMes, IPr* and IPr# derivative sequence **2g-i** (Entries 8-11, Table 3). It appears that the lower steric demand and possibly weaker binding of dimethyl sulfide with respect to tetrahydrothiophene results in better catalytic activity (*e.g.* **2a** vs **2f**). In summary, the catalytic trend observed is **2a** ≈ **PEPPSI** > **2e**.

With the optimal reaction conditions established for the Suzuki-Miyaura coupling (Entry 1, Table 3), we explored the substrate scope using various (hetero)aryl chlorides and aryl boronic acids (Scheme 3). Notably, when 3-chloropyridine was employed as substrate, heating was indispensable to achieve higher yields (**5j** and **5k**). In general, good to excellent yields were achieved using these mild reaction conditions for a wide scope of aryl chlorides. Electron donating and withdrawing groups on the arene ring resulted in insignificant fluctuations of the isolated yields. Acetyl-, trifluoromethyl- and carbaldehyde-functional groups were well tolerated (**5d-f**). *Para*-fluorobenzene boronic acid presented excellent reactivity with deactivated aryl chlorides (**5l, m**). The use of aryl chlorides bearing electron-donating groups and *ortho*-substituted aryl boronic acids expectedly led to somewhat lower isolated yields (**5p** and **5r**).

Conclusion

In this contribution, a series of novel *trans*-[Pd(NHC)Cl_2(DMS/THT)] complexes were synthesized by reacting NHC·HCl imidazolium salts with *trans*-[$PdCl_2$(DMS/THT)$_2$] palladium precursors in the presence of the weak base K_2CO_3 under aerobic conditions (acetone, 40 °C, 2h). The multigram syntheses of *trans*-[Pd(IPr)Cl_2(DMS/THT)] complexes (**2a** and **2f**) were also showcased. All synthesized complexes were fully characterized by NMR spectroscopy, elemental analysis and, in the case of complexes **2a-d**, **2f**, **2h** , by single-crystal X-ray diffraction.

Remarkably, in the Buchwald-Hartwig amination reaction, most of the synthesized complexes exhibited superior performances than that exhibited by Pd-PEPPSI. Particularly, *trans*-[Pd(IPr#)Cl_2(DMS)] (**2d**) showed the best catalytic activity, which was exemplified in the Buchwald-Hartwig amination of various (hetero)aryl chlorides in 2-MeTHF using 0.2 mol% catalyst loading. Several challenging electrophiles and nucleophiles were included in the scope of C-N coupling and the corresponding final products were isolated in good to excellent yields. Regarding the Suzuki-Miyaura reactions, *trans*-[Pd(IPr)Cl_2(DMS)] (**2a**) displayed excellent catalytic activity (20 examples) in the green solvent EtOH under air at room temperature using a 0.5 mol% catalyst loading. Similar catalytic activity was observed for the Pd-PEPPSI complex. We believe the new complexes, bearing volatile and innocuous organic moieties represent greener and, in some cases, more efficient alternatives to the well-known PEPPSI complexes that bear pyridine fragments, chloropyridine, being an exceptionally undesirable entity released when these are deployed in cross-coupling reactions.

Experimental Section

General Information

All reactions were performed under air unless otherwise mentioned. All solvents and other reagents were purchased from commercial sources and used as received without further purification unless otherwise stated. ^{1}H NMR and ^{13}C NMR spectra were recorded on a Bruker Avance-400 or 300 instruments at 298K. Chemical shifts (ppm) in ^{1}H and ^{13}C NMR spectra are referenced to the residual solvent peak ($CDCl_3$: δ_H = 7.26 ppm, δ_C = 77.23 ppm; DMSO-d_6: δ_H = 2.500 ppm, δ_C = 39.510 ppm). Coupling constants (J) are given in hertz. Abbreviations used in the designation of the signals: s = singlet, d = doublet, t = triplet, m = multiplet, q = quadruplet. All GC analyses were performed on Agilent 7890A Gas Chromatograph with FID detector using J&W HP-5 column (30 m, 0.32 mm). Elemental analyses were performed at Université de Namur, rue de Bruxelles, 55 B-5000 Namur, Belgium.

Procedures for the synthesis of *trans*-[$PdCl_2(DMS)_2$]:

$PdCl_2$ (1.00 mg, 5.64 mmol) and 10 mL of MeOH were charged into a 50 mL round-bottom flask equipped with stirring bar. Dimethyl sulfide (DMS, 907 µL, 12.4 mmol) was added and the reaction mixture was stirred at 35 °C overnight. Afterwards the volatiles were removed under vacuum and DCM was added. The unreacted $PdCl_2$ was separated by sintered glass filter and, from the resulting solution, the solvent was evaporated under vacuum. *trans*-[$PdCl_2(DMS)_2$] was obtained as an orange solid (1.67 g, 97%).
^{1}H NMR (400MHz, $CDCl_3$): δ (ppm) 2.41(s, 6H, CH_3)
$^{13}C\{^{1}H\}$ NMR (100MHz, $CDCl_3$): δ (ppm) 22.8 (CH_3)

Procedures for the synthesis of *trans*-[$PdCl_2(THT)_2$]:

$PdCl_2$ (1.50 g, 8.46 mmol), 15 mL of MeOH were charged into a 50 mL round-bottom flask equipped with stirring bar. Tetrahydrothiophene (THT, 1650 µL, 18.61 mmol) was added and the reaction mixture was stirred at 50 °C overnight. Afterwards the volatiles were removed under vacuum and DCM was added. The unreacted $PdCl_2$ was separated by sintered glass filter and, from the resulting solution, the solvent was evaporated under vacuum. *trans*-[$PdCl_2(THT)_2$] was obtained as a brown solid (2.73 g, 91%).
^{1}H NMR (400MHz, $CDCl_3$): δ (ppm) 3.22 (s, 4H, CH_2), 2.11 (s, 4H, CH_2)
$^{13}C\{^{1}H\}$ NMR (100MHz, $CDCl_3$): δ (ppm) 37.7 ($S(CH_2)_2$), 30.2 (CH_2)
Elemental analysis: Calculated: C 27.17, H 4.56 Found: C 27.52 H 4.34.

Procedures for the synthesis of *trans*-[Pd(NHC)Cl_2(DMS)]:

Synthesis of *trans*-[Pd(IPr)Cl_2(DMS)] (2a)

IPr•HCl (200.0 mg, 0.47 mmol), *trans*-[$PdCl_2(DMS)_2$] (141.8 mg, 0.47 mmol), K_2CO_3 (140.8 mg, 0.941 mmol), 2 mL of acetone were charged into a 4 mL vial equipped with stirring bar. The reaction mixture was stirred at 40 °C for 2 hours. Afterwards the volatiles were removed under vacuum and DCM was added. The mixture was filtered through a pad of florisil, which was washed until a clear filtrate was obtained. The solvent was removed under vacuum and the solid was washed with pentane. *trans*-[Pd(IPr)Cl_2(DMS)] was obtained as a yellow solid (274 mg, 93%).
Multigram-scale: IPr•HCl (1.0 g, 2.35 mmol), *trans*-[$PdCl_2(DMS)_2$] (0.7 mg, 2.35 mmol), K_2CO_3 (0.65 mg, 4.7 mmol), 6 mL of acetone were charged into a 30 mL vial equipped with stirring bar. The reaction mixture was stirred at 40 °C for 4 hours. After allowing the reaction to cool to room temperature, the volatiles were removed under vacuum and the DCM was added. The mixture was filtered through a pad of florisil, which was washed until a clear filtrate was obtained. The solvent was removed under vacuum and the solid was washed with pentane. *trans*-[Pd(IPr)Cl_2(DMS)] was obtained as a yellow solid (1.39 g, 94%).
^{1}H NMR (400 MHz, $CDCl_3$): δ (ppm) 7.49 (t, *J* = 8.0 Hz, 2H, 4-CH_{Ar}), 7.34 (d, *J* = 7.8 Hz, 4H, 3,5-CH_{Ar}), 7.12 (s, 2H, CH=CH), 3.10 (m, 4H, $\underline{CH}(CH_3)_2$), 1.95 (s, 6H, $S(CH_3)_2$), 1.43 (d, *J* = 6.6 Hz, 12H, $CH(\underline{CH_3})_2$), 1.10 (d, *J* = 6.9 Hz, 12H, $CH(\underline{CH_3})_2$).
$^{13}C\{^{1}H\}$ NMR (100MHz, $CDCl_3$): δ (ppm) 159.4 (C^{Im}-Pd), 146.8 (C_{Ar}-iPr), 135.2 (C_{Ar}-N), 130.3 (4-CH_{Ar}), 125.1 (CH=CH), 124.1 (3,5-CH_{Ar}), 28.9 ($\underline{CH}(CH_3)_2$), 26.5 ($CH(\underline{CH_3})_2$), 23.3 ($CH(\underline{CH_3})_2$), 20.1($S(CH_3)_2$).
Elemental analysis: Calculated: C 55.46, H 6.74, N 4.46 Found: C 55.49 H 6.73, N 4.22.

Synthesis of *trans*-[Pd(IPr^{Cl})Cl_2(DMS)] (2b)

IPr^{Cl}•HCl (100.0 mg, 0.202 mmol), *trans*-[$PdCl_2(DMS)_2$] (60.8 mg, 0.202 mmol), K_2CO_3 (56 mg, 0.404 mmol), 1 mL of acetone were charged into a 4 mL vial equipped with stirring bar. The reaction mixture was stirred at 40 °C for 2 hours. Afterwards the volatiles were removed under vacuum and DCM was added. The mixture was filtered through a pad of florisil, which was washed until a clear filtrate was obtained. The solvent was removed under vacuum and washed with pentane. *trans*-[Pd(IPr^{Cl})Cl_2(DMS)] was obtained as a yellow solid (63 mg, 90%).
^{1}H NMR (400 MHz, $CDCl_3$): δ (ppm) 7.56 (t, *J* = 8.0 Hz, 2H, 4-CH_{Ar}), 7.38 (d, *J* = 7.8 Hz, 4H, 3,5-CH_{Ar}), 3.05-2.93 (m, 4H, $\underline{CH}(CH_3)_2$), 1.94 (s, 6H, $S(CH_3)_2$), 1.42 (d, *J* = 6.5 Hz, 12H, $CH(\underline{CH_3})_2$), 1.17 (d, *J* = 6.8 Hz, 12H, $CH(\underline{CH_3})_2$).
$^{13}C\{^{1}H\}$ NMR (100MHz, $CDCl_3$): δ (ppm) 163.8 (C^{Im}-Pd), 147.9 (C_{Ar}-iPr), 132.4 (C_{Ar}-N), 131.3 (4-CH_{Ar}), 124.9 (3,5-CH_{Ar}), 120.8 (C-Cl), 29.1 ($\underline{CH}(CH_3)_2$), 25.6 ($CH(\underline{CH_3})_2$), 24.8 ($CH(\underline{CH_3})_2$), 20.3 ($S(CH_3)_2$).
Elemental analysis: Calculated: C 49.98, H 5.79, N 4.02 Found: C 50.22 H 6.0, N 3.99.

Synthesis of *trans*-[Pd(IPr*)Cl_2(DMS)] (2c)

IPr*•HCl (200.0 mg, 0.21 mmol), *trans*-[$PdCl_2(DMS)_2$] (60 mg, 0.21 mmol), K_2CO_3 (54 mg, 0.42 mmol), 1.5 mL of acetone were charged into a 4 mL vial equipped with stirring bar. The reaction mixture was stirred at 40 °C for 2 hours. Afterwards the volatiles were removed under vacuum and DCM was added. The mixture was filtered through a pad of florisil, which was washed until a clear filtrate was obtained. The volume of DCM was reduced under vacuum and the final product was precipitated by addition of pentane. *trans*-[Pd(IPr*)Cl_2(DMS)] was obtained as a pale yellow solid (210 mg, 95%).
^{1}H NMR (400 MHz, $CDCl_3$): δ (ppm) 7.42 (d, *J* = 7.3 Hz, 8H, CH_{Ar}), 7.22 (m, 12H, CH_{Ar}), 7.04-6.98 (m, 12H, CH_{Ar}), 6.75 (s, 4H, CH_{Ar}), 6.70 (d, *J* = 7.8 Hz, 8H, CH_{Ar}) 6.20 (s, 4H, $\underline{CH}(Ph)_2$), 4.80 (s, 2H, CH=CH), 2.30 (s, 6H, $S(CH_3)_2$), 2.20 (s, 6H, CH_3).
$^{13}C\{^{1}H\}$ NMR (100MHz, $CDCl_3$): δ (ppm) 156.1 (C^{Im}-Pd), 144.5 (C_{Ar}), 144.5 (C_{Ar}), 141.8 (C_{Ar}), 138.5 ($\underline{C_{Ar}}$-CH_3), 135.2 (C_{Ar}-N), 130.8 (CH_{Ar}), 130.8 (CH_{Ar}), 129.5 (CH_{Ar}),128.3 (CH_{Ar}), 128.1 (CH_{Ar}), 126.3 (CH_{Ar}), 126.2 (CH_{Ar}), 123.8 (CH=CH), 51.0 ($\underline{CH}(Ph)_2$), 22.1 ($S(CH_3)_2$), 20.4 (CH_3)
Elemental analysis: Calculated: C 73.98, H 5.42, N 2.43 Found: C 73.87 H 5.15, N 1.99

Synthesis of *trans*-[Pd($IPr^{\#}$)Cl_2(DMS)] (2d)

$IPr^{\#}$•HCl (100.0 mg, 0.08 mmol), *trans*-[$PdCl_2(DMS)_2$] (24 mg, 0.08 mmol), K_2CO_3 (22 mg, 0.16 mmol), 1 mL of acetone charged into a 4 mL vial equipped with stirring bar. The reaction mixture was stirred at 40 °C for 2 hours. Afterwards the volatiles were removed under vacuum and DCM was added. The mixture was

filtered through a pad of florisil, which was washed until a clear filtrate was obtained. The volume of DCM was reduced under vacuum and the final product was precipitated by addition of pentane. *trans*-[Pd(IPr#)Cl_2(DMS)] was obtained as a pale yellow solid (100 mg, 86%).
^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 7.27 (m, 8H, CH_{Ar}), 7.12 (m, 24H, CH_{Ar}), 6.97 (m, 20H, CH_{Ar}), 6.72 (s, 4H, CH_{Ar}), 6.65 (d, *J* = 7.0 Hz, 8H, CH_{Ar}), 6.15 (s, 4H, $\underline{CH}(Ph)_2$), 5.35 (s, 2H, $\underline{CH}(Ph)_2$), 4.81 (s, 2H), 2.22 (s, 6H, $S(CH_3)_2$).
$^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ (ppm) 157.0 (C^{Im}-Pd), 144.6 (C_{Ar}), 144.0 (C_{Ar}),143.9 (C_{Ar}),143.8 (C_{Ar}), 142.0 (C_{Ar}), 135.6 (C_{Ar}), 131.1 (CH_{Ar}), 130.5 (CH_{Ar}), 129.4 (CH_{Ar}), 128.3 (CH_{Ar}), 128.0 (CH_{Ar}), 126.3 (CH_{Ar}), 126.2 (CH_{Ar}), 123.4 (CH=CH), 56.4 ($\underline{CH}(Ph)_2$), 51.2 ($\underline{CH}(Ph)_2$), 20.5 (CH_3).
Elemental analysis: Calculated: C 78.31, H 5.41, N 1.92 Found: C 77.90, H 5.35, N 1.81.

Synthesis of *trans*-[Pd(SIPr)Cl_2(DMS)] (2e)

SIPr•HCl (100.0 mg, 0.234 mmol), *trans*-[$PdCl_2(DMS)_2$] (70.5 mg, 0.234 mmol), K_2CO_3 (64.6 mg, 0.468 mmol), 1 mL of acetone were charged into a 4 mL vial equipped with stirring bar. The reaction mixture was stirred at 40 °C for 13 hours. Afterwards the volatiles were removed under vacuum and DCM was added. The mixture was filtered through a pad of florisil, which was washed until a clear filtrate was obtained. The solvent was removed under vacuum and the solid was washed with pentane. *trans*-[Pd(IPr)Cl_2(DMS)] was obtained as a orange solid (115 mg, 78%).
^{1}H NMR (300 MHz, $CDCl_3$) δ (ppm) 7.41 (t, *J* = 7.8 Hz, 2H, 4-CH_{Ar}), 7.28 (d, *J* = 7.9 Hz, 4H, 3,5-CH_{Ar}), 4.05 (s, 4H, CH_2=CH_2), 3.51 (m, 4H, $\underline{CH}(CH_3)_2$),), 1.91 (s, 6H $S(CH_3)_2$), 1.50(d, *J* = 6.6 Hz, 12H, $CH(\underline{CH_3})_2$), 1.24 (d, *J* = 6.9 Hz, 12H, $CH(\underline{CH_3})_2$).
$^{13}C\{^1H\}$ NMR (75 MHz, $CDCl_3$): δ (ppm) 189.3 (C^{Im}-Pd), 147.8 (C_{Ar}-iPr), 135.5 (C_{Ar}-N), 129.6 (4-CH_{Ar}), 124.5 (3,5-CH_{Ar}), 54.1(CH_2=CH_2), 28.9 ($\underline{CH}(CH_3)_2$), 27.0 ($CH(\underline{CH_3})_2$), 24.3 ($CH(\underline{CH_3})_2$), 20.0($S(CH_3)_2$).
Elemental analysis: Calculated: C 55.28, H 7.04, N 4.05 Found: C 55.51, H 7.09, N 4.04.

Procedures for the synthesis of *trans*-[Pd(NHC)Cl_2(THT)]:

Synthesis of *trans*-[Pd(IPr)Cl_2(THT)] (2f)

IPr•HCl (200.0 mg, 0.47 mmol), *trans*-[$PdCl_2(THT)_2$] (166.3 mg, 0.47 mmol), K_2CO_3(130.0 mg, 0.94 mmol), 1.5 mL of acetone were charged into a 4 mL vial equipped with stirring bar. The reaction mixture was stirred at 40 °C for 2 hours. Afterwards the volatiles were removed under vacuum and DCM was added. The mixture was filtered through a pad of florisil, which was washed until a clear filtrate was obtained. The solvent was removed under vacuum and the solid was washed with pentane. *trans*-[Pd(IPr)Cl_2(THT)] was obtained as a yellow solid (293.0 mg, 95%).
Multigram-scale: IPr•HCl (1000.0 mg, 2.35 mmol), *trans*-[$PdCl_2(THT)_2$] (831.2 mg, 2.35 mmol), K_2CO_3(650.0 mg, 4.7 mmol), 6 mL of acetone were charged into 30 mL vial equipped with stirring bar. The reaction mixture was stirred at 40 °C for 4 hours. Afterwards the work-up was conducted following the small-scale procedure and the final product was obtained with 97% yield (1.49 g).
^{1}H NMR (400 MHz, $CDCl_3$): δ (ppm) 7.49 (t, *J* = 8.0 Hz, 2H, 4-CH_{Ar}), 7.33 (d, *J* = 7.8 Hz, 4H, 3,5-CH_{Ar}), 7.12 (s, 2H, CH=CH), 3.10 (m, 4H, $\underline{CH}(CH_3)_2$), 2.81 (s, 4H, $S(CH_2)_2$), 1.73 (m, 4H, CH_2-CH_2), 1.42 (d, *J* = 6.6 Hz, 12H, $CH(\underline{CH_3})_2$), 1.09 (d, *J* = 6.9 Hz, 12H, $CH(\underline{CH_3})_2$).
$^{13}C\{^1H\}$ NMR (100MHz, $CDCl_3$): δ (ppm) 159.7 (C^{Im}-Pd), 146.9 (C_{Ar}-iPr), 135.3 (C_{Ar}-N), 130.3 (4-CH_{Ar}), 125.1 (CH=CH), 124.1 (3,5-CH_{Ar}), 34.9 ($S(CH_2)_2$), 29.9 (CH_2-CH_2), 28.9 ($\underline{CH}(CH_3)_2$), 26.5 ($CH(\underline{CH_3})_2$), 23.3 ($CH(\underline{CH_3})_2$)
Elemental analysis: Calculated: C 56.93, H 6.78, N 4.28 Found: C 57.16 H 6.99, N 4.03.

Synthesis of *trans*-[Pd(IMes)Cl_2(THT)] (2g)

IMes•HCl (200.0 mg, 0.586 mmol), *trans*-[$PdCl_2(THT)_2$] (207.3 mg, 0.586), K_2CO_3(162 mg, 1.172 mmol), 1.5 mL of acetone were charged into a 4 mL vial equipped with stirring bar. The reaction mixture was stirred at 40 °C for 4 hours. Afterwards the volatiles were removed under vacuum and DCM was added. The mixture was filtered through a pad of florisil, which was washed until a clear filtrate was obtained. The solvent was removed under vacuum and the solid was washed with pentane. *trans*-[Pd(IMes)Cl_2(THT)] was obtained as a pale yellow solid (324 mg, 97%).
^{1}H NMR (400 MHz, $CDCl_3$): δ (ppm) 7.07 (s, 2H, CH=CH), 7,03 (s, 4H, CH_{Ar}), 2.81(s, 4H, $S(CH_2)_2$), 2.37 (s, 6H, CH_3), 2.31 (s, 12H, CH_3), 1.76 (s, 4H, CH_2-CH_2).
$^{13}C\{^1H\}$ NMR (100MHz, $CDCl_3$): δ (ppm) 157.4 (C^{Im}-Pd), 139.3 (4-C_{Ar}), 136.5 (2,6- C_{Ar}),135.3 (C_{Ar}-N), 129.3 (3,5-CH_{Ar}), 124.1 (CH=CH), 35.0 ($S(CH_2)_2$), 29.9 (CH_2-CH_2), 21.4 (CH_3), 19.2 (CH_3)
Elemental analysis: Calculated: C 52.69, H 5.66, N 4.92 Found: C 52.49 H 5.55, N 4.87.

Synthesis of *trans*-[Pd(IPr^{Cl})Cl_2(THT)] (2h)

IPr^{Cl}•HCl (100.0 mg, 0.202 mmol), *trans*-[$PdCl_2(THT)_2$] (61.4 mg, 0.202), K_2CO_3 (56 mg, 0.404 mmol), 1.5 mL of acetone were charged into a 4 mL vial equipped with stirring bar. The reaction mixture was stirred at 40 °C for 2 hours. Afterwards the volatiles were removed under vacuum and DCM was added. The mixture was filtered through a pad of florisil, which was washed until a clear filtrate was obtained. The solvent was removed under vacuum and the solid was washed with pentane. *trans*-[Pd(IPr^{Cl})Cl_2(THT)] was obtained as a yellow solid (67 mg, 91%).
^{1}H NMR (400 MHz, $CDCl_3$): δ (ppm) 7.56 (t, *J* = 7.8 Hz, 2H, 4-CH_{Ar}), 7.38 (d, *J* = 7.8 Hz, 4H, 3,5- CH_{Ar}), 2.98 (m, 4H, $\underline{CH}(CH_3)_2$), 2.79 (s, 4H, $S(CH_2)_2$), 1.72 (m, 4H, CH_2-CH_2), 1.42 (d, *J* = 6.5 Hz, 12H, $CH(\underline{CH_3})_2$), 1.17 (d, *J* = 6.9 Hz, 12H, $CH(\underline{CH_3})_2$).
$^{13}C\{^1H\}$ NMR (100MHz, $CDCl_3$): δ (ppm) 164.1 (C^{Im}-Pd), 146.8 (C_{Ar}-iPr), 132.4 (C_{Ar}-N), 131.3 (4-CH_{Ar}), 124.9 (3,5-CH_{Ar}), 120.8 (C-Cl), 35.1 ($S(CH_2)_2$), 29.8 (CH_2-CH_2) 29.1 ($\underline{CH}(CH_3)_2$), 25.6 ($CH(\underline{CH_3})_2$), 24.8 ($CH(\underline{CH_3})_2$).
Elemental analysis: Calculated: C 51.50, H 5.86, N 3.87 Found: C 51.87 H 6.21, N 3.68

Synthesis of *trans*-[Pd(IPr*)Cl_2(THT)] (2i)

IPr*•HCl (200.0 mg, 0.21 mmol), *trans*-[$PdCl_2(THT)_2$] (73.6 mg, 0.21), K_2CO_3(57.6 mg, 0.42 mmol), 1.5 mL of acetone were charged into a 4 mL vial equipped with stirring bar. The reaction mixture was stirred at 40 °C for 2 hours. Afterwards the volatiles were removed under vacuum and DCM was added. The volume of DCM was reduced under vacuum and the final product was precipitated by addition of pentane. *trans*-[Pd(IPr*)Cl_2(THT)] was obtained as a pale yellow solid (221 mg, 91%).
^{1}H NMR (400 MHz, $CDCl_3$): δ (ppm) 7.42 (d, *J* = 7.3 Hz, 8H, CH_{Ar}), 7.22 (m, 12H, CH_{Ar}), 7.00(m, 12H, CH_{Ar}), 6.74 (s, 4H, CH_{Ar}), 6.70 (d, *J* = 6.9 Hz, 8H, CH_{Ar}), 6.18 (s, 4H, $\underline{CH}(Ph)_2$), 4.77 (s, 2H, CH=CH), 3.15 (s, 4H, $S(CH_2)_2$), 2.21 (s, 6H, CH_3), 2.00 (m, 4H, CH_2-CH_2)
$^{13}C\{^1H\}$ NMR (100MHz, $CDCl_3$): δ (ppm) 156.3 (C^{Im}-Pd), 144.6 (C_{Ar}), 144.5 (C_{Ar}), 141.8 (C_{Ar}), 138.5 ($\underline{C_{Ar}}$-CH_3), 135.2 (C_{Ar}-N), 130.8 (CH_{Ar}), 130.7 (CH_{Ar}), 129.5 (CH_{Ar}),128.3 (CH_{Ar}), 128.1 (CH_{Ar}), 126.3 (CH_{Ar}), 126.2 (CH_{Ar}), 123.7 (CH=CH), 51.0 ($CH(Ph)_2$), 34.8 ($S(CH_2)_2$), 30.4 (CH_2-CH_2), 22.1 (C_{Ar}-$\underline{CH_3}$)
Elemental analysis: Calculated: C 74.39, H 5.47, N 2.38 Found: C 74.07 H 5.37, N 1.55

General procedure of Buchwald-Hartwig amination reaction.

trans-[Pd(NHC)Cl_2(DMS)] (0.2 mol%), aryl chloride (1.0 mmol), amine (1.2 mmol) (if the substrate was solid) and a stirring bar were charged into a 4 mL vial. Entered the vial into glovebox, KO^{t}Bu (1.2 mmol) was added, the cap was closed, and the vial

was taken out. Under argon atmosphere, aryl chloride (1.0 mmol), amine (1.2 mmol) (if the substrate was liquid) and degassed dry 2-MeTHF (2.0 mL) were added at room temperature and the reaction mixture was stirred at 80 °C for the indicated time. After the indicated time, the reaction mixture was diluted with 10 mL of DCM, poured it into separation funnel, and washed with 10 mL water. Water phase was extracted with DCM (3 × 10 mL) and organic layers were combined and dried by anhydrous $MgSO_4$. Purification by chromatography on silica gel (EtOAc/Petroleum Ether) obtained the main compound.

4-(4-methoxyphenyl)morpholine (4a)
According to the general procedure, the corresponding final product (95% yield) was obtained as a white solid.
^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 6.87 (m, 4H), 3.86 (m, 4H), 3.77 (s, 3H), 3.06 (m, 4H)

4-methoxy-N-methyl-N-phenylaniline (4b)
According to the general procedure, the corresponding final product (97% yield) was obtained as a pale yellow oil.
^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 7.21 (m, 2H), 7.10 (d, *J* = 9.0 Hz, 2H), 6.90 (d, *J* = 9.0 Hz, 2H), 6.80 (m, 3H), 3.82 (s, 3H), 3.27 (s, 3H).

4-(4-(trifluoromethyl)phenyl)morpholine (4c)
According to the general procedure, the corresponding final product (82% yield) was obtained as a white solid.
^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 7.50 (d, *J* = 8.5 Hz, 2H), 6.92 (d, *J* = 8.6 Hz, 2H), 3.86 (m, 4H), 3.24 (m, 4H).

N-methyl-N-phenyl-4-(trifluoromethyl)aniline (4d)
According to the general procedure, the corresponding final product (92% yield) was obtained as a pale-yellow oil.
^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 7.40 (m, 4H), 7.19 (m, 3H), 6.85 (d, *J* = 8.6 Hz, 2H), 3.35 (s, 3H).

4-(p-tolyl)morpholine (4e)
According to the general procedure, the corresponding final product (92% yield) was obtained as white solid.
^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 7.10 (d, *J* = 8.2 Hz, 2H), 6.85 (d, *J* = 8.5 Hz, 2H), 3.87 (m, 4H), 3.10 (m, 4H), 2.29 (s, 3H).

4-phenylmorpholine (4f)
According to the general procedure, the corresponding final product (94% yield) was obtained as oil.
^{1}H NMR (300 MHz, $CDCl_3$) δ (ppm) 7.29 (m, 2H), 6.91 (m, 3H), 3.87 (m, 4H), 3.17 (m, 4H).

N,N-diethyl-4-(trifluoromethyl)aniline (4g)
According to the general procedure, the corresponding final product (58% yield) was obtained as oil.
^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 7.42 (d, *J* = 8.8 Hz, 2H), 6.66 (d, *J* = 8.2 Hz, 2H), 3.39 (q, *J* = 7.1 Hz, 4H), 1.19 (t, *J* = 7.1 Hz, 6H).

N-methyl-N-phenylpyridin-3-amine (4h)
According to the general procedure, the corresponding final product (92% yield) was obtained as oil.
^{1}H NMR (300 MHz, $CDCl_3$) δ (ppm) 8.31 (d, *J* = 2.7 Hz, 1H), 8.14 (dd, *J* = 4.6, 1.4 Hz, 1H), 7.34 (m, 2H), 7.23 (m, 1H), 7.15 (m, 1H), 7.09 (m, 3H), 3.34 (s, 3H).

4-(quinolin-6-yl)morpholine (4i)
According to the general procedure, the corresponding final product (78% yield) was obtained as white solid.
^{1}H NMR (300 MHz, $CDCl_3$) δ (ppm) 8.72 (dd, *J* = 4.2, 1.7 Hz, 1H), 8.02 (d, *J* = 8.7 Hz, 2H), 7.48 (dd, *J* = 9.3, 2.8 Hz, 1H), 7.33 (dd, *J* = 8.2, 4.2 Hz, 1H), 7.02 (d, *J* = 2.8 Hz, 1H), 3.91 (m, 4H), 3.29 (m, 4H).

4-methoxy-N-phenylaniline (4j)
According to the general procedure, the corresponding final product (88% yield) was obtained as white solid.
^{1}H NMR (400 MHz, DMSO-d6) δ (ppm) 7.81 (s, 1H), 7.16 (m, 2H), 7.04 (d, *J* = 8.9 Hz, 2H), 6.91 (d, *J* = 7.6 Hz, 2H), 6.86 (d, *J* = 8.9 Hz, 2H), 6.70 (t, *J* = 7.3 Hz, 1H), 3.71 (s, 3H).

bis(4-methoxyphenyl)amine (4k)
According to the general procedure, the corresponding final product (97% yield) was obtained as white solid.
^{1}H NMR (300 MHz, DMSO-d6) δ (ppm) 7.50 (s, 1H), 6.91 (d, *J* = 9.0 Hz, 4H), 6.80 (d, *J* = 9.0 Hz, 4H), 3.68 (s, 6H).

4-methoxy-N-(p-tolyl)aniline (4l)
According to the general procedure, the corresponding final product (% yield) was obtained as white solid.
^{1}H NMR (300 MHz, DMSO-d6) δ (ppm) 7.66 (s, 1H), 6.98 (m, 4H), 6.84 (m, 4H), 3.70 (s, 3H), 2.19 (s, 3H).

4-fluoro-N-phenylaniline (4m)
According to the general procedure, the corresponding final product (92% yield) was obtained as white solid.
^{1}H NMR (300 MHz, $CDCl_3$) δ (ppm) 7.25 (m, 2H), 7.06 (m, 2H), 7.00 (m, 4H), 6.91 (t, *J* = 7.3 Hz, 1H), 5.59 (s, 1H).

2,4-dimethyl-N-(p-tolyl)aniline (4n)
According to the general procedure, the corresponding final product (97% yield) was obtained as white solid.
^{1}H NMR (300 MHz, $CDCl_3$) δ (ppm) 7.08 (m, 3H), 7.02 (s, 1H), 6.95 (d, *J* = 8.1 Hz, 1H), 6.83 (d, *J* = 8.4 Hz, 2H), 5.22 (s, 1H), 2.30 (s, 6H), 2.22 (s, 3H).

2,4,6-trimethyl-N-(p-tolyl)aniline (4o)
According to the general procedure, the corresponding final product (97% yield) was obtained as yellow oil.
^{1}H NMR (300 MHz, $CDCl_3$) δ (ppm) 6.97 (d, *J* = 8.0 Hz, 2H), 6.94 (s, 2H), 6.43 (d, *J* = 8.4 Hz, 2H), 5.02 (s, 1H), 2.31 (s, 3H), 2.25 (s, 3H), 2.18 (s, 6H).

2,6-diethyl-N-(p-tolyl)aniline (4p)
According to the general procedure, the corresponding final product (97% yield) was obtained as yellow oil.
^{1}H NMR (300 MHz, $CDCl_3$) δ (ppm) 7.18 (m, 3H), 6.96 (d, *J* = 8.0 Hz, 2H), 6.42 (d, *J* = 8.4 Hz, 2H), 5.08 (s, 1H), 2.59 (q, *J* = 7.5 Hz, 4H), 2.24 (s, 3H), 1.15 (t, *J* = 7.6 Hz, 6H).

2,6-diisopropyl-N-(p-tolyl)aniline (4q)
According to the general procedure, the corresponding final product (75% yield) was obtained as yellow oil.
^{1}H NMR (300 MHz, $CDCl_3$) δ (ppm) 7.29 (m, 1H), 7.20 (m, 2H), 6.95 (d, *J* = 8.0 Hz, 2H), 6.41 (d, *J* = 8.4 Hz, 2H), 5.04 (s, 1H), 3.20 (hept, *J* = 6.9 Hz, 2H), 2.24 (s, 3H), 1.15 (d, *J* = 6.9 Hz, 12H).

N-cyclohexylaniline (4r)
According to the general procedure, the corresponding final product (92% yield) was obtained as yellow oil.
^{1}H NMR (300 MHz, $CDCl_3$) δ (ppm) 7.16 (m, 2H), 6.66 (t, *J* = 7.3 Hz, 1H), 6.60 (d, *J* = 7.6 Hz, 2H), 3.54 (s, 1H), 3.26 (m, 1H), 2.07 (m, 2H), 1.78 (m, 2H), 1.66 (m, 1H), 1.38 (m, 2H), 1.19 (m, 3H).

N-butyl-4-methylaniline (4s)
According to the general procedure, the corresponding final product (50% yield) was obtained as colorless oil.
^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 6.99 (d, *J* = 8.0 Hz, 2H), 6.54 (d, *J* = 8.4 Hz, 2H), 3.45 (s, 1H), 3.09 (m, 2H), 2.24 (s, 3H), 1.59 (m, 2H), 1.43 (m, 2H), 0.96 (t, *J* = 7.3 Hz, 3H).

N-heptyl-4-methylaniline (4t)
According to the general procedure, the corresponding final product (51% yield) was obtained as pale-yellow oil.

^{1}H NMR (300 MHz, $CDCl_3$) δ (ppm) 6.98 (d, *J* = 8.0 Hz, 2H), 6.54 (d, *J* = 8.4 Hz, 2H), 3.45 (s, 1H), 3.08 (m, 2H), 2.24 (s, 3H), 1.60 (m, 2H), 1.32 (m, 8H), 0.90 (m, 3H).

General procedure of Suzuki-Miyaura cross-coupling of aryl chlorides under air.

Aryl chloride (0.5 mmol), aryl boronic acid (0.55 mmol), K_2CO_3 (0.75 mmol), 0.5 mol% *trans*-[Pd(NHC)Cl_2(DMS)] and a magnetic stirring bar were added into 4 mL vial under air. Then EtOH (1.0 mL) was added at room temperature and the reaction mixture was stirred for the indicated time. Subsequently, the reaction mixture was diluted with 10 mL of DCM, poured it into separation funnel, and washed with 10 mL of water. Water phase was extracted with DCM (3 × 10 mL) and organic layers were combined and dried by anhydrous $MgSO_4$. Purification by chromatography on silica gel (EtOAc/Petroleum Ether) afforded the main product.

4-methoxy-1,1'-biphenyl (5a)
According to the general procedure, the corresponding final product (85% yield) was obtained as a white solid.
^{1}H NMR (300 MHz, $CDCl_3$): δ (ppm) 7.55 (m, 4H), 7.42 (m, 4H), 7.31 (m, 4H), 3.86 (s, 3H)

1,1'-biphenyl (5b)
According to the general procedure, the corresponding final product (97% yield) was obtained as a white solid.
^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 7.60 (d, *J* = 7.1 Hz, 4H), 7.45 (t, *J* = 7.5 Hz, 4H), 7.35 (t, *J* = 7.4 Hz, 2H).

4-methyl-1,1'-biphenyl (5c)
According to the general procedure, the corresponding final product (92% yield) was obtained as a white solid.
^{1}H NMR (300 MHz, $CDCl_3$) δ (ppm) 7.59 (m, 2H), 7.50 (d, *J* = 8.2 Hz, 2H), 7.43 (t, *J* = 7.4 Hz, 2H), 7.33 (m, 1H), 7.26 (d, *J* = 7.9 Hz, 2H), 2.41 (s, 3H).

4-(trifluoromethyl)-1,1'-biphenyl (5d)
According to the general procedure, the corresponding final product (92% yield) was obtained as a white solid.
^{1}H NMR (300 MHz, $CDCl_3$) δ (ppm) 7.70 (s, 4H), 7.60 (m, 2H), 7.48 (m, 2H), 7.43 (m, 1H).

1-([1,1'-biphenyl]-4-yl)ethan-1-one (5e)
According to the general procedure, the corresponding final product (96% yield) was obtained as a white solid.
^{1}H NMR (300 MHz, $CDCl_3$) δ (ppm) 8.04 (d, *J* = 8.4 Hz, 2H), 7.69 (d, *J* = 8.4 Hz, 2H), 7.63 (m, 2H), 7.48 (t, *J* = 7.3 Hz, 2H), 7.42 (m, 1H), 2.64 (s, 3H).

[1,1'-biphenyl]-4-carbaldehyde (5f)
According to the general procedure, the corresponding final product (90% yield) was obtained as a white solid.
^{1}H NMR (300 MHz, $CDCl_3$) δ (ppm) 10.07 (s, 1H), 7.96 (d, *J* = 8.4 Hz, 2H), 7.76 (d, *J* = 8.3 Hz, 2H), 7.64 (m, 2H), 7.50 (m, 2H), 7.44 (m, 1H).

3-phenylpyridine (5g)
According to the general procedure (80ºC), the corresponding final product (95% yield) was obtained as a white solid.
^{1}H NMR (300 MHz, $CDCl_3$) δ (ppm) 8.86 (d, *J* = 1.9 Hz, 1H), 8.60 (dd, *J* = 4.8, 1.5 Hz, 1H), 7.90 (d, *J* = 7.9 Hz, 1H), 7.59 (m, 2H), 7.49 (t, *J* = 7.2 Hz, 2H), 7.41 (m, 2H).

4-methoxy-4'-methyl-1,1'-biphenyl (5h)
According to the general procedure, the corresponding final product (79% yield) was obtained as white solid.

^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 7.51 (d, *J* = 8.9 Hz, 2H), 7.45 (d, *J* = 8.1 Hz, 2H), 7.23 (d, *J* = 8.4 Hz, 2H), 6.97 (d, *J* = 8.9 Hz, 2H), 3.85 (s, 3H), 2.39 (s, 3H).

4,4'-dimethyl-1,1'-biphenyl (5i)
According to the general procedure, the corresponding final product (76% yield) was obtained as a white solid.

^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 7.48 (d, *J* = 8.1 Hz, 2H), 7.24 (d, *J* = 7.9 Hz, 2H), 2.40 (s, 3H).

4-methyl-4'-(trifluoromethyl)-1,1'-biphenyl (5j)
According to the general procedure, the corresponding final product (93% yield) was obtained as a white solid.
^{1}H NMR (300 MHz, $CDCl_3$) δ (ppm) 7.68 (s, 4H), 7.50 (d, *J* = 8.2 Hz, 2H), 7.29 (d, *J* = 8.4 Hz, 2H), 2.42 (s, 3H).

3-(p-tolyl)pyridine (5k)
According to the general procedure (80ºC), the corresponding final product (90% yield) was obtained as a white solid.
^{1}H NMR (300 MHz, $CDCl_3$) δ (ppm) 8.83 (d, *J* = 2.3 Hz, 1H), 8.56 (dd, *J* = 4.9, 1.5 Hz, 1H), 7.94 (m, 1H), 7.53 (d, *J* = 8.7 Hz, 2H), 7.43 (m, 1H), 7.03 (d, *J* = 8.7 Hz, 2H), 3.87 (s, 3H).

4-fluoro-4'-methoxy-1,1'-biphenyl (5l)
According to the general procedure, the corresponding final product (98% yield) was obtained as a white solid.
^{1}H NMR (300 MHz, $CDCl_3$) δ (ppm) 7.49 (m, 4H), 7.10 (t, *J* = 8.8 Hz, 2H), 6.97 (d, *J* = 8.8 Hz, 2H), 3.85 (s, 3H).

4-fluoro-4'-methyl-1,1'-biphenyl (5m)
According to the general procedure, the corresponding final product (98% yield) was obtained as a white solid.
^{1}H NMR (300 MHz, $CDCl_3$) δ (ppm) 7.50 (m, 2H), 7.44 (d, *J* = 8.1 Hz, 2H), 7.25 (d, *J* = 8.5 Hz, 2H), 7.11 (t, *J* = 8.6 Hz, 2H), 2.40 (s, 3H).

4,4'-dimethoxy-1,1'-biphenyl (5n)
According to the general procedure, the corresponding final product (87% yield) was obtained as a white solid.
^{1}H NMR (300 MHz, $CDCl_3$) δ (ppm) 7.48 (d, *J* = 8.8 Hz, 4H), 6.96 (d, *J* = 8.8 Hz, 4H), 3.85 (s, 6H).

3,4'-dimethoxy-1,1'-biphenyl (5o)
According to the general procedure, the corresponding final product (78% yield) was obtained as a white solid.
^{1}H NMR (300 MHz, $CDCl_3$) δ (ppm) 7.53 (d, *J* = 8.9 Hz, 2H), 7.33 (t, *J* = 7.9 Hz, 1H), 7.14 (m, 1H), 7.08 (m, 1H), 6.98 (d, *J* = 8.8 Hz, 2H), 6.86 (m, 1H), 3.86 (s, 3H), 3.85 (s, 3H).

2,4'-dimethoxy-1,1'-biphenyl (5p)
According to the general procedure, the corresponding final product (68% yield) was obtained as a white solid.
^{1}H NMR (300 MHz, $CDCl_3$) δ (ppm) 7.47 (d, *J* = 8.9 Hz, 2H), 7.29 (m, 2H), 7.01 (m, 2H), 6.94 (m, 2H), 3.84 (s, 3H), 3.81 (s, 3H).

3-methoxy-4'-methyl-1,1'-biphenyl (5q)
According to the general procedure, the corresponding final product (85% yield) was obtained as a white solid.
^{1}H NMR (300 MHz, $CDCl_3$) δ (ppm) 7.49 (d, *J* = 8.2 Hz, 2H), 7.34 (t, *J* = 7.9 Hz, 1H), 7.23 (m, 2H), 7.17 (m, 1H), 7.12 (m, 1H), 6.88 (m, 1H), 3.86 (s, 3H), 2.40 (s, 3H).

2-methoxy-4'-methyl-1,1'-biphenyl (5r)
According to the general procedure, the corresponding final product (80% yield) was obtained as a white solid.
^{1}H NMR (300 MHz, $CDCl_3$) δ (ppm) 7.44 (d, *J* = 8.1 Hz, 2H), 7.31 (m, 2H), 7.24 (d, *J* = 7.8 Hz, 2H), 7.02 (m, 2H), 3.82 (s, 3H), 2.40 (s, 3H).

2-(p-tolyl)naphthalene (5s)
According to the general procedure, the corresponding final product (74% yield) was obtained as a white solid.

^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 8.02 (s, 1H), 7.89 (m, 3H), 7.74 (dd, *J* = 8.5, 1.8 Hz, 1H), 7.63 (d, *J* = 8.1 Hz, 2H), 7.49 (ddd, *J* = 7.2, 6.3, 3.4 Hz, 2H), 7.30 (d, *J* = 7.9 Hz, 2H), 2.43 (s, 3H).

1-(p-tolyl)naphthalene (5t)
According to the general procedure, the corresponding final product (72% yield) was obtained as a white solid.
^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 7.92 (t, *J* = 8.9 Hz, 2H), 7.86 (d, *J* = 8.2 Hz, 1H), 7.51 (m, 2H), 7.42 (m, 4H), 7.32 (m, 2H), 2.47 (s, 3H).

XRD analysis
Crystals that were of suitable quality for single crystal X-ray diffraction analysis were obtained in all cases by slow diffusion of the antisolvent (pentane or hexane) into saturated solutions of the complexes (in dichloromethane or $CDCl_3$) in fridge. X-ray intensity data were collected at 100 K, on a Rigaku Oxford Diffraction Supernova Dual Source diffractometer equipped with an Atlas CCD detector. CCDC 2150829 (**2a**), 2150830 (**2b**), 2150831 (**2c**), 2150832 (**2d**), 2150833 (**2f**), 2150834 (**2h**) and 2150835 (**2i**) the supplementary crystallographic data for this paper.

Acknowledgements

We are grateful to the SBO (D2M to SPN), the FWO (to CSJC) and the BOF (starting and senior grants to SPN and CSJC) as well as the iBOF C3 project for financial support. Y. L. and M. P. thank the CSC for PhD fellowships. K. V. H. thanks the Research Foundation – Flanders (FWO) (project AUGE/11/029) for funding.

Conflict of interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available in the supplementary material of this article.

Keywords: Buchwald-Hartwig amination • *N*-heterocyclic carbene ligands • Palladium complexes • Sustainability • Suzuki-Miyaura cross-coupling

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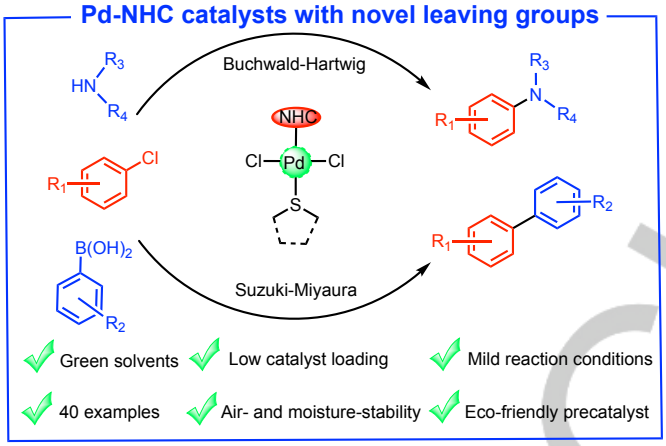

A novel family of air- and moisture-stable Pd(NHC)Cl_2(DMS/THT) was synthesized using a simple and eco-friendly synthetic protocol. These catalysts displayed outstanding performance in Buchwald-Hartwig and Suzuki-Miyaura reaction in green solvents.