Journal Pre-proof

Effect of phosphonium ionic liquid/Pd ratio on the catalytic activity of palladium nanoparticles in Suzuki cross-coupling reaction

D. Arkhipova , V. Ermolaev , V. Miluykov , G. Gaynanova ,
L. Zakharova , G. Wagner , O. Oeckler , E. Hey-Hawkins

Please cite this article as: D. Arkhipova , V. Ermolaev , V. Miluykov , G. Gaynanova , L. Zakharova , G. Wagner , O. Oeckler , E. Hey-Hawkins , Effect of phosphonium ionic liquid/Pd ratio on the catalytic activity of palladium nanoparticles in Suzuki cross-coupling reaction, *Journal of Organometallic Chemistry* (2020), doi: https://doi.org/10.1016/j.jorganchem.2020.121454

Palladium nanoparticles (PdNPs) stabilized with phosphonium ionic liquid (PIL) effectively catalyze cross-coupling reaction of 1,3,5-tribromobenzene and phenylboronic acid

PIL/Pd ratio influences on catalytic activity of PdNPs

Transmission electron microscopy (TEM) and Dynamic light scattering (DLS) methods were used for catalytic system characterization

Palladium nanoparticles (PdNPs) stabilized with phosphonium ionic liquid (PIL) effectively catalyze cross-coupling reaction of 1,3,5-tribromobenzene and phenylboronic acid

Transmission electron microscopy (TEM) and Dynamic light scattering (DLS) methods were used for catalytic system characterization

Effect of phosphonium ionic liquid/Pd ratio on the catalytic activity of palladium nanoparticles in Suzuki cross-coupling reaction

D. Arkhipova,[a] V. Ermolaev,[a]* V. Miluykov,[a] G. Gaynanova,[a] L. Zakharova,[a] G. Wagner[b], O. Oeckler,[b] E. Hey-Hawkins[c]

Abstract

Phosphonium salts were synthesized and used as support for palladium nanoparticles. It was demonstrated that the catalytic behavior of palladium nanoparticles in Suzuki cross-coupling reactions is determined by the ratio of the phosphonium ionic liquid to palladium source and the nature of the stabilizer. Transition electron microscopy and dynamic light scattering techniques allowed to determine the most effective range of stabilizer concentration in the reaction media.

Key words: phosphonium ionic liquids, palladium nanoparticles, catalytic system tuning, TEM, DLS

1. Introduction

In the last two decades, ionic liquids (ILs) have received particular interest due to their attractive features such as limited volatility and flammability, recyclability, broad temperature range of the liquid state, high thermal and chemical stability, wide electrochemical potential window, solubility and miscibility depending on the choice of cations and anions [1,2,3]. In addition, ILs form preorganized structures through ionic interaction and hydrogen bonding that induce structural directionality. Such a supramolecular network is an "entropic driver" for the synthesis of well-defined nanosized objects [4].

For a good reason, the strategy of IL applications became a widely used approach [5] for design and stabilization of highly efficient transition metal nanocatalysts for organic synthesis [6,7]. Due to its unique solvent properties and wide range of miscibility, ILs have the additional function as a reaction media [8,9]. The need to reduce the use of toxic volatile organic compounds in production processes, improve atom efficiency and minimize waste became the driving force of the explosive growth in the number of publications on the use of ionic liquids as solvents [10,11].

In spite of the fact that ILs are often claimed as an environmentally friendly alternative to common organic solvents [97,12,13] there are many factors that should be considered before calling ionic liquids "green" solvents [43]. The hazards of IL itself must be taken into account [14] as well as the negative environmental impact of its manufacturing [15]. Despite the superior efficiency of ILs as a nanoparticle (NP) stabilizer, it is essential to include a rational approach in their synthesis and applications [16]. Along with usage of the supported ionic liquids [17,18], one of the ways to partially avoid hazards caused by ILs is decreasing their quantity in reaction media. Instead of using "neat" ILs [19] for the synthesis of the nanocatalyst, a co-solvent approach was proposed. For example, a co-solvent reduces the viscosity of the reaction media [20], in other cases, it allows the effective separation of the reaction products from the catalyst [108].

a) Arbuzov Institute of Organic and Physical Chemistry, FRC Kazan Scientific Center, Russian Academy of Sciences, ak. Arbuzov str, 8, 420088, Kazan, Russia. Fax: +7 (843) 273-18-72; Tel: +7 (843) 273-93-65; E-mail: ermolaev@iopc.ru.

b) Leipzig University, Faculty of Chemistry and Mineralogy, Institute of Mineralogy, Crystallography and Materials Science, Scharnhorststr. 20, D-04275 Leipzig, Germany, Tel.: +49 341 9736250; E-mail: gewagner@rz.uni-leipzig.de.

c) Leipzig University, Faculty of Chemistry and Mineralogy, Institute of Inorganic Chemistry, Johannisallee 29, D-04103 Leipzig, Germany. Tel: +49 341 9736151; Fax:+49 341 9739319; E-Mail: hey@uni-leipzig.de.

However, the amount of IL applied for NP stabilization is often not discussed and the exact quantity seems to be random [86,21]. We suppose that the concentration of the stabilizing agent is worth being considered since it can have a crucial influence on the catalytic activity and stability of NPs. Previously, it was found that increasing the concentration of stabilizing polymer (poly(N-vinyl-2-pyrrolidone)) in 40% ethanol solution resulted in reduction of the size of the NPs [22]. Another study displayed that an increase in the PEG/Pd ratio in water led to a decrease in both the size and the catalytic activity of the PdNPs in the Hiyama cross-coupling reaction [23].

There are a few similar studies for ILs. One of them is devoted to the Heck reaction catalyzed by PdNPs stabilized with N-containing ILs as was reported by Roszak and co-workers [24]. Increasing the IL/Pd ratio gave different effects in the catalytic activity of the PdNPs depending on the structure of the IL. It should be noted that DMF which was used as reaction medium could serve as an extra stabilizer for NPs [25]. In a preliminary study we have shown the same trends in the behavior of PdNPs coated with phosphonium IL (PIL) [26] in Sonogashira [27] and Suzuki [28] reactions.

As the amount of the supporting agent in the solution has a significant influence on the size and catalytic activity of PdNPs, the present study focusses on controlling the catalytic activity of PdNPs through varying the concentration of PIL in a wide range to determine the minimum amount required as stabilizing agent.

2. Experimental

2.1. Materials and methods

All procedures associated with the preparation of the starting materials, synthesis, and isolation of products were carried out under inert atmosphere using standard Schlenk techniques.

NMR spectra were recorded on a Bruker MSL-400 instrument ([1]H 400 MHz, [31]P 161.7 MHz, [13]C 100.6 MHz). SiMe$_4$ was used as internal reference for ^{1}H chemical shifts, and 85% H$_3$PO$_4$ as external reference for ^{31}P NMR.

The ESI MS measurements were performed using an AmazonX ion trap mass spectrometer (Bruker Daltonic GmbH, Germany) in positive (and/or negative) mode in the mass range of 70–3000. The capillary voltage was 3500 V, nitrogen drying gas 10 L·min^{-1}, and desolvation temperature 250 °C. A methanol/water solution (70:30) was used as a mobile phase at a flow rate of 0.2 mL·min^{-1} by binary pump (Agilent 1260 chromatograph, USA). The sample was dissolved in methanol to a concentration of 10^{-6} g·L^{-1}. The instrument was calibrated with a tuning mixture (Agilent G2431A, USA). For instrument control and data acquiring the TrapControl 7.0 software (Bruker Daltonik GmbH, Germany) was used. Data processing was performed by DataAnalysis 4.0 SP4 software (Bruker Daltonik GmbH, Germany).

TEM images of the catalyst surface before and after the reaction were obtained using a PHILIPS/FEI CM20 transmission electron microscope. The particle size distribution was determined on a Veeco MultiMode V scanning probing microscope using the intermittent-contact atomic force method.

The conversion of 1,3,5-triphenylbenzene was estimated by gas chromatography coupled with mass spectrometry on a DFS Thermo Electron Corporation instrument (Germany) using electron ionization (70 eV), temperature of the ion source was 250 °C, an ID-BP5X capillary column (analog of DB-5MS, length 50 m, diameter 0.32 mm, thickness of the phase layer 0.25 μm), and helium as a carrier gas. The mass spectrometric data were processed using the Xcalibur program. Prior to injection, a sample of the studied substance was dissolved in chromatographically pure ethanol in a concentration of ~10^{-3} g·μL^{-1} (volume of the injected sample 0.1 μL). The chromatographic regime was as follows: temperature of the injector 250 °C, flow split 1:10; temperature-programmed column: initial temperature 120 °C (1 min), then heating with a rate of 20 °C·min^{-1} to 280 °C, and final temperature 280 °C (15 min); the flow

rate of the carrier gas through the column was 2 mL·min^{-1}. The temperature of the communication device with the mass spectrometer was 280 °C.

Dynamic light scattering measurements were performed with a Malvern Instrument Zetasizer Nano. A He-Ne gas laser with 4 mW power and 633 nm wavelength was used as a source of radiation. The measurements were carried out at 173° scattering angle. Dynamic light scattering (DLS) is a well-established technique for determining the effective radius (R) and size distribution of aggregates that is based on spherical approximation and the Stokes-Einstein equation: $D = kT/6\pi\eta R$, where D is the diffusion coefficient, k the Boltzmann constant, T the absolute temperature, η the solvent viscosity, and R the hydrodynamic radius. Data were analyzed by second-order cumulant expansion method. All measurements were performed at least five times for each sample. Results of dynamic light scattering is averaged by the number of particles.

Tri-*n*-butylphosphine (Sigma-Aldrich), tri-*tert*-butylphosphine (Dal-Chem), *n*-decyl bromide (Sigma-Aldrich), phenylboronic acid (Alfa Aesar), 1,3,5-tribromobenzene (Alfa Aesar), Pd(OAc)$_2$ (Alfa Aesar), KOH, NaBF$_4$, LiNTf$_2$ (analytical grade, without additional purification) were used in the work.

For additional information and spectra see supplementary material.

2.2. IL synthesis

2.2.1 Synthesis of tri-*tert*-butyl(decyl)phosphonium bromide (**1a**)

4.39 g (21.68 mmol) tri-*tert*-butylphosphine was added to 1.8 ml (21.68 mmol) 1-bromodecane without any solvent, and the resulting mixture was stirred for 5 hours at 120 °C. After completion of the reaction the mixture became a colourless solid. It was suspended in light petroleum ether (2x10 ml) and filtered. The solvent was dryied *in vacuo*. The product was obtained as a white powder; yield 8.14 g (88.7%), m.p. 122 °C.

^{31}**P{^{1}H} NMR** (161.7 MHz, CDCl$_3$): δ (ppm) 49.5 (s). ^{1}**H NMR** (400 MHz, CDCl$_3$): δ (ppm) 2.67 (m, 2H, P-CH$_2$), 1.94 (m, 2H, P-CH$_2$-C*H*$_2$), 1.70 (d, 27H, P(C(CH$_3$)$_3$)$_3$), 1.40-1.22 (m, 14H), 0.89 (t, 3H, CH$_2$-C*H*$_3$). MS [ESI+] found MH$^+$ 343.4; the phosphonium cation in C$_{22}$H$_{48}$PBr (C$_{22}$H$_{48}$P$^+$) requires 343.59.

2.2.2 Synthesis of tri-*tert*-butyl(decyl)phosphonium tetrafluoroborate (**1b**)

1.37 g (12.45 mmol) sodium tetrafluoroborate was added to a solution of 3.53 g (8.3 mmol) **1a** dissolved in 5 ml of water. A white solid precipitated. The solid was filtered from the reaction mixture and washed with 25 ml of water to remove inorganic salts. Then **1b** was dissolved in 10 ml CH$_2$Cl$_2$ and dried over MgSO$_4$ during 12 h. The solution was filtered and the solvent evaporated *in vacuo*. The product was obtained as a white powder; yield 3.07 g (85.6%), m.p. 106 °C.

^{31}**P{^{1}H} NMR** (161.7 MHz, CDCl$_3$): δ (ppm) 48.9 (s). ^{1}**H NMR** (400 MHz, CDCl$_3$): δ (ppm) 2.35 (m, 2H, P-CH$_2$), 1.91 (m, 2H, P-CH$_2$-C*H*$_2$), 1.65 (d, $^3J_{PH}$ = 13.7 Hz, 27H, P(C(CH$_3$)$_3$)$_3$), 1.37-1.25 (m, 14H), 0.88 (t, $^3J_{HH}$ = 6.6 Hz, 3H, CH$_2$-C*H*$_3$). ^{13}**C{^{1}H} NMR** (100.6 MHz, CDCl$_3$): δ (ppm) 39.3 (d, $^1J_{PC}$ = 29.5 Hz, *C*(CH$_3$)$_3$), 31.8 (d, $^2J_{PC}$ = 12.8 Hz, P-CH$_2$-*C*H$_2$), 31.8 (s, CH$_2$), 29.9 (s, C(*C*H$_3$)$_3$), 29.5 (s, CH$_2$), 29.33 (s, CH$_2$), 29.2 (s, CH$_2$), 29.2 (s, CH$_2$), 25.1 (d, $^3J_{PH}$ = 6.6 Hz, P-CH$_2$-CH$_2$-*C*H$_2$), 22.6 (s, *C*H$_2$-CH$_3$), 18.7 (d, $^1J_{PC}$ = 34.7 Hz, P-CH$_2$), 14.1 (s, CH$_2$-*C*H$_3$). MS [ESI+] found MH$^+$ 343.4; the phosphonium cation in C$_{22}$H$_{48}$BF$_4$P (C$_{22}$H$_{48}$P$^+$) requires 343.59.

2.2.3 Synthesis of tri-*tert*-butyl(decyl)phosphonium bis(trifluoromethanesulfonyl)imide (**1c**)

1.93 g (6.73 mmol) lithium bis(trifluoromethanesulfonyl)imide was added to 1.90 g (4.49 mmol) tri-*tert*-butyl(decyl)phosphonium bromide (**1a**) in 5 ml of water resulting in a two-layered mixture. 10 ml CH$_2$Cl$_2$ was added to extract the product. The organic layer was washed with water twice and dried over MgSO$_4$ overnight. Then the solution was filtered and the solvent evaporated *in vacuo*. The product was obtained as a colorless viscous liquid; yield 2.22 g (79.3%).

^{31}**P{^{1}H} NMR** (161.7 MHz, CDCl$_3$): δ (ppm) 49.3 (s). ^{1}**H NMR** (400 MHz, CDCl$_3$): δ (ppm) 2.21 (m, 2H, P-CH$_2$), 1.90 (m, 2H, P-CH$_2$-C*H*$_2$), 1.64 (d, $^3J_{PH}$ = 14.0 Hz, 27H, P(C(CH$_3$)$_3$)$_3$), 1.40-1.24 (m, 14H),

0.89 (t, $^3J_{HH}$ = 7.02 Hz, 3H, CH$_2$-CH_3). **^{13}C{^{1}H} NMR** (100.6 MHz, CDCl$_3$): δ 120.0 (d, $^1J_{FC}$ = 322.0 Hz, CF$_3$), 39.3 (d, $^1J_{PC}$ = 29.3 Hz, *C*(CH$_3$)$_3$), 32.8 (s, CH$_2$), 31.8 (d, $^2J_{PC}$ = 12.2 Hz, P-CH$_2$-*C*H$_2$), 29.8 (s, C(*C*H$_3$)$_3$), 29.4 (s, CH$_2$), 29.3 (s, CH$_2$), 29.2 (s, CH$_2$), 29.0 (s, CH$_2$), 25.0 (d, $^3J_{PC}$ = 6.6 Hz, P-CH$_2$-CH$_2$-*C*H$_2$), 22.6 (s, *C*H$_2$-CH$_3$), 18.7 (d, $^1J_{PC}$ = 34.9 Hz, P-CH$_2$), 14.1 (s, CH$_2$-*C*H$_3$). MS [ESI+] found MH$^+$ 343.4; the phosphonium cation in C$_{24}$H$_{48}$F$_6$NO$_4$S$_2$P (C$_{22}$H$_{48}$P$^+$) requires 343.59.

2.2.4 Synthesis of tri-*n*-butyl(decyl)phosphonium bromide (**2a**)

15.0 ml (60 mmol) tri-*n*-butylphopsphine was added to 12.5 ml (60 mmol) 1-bromodecane without any solvent, and the resulting mixture was stirred for 2 hours at 80 °C. After completion of the reaction the mixture was suspended in light petroleum ether (2x50 ml) and decanted. The solvent was dryied *in vacuo*. The product was obtained as a colorless viscous liquid; yield 21.5 g (84.5%).
^{31}P{^{1}H} NMR (161.7 MHz, CDCl$_3$): δ (ppm) 32.8 (s). **^{1}H NMR** (400 MHz, CDCl$_3$): δ (ppm) 2.53-2.39 (m, 8H, P-CH$_2$), 1.54 (m, 16H, P-CH$_2$-CH_2-CH_2), 1.25 (m, 12H), 0.97 (t, $^3J_{PH}$ = 7.05 Hz, 9H, CH$_2$-CH_3), 0.87 (t, $^3J_{PH}$ = 6.87 Hz, 3H, CH$_2$-CH_3).

2.2.5 Synthesis of tri-*n*-butyl(decyl)phosphonium tetrafluoroborate (**2b**)

3.89 g (35.4 mmol) sodium tetrafluoroborate was added to a solution of 10.0 g (23.6 mmol) **2a** dissolved in 50 ml of water at room temperature. 50 ml CH$_2$Cl$_2$ was added to extract the product. The organic layer was collected and dried over MgSO$_4$ for 12 h. The solution was filtered and the solvent evaporated *in vacuo*. The product was obtained as a transparent viscous liquid; yield 8.26 g (81.4%).
^{31}P{^{1}H} NMR (161.7 MHz, CDCl$_3$): δ (ppm) 33.2 (s). **^{1}H NMR** (400 MHz, CDCl$_3$): δ (ppm) 2.18 (m, 8H, P-CH$_2$), 1.51 (m, 16H, P-CH$_2$-CH_2-CH_2), 1.23 (m, 12H), 0.95 (t, $^3J_{HH}$ = 6.38 Hz, 9H, CH$_2$-CH_3), 0.85 (t, $^3J_{HH}$ = 6.57 Hz, 3H, CH$_2$-CH_3).

2.2.6 Synthesis of tri-*n*-butyl(decyl)phosphonium bis(trifluoromethanesulfonyl)imide (**2c**)

2.24 g (7.79 mmol) lithium bis(trifluoromethanesulfonyl)imide was added to a solution of 2.2 g (5.19 mmol) **2a** dissolved in 10 ml of water at room temperature. 15 ml CH$_2$Cl$_2$ was added to extract the product. The organic layer was collected and dried over MgSO$_4$ for 12 h. The solution was filtered and the solvent evaporated *in vacuo*. The product was obtained as a transparent liquid; yield 2.82 g (87 %).
^{31}P{^{1}H} NMR (161.7 MHz, CDCl$_3$): δ (ppm) 33.1 (s). **^{1}H NMR** (400 MHz, CDCl$_3$): δ (ppm) 2.13 (m, 8H, P-CH$_2$), 1.52 (m, 16H, P-CH$_2$-CH_2-CH_2), 1.28 (m, 12H), 0.99 (t, 9H, CH$_2$-CH_3), 0.90 (t, $^3J_{HH}$ = 6.38 Hz, 3H, CH$_2$-CH_3).

2.3. Typical procedure for preparation of PdNPs

0.45 mg (0.002 mmol) palladium acetate and an appropriate amount of phosphonium salt given in Tables 1 and 2 were dissolved in 10 ml ethanol and stirred for 20 minutes at room temperature. The color of the solution changed from transparent to light brownish grey. TEM samples were prepared as follows: one drop of the solution was put on a copper grid and dried *in vacuo*.

Table 1. The amount of PILs **1b**, **2b**

PIL/Pd ratio	PIL amount	
	1b, g (mmol)	**2b,** g (mmol)
13 (26 for **2b**)	0.01 (0.023)	0.02 (0.046)
65 (78 for **2b**)	0.05 (0.116)	0.06 (0.139)
131	0.10 (0.232)	0.10 (0.232)
326	0.25 (0.580)	0.25 (0.580)
653	0.50 (1.161)	0.50 (1.161)
1305	1.00 (2.323)	1.00 (2.323)
1958	1.50 (3.485)	1.50 (3.485)

2611	2.00 (4.647)	2.00 (4.647)

Table 2. The amount of PILs **1c**, **2c**

PIL/Pd ratio	PIL amount	
	1c g, (mmol)	**2c** g, (mmol)
16	0.02 (0.032)	0.02 (0.032)
48	0.06 (0.096)	0.06 (0.096)
80	0.10 (0.160)	0.10 (0.160)
200	0.25 (0.401)	0.25 (0.401)
401	0.50 (0.802)	0.50 (0.802)
802	1.00 (1.603)	1.00 (1.603)
1162	1.45 (2.325)	1.45 (2.325)
1411	1.76 (2.822)	-
1764	2.20 (3.527)	-

2.4 General procedure for the Suzuki cross-coupling reaction

0.18 g (0.57 mmol) 1,3,5-tribromobenzene, 0.32 g (2.6 mmol) phenylboronic acid, and 0.15 g (2.6 mmol) potassium hydroxide were added to a fresh suspension of PdNPs (see 2.3). The reaction mixture was stirred for 16 hours at 30 °C. Organic compounds were extracted with 10 ml toluene and analyzed by GC-MS without product isolation. The conversion was calculated by using the correction factor which was obtained by GC-MS analysis of an equimolar mixture of 1,3,5-tribromobenzene and 1,3,5-triphenylbenzene.

3. Results and discussion

The phosphonium salts under investigation (Figure 1) were synthesized according to previously described methods (**1a-c** [29], **2a-b** [30], **2c** [31]).

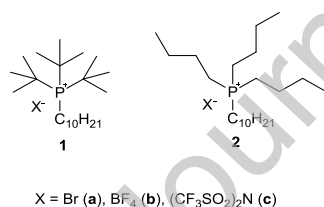X = Br (**a**), BF$_4$ (**b**), (CF$_3$SO$_2$)$_2$N (**c**)

Figure 1. The structure of PILs.

PdNPs were obtained by reduction of palladium acetate in ethanol in the presence of the corresponding PIL. No additional reducing agent was used. The quantity of PIL was varied while the amount of palladium acetate and ethanol remained constant.

In preliminary studies, sterically hindered PILs were found to support the formation of PdNPs which were the effective catalyst in Suzuki [32] and Sonogashira [27~~21~~] cross-coupling reactions. The wide scope of substrates involved in the reaction resulted in high conversion, e.g. chloroarenes, and successful recycling of the catalytic system was achieved [33].

The cross-coupling reaction of 1,3,5-tribromobenzene and phenylboronic acid (Figure 2) was carried out using *in situ* prepared PdNPs under mild conditions (30 °C, 0.36 mol% [Pd]). Tri-substituted benzene was formed predominantly; products of mono- and di-substitution were detected as traces. The

6

PdNPs showed catalytic activity and considerable stability. No "Pd black" precipitation was observed in the system before and after the reaction.
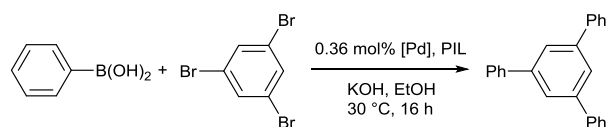

Figure 2. Suzuki cross-coupling of 1,3,5-tribromobenzene and phenylboronic acid.

The results of the catalytic reactions are presented in Tables 3 and 4. The conversion was estimated by GC-MS without product isolation. It should be noted that increasing the temperature up to 50 °C allowed to achieve almost total conversion of 1,3,5-tribromobenzene to 1,3,5-triphenylbenzene (Table 3, entry 4). The control experiment without stabilizing agent gave only 6% conversion; moreover, palladium black formation was observed.

Table 3. The conversion of 1,3,5-tribromobenzene to 1,3,5-triphenylbenzene (%) for **1b**, **2b**.

Entry	PIL/Pd ratio	Conversion for **1b**, %	Conversion for **2b**, %
1.	12 (23 for **2b**)	14.3	17.9
2.	58 (70 for **2b**)	31.2	21.6
3.	116	67.4	45.8
4.	290	76.5 (94.5[*])	26.8
5.	581	54.3	29.2
6.	1162	58.9	31.7
7.	1743	11.6	7.7
8.	2323	19.4	2.2

[*]Reaction was conducted at 50 °C.

0.45 mg (0.002 mmol) palladium acetate and an appropriate amount of phosphonium salt **1b** or **2b** (Table 1), 0.18 g (0.57 mmol) 1,3,5-tribromobenzene, 0.32 g (2.6 mmol) phenylboronic acid, 0.15 g (2.6 mmol) potassium hydroxide, 10 ml EtOH as solvent.

Table 4. The conversion of 1,3,5-tribromobenzene to 1,3,5-triphenylbenzene (%) for **1c**, **2c**.

Entry	PIL/Pd ratio	Conversion for **1c**, %	Conversion for **2c**, %
9.	16	48.5	12.7
10.	48	64.6	19.8
11.	80	53.4	30.0
12.	200	3.1	13.2
13.	401	8.8	24.3
14.	802	4.3	10.5
15.	1162	2.0	17.3
16.	1411	23.2	-
17.	1764	2.7	-

0.45 mg (0.002 mmol) palladium acetate and an appropriate amount of phosphonium salt **1c** or **2c** (Table 2), 0.18 g (0.57 mmol) 1,3,5-tribromobenzene, 0.32 g (2.6 mmol) phenylboronic acid, 0.15 g (2.6 mmol) potassium hydroxide, 10 ml EtOH as solvent.

As shown in Figure 3, the appropriate amount of PIL for the maximum conversion in the Suzuki reaction is quite small and slightly varies depending on the structure of the stabilizing agent. The increase of the amount of stabilizing agent in the reaction mixture leads to slow deactivation of the system followed by a second lower maximum. Accordingly, the use of 'neat' ILs as stabilizer for NPs and reaction medium is inexpedient.
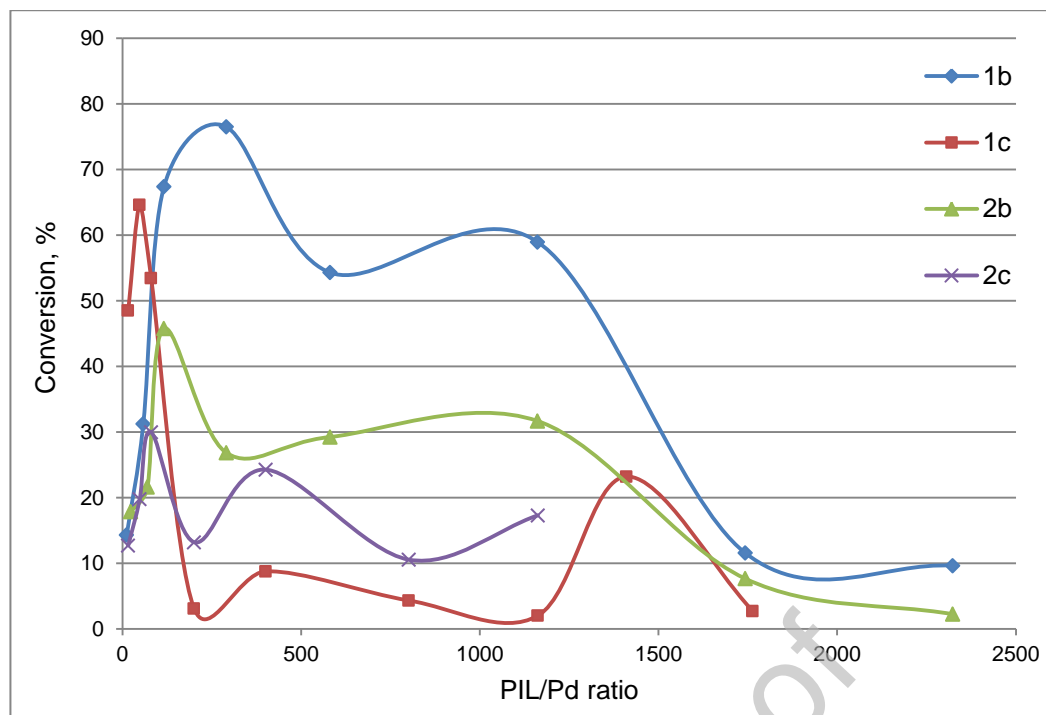
Figure 3. The influence of the structure and quantity of PIL on the conversion in the Suzuki coupling reaction (Figure 2).

A similar dependence of the conversion on the PIL/Pd ratio for phosphonium salts with different structures is quite unusual and requires a detailed investigation. The key factors determining the efficiency of nanocatalysis are the size and surface area of the NPs. TEM measurements of PdNPs in **1b** were performed (Figures 4-7).
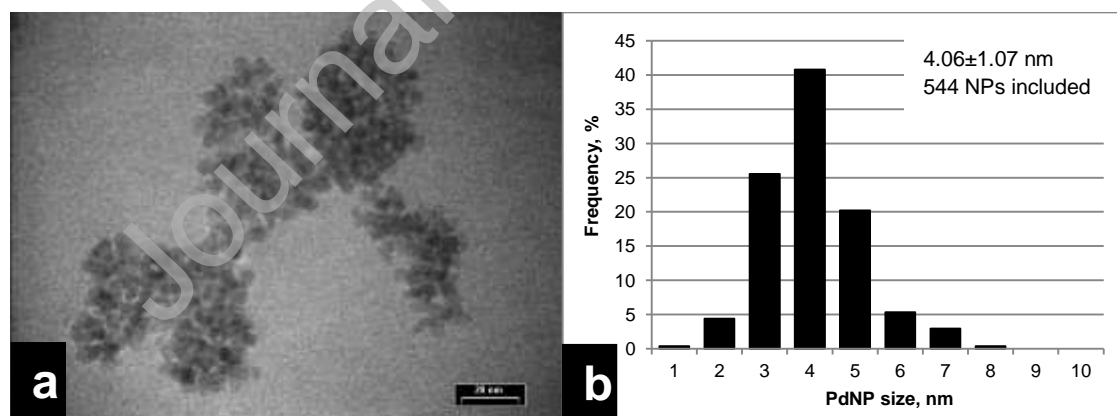

Figure 4. TEM image (a) and size distribution (b) of PdNPs in the absence of PIL.
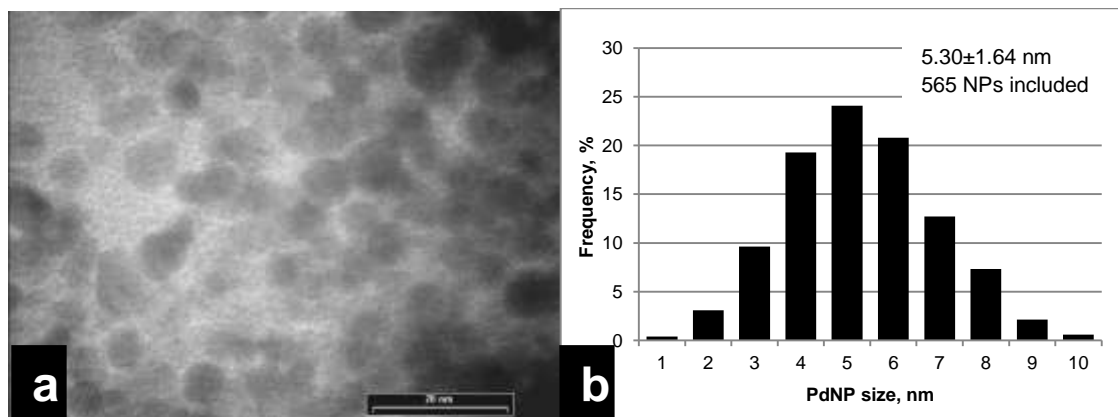
Figure 5. TEM image (a) and size distribution (b) of PdNPs at a ratio **1b**/Pd = 12/1.
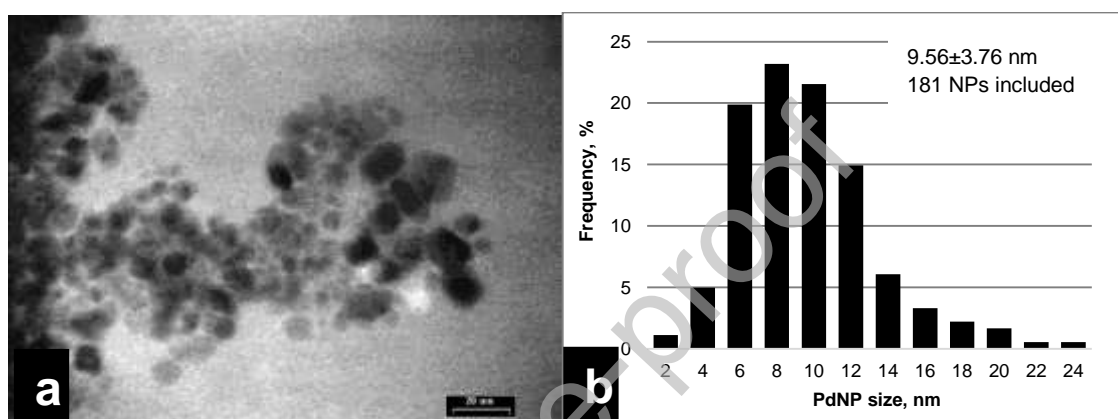

Figure 6. TEM image (a) and size distribution (b) of PdNPs at a ratio **1b**/Pd = 58/1.
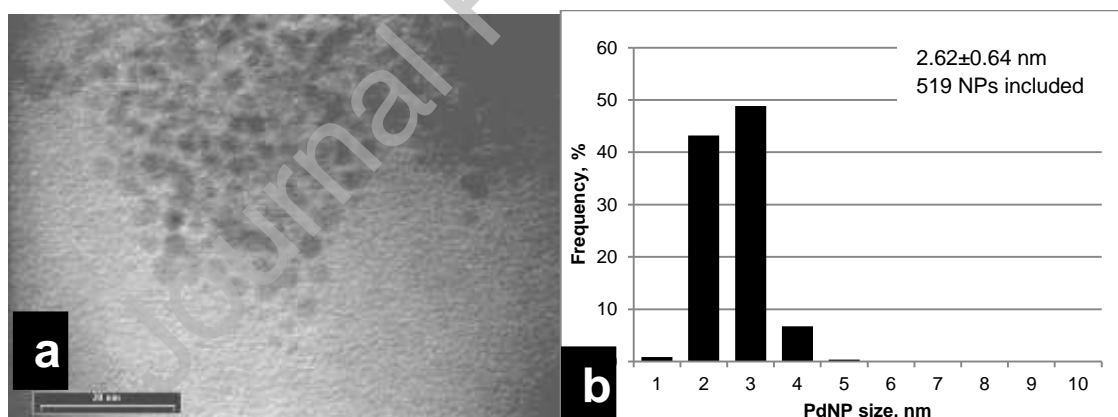

Figure 7. TEM image (a) and size distribution (b) of PdNPs at a ratio of **1b**/Pd = 116/1.

Whilst small PdNPs with quite narrow size distribution (4.06±1.07 nm) are formed in the absence of PILs (Figure 4), they exhibit low catalytic activity. "Pd black" precipitation indicates fast PdNPs aggregation, and the detected product is formed after a few minutes of the reaction.

The increase of the **1b**/Pd ratio (Fig. 5-7) leads to an increase of the conversion of 1,3,5-tribromobenzene; however, no straight correlation between the size of PdNPs and their catalytic activity is observed. When the ratio changes from 12/1 to 58/1, the average size of NPs grows. Despite the reduced surface Pd atoms, an increase in the conversion is observed (Table 5). Noteworthy, at a ratio of 116/1, the size of the PdNPs drops to 2.62±0.64 nm and the number of surface Pd atoms quadruples, although the conversion only doubles. Definitely, some more important factors which influence the nanocatalyst activity must exist,

9

such as the lifetime of NPs and their surrounding in solution. Furthermore, it is impossible to obtain high quality images of PdNPs at ratios above 116/1 due to the opaqueness of the samples with a high content of PILs. The TEM method is, therefore, not suitable for a comprehensive explanation of the catalytic activity of PdNPs.

Table 5. Parameters of PdNPs.

1b/Pd ratio	0	12/1	58/1	116/1
Mean diameter of PdNPs	4.06 nm	5.30 nm	9.56 nm	2.62 nm
Number of Pd atoms in NP	~ 2369	~ 5273	~ 30928	~ 623
Quantity (proportion) of surface atoms	~ 711 (30%)	~ 1212 (23%)	~ 3942 (13%)	~ 291 (47%)

Earlier, quantum-chemical calculations demonstrated a moderate influence of the cation structure variation of PILs on their interaction with Pd_6 clusters and Pd atoms [34]. However, the results obtained in our research show the key role of the cation in the catalytic process. These results led us to apply dynamic light scattering (DLS) as a method that allows to investigate a catalytic system including PdNPs, PIL, and solvent altogether. The hydrodynamic diameters of the catalytic compositions based on **1c** and **2b** are given in Fig. 8-10. Comparison of the dependences of catalytic activity of PdNPs and the hydrodynamic diameter of aggregates on the PIL/Pd ratio reveals a correlation between them.
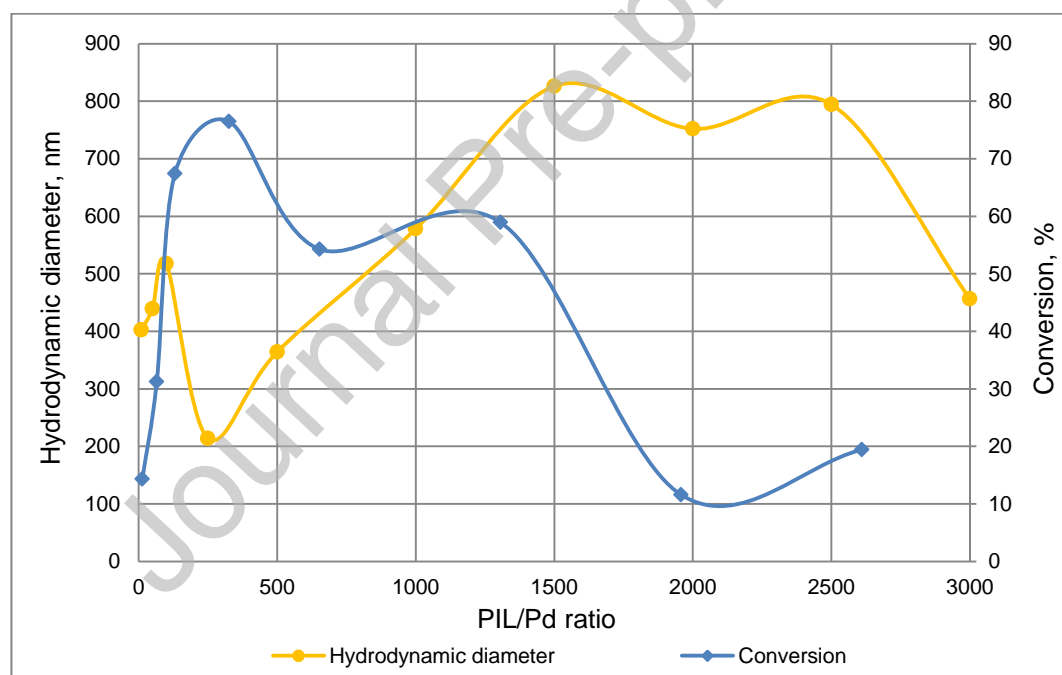

Figure 8. The conversion and the hydrodynamic diameter of aggregates formed by PIL **1b** and PdNPs depending on the Pd/PIL ratio.
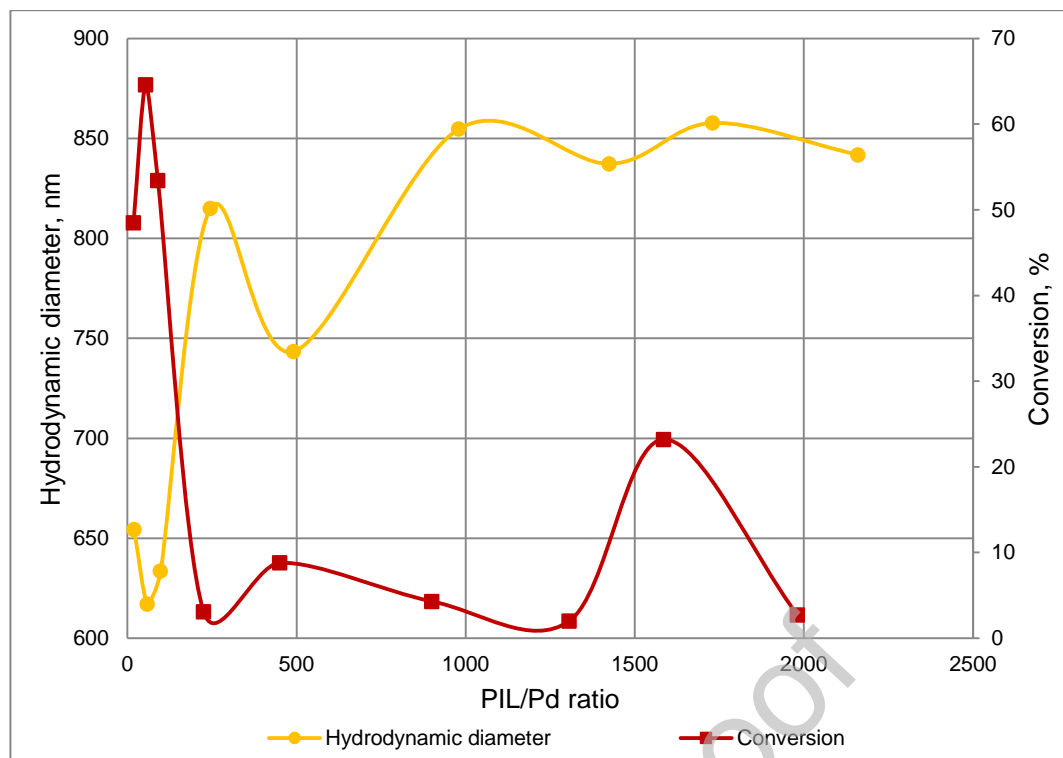
Figure 9. The conversion and the hydrodynamic diameter of aggregates formed by PIL **1c** and PdNPs depending on the Pd/PIL ratio.
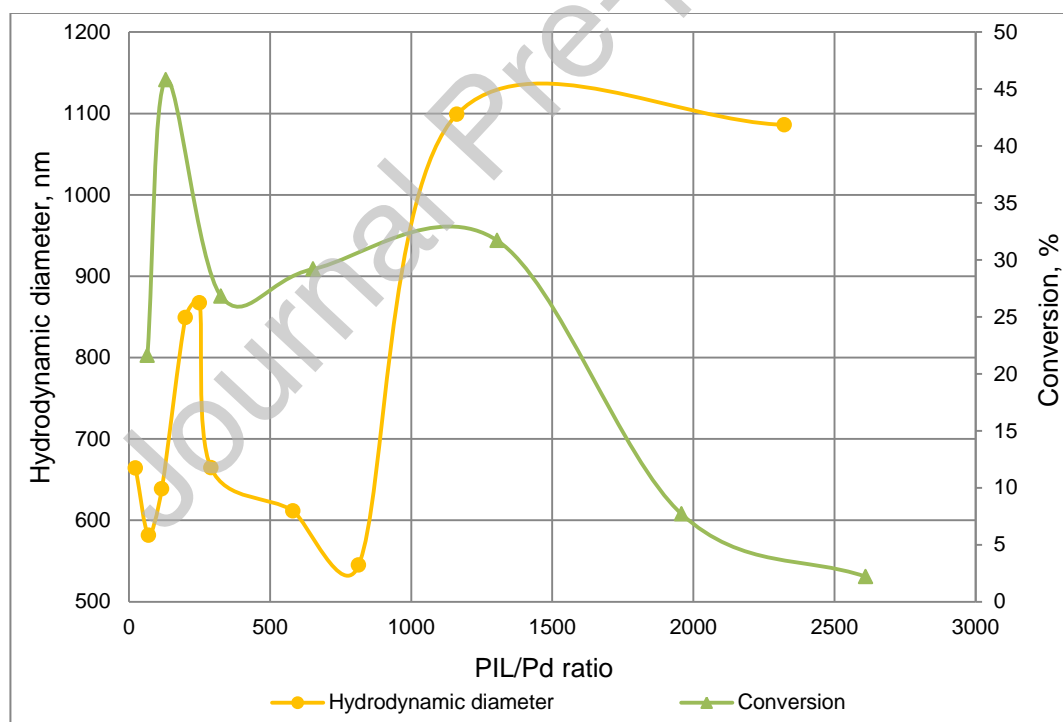

Figure 10. The conversion and the hydrodynamic diameter of the aggregates formed by PIL **2b** and PdNPs depending on the Pd/PIL ratio.

Fig. 8-10 show an inversely proportional dependence of the hydrodynamic diameter of the aggregates and the catalytic activity of PdNPs on the Pd/PIL ratio. However the maximum of conversion for salt **1b** was achieved with aggregates of 200 nm, and for the two another salts, this value is about 600 nm.

The maximum conversion for the catalytic system containing **1b** is 76.5% at a PIL/Pd ratio of 290/1. It corresponds to the minimum of the hydrodynamic diameter of aggregates, that is 200 nm. A conversion of 64.6% of 1,3,5-tribromobenzene in the case of **1c** is reached at a Pd/PIL ratio of 48/1 and corresponds to the minimum of hydrodynamic diameter of aggregates, i.e. about 600 nm. Finally, the catalytic system including **2b** demonstrates the maximum conversion of 45.8% at Pd/PIL ratio of 116/1 with an average size of aggregates of 600 nm. Although the structures of the investigated PILs are similar, the highest activity of each catalytic system has been achieved at different PIL/Pd ratio.

According to TEM and DLS data, the size of PdNPs and PIL/Pd aggregates are changing unrelated with increasing amounts of PILs in the reaction mixture. With TEM, only the PdNPs are observable, whereas DLS allows to explore the whole catalytic system consisting of both PdNPs and surrounding PIL molecules. Thereby, the DLS method is more suitable for characterization of the catalytic system and allows to choose the most effective concentration range of the stabilizers.

Conclusions

We have found that small amounts of PILs are sufficient for the formation and stabilization of PdNPs and result in a high catalytic activity in Suzuki cross-coupling reactions. To the best of our knowledge, this is the first investigation of the influence of different quantities of PILs on the formation and stabilization of PdNPs. The PIL/Pd ratio influences the size, the hydrodynamic diameter of aggregates and the catalytic behavior of the resulting PdNPs. Noteworthy, the highest conversion was achieved with sterically demanding PILs as stabilizers. Therefore, the right selection of PIL and PIL/Pd ratio allows to obtain the desired products in high yields meeting the principles of green chemistry.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

[1] J.P. Hallett, T. Welton, Room-Temperature Ionic Liquids: Solvents for Synthesis and Catalysis. 2, Chem. Rev. 111 (2011) 3508-3576. https://doi.org/ 10.1021/cr1003248.

[2] J. Łuczak, M. Paszkiewicz, A. Krukowska, A. Malankowska, A. Zaleska-Medynska, Ionic liquids for nano- and microstructures preparation. Part 1: Properties and multifunctional role, Adv Colloid Interface Sci. 230 (2016) 13-28. https://doi.org/10.1016/j.cis.2015.08.006.

[3] S. Khazalpour, M. Yarie, E. Kianpour et al., Applications of phosphonium-based ionic liquids in chemical processes, J. Iran Chem. Soc. (2020). https://doi.org/10.1007/s13738-020-01901-6.

[4] J. Dupont, From Molten Salts to Ionic Liquids: A "Nano" Journey, Acc. Chem. Res. 44 (2011) 1223-1231. https://doi.org/10.1021/ar2000937.

[5] R.S. Kalb, Toward Industrialization of Ionic Liquids. In: M. Shiflett (Ed.) Commercial Applications of Ionic Liquids. Green Chemistry and Sustainable Technology. Springer, Cham, 2020, pp. 261-282. https://doi.org/10.1007/978-3-030-35245-5_11.

[6] B. Zhang, N. Yan, Towards rational design of nanoparticle catalysis in ionic liquids, Catalysts 3 (2013) 543-562. https://doi.org/10.3390/catal3020543.

[7] Z. He, P. Alexandridis, Ionic liquid and nanoparticle hybrid systems: Emerging applications, Adv. Colloid Interface Sci. 244 (2017) 54-70. https://doi.org/10.1016/j.cis.2016.08.004.

[8] N. Leadbeater, Opening an Aladdin's cave: the Suzuki coupling in a room-temperature ionic liquid, Chem. Commun. 50 (2014) 1515-1518. https://doi.org/10.1039/C3CC44932G.

[9] R.L. Vekariya, A review of ionic liquids: Applications towards catalytic organic transformations, J. Mol. Liq. 227 (2017) 44-60. https://doi.org/10.1016/j.molliq.2016.11.123.

[10] R. Sheldon, Catalytic reactions in ionic liquids, Chem. Commun. 23 (2001) 2399-2407. https://doi.org/10.1039/B107270F.

[11] K. Li, H. Choudhary, R.D. Rogers, Ionic liquids for sustainable processes: Liquid metal catalysis, Curr. Opin. Green Sustain. Chem. 11 (2018) 15-21. https://doi.org/10.1016/j.cogsc.2018.02.011.

[12] S.A. Dharaskar, Ionic Liquids (A Review): The Green Solvents for Petroleum and Hydrocarbon Industries, Res. J. Chem. Sci. 2 (2012) 80-85. http://www.isca.in/rjcs/Archives/v2/i8/15.ISCA-RJCS-2012-110.php.

[13] M. Kissoudi, V. Samanidou, Recent advances in applications of ionic liquids in miniaturized microextraction techniques, Molecules 23 (2018) 1437/1-1437/12. https://doi.org/10.3390/molecules23061437.

[14] S.P.F. Costa, A.M.O. Azevedo, P.C.A.G. Pinto, M.L.M.F.S. Saraiva, Environmental Impact of Ionic Liquids: Recent Advances in (Eco)toxicology and (Bio)degradability ChemSusChem 2017, 10, 2321-2347. https://doi.org/10.1002/cssc.201700261.

[15] G. Cevasco, C. Chiappe, Are ionic liquids a proper solution to current environmental challenges? Green Chem. 16 (2014) 2375-2385. https://doi.org/10.1039/C3GC42096E.

[16] Ph.G. Jessop, Fundamental properties and practical applications of ionic liquids: concluding remarks, Faraday Discuss. 206 (2018) 587-601. https://doi.org/10.1039/C7FD90090B.

[17] V. Campisciano, F. Giacalone, M. Gruttadauria, Supported Ionic Liquids: A Versatile and Useful Class of Materials, Chem. Rec. 17 (2017) 918-938. doi: 10.1002/tcr.201700005.

[18] K. Manojkumar, A. Sivaramakrishna, K. Vijayakrishna, A short review on stable metal nanoparticles using ionic liquids, supported ionic liquids, and poly(ionic liquids), J. Nanoparticle Res. 18 (2016) 103. https://doi.org/10.1007/s11051-016-3409-y.

[19] Y. Hu, H. Yang, Y. Zhang, Zh. Hou, X. Wang, Y. Qiao, H. Li, B. Feng, Q. Huang, The functionalized ionic liquid-stabilized palladium nanoparticles catalyzed selective hydrogenation in ionic liquid, Catalysis Commun. 10 (2009) 1903-1907. https://doi.org/10.1016/j.catcom.2009.06.025.

[20] J. McNulty, A. Capretta, J. Wilson, J. Dyck, G. Adjabeng, A. Robertson, Suzuki cross-coupling reactions of aryl halides in phosphonium salt ionic liquid under mild conditions, Chem. Commun. (2002) 1986-1987. https://doi.org/10.1039/b204699g.

[21] Y. Zhang, Y. Cao, D. Chen, P. Cui, J. Yang, Ionic liquid assisted synthesis of palladium nanoclusters for highly efficient formaldehyde oxidation, Electrochim. Acta 269 (2018) 38-44. https://doi.org/10.1016/j.electacta.2018.02.155.

[22] T. Teranishi, M. Miyake, Size Control of Palladium Nanoparticles and Their Crystal Structures, Chem. Mater. 10 (1998) 594-600. https://doi.org/10.1021/cm9705808.

[23] D. Srimani, S. Sawoo, A. Sarkar, Convenient Synthesis of Palladium Nanoparticles and Catalysis of Hiyama Coupling Reaction in Water, Org. Lett., 9 (2007) 3639-3642. https://doi.org/10.1021/ol7015143.

[24] R. Roszak, A. M. Trzeciak, J. Pernak, N. Boruck, Effect of chiral ionic liquids on palladium-catalyzed Heck arylation of 2,3-dihydrofuran, Appl. Catal. A: Gen., 409-410 (2011) 148-155. https://doi.org/10.1016/j.apcata.2011.09.038.

[25] H. Oka, K. Kitai, T. Suzuki, Y. Obora, N,N-Dimethylformamide-stabilized copper nanoparticles as a catalyst precursor for Sonogashira–Hagihara cross coupling, RSC Adv., 7 (2017) 22869-22874. https://doi.org/10.1039/C6RA27910D.

[26] M. Selva, A. Perosa, G. Fiorani, Phosphonium salts and P-ylides, in: D.W. Allen, D. Loakes, J.C. Tebby (Eds.), Organophosphorus Chemistry: Volume 48, Royal Society of Chemistry, Cambridge, U. K., 2019, pp. 145-198. https://doi.org/10.1039/9781788016988-00145.

[27] V. Ermolaev, V. Miluykov, D. Arkhipova, E. Zvereva, O. Sinyashin, Decyl(Tri-*Tert*-Butyl)Phosphonium Tetrafluoroborate/Palladium Acetate: An Effective Catalyst for Cross-Coupling Reaction of Arylbromides with Phenylacetylene in Copper-Free Conditions, Phosphorus, Sulfur, Silicon Relat. Elem. 188 (2013) 168-170. https://doi.org/10.1080/10426507.2012.744013.

[28] D. M. Arkhipova, V. V. Ermolaev, V. A. Miluykov, G. A. Gaynanova, F. G. Valeeva, L. Ya. Zakharova, A. I. Konovalov, D. R. Islamov, O. N. Kataeva, O. G. Sinyashin, Structure and supramolecular organization of tri-*n*-butyl(octadecyl)phosphonium tetrafluoroborate and its influence on catalytic activity of stabilized palladium nanoparticles, Russ. Chem. Bull., Int. Ed. 64 (2015) 2486-2492. https://doi.org/10.1007/s11172-015-1181-2.

[29] V. Ermolaev, V. Miluykov, I. Rizvanov, D. Krivolapov, E. Zvereva, S. Katsyuba, O. Sinyashin, R. Schmutzler, Phosphonium ionic liquids based on bulky phosphines: synthesis, structure and properties, Dalton Trans. 39 (2010) 5564-5571. https://doi.org/10.1039/B924636C.

[30] L. Weng, X. Liu, Y. Liang, Q. Xue, Effect of tetraalkylphosphonium based ionic liquids as lubricants on the tribological performance of a steel-on-steel system, Tribol. Lett. 26 (2007) 11-17. https://doi.org/10.1007/s11249-006-9175-8.

[31] K. Takeyama, T. Saito, N. Sasakibara, K. Ikegami (2012) US 20120025143A1, TOKAI RUBBER INDUSTREIS Ltd. Sumitomo Riko Co Ltd.

[32] A. Ibragimova, D. Arkhipova, G. Vagapova, V. Ermolaev, I. Galkina, L. Nigmatullina, I. Rizvanov, L. Zakharova, V. Milyukov, A. Konovalov, O. Sinyashin, Influence of the medium self-organization on the catalytic activity of palladium nanoparticles stabilized by amphiphilic phosphonium salts in the Suzuki reaction, Russ. Chem. Bull., Int. Ed., 63 (2014) 1297-1300. https://doi.org/10.1007/s11172-014-0593-8.

[33] V. V. Ermolaev, D. M. Arkhipova, L. Sh. Nigmatullina, I. Kh. Rizvanov, V. A. Milyukov, O. G. Sinyashin, Palladium nanoparticles stabilized by sterically hindered phosphonium salts as Suzuki cross-coupling catalysts, Russ. Chem. Bull., Int. Ed. 62 (2013) 657-660. https://doi.org/10.1007/s11172-013-0088-z.

[34] E.E. Zvereva, S. Grimme, S.A. Katsyuba, V.V. Ermolaev, D.A. Arkhipova, N. Yan, V.A. Miluykov, O.G. Sinyashin, A. Aleksandrov, Solvation and stabilization of palladium nanoparticles in phosphonium-based ionic liquids: a combined infrared spectroscopic and density functional theory study, Phys. Chem. Chem. Phys. 16(38) (2014) 20672-80. https://doi.org/10.1039/C4CP02547D.