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Chitosan as a support for heterogeneous Pd catalysts in liquid phase catalysis

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ABSTRACT

Four different chitosan-supported palladium catalysts were prepared, whereby two of them were modified as Schiff base by reaction with salicylaldehyde and 2-pyridinecarboxaldehyde before complexation with palladium. The remaining differ in their preparation method: co-precipitation or adsorption. The properties of the catalysts were characterized by FTIR, XPS, ICP-MS, and TGA. Comparison of the catalysts activity was assessed in microwave-assisted Suzuki reactions in aqueous media, resulting in good yields and excellent selectivities concerning cross-coupling product. Additionally, the catalysts prove their activity under conductive heating conditions. The study was extended to microwave-assisted Heck and Sonogashira reactions in DMF, confirming the efficiency of chitosan-supported palladium derivatives as catalysts for C–C couplings. Experiments revealed that catalysts prepared by co-precipitation furnished inferior yields concerning the employed C–C coupling reactions. Modification of chitosan with 2-pyridinecarboxaldehyde and subsequent palladium deposition resulted in highly active catalysts affording high product selectivities and yields.

1. Introduction

Palladium is one of the most common transition metals in organic synthesis, especially for C–C and C–X coupling reactions [1]. For a long time its use was limited to homogeneous catalysis causing difficulties in recycling and purification. Environmental-friendly heterogeneous catalysts strongly stimulate the growth of this research area [2,3]. In the last two decades a variety of solid-supported palladium catalysts has been developed by immobilizing Pd on various supports. These novel catalysts are mainly based on alumina, silica, and other inorganic oxides like zeolites, active carbon, and polymers [4–9].

Chitosan is a linear copolymer in which 2-amino-2-deoxy-D-glucopyranose (glucosamine) is linked to 2-acetamido-2-deoxy-D-glucopyranose (*N*-acetyl glucosamine) by a β-(1,4) glycosidic bond (Scheme 1). This structure offers numerous modification possibilities – the capabilities of this material seem unlimited. Chitosan is produced by the *N*-deacetylation of chitin, which is the second most abundant natural polymer after cellulose. It is estimated that about 150,000 tons of chitin are available for commercial use annually. However, only a few thousand tons are actually used world wide. There are also other possibilities to produce chitosan, but fishery waste is the easiest. Despite the insolubility of chitosan in the majority of common solvents, it can generate films, colloids, powders, flakes, gel-beads, and fibers which make chitosan an excellent candidate as a support for liquid phase catalysis [10]. The increasing interest in chitosan is due to its chemo-physical and biological properties (hydrophilic, positively charged, biodegradable, non-toxic and biocompatible). It has a high sorption capacity for metal ions and it is prone to chemical modification. As a result, many applications for such materials are conceivable including waste water treatment, pharmaceutical and cosmetic preparations, heavy metal complexation, and heterogeneous catalysis [11].

Indeed, several applications have already proven the catalytic activity of chitosan-supported metals in reduction reactions (chromate, phenol, nitro-aromatics), asymmetric hydrogenations, allylic substitution, cyclopropanation of olefins, oxidation reactions (alkylbenzenes, aromatics) and carbonylation [12–17]. Macquarrie and coworkers reported the use of chitosan as a support to anchor a palladium–pyridyl imine complex to promote Suzuki and Heck reactions [18], whereas Xu et al. used a chitosan-supported imine palladacycle complex with salicylaldehyde as the anchoring group [19].

In this paper the different preparation methods of chitosan-supported Pd catalysts are compared with each other. Thus, four different catalysts were prepared and analyzed as well as applied in Suzuki, Heck, and Sonogashira cross-coupling reactions. Amongst others the methods described by Hardy et al. [18] and Xu et al.

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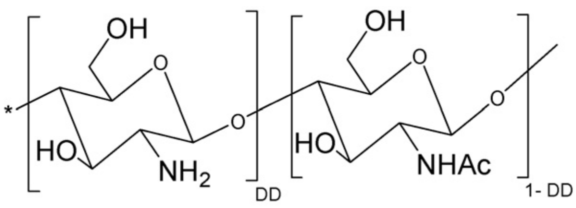


Scheme 1. Structure of chitin (DD < 0.75) and chitosan (DD > 0.75). DD, degree of deacetylation.

[19] were used for the catalyst preparation. Their application in Suzuki reaction under thermal conditions and under microwave irradiation was investigated. Additionally, the chitosan–palladium catalysts were used in microwave-promoted Heck and Sonogashira reactions. These experiments were carried out under conditions similar to those recently reported for the microwave-promoted C–C couplings using porous glass-supported Pd as catalyst [20].

2. Experimental

All chemicals were purchased from Sigma–Aldrich and were used without further purification. Chitosan of medium molecular weight (from crab shells, 448877, Sigma–Aldrich) was used as support material.

2.1. Catalysts preparation

2.1.1. Co-precipitation method (*A1*)

A1 was prepared following a modified procedure described in [21]. $PdCl_2$ (0.1 mmol, 0.0182 g, 1 wt.% Pd) which was dissolved in 0.1 M HCl was added to a 1.5 wt.% solution of 1 g chitosan in 0.1 M HCl. The mixture was stirred at room temperature until a clear yellow solution was obtained. This yellow solution of the homogeneous palladium–chitosan complex was added dropwise to a beaker containing a 0.5 M NaOH solution (350 ml). This led to an immediate coagulation of the drops into spherical globules (beads) with a diameter of approx. 1–3 mm. The beads formed were filtered and washed with deionized water until neutrality. Then, the catalyst was air-dried at room temperature for 48 h.

2.1.2. Adsorption method (*A2*)

A2 was prepared following a procedure described in [21]. A 1.5 wt.% chitosan solution (1 g chitosan solved in 0.1 M HCl) was added dropwise to a beaker containing a 0.5 M NaOH solution (350 ml). The resulting pure chitosan beads were filtered-off and washed with deionized water until neutrality and were air-dried at room temperature for 48 h. The $PdCl_2$ (0.5 mmol, 0.083 g, 5 wt.% Pd) was suspended in 20 ml deionized water and stirred with 1.0 g of the dried pure chitosan beads for 20 min. The beads were then filtered-off, washed with deionized water and dried for 24 h at room temperature.

2.1.3. Cross-linking with salicylaldehyde (*B1*)

B1 was prepared following a modified procedure described in [19]. Chitosan (4 g), salicylaldehyde (63 mmol, 7.724 g) and glacial acetic acid (6.5 ml) were refluxed in methanol (65 ml) for 10 h. After completion of the reaction, the yellow chitosan-Schiff base (**B**) was collected by filtration, washed five times with ethanol and dried at 70 °C. **B** (1.5 g) was then stirred for 10 h at room temperature with palladium chloride (0.3 mmol, 0.053 g, 2 wt.% Pd) in MeOH (30 ml) in the presence of NaOAc (0.3 mmol, 0.026 g). Then, the chitosan-supported imine palladacycle catalyst **B1** was filtered, washed with ethanol, and dried at 70 °C over night.

2.1.4. Cross-linking with 2-pyridinecarboxaldehyde (*C1*)

C1 was prepared following a modified procedure described in [18]. 2-Pyridinecarboxaldehyde (12 mmol, 1.147 g) was added to a chitosan suspension (2.0 g) in ethanol (100 ml). The mixture was heated under reflux for 18 h. After cooling the mixture was filtered-off and the resulting chitosan-Schiff base (**C**) was washed with ethanol and dried at 60 °C overnight in a drying oven. **C** (1.0 g) was added to a solution of palladium-(II)-acetate (0.5 mmol, 0.113 g, 5 wt.% Pd) in acetone (50 ml) and stirred overnight. The solid catalyst was washed by heating under reflux in a sequence of solvents (ethanol, toluene and acetonitrile, 3 h each) to remove any unbound Pd species. Finally, the catalyst was dried at 90 °C overnight in a drying oven to give catalyst **C1**.

2.2. Suzuki reaction

2.2.1. Thermal heating in o-xylene

The reaction was prepared following a modified procedure described in [18]. **C1** was suspended in *o*-xylene (20 ml) and phenylboronic acid (7.5 mmol, 0.914 g), bromobenzene (5.1 mmol, 0.805 g), K_2CO_3 (10 mmol, 1.382 g), and *n*-undecane (4.4 mmol, 0.686 g) as internal standard were added. The mixture was heated under reflux and monitored by gas chromatography (GC). For reuse purposes the catalyst was filtered-off from the reacted mixture, washed with water, ethanol and acetone and dried overnight at 90 °C in a drying oven. The same protocol was used for *p*-bromophenol and *p*-bromotoluene.

2.2.2. Thermal heating in water

Phenylboronic acid (4.2 mmol, 0.514 g), *p*-bromoacetophenone (4 mmol, 0.796 g), Na_2CO_3 (16 mmol, 1.696 g), deionized water (8 ml) and requested amount of catalyst, were added to a 100-ml flask equipped with a magnetic stirrer. Reactions were performed in the carousel 6-place reaction station. The heating-up (to boiling temperature) took approximately 20 min, and then the mixture was refluxed (outside temperature 130–140 °C) for 1 h. After the reaction was complete the mixture was cooled down in a water bath under stirring. A sample for GC-analysis was prepared by extraction with MTBE (30 ml) at room temperature. For reuse purposes the catalyst was filtered-off from the reacted mixture, washed with water, ethanol and acetone and dried overnight at 80 °C in a drying oven.

2.2.3. Microwave-assisted Suzuki reaction

The reaction was prepared following a modified procedure accomplished in former work of our group, cf. [20]. Phenylboronic acid (2.1 mmol, 0.256 g), *p*-bromophenol (2 mmol, 0.346 g), Na_2CO_3 (8 mmol, 0.848 g), deionized water (4 ml) and the requested amount of catalyst were added to a microwave-suited mono-prep vessel (MLS GmbH Leutkirch) equipped with a magnetic stirring bar. Reactions were performed in the microwave device *praktika* (MLS GmbH Leutkirch; temperature program: up to 150 °C in 2 min at 500 W, hold for 10 min at 150 °C at max. 400 W). After the reaction was complete the mixture was cooled down under stirring. A sample for GC-analysis was prepared by extraction with MTBE (10 ml) at room temperature. The same protocol was followed for *p*-bromoacetophenone.

2.3. Heck and Sonogashira reactions

Iodobenzene (2 mmol, 0.408 g), styrene (3.2 mmol, 0.333 g) or phenyl acetylene (3.2 mmol, 0.328 g), NaOAc (0.264 g, 3.2 mmol), *n*-undecane (1 mmol, 0.156 g) as internal standard, a quantity of catalyst and 20 ml *N*,*N*-dimethylformamide (DMF) were transferred into a mono-prep vessel (MLS GmbH Leutkirch), placed in the microwave device *praktika* (temperature program: up to 190 °C in 2 min at max. 500 W, hold at 190 °C for 10 min at max. 400 W). The reaction was monitored by GC.

2.4. Characterization

2.4.1. Gas chromatography (GC)

The GC-analyses of the extracted C–C coupling reaction mixtures were carried out by GC-FID and GC-MSD. Conditions GC-FID for Suzuki reaction*:* HP-5, 30 m × 0.32 mm × 0.25 μm, H_2: 5 psi (for *o*-xylene) and 12 psi (for MTBE), program: 50 °C (hold for 3 min), 5 K min^{-1} up to 150 °C, 20 K min^{-1} up to 200 °C (hold for 5 min), injector temperature: 280 °C, detector temperature: 300 °C. Conditions GC-FID for Heck and Sonogashira*:* HP-5, 30 m × 0.32 mm × 0.25 μm, H_2: 12 psi, program: 70 °C, 20 K min^{-1} up to 290 °C (hold for 14 min), injector temperature: 280 °C, detector temperature: 300 °C. The same settings were used for GC-MSD but with He as carrier gas.

2.4.2. Fourier-transform infrared spectroscopy (FTIR)

Transmission FTIR-spectra were recorded in the range of 4000–550 cm^{-1} at a resolution of 4 cm^{-1} using a "spectrum 100 series" spectrometer (PerkinElmer precisely, Wiesbaden, Germany). The catalysts were placed in solid form on the ZnSe-crystal (ATR-method, ATR-correction with contact: 0, software: spectrum).

2.4.3. Inductively coupled plasma mass spectrometry (ICP-MS)

For ICP-MS analysis small amounts of the Pd catalysts were digested with HNO_3 and aqua regia (1 HNO_3/3 HCl). The residue was dissolved in 1 ml aqua regia and diluted with 10 ml deionized water. The measurements were performed by a Quadrupole-ICP-MS X Series II (ThermoFisher Scientific, Bremen, Germany).

2.4.4. X-ray photoelectron spectroscopy (XPS)

To define the oxidation state of the adsorbed palladium, the energy of the binding electrons was determined by X-ray photoelectron spectroscopy with a Quantum 2000 (PHI Co., Chanhassen, MN, USA) with a focused monochromatic Al K_α source (1486.7 eV) for excitation. The pass energy was 23.5 eV and the reference was the C1s peak of the C–C bond. Two signals at 341 eV and 336 eV indicate Pd(II)-species and signals at 338 eV and 333 eV suggest Pd(0)-species.

2.4.5. Elementary analysis

The C-, H-, N-, and Cl-contents of the catalysts were determined by elementary analysis. The investigations were accomplished with an Elementar Analysator Vario EL III (Analytik Jena GmbH, Germany).

2.4.6. Thermo-gravimetric analysis (TGA)

TG curves (heating rate 10 °C min^{-1}) of the support material and the catalysts were recorded by the DTG-60 (Simultaneous DTA-TG Apparatus, Shimadzu, Kyoto, Japan) under atmospheric conditions (air 30 ml min^{-1}).

3. Results and discussion

3.1. Preparation and characterization of the catalyst systems

3.1.1. Unmodified chitosan–Pd catalysts

With the co-precipitation method (**A1**, cf. Section 2.1.1) $PdCl_2$ was consistently distributed in the chitosan solution and precipitated together with the biopolymer, which implies that the Pd is arranged homogeneously in the chitosan sphere. The FTIR-spectrum for **A1** in Fig. 1 does not differ much from that of untreated chitosan. The available Pd amount for surface analysis and consequently catalysis is very small, because all weighed in Pd (0.08 mmol g^{-1}) is distributed in the whole particle (and so only a very small portion is located on the particle surface), in agreement with the surface-sensitive XPS analysis which showed weak peaks from the fraction of Pd located on the particle surface (cf. Fig. 2). Nevertheless, signals of a Pd(II)-species (341 eV and 336 eV) could still be identified.

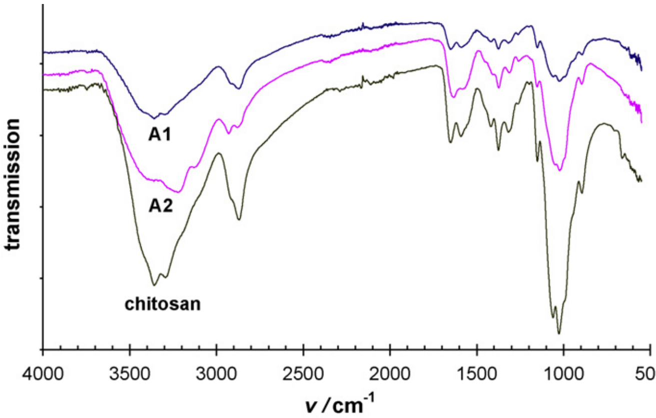


Fig. 1. Recorded FTIR-spectra (ATR-method) of chitosan (bottom), catalyst **A2** (middle) and catalyst **A1** (top).

It should be noted that the $PdCl_2$ employed has a low solubility in water, ethanol, and methanol and a coarse consistence which leads to difficulties of preparing a suspension with a consistent particle distribution for the adsorption method (**A2**, cf. Section 2.1.2). With the adsorption method (see Section 2) the Pd(II)-salt was not adsorbed quantitatively. However, the amount of Pd adsorbed is located on the support surface and is therefore available for catalysis. The FTIR-spectrum of **A2** in Fig. 1 shows in the range of 3540–3080 cm^{-1} the OH-/NH-bands which are shifted to lower wave numbers in comparison to the pure chitosan spectrum, indicating that the complexation of $PdCl_2$ influences either the OH- or the NH-vibrations. Due to the Pd coordination the bond to the H-atom becomes longer and weaker resulting in this shift. However, since the band becomes wider (that means only the NH-band is shifted) the Pd is mainly coordinated to the N-atom. With respect to the lower Pd loading on the **A1** surface the FTIR spectrum of **A1** does not show this shift so clearly.

XPS analysis of **A2** catalyst for the $3d_{3/2}$- ($E_b = 341.2$ eV) and $3d_{5/2}$-core level ($E_b = 336.2$ eV) of palladium indicated the presence of Pd(II)-species, cf. Fig. 2. ICP-MS analyses revealed that only approximately 25% of the submitted Pd (5 wt.%) was adsorbed on the chitosan beads (approx. 0.12 mmol g^{-1}). That shows a quantitative adsorption of the provided Pd cannot be assumed. It refers to optical observations (confirmed by microscopical pictures, 5000-fold magnification) that the Pd–chitosan layer of **A2** is not closed. During drying the catalyst the outer layer can burst and so there are Pd-free points on the globules, what makes the loading inhomogeneous.

The produced beads of **A1** and **A2** have a diameter of approximately 2 mm and are not perfectly round. Elementary analysis showed that the C/H-, C/N- and H/N-ratios of both catalysts are similar to pure chitosan. No chemical modification of chitosan took place as already seen in Fig. 1. The chloride content of **A2** was higher than that of **A1** in elementary analysis. This is caused by the higher Pd loading of **A2** and the assumption that two of the four coordinating centers of Pd are taken by chloride in the adsorption complex, and according to Kramareva et al. residual halogen atoms are removed by the alkaline treatment during the co-precipitation method (**A1**) indicating chelate ligands instead of monodentate ligands [21].

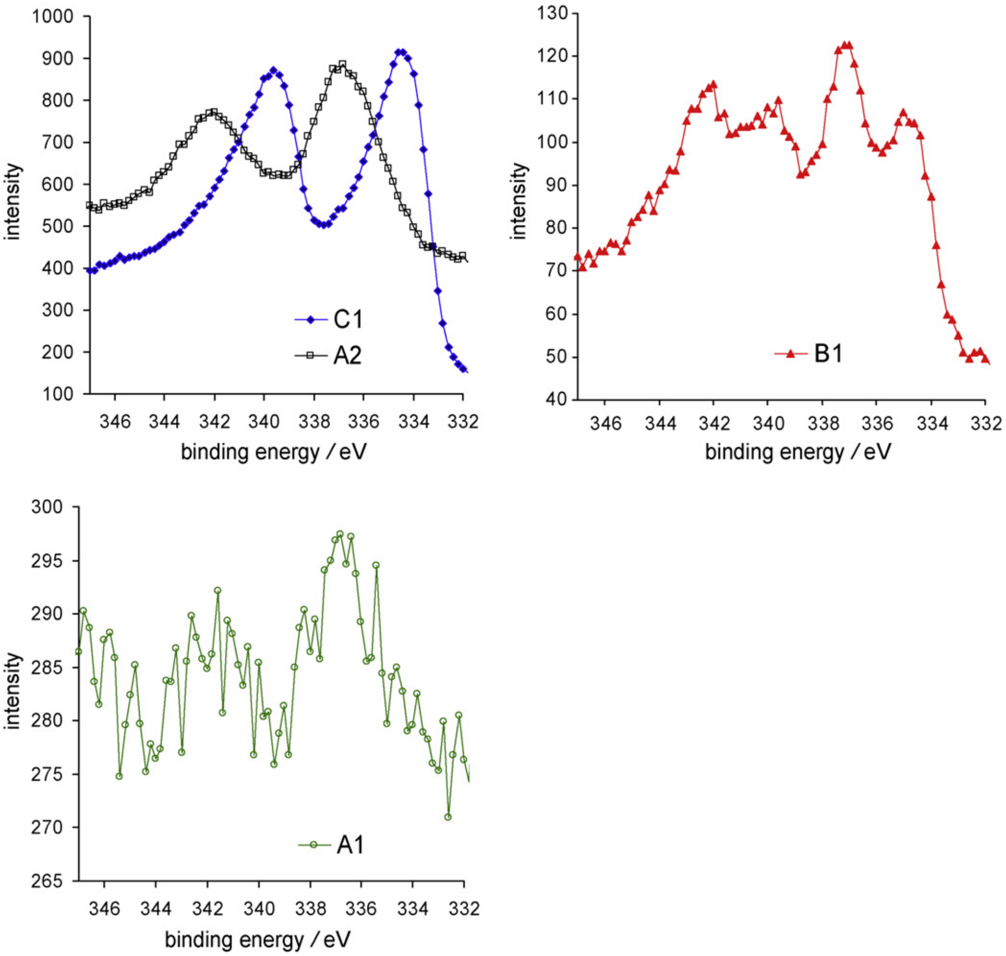


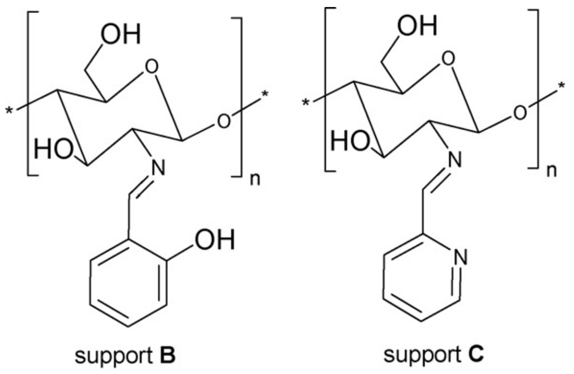
Fig. 2. XPS-spectra of the catalyst systems **A2**, **C1**, **A1** and **B1**. Peaks at 342 + 337 eV and 340 + 335 eV are assigned to Pd(II)- and Pd(0)-species, respectively.

3.1.2. Modified chitosan–Pd catalysts

In Scheme 2 the modified chitosan supports **B** and **C** are shown. It is known that chitosan already has good complexation properties due to its structure (chelate ligand). In both cases the amino-group of chitosan was functionalized by an aromatic aldehyde to offer the Pd a more stable environment for complexation. On the one hand chitosan was modified with salicylaldehyde (**B**) and on the other hand with the pyridine derivative 2-pyridinecarboxaldehyde (**C**).

The FTIR-spectra in Fig. 3 indicate the differences between the catalysts obtained from the two modes of modification. Comparison of **B** to unmodified chitosan reveals differences at 750 ($\delta_{=C-H}$ → substituted benzene), 1210 (ν_{-C-O} → phenol), 1270 (ν_{-C-H} → amine), 1490 and 1625 (aromatics), and 3055 cm^{-1} ($\nu_{=C-H}$ → aromatic compounds). These bands are due to a modification with a substituted phenol derivative. In the region of OH- and NH-vibrations it is evident that two bands (3350 cm^{-1} and 3280 cm^{-1} → prim. amine) became one band (at 3446 cm^{-1}), which is shifted to higher wave numbers.

The successful functionalization to an imine is indicated by several observations. Firstly, the intensity of the NH-bands decreased



Scheme 2. Structure of the modified chitosan supports of catalyst systems **B1** (salicylaldehyde) and **C1** (2-pyridinecarboxaldehyde).

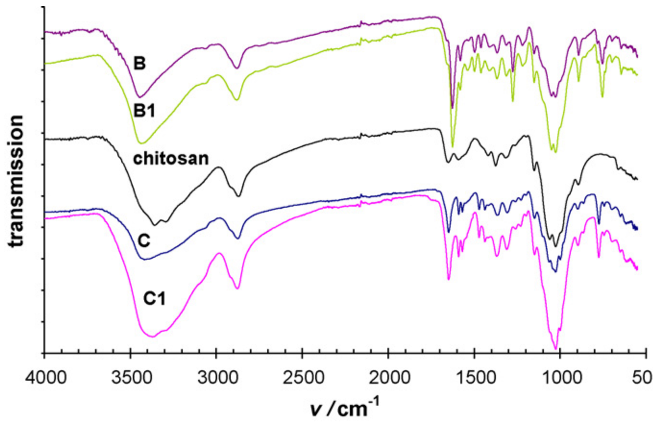


Fig. 3. Recorded FTIR-spectra (ATR-method) of support **B**, catalyst **B1**, chitosan, support **C** and catalyst **C1**.

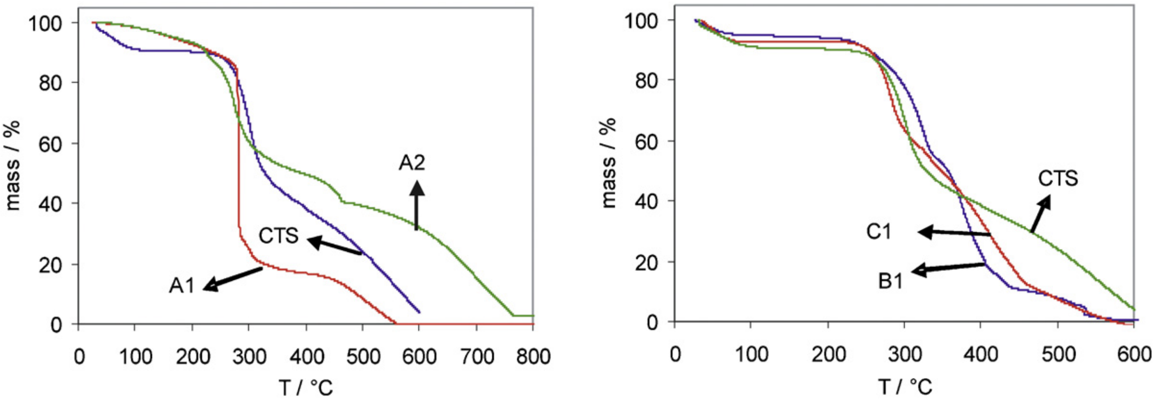


Fig. 4. Recorded TG-curves of chitosan (CTS) and the prepared catalyst systems **A1**, **A2**, **B1**, and **C1** under atmospheric conditions.

(mask by OH absorption), and no C=O-bands (free aldehyde) are visible in the FTIR-spectrum of Fig. 3. Secondly, elementary analysis confirmed the chemical modification, because the C/H-ratio rose from 5.6 to 9.1 and the C/N-ratio also increased from 5.5 to 10.6. Furthermore, XPS data shown in Fig. 2 indicate the coexistence of different oxidation states of palladium, Pd(II) and Pd(0). ICP-MS analyses indicated 1.4 wt.% Pd (70% of the weighed in Pd; 0.13 mmol g^{-1}) for **B1**. The salicylaldehyde-modified chitosan showed good adsorption properties – the imine offers the Pd a better possibility for complexation than pure chitosan – but because of the used flakes also a larger surface area than the chitosan beads.

The preparation of **C1** as described in the experimental section takes a long time because of the additional washing steps to avoid leaching later. During the refluxing in ethanol the color of **C1** turns from orange to dark brown with a whiff of anthracite gray, indicating a change in valency of Pd. Comparison of the three FTIR-spectra showed a new band at 770 cm^{-1} in the spectra of **C** and **C1**, which is a characteristic band for disubstituted benzenes (cf. Fig. 3). At 1645 cm^{-1} a noticeably stronger absorbance caused by the additional C=N vibration can be seen. It is also evident that the wide OH/NH-band of chitosan shifted to higher wave numbers and turned into one band. The band of **C1** is less shifted than that of **C**. This may be due to the removal of excess imine-functions during the washing steps. The introduction of an aromatic nitrogen compound in the catalyst system is also confirmed by elementary analysis, causing a decrease of the H/N ratio from 1.0 to 0.8 and an increase of the C/H-ratio from 5.6 to 6.9. As shown in Fig. 2, XPS analysis indicates well-defined Pd(0)-species on the catalyst surface. ICP-MS indicated a Pd content of 3.3 wt.% (0.31 mmol g^{-1}) which is twice as high as that indicated in the publication of Macquarrie et al. who performed the washing step three times [18]. Reproducibility of the Pd content depends mainly on the exact performing of the washing step.

Comparison of the catalysts **A2**, **B1**, and **C1** the different oxidation states of Pd after preparation attract attention (cf. Fig. 2). This is probably due to the employment of alcohol during the preparation step. After thermal treatment of **C1** in boiling ethanol the change in valency of Pd could be observed by change in colour (yellow to dark brown). For **A2** (Pd(II) species) no ethanol was used, but **B1** (Pd(II) and Pd(0) species) was stirred in methanol at room temperature for a few hours. The stirring in alcohol at air lead to partial reduction of Pd, which is furthermore supported by increased temperature. After reaction only Pd(0) is detected by XPS analysis.

Thermal stability is necessary for the catalytic activity and recyclability of a catalyst, because C–C coupling reactions are carried out under high temperature conditions. The TG-curves in Fig. 4 show that the catalyst systems are stable up to 230 °C. Therefore the supports are suited for liquid phase catalysis up to 200 °C. The first mass decrease is caused by the evaporation of the assimilated water. Then the complex begins to lose weight significantly due to the oxidative decomposition of the polymer support chitosan. That corresponds approximately to the thermal stability of pure chitosan.

Table 1
Overview of the thermal Suzuki coupling reaction in *o*-xylene with catalyst **C1**.

R[a]	Catalyst use	*t* (h)	*Y* (%)	*S* (%)
H	1	1	83	97
	2	1	90	>99
CH_3	1	1	78	99
	1	2	95	>99
	3	2	80	>99
	4	2	67	>99
OH	1	1	58	99
	1	2	62	>99
$COCH_3$	1	1	87	>99
	2	1	70	>99
	3	1	49	>99

Condition: 5.1 mmol aryl bromide, 7.5 mmol phenylboronic acid, 10 mmol K_2CO_3, 25 mg catalyst **C1** (0.15 mol% Pd), 20 ml refluxing *o*-xylene.

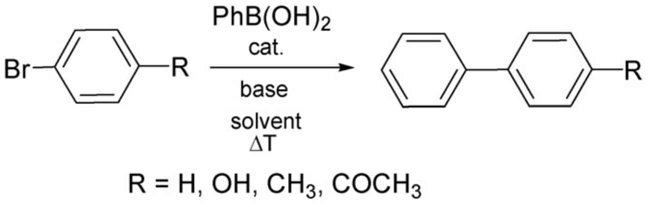
[a] Functional group of aryl bromide, cf. Scheme 3.

3.2. *Catalyst activity in Suzuki coupling reactions*

Phenylboronic acid was coupled to some aryl bromides in *o*-xylene and water for thermal Suzuki reaction and also in water for investigation of the Suzuki reaction under microwave irradiation (cf. Scheme 3).

3.2.1. *Thermal Suzuki reaction in o-xylene*

The results of the thermal Suzuki reaction in *o*-xylene are listed in Table 1. With respect to the results reported by Macquarrie and coworkers the yields for bromobenzene and *p*-bromotoluene could be confirmed [18]. Further, as expected good results (87%) were found for the activated *p*-bromoacetophenone after 1 h in



Scheme 3. Schematic illustration of Suzuki model reactions.

Table 2
Parameters and results of the microwave-promoted Suzuki coupling reactions of *p*-bromophenol with phenylboronic acid in water (cf. Scheme 3).

Catalyst	mol% Pd	*t* (min)	*Y* (%)	*S* (%)
A1	0.12	10	58	97
	0.28	10	73	96
	[a]	10	81	>99
A2	0.19	10	>99	>99
	0.19	5	>99	>99
	[a]	5	64	>99
B1	0.20	10	>99	>99
	[a]	10	72	95
	0.20	5	>99	>99
	0.20	10	99[b]	99
C1	0.25	10	55	98
	0.48	10	45	95

Condition: 2 mmol *p*-bromophenol, 2.1 mmol phenylboronic acid, 8 mmol Na_2CO_3, 4 ml water; microwave settings: $T = 150\,°C$, $P_{max} = 400\,W$.

[a] 2nd catalyst use.

[b] Reaction temperature was 130 °C.

the first run of catalyst **C1**. Additionally, *p*-bromophenol was coupled, but Table 1 shows that the activity of **C1** for the deactivated *p*-bromophenol is considerably weaker with 62% yield after 2 h. However, the reaction was as selective as the other coupling reactions (99% and more) with respect to the educt.

Bromobenzene is very reactive but the Suzuki coupling product biphenyl is also a by-product of the homocoupling of phenylboronic acid, so we investigated the recycling properties of **C1** with *p*-bromotoluene and *p*-bromoacetophenone. Despite washing the catalyst with aqueous ethanol, methyl-*tert*-butylether (MTBE) and methanol before reuse, it was found that with every recycling step the activity decreased (between the first and the second run by nearly 50%) and with increasing reuse, the selectivity decreased slowly as well. After using warm solvents for washing the catalyst, better yields and selectivities were reached (cf. Table 1), although GC-analyses showed no significant 2-pyridinecarboxaldehyde leaching either in the reaction or in the filtrate solution. However, elementary analyses indicate desubstitution because of a decrease in C/H and increase of the C/N ratio.

3.2.2. Microwave-assisted Suzuki reaction in water

The microwave-assisted Suzuki reaction was investigated for all four catalyst systems and the coupling of phenylboronic acid with *p*-bromophenol and *p*-bromoacetophenone (cf. Tables 2 and 3). **B1** and **A2** showed the best activities. For *p*-bromophenol the yield was quantitative even after shorter reaction times (5 min) or lower temperature (130 °C) (cf. Table 2). In a comparison between the two different educts, surprisingly the deactivated *p*-bromophenol seems to be the more active Suzuki reactant. However, the activity of **C1** in the Suzuki reaction of *p*-bromophenol (cf. Table 2) is much lower than in the reaction of *p*-bromoacetophenone (cf. Table 3). Higher catalyst amounts of **C1** decrease the yield and selectivity of the Suzuki product considerably (with 100 mg **C1** only by-products of the educts were found). Longer reaction times did not improve the yield significantly either although selectivity decreased. **A1** is also active in this reaction but needs higher catalyst amounts for good yields because of the smaller amount of available Pd on the catalyst surface, as mentioned above.

Table 3
Parameters and results of the microwave-promoted Suzuki coupling reactions of *p*-bromoacetophenone with phenylboronic acid in water (cf. Scheme 3).

Catalyst	mol% Pd	*t* (min)	*Y* (%)	*S* (%)
A1	0.25	10	64	98
A2	0.19	10	81	>99
	0.19	15	84	>99
	[a]	15	74	>99
	[b]	15	40	>99
B1	0.20	10	89	>99
	[a]	10	63	>99
	0.20	15	94	99
C1	0.48	10	79	98
	[a]	10	71	>99
	[b]	10	57	94

Condition: 2 mmol *p*-bromoacetophenone, 2.1 mmol phenylboronic acid, 8 mmol Na_2CO_3, 4 ml water; microwave settings: $T = 150\,°C$, $P_{max} = 400\,W$.

[a] 2nd catalyst use.

[b] 3rd catalyst use.

Recently Yi et al. published results for microwave-promoted Suzuki reactions in water catalyzed by chitosan-supported Pd(0) [22]. They used cross-linked chitosan (cross-linking agents: glutaraldehyde or diglycidyl ether polyethylene glycol) for Pd-support and tetrabutyl-ammonium bromide (TBAB) as phase-transfer catalyst (PTC). Our results show, that for **A2** and **B1** it is not necessary to use an additional PTC under these conditions.

In comparison to the results of the Suzuki reaction in *o*-xylene (cf. Section 3.2.1) and in water at nearly the same reaction temperature the yields are similar for catalyst **C1** (cf. Tables 1–3). However, in direct comparison the approaches differ not only in the choice of the solvent, but also in reaction time and in the ratio between Pd and aryl compound. The reaction time in *o*-xylene is six times as much as that in water but the ratio Pd/aryl in water is at least twice as much as the ratio in *o*-xylene. The calculation of the TOF results in 980 h^{-1} (0.48 mol% Pd) for the reaction of *p*-bromoacetophenone in water and reaches 570 h^{-1} (0.15 mol% Pd) for the reaction in *o*-xylene. For *p*-bromophenol TOF are 1330 (0.25 mol% Pd) and 560 h^{-1} (0.48 mol% Pd) in water and 380 h^{-1} (0.15 mol% Pd) for the reaction of *p*-bromophenol in *o*-xylene.

3.2.3. Thermal Suzuki reaction in water

As mentioned, for Suzuki reaction in water these investigations resulted in very good yields and selectivities, but the temperature is very high, which of course in general increases the reaction rate. Hence, also Suzuki reactions in water under thermal heating were accomplished in a 6-place reaction station. The yields shown in Fig. 5 are even higher after 1 h without the assistance by a PTC and also the selectivities are very high (>99%). Except for catalyst **A1** the recycling behavior is much better than under microwave irradiation, 74% and 84% for **A2** and **B1**, respectively, in the 3rd cycle (cf. Fig. 5). This could be caused by the lower reaction temperature. It is known that chitosan is only stable up to 230 °C (cf. Fig. 4) and maybe the inhomogeneous heating of the metal-loaded support surface, caused by microwaves, leads to any modifications.

C1 even indicates an increase in activity with increasing reuse independent from the catalyst amount. Thus, results underline that the catalyst undergo activation during application and work-up. This behavior is rather uncommon for Pd catalysts in Suzuki reactions. Perhaps, a change of the coordination site of Pd during reaction and work-up is responsible for this effect. In addition a few approaches with one mol-equivalent TBAB were performed for **B1** and **C1**. As expected, for **B1** the yield of *p*-acetylbiphenyl became quantitative also in the 2nd cycle. For **C1** the use of a PTC was unfavorable, the reaction yields approx. 20% of the coupling product with a selectivity of 93% for all three reaction cycles. At the moment there are no verified explanations for these uncommon results obtained for **C1**. For *p*-bromophenol the use of **B1** (30 mg) gave quantitative yield without any PTC and decreased to 86% with PTC. Unlike **C1** (30 mg) yielded for *p*-bromophenol 2% of the Suzuki coupling product without and 11% with PTC.

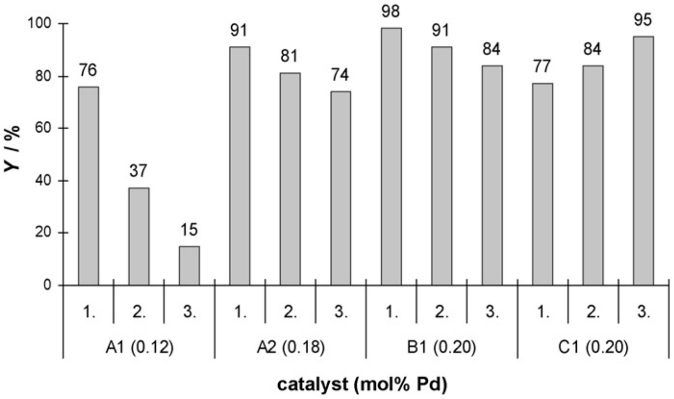
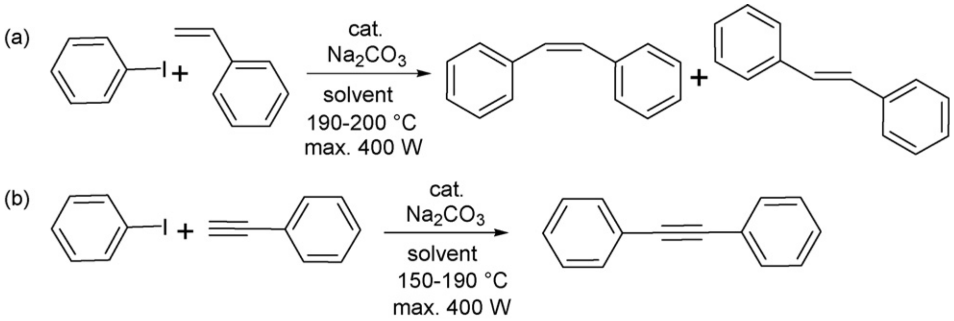


Fig. 5. Results of the Suzuki coupling reaction of *p*-bromoacetophenone (4 mmol) with phenylboronic acid (4.2 mmol) in refluxing water (1 h) in the presence of Na_2CO_3 (16 mmol). All selectivities over 99% (1, 2, and 3 indicate the catalyst run).



Scheme 4. Schematic illustrations of Heck and Sonogashira model reaction: (a) Heck reaction of styrene and iodobenzene to *cis*- and *trans*-stilbene. (b) Sonogashira reaction of iodobenzene and phenyl acetylene to tolane under microwave irradiation.

3.3. Catalyst activity in Heck reaction and Sonogashira reaction

3.3.1. Microwave-assisted Heck reaction

N,*N*-Dimethylformamide (DMF) and *N*,*N*-dimethylacetamide were used as solvents, and analysis of the product mixtures revealed that DMF gave better styrene conversions in the Heck reaction (cf. Scheme 4a). In contrast to the results of the Suzuki reaction **C1** resulted in the best yields (84%) and **B1** resulted in the worst yields (22%) after 10 min at 190 °C (cf. Table 4).

Liu et al. reported under thermal conditions a yield of 80% (DMF, 120 °C, 8 h) for the Heck coupling of iodobenzene and styrene with their chitosan–salicylaldehyde–Pd catalyst (**B1**-analogous, but other preparation) [23]. Their chitosan–palladium catalyst (**A2**-analogous, but not in form of beads) formed after 5 h at 80 °C in DMF 93% *trans*-cinnamic acid [19]. They used an organic base, longer reactions times and milder reaction conditions. Cross-linked chitosan–salicylaldehyde–Pd catalyst of Cui et al. (cross-linking agent: epoxy chloropropane) gave 97% yield at 80 °C in DMF after 3 h with an organic base [24]. In another paper Zhang et al. tested a chitosan microsphere-resin in the Heck reaction (90 °C) with sodium acetate as inorganic base in water, but even after 14 h no Heck coupling product was found [25]. As expected, higher temperatures increase the reaction rate, and as shown in Table 4 same yields could be confirmed even after 20 min with good selectivities and the use of an inorganic base in DMF.

Compared to Macquarrie and coworkers, who used for their coupling of styrene and bromobenzene (100 °C, in anhydrous dioxane) a **C1**-analogous catalyst yielding 88% of the coupling product within 42 h, the yields for **C1** listed in Table 4 are just as good (87%) after as little as 20 min [18]. Of course, this is mainly affected by the increased reaction temperature and the higher Pd loading of the catalyst. Additionally, NaOAc instead of triethylamine was used, which is soluble in DMF at high temperatures without a phase-transfer catalyst.

Table 4
Results of the Heck reaction assisted by microwave irradiation (cf. Scheme 4a).

Catalyst	mol% Pd	*t* (min)	*Y*[a] (%)	*S*[a] (%)
A1	0.24	10	40	89
A2	0.19	10	82	94
		20	90	94
B1	0.20	10	20	74
		20	82	93
C1	0.48	10	84	96
		20	87	94

Condition: 2 mmol iodobenzene, 3.2 mmol styrene, 3.2 mmol NaOAc, 20 ml DMF; microwave settings: $T = 150\,^\circ C$, $P_{max} = 400\,W$.

[a] *cis*- and *trans*-stilbene.

3.3.2. Microwave-assisted Sonogashira reaction

Up to the present time, a chitosan-supported Pd catalyzed Sonogashira reaction was not found in literature. However, Macquarrie and coworkers published microwave-assisted Sonogashira coupling reactions catalyzed by biomaterial-supported Pd catalysts, for example with starch [9d,26]. In the Sonogashira reaction of iodobenzene and phenyl acetylene without additional Cu(I) it was observed that all chitosan-supported catalysts have a lower selectivity than in the other C–C coupling reactions (cf. Table 5). The conversion of iodobenzene is excellent even after 3 min of microwave irradiation, but the reactions yielded in a lot of partially unknown side-products (known side-products were benzene, stilbene and triphenylethylene). Thus, it can be concluded that the unintended products result either from dehalogenation of

Table 5
Results of the microwave-promoted Sonogashira reaction of phenylacetylene with iodobenzene to tolane (cf. Scheme 4b).

Catalyst	mol% Pd	t (min)	T (°C)	Y^a (%)	S^a (%)
A1	0.40	10	170	70	60
	0.80	10	190	64	64
A2	0.19	10	150	67	62
	0.60	10	190	54	54
B1	0.20	3	170	48	47
	0.65	10	190	20	20
C1	0.48	10	190	39	39
	0.48	5	150	50	45
	0.48	10	150	49	48
	0.48	15	150	41	41

Condition: 2 mmol iodobenzene, 3.2 mmol phenylacetylene, 3.2 mmol NaOAc, 20 ml DMF; microwave settings: P_{max} = 400 W.
[a] Yields refer to the peak area.

iodobenzene (benzene) or from intermolecular reactions of phenylacetylene or of the coupling products. Those side reactions are the reason for the inferior selectivities reported in Table 5. The **A** catalysts resulted in somewhat higher yields and selectivities than **B1** and **C1**. The selectivities are comparable to those reported previously for the use of the starch-supported Pd catalyst [9d,26]. Higher catalyst amounts (100–200 mg) led to a decrease of selectivity. Shorter reaction times and lower temperatures did not result in significant higher or lower product yields but decreased the formation of side-products and would limit the risk of possible catalyst damage due to excessive high temperatures at the catalyst surface in consequence of hot spots.

4. Conclusion

The co-precipitation method is not suitable for the preparation of catalysts where higher and easily accessible Pd-amounts are required. Only a small fraction of the weighed in Pd is located on the catalyst surface and can act as catalyst. Prior the adsorption method similar to the preparation of **A2**, the supports for **B1** and **C1** were both modified as imino derivatives. **A2** showed high activity in Suzuki and Heck couplings and also acceptable selectivities in Sonogashira reaction. Especially in comparison to the mentioned thermal Heck reactions, **C1** and **A2** showed that the microwave irradiation was advantageous shortening reaction times and increasing yields. For Suzuki reaction in water under microwave conditions, **B1** and **A2** showed the highest activity. Also the Suzuki reaction in water under conventional heating (1 h under reflux) gave good yields even without PTC for activated (bromoacetophenone) and deactivated bromoaryls (bromophenol). In Sonogashira reaction all four catalysts were less selective and gave some side-products beside the coupling product in comparison to the other investigated C–C coupling reactions. With respect to other publications in this field of Sonogashira reactions the results are acceptable, although no direct comparison is possible because to the best of the authors' knowledge this is the first example of a Sonogashira reaction using chitosan-based catalysts.

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