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Heterogeneous Palladium–Chitosan–CNT Core–Shell Nanohybrid Composite for *Ipso*-hydroxylation of Arylboronic Acids

Eun-Jae Shin[1] · Han-Sem Kim[2] · Seong-Ryu Joo[1] · Ueon Sang Shin[2,3] · Seung-Hoi Kim[1]

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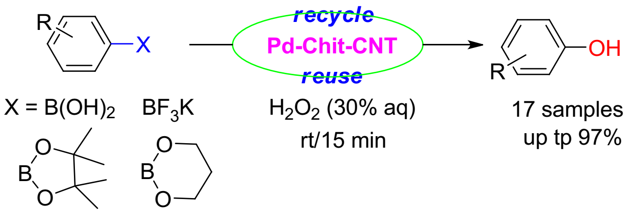
Abstract

A novel palladium-nanohybrid (Pd–Chitosan–CNT) catalytic composite has been developed using CNT–chitosan nanocomposite and palladium nitrate. The prepared catalytic platform displays excellent catalytic reactivity for the *ipso*-hydroxylation of various arylboronic acids with a mild oxidant aqueous H_2O_2 at room temperature, affording the corresponding phenols in excellent yields. Significantly, the easy recovery and reusability by simple manipulation demonstrate the green credentials of this catalytic platform.

Graphical Abstract



Keywords Palladium–chitosan–CNT nanohybrid · Arylboronic acid · Phenol · *Ipso*-hydroxylation · Hydrogen peroxide

Boronic acids containing one C–B bond and two OH groups are trivalent organoboron derivatives. Owing to their unique nature such as low toxicity, high stability in air, mild organic Lewis acid and ease of handling, boronic acids have found remarkable applications in a wide range of chemistry areas [1]. Among the outstanding performances of boronic acids, the palladium-catalyzed cross-coupling reaction, i.e. the Suzuki–Miyaura reaction, has been recognized as one of the most precious reactions in organic synthesis [2, 3]. Along with this transformation, the oxidation of boronic acids to the corresponding alcohols in the presence of a suitable oxidant is also a highly valuable synthetic process.

In consideration of the important role of phenols as versatile intermediates and building blocks in the chemical and pharmaceutical industries [4–6], the oxidative conversion of arylboronic acids could be a straightforward approach for the production of phenolic compounds.

The first study on the oxidation of arylboronic acids with alkaline hydrogen peroxide to produce phenols was reported by Challenger [7]. Since then, numerous efforts have been devoted to search for more efficient reaction conditions. Milder oxidants such as anhydrous trimethylamine *N*-oxide

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✉ Ueon Sang Shin
usshin12@dankook.ac.kr

✉ Seung-Hoi Kim
kimsemail@dankook.ac.kr

[1] Department of Chemistry, Dankook University, Cheonan 31116, Republic of Korea

[2] Department of Nanobiomedical Science & BK21 PLUS NBM Global Research Center for Regenerative Medicine, Dankook University, Cheonan 31116, Republic of Korea

[3] Institute of Tissue Regeneration Engineering (ITREN), Dankook University, Cheonan 31116, Republic of Korea

[8, 9], oxone [10–13], hypervalent iodine [14], hydroxylamine [15] and peroxides [16, 17] have been explored. In addition, metal-free bio-catalysts [18, 19] and light-active photo-catalysts have been successfully used for the *ipso*-hydroxylation of arylboronic acids [20–24]. Finally, various copper complexes have also been reported to effectively catalyze this transformation [25–29].

In order to accomplish the oxidation of arylboronic acids, aqueous hydrogen peroxide is generally considered a versatile oxidant due to environmentally benign oxidant that displays high efficiency per weight of oxidant and, is easy to handle [30]. For these reasons, numerous studies using H_2O_2 for the *ipso*-hydroxylation of arylboronic acids have been recently conducted. In most cases, the system involves a combination of H_2O_2 with urea [31], biosilica [32], PEG-400 [33], H_3BO_3 [34], Al_2O_3 [35], I_2 [36], amberlite IR-120 resin [37] and poly(*N*-vinylpyrrolidone) or poly(4-vinylpyridine) [38]. Lately, the use of nanoparticles in the hydroxylation of boronic acids is an emerging approach toward the preparation of phenol derivatives. In this context, a very recent report described a ligand-free hydroxylation of phenylboronic acid using reusable Pd-nanoparticles [39]. The biosynthesis of Fe_2O_3@SiO_2 nanoparticles and their application in *ipso*-hydroxylation reaction was also reported [40]. A method for the synthesis of phenols using mont K-10-supported silver nanoparticles was also appeared [41].

Notwithstanding the previous protocols with excellent activity, continuous efforts are being devoted to the improvement the efficiency of boronic acid hydroxylation process with a special focus on greener conditions and more efficient catalysts.

On account of the aspects of sustainable chemistry, recycling environmentally hazardous catalysts could be suitable way to reduce the economic and environmental burden. To address this issue, heterogeneous metal-catalytic systems that are recyclable and reusable are considered a suitable approach [42]. In order to achieve this goal, palladium–metal and/or –complexes have been most frequently employed [43–56].

In the context of our ongoing concerns on metal-catalyzed transformation, we were interested in developing an environmentally friendly catalytic system with good recyclability and sustainability of the catalyst. Interestingly, we have recently developed chitosan–carbon nanotube (CNT) nanocomposites using a high-pressure homogenizer, resulting in close-packing CNT–core and chitosan–shell nanofibers [57]. Since the surface of the nanocomposite material was wrapped with chitosan which exhibits excellent adsorptivity toward metal ions, we decided to explore the possibility of embedding transition metal on the surface. To our delight, palladium-metal was successfully deposited onto the CNT–chitosan film, furnishing a Pd–chitosan–CNT nanohybrid (hereafter denoted as Pd–Chit–CNT).

With this novel catalytic platform in hand, we immediately exploited its application in organic functional group transformations. Herein, we wish to report its promising performance in the i*pso*-hydroxylation of arylboronic acids, furnishing the corresponding phenols.

A $Pd(NO_3)_2$–chitosan–CNT solution was first prepared by the homogenization of a solution of palladium nitrate (10 wt%), chitosan, and pristine CNTs at room temperature. Next, the solution was treated with hydrazine monohydrate to reduce the palladium nitrate. After suitable treatments, such as neutralization, dialysis, washing, and drying, the Pd–Chit–CNT nanohybrid membrane was successfully obtained as a thin black film.

For qualitative analysis, the FT-IR spectrum of the prepared Pd–Chit–CNT membrane was compared to those of pristine CNT and chitosan, showing the characteristic bands at 3200–3630 cm^{-1} (–OH and –NH for Chit part stretching), 2915 and 2865 cm^{-1} (–CH stretching of $–CH_2$ for Chit part), 1648 cm^{-1} (C=O for Chit part stretching), and 1634 cm^{-1} (C=C for pCNT part stretching). Significantly, the C=O stretching band of pure chitosan was shifted from 1648 to 1515 cm^{-1} in the composite because of either the increased participation of C=O functional groups in a network of intermolecular hydrogen bonds or reorganizing the network of intermolecular hydrogen bonds. The core–shell structure and presence of Pd nanoparticles were investigated by FE-SEM analysis of the Pd–Chit–CNT, Chit–CNT, and pristine CNT samples. The images of Pd–Chit–CNT and Chit–CNT clearly showed the rough surface of individual CNT, indicating the presence of a chitosan layer on the CNT surfaces. Also, Pd nanoparticles (approximately 10–20 nm) are clearly observed deposited on or inserted in the chitosan layer over the CNTs.

When the pyrolysis behaviors of pure chitosan and CNTs in the temperature range of 25–900 °C was compared to that of the nanohybrid membrane (Pd–Chit–CNT), a different thermal degradation pattern and/or incomplete degradation behavior were observed. For instance, intensive weight loss occurred in three steps between 200 and 600 °C for pure chitosan, while this occurred between 600 and 700 °C for pure CNT. Pyrolysis of the Pd–Chit–CNT nanohybrid membrane before use as a catalyst afforded a degradation pattern similar to that of pure chitosan, demonstrating the nonflammable nature of Pd metal (10 wt%). Interestingly, the degradation pattern after the catalysis showed a pattern very similar to that of fresh Pd–Chit–CNT, indicating that the Pd concentration on the membrane was not reduced after use (Fig. 1).

Our initial investigation focused on the activity of the Pd–Chit–CNT catalyst system for the *ipso*-hydroxylation of arylboronic acids. A mixture of phenylboronic acid (**1a**) and aqueous hydrogen peroxide (30%) as the oxidant in the absence of Pd–Chit–CNT was stirred at room temperature for 15 min, giving rise to only a small amount of phenol

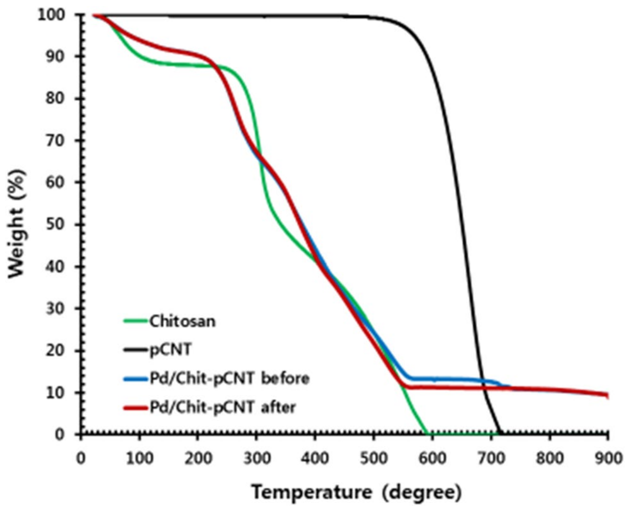


Fig. 1 Thermo gravimetric analysis curves

(entry 1, Table 1). The incorporation of the Pd–Chit–CNT-catalyst dramatically increased the isolated yield up to 95% under similar conditions (entry 3, Table 1). The conversion was completed at room temperature within 15 min regardless of the amount of H_2O_2, producing the product in a similar fashion (entries 3–5, Table 1). However, a critical effect of the amount of catalyst was observed, whereby lower catalyst loadings afforded lower yields of the product (entries 6 and 7, Table 1). Next, we attempted to identify any solvent effects on the conversion, which resulted in no improvement of the isolated yield (entries 8–10, Table 1).

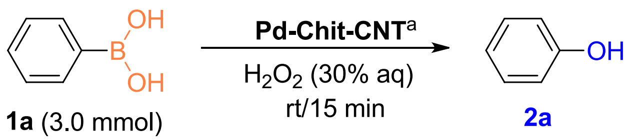
With the most suitable reaction conditions in hand (entry 4, Table 1), we next turned our attention to the substrate scope. A series of electronically diversified arylboronic acids were tested and smoothly oxidized to the corresponding phenols in good to excellent yields. The results are summarized in Table 2.

Interestingly, our catalytic platform tolerates a wide range of functionalities including electron-donating and electron-withdrawing groups such as OCH_3, Me, *t*-butyl, F, Cl, CN, CHO, NO_2, and $COCH_3$.

No significant effects were observed for sterically demanding ortho-substituents and good yield of isolated product (**2b**) was obtained. Naphthaleneboronic acids also underwent this *ipso*-hydroxylation transformation in excellent yield under the same reaction conditions.

Since Pd–Chit–CNT is a solid heterogeneous catalyst, it should be easily recovered by a simple operation. Accordingly, the recyclability of the catalyst was tested for the model reaction with phenylboronic acid (**1a**). The Pd–Chit–CNT catalyst was simply filtered after the reaction, and then washed with distilled water followed by ether. After drying at room temperature, it was reused for the subsequent hydroxylation reactions without any further activation. These experiments proved the excellent recyclability of the catalyst with no significant loss of activity in terms of isolated yield even after six consecutive runs (Table 3).

Table 1 Optimization of the *ipso*-hydroxylation of phenylboronic acid (**1a**)



Entry	Pd-cat (mg)[a]	H_2O_2 (mL)	Solvent[b]	Yield (%)[c]
1	–	5.0	–	28
2	3.0	–	H_2O_2	NR[d]
3	3.0	5.0	–	95
4	3.0	3.0	–	95
5	3.0	1.0	–	93
6	2.0	3.0	–	64
7	1.0	3.0	–	50
8	3.0	3.0	H_2O_2	89
9	3.0	3.0	CH_3CN	61
10	3.0	3.0	EtOH	32

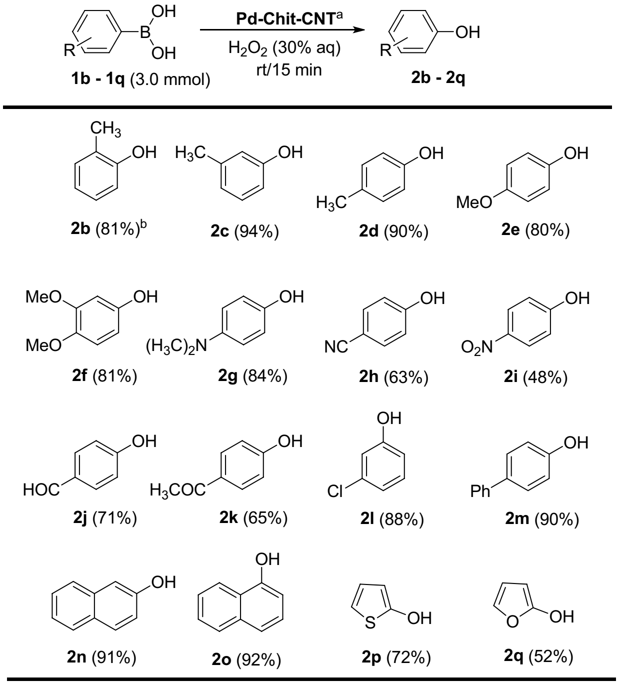
[a] 10 wt% Pd-content

[b] 5.0 mL of solvent used

[c] Isolated yield

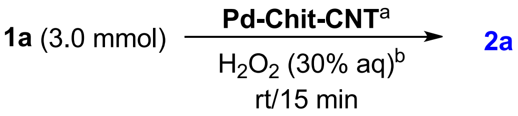
[d] No reaction occurred at room temperature in 24 h

Table 2 Scope of boronic acids



[a] 10 wt% Pd-content [b] number in parenthesis is isolated yield

Table 3 Reusability test

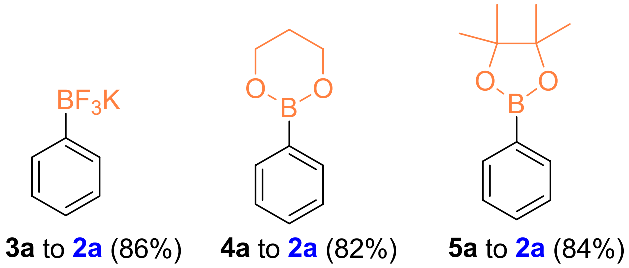


$$\mathbf{1a}\ (3.0\ \text{mmol}) \xrightarrow[\substack{H_2O_2\ (30\%\ aq)^{b} \\ rt/15\ min}]{\text{Pd-Chit-CNT}^{a}} \mathbf{2a}$$

Run	1st	2nd	3rd	4th	5th	6th
Yield (%)	96	95	95	93	94	93

[a] 10 wt% Pd-content, 3.0 mg used

[b] 3.0 mL used



Scheme 1 Application to arylboronic acid derivatives

Surprisingly, not only arylboronic acids, but other boronic acid surrogates such as potassium phenyltrifluoroborate (**3a**) and phenyl boronic esters (**4a**, and **5a**) were also found to be suitable substrates for hydroxylation under the same conditions. The corresponding product phenol (**2a**) was furnished in satisfactory yields from the corresponding derivatives (Scheme 1).

Although the use of heterogeneous catalytic systems presents several advantages in organic synthesis, one of their fundamental limitations is leaching of the metal catalyst into the solution, especially when the reaction is carried out in aqueous media [28]. Therefore, we additionally performed leaching tests by collecting aliquots of the aqueous phase during the reaction, which were subsequently analyzed by ICP-AES, revealing the leaching of only 0.07% of palladium. This strongly indicates that our catalytic platform is robust enough for use as an eco-friendly heterogeneous catalyst. To examine the feasible utility of our system, conditional tests were executed. The *ipso*-hydroxylation of **1a** was carried out using commercially available $Pd(PPh_3)_2Cl_2$ and $Pd(OAc)_2$ instead of Pd–Chit–CNT nanohybrid film under the same condition used before, giving rise to **2a** in 37% and 70% isolated yield, respectively. The results clearly verified the efficiency of our nanohybrid system.

To further characterize the active surface of the catalyst, we analyzed and compared the surface of Pd–Chit–CNT films before and after use by SEM. As shown in Fig. 2, no significant differences were detected. (more detailed information on the preparation and characterization of Pd–Chit–CNT is provided in the Supporting Information).

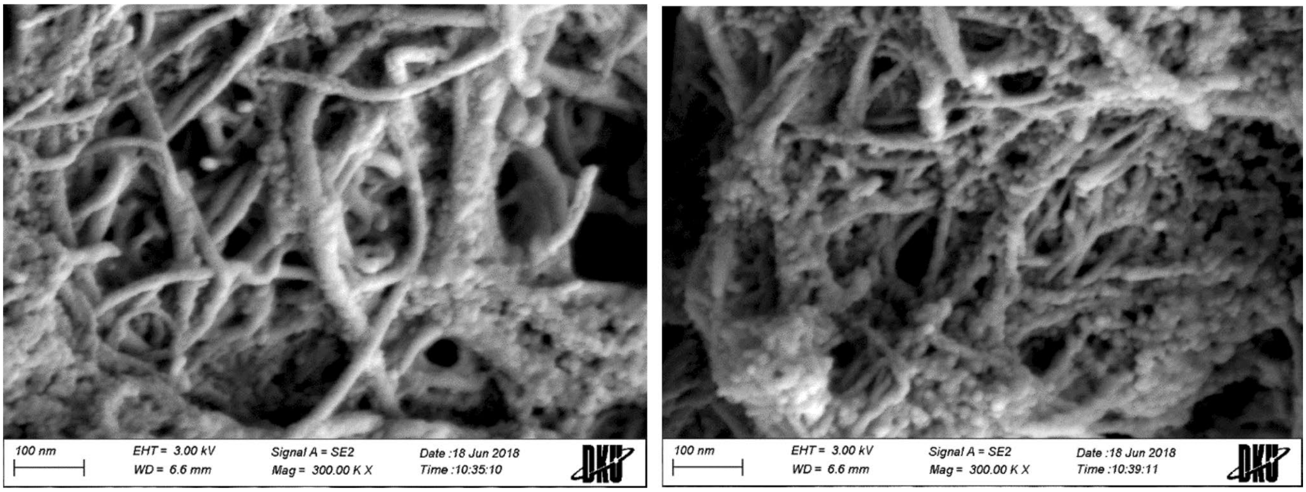


Fig. 2 SEM images of Pd–Chit–CNT; before (left) and after use (right)

1 Conclusion

A newly designed palladium catalyst platform, nanohybrid Pd–Chit–CNT, was successfully prepared using a modified high-pressure homogenizer. The as-prepared platform in combination with hydrogen peroxide was effectively employed in the *ipso*-hydroxylation of arylboronic acids, leading to the corresponding phenols in excellent yields. Moreover, the platform could be efficiently recovered by simple manipulation and reused in subsequent reactions. A preliminary study on the catalyst-leaching into the solution also confirmed that Pd–Chit–CNT is a robust heterogeneous catalyst. Our strategy thus represents an alternative protocol for the facile synthesis of phenol derivatives. The application of this new catalytic system is currently being extended to other functional group transformations in our laboratory.

Compliance with Ethical Standards

Conflict of interest The authors declare no conflict of interest.

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