

Heterogeneous alkenylation of aromatics under oxygen

Jan Hájek ^a, Mieke Dams ^a, Christophe Detrembleur ^b, Robert Jérôme ^b, Pierre A. Jacobs ^a, Dirk E. De Vos ^a

^a Center for Surface Chemistry and Catalysis, Katholieke Universiteit Leuven, Kasteelpark Arenberg 23, Leuven, Belgium ^b Center for Education and Research on Macromolecules (CERM), University of Liège, Sart-Tilman, Liège, Belgium

Abstract

A novel heterogeneous Pd/polymer catalyst containing co-catalytic functional groups catalyses the direct alkenylation of anisole with ethyl *trans*-cinnamate under oxygen. The properties of the polymeric catalyst were compared to other immobilised catalysts. The activity of the polymeric catalyst typically increased with temperature and oxygen pressure exhibiting the optimal activity up to 100 TON at 383 K under 1.2 MPa of O₂. The most abundant product was 3-(*p*-methoxyphenyl)-3-phenylpropanoate (≈45%). The reaction selectivity was practically independent of the conditions. Split-tests and AAS measurements confirm heterogeneous character of the catalyst.

Keywords: Oxidative coupling ; palladium catalyst ; heterogeneous alkenylation

1. Introduction

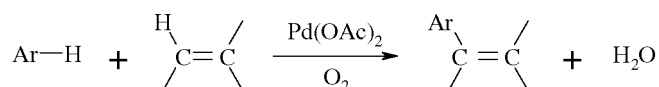
Arylalkenes are valuable products and intermediates for the synthesis of fine chemicals [1, 2]. The conventional route towards arylalkenes comprises alkylation of aromatics [3, 4] and subsequent high-temperature dehydrogenation of arylalkanes. Synthetically versatile alternative is the halogenation of aromatics followed by the Heck reaction [4-6].

In comparison with the two-step technologies, the direct alkenylation of aromatics with olefins is an attractive and waste-free approach [7, 8]. Moreover, the reaction has a broad scope since almost any material having an aromatic or olefinic bond can be used [9, 10].

In the presence of typically palladium(II) acetate catalyst, usually electrophilic Pd(II) is formed. At the end of the catalytic cycle the active Pd(II) species are reduced to Pd(0), requiring continuous reoxidation for the reaction to proceed [11]. The convenient oxidants are Ag(I), Cu(II), peroxides, oxygen, or the air. The regeneration of Pd(II) faces two main difficulties - inadequate reoxidation and clustering of Pd(0) particles. For this reason, the overall catalytic activity remains relatively low, although the so-called oxidative coupling was discovered already in 1970's [12, 13].

Starting from copper(II) and silver(I) acetates [11, 13] considerable improvement was achieved with *tert*-butyl hydroperoxide [10], yielding turnover numbers (TON) up to 280. With the air or dioxygen TON up to 121 were obtained [14, 15]. Such systems produce water as the only by-product (Scheme 1) but the reoxidation is more challenging.

Scheme 1.



The oxidative coupling under oxygen can be carried over palladium carboxylates [16]. Promising results were also reported with heteropolyoxometalates as co-catalysts [14, 15, 17-19]. While there is considerable effort focused on designing highly active homogeneous systems, there are no reports on heterogeneous catalysts.

The heterogenisation of an Pd alkenylation catalyst is complex task. The metal changes its state in each catalytic cycle, Pd(II) is susceptible to leaching and Pd(0) tends to form inactive clusters [20, 21]. The concept of the present work on immobilization of a homogeneous catalyst is based on our previous studies [22, 23]. The activity in the reaction between anisole (methoxybenzene) and ethyl *trans*-cinnamate was dramatically improved by the addition of benzoic acid (TON = 780). The heterogeneous catalyst introduced in this work was tested in the coupling of anisole with ethyl *trans*-cinnamate, too. It has to be noted, however, that the reaction is universal taking into account some common trends and rules [9, 10, 24].

Generally the reactivity of aromatics increases in order: furans > indole > naphthalene > anisole > toluene ≈ benzene. The reactivity of alkenes increases in the presence of phenyl group. The substitution on olefinic carbons decreases their reactivity. The order is then evident: PhCH=CH—CO₂C₂H₅ >> CH₂=CH-CO₂C₂H₅ > CH₃-

$\text{CH}=\text{CH}-\text{CO}_2-\text{C}_2\text{H}_5 > \text{CH}_2=\text{CH}-\text{CN}$. Oxidative coupling is tolerant to a range of functional groups, except to reactants bearing functional groups that can interact or are poisonous for the catalyst such as -SH, -OH, -NH₂, and -NH-. Low reactivity was observed for olefins bearing -CN, -CHO, and -CO₂H. These substituents are assumed to strongly interact with palladium. The carbonyl group can be easily converted to carboxylic, under the reaction conditions.

We herewith report first heterogeneous, polymer supported Pd catalyst containing aromatic carboxylic acid groups, as active catalyst for the direct oxidative alkenylation under dioxygen.

2. Experimental

2. 1. Catalyst synthesis

The catalysts were prepared by wet impregnation of the supports with Pd(II) acetate (47% Pd, Fluka). The suspension of the support and calculated amount of Pd(OAc)₂ were shaken for one hour in 50 ml of toluene (99.99%, Fisher) with the addition of 100 µl of bidistilled water. The impregnated supports were carefully dried in rotary evaporator at 333 K under a vacuum of 10 kPa.

The 5 wt% Pd/C was from Johnson Matthey. The commercial products were supports Celite 521 (94% SiO₂, Acros), 3-carboxypropyl functionalized SiO₂ (Varian), 4-carboxybutyl functionalized SiO₂ (Aldrich), Amberlite IRC-50 (Fluka) and Dowex MWC-1 (Fluka). Home-made SiO₂ (790 m²/g) was synthesised via sol-gel method according to De Witte et al. [25].

The polymeric support poly(4-vinylbenzoic acid)-co-poly(methylmethacrylate)-co-poly(ethylene glycol dimethacrylate) was prepared via radical polymerisation. The typical composition was 82.5 wt% of methylmethacrylate (MMA), 10 wt% of ethylene glycol dimethacrylate (EGDMA), and 7.5 wt% (0.5 mmol -COOH/g) of 4-vinylbenzoic acid (VBA). The calculated amounts of MMA (99%, Aldrich), EGMA (98%, Aldrich), and VBA (97%, Aldrich) were dissolved in tetrahydrofuran (THF) in a Schlenk tube. The mixture was degassed and polymerised in argon atmosphere for 24 h at 333 K using isobutyronitrile (98%, Fluka). The obtained crosslinked copolymer was finely crushed, dispersed in THF, and the suspension stirred for 24 h. The purified support was filtered, rinsed with THF and dried in vacuum at 353 K. The purification was repeated for a second time. In the last step the pure copolymer was dried in vacuum at 353 K for 24 h.

2. 2. Oxidative coupling

Alkenylations were carried out under O₂ in stirred 10 ml stainless steel reactors. Under standard conditions the reactor contained 0.15 g of the catalyst (0.03 mmol Pd), 0.53 g (3 mmol) of ethyl *trans*-cinnamate (99%, Aldrich), and 4 ml of anisole (99%, Acros). Periodically withdrawn samples were analyzed by GC (Agilent 6850) equipped with FID and a 32 m capillary column HP-1 (Agilent). Reaction products were identified by GC-MS (Agilent 6890N, 30 m column HP-5ms) using reference compounds obtained selectively via Heck reaction from the corresponding aryl iodides.

Reactions were usually followed for 96 h. The catalytic activity was evaluated by comparing substrate conversion and turnover numbers (TON) at particular reaction times. TON was defined as molar ratio between the reacted ethyl cinnamate (EC) and the amount of palladium present in the catalyst.

The so-called split-tests were performed under the standard conditions. The liquid-phase and the solid catalyst were separated via filtration after 4 h of reaction. The further reaction progress in the filtrate was monitored [26].

3. Results and discussion

The homogeneous alkenylation of anisole with ethyl *trans*-cinnamate can be conducted with very high effectiveness in the presence of Pd(II) acetate and benzoic acid [22, 23]. The comparison among solid Pd catalysts in coupling of anisole to ethyl *trans*-cinnamate is shown in the Table 1.

The reduced 5 wt% Pd/C catalyst (Johnson Matthey) had negligible activity, even in the presence of benzoic acid (entry 1, 2). Apparently no Pd(II) was available to initiate the C-H activation.

High olefin conversions were observed over Pd(OAc)₂ impregnated SiO₂ and Celite (entries 3-5). However, the activity is ascribed to the homogeneous character of the reaction confirmed by the presence of Pd in the liquid-phase and by catalytic activity in the filtrate.

The immobilization of the dissolved acid onto the support is another desirable improvement towards a catalyst heterogenisation. Commercial silicas with covalently attached (CH₂)_n COOH groups (*n* = 3, 4) contain relatively low amounts of acid groups (0.35-1.2 mmol/g). Impregnation of these materials with Pd(OAc)₂ gives catalysts with a clear activity in the oxidative alkenylation (entry 6, 7). Moreover split tests and AAS did suggest less extensive leaching of Pd(OAc)₂.

The commercial, weakly acidic acrylic resins with attached -COOH, here represented by Dowex MWC-1 and Amberlite IRC-50 displayed very low activity (entry 8, 9). The result might be explained by high concentration of -COOH (10 mmol/g). Due to close proximity of the acidic groups, that can favour double coordination of the Pd(II), the formation of electrophilic Pd(II) species with a vacant coordination site for an incoming arene might be impeded (compare entries 10 and 11 in Table 1).

Table 1 : Supported Pd catalysts for the oxidative alkenylation of anisole^a

Entry	Catalyst	Support acidity [mmol -COOH/g]	Pd [wt%]	X [%] ^b	Leaching
1	Pd/C	-	5	0.2	X ^c
2	Pd/C + BA ^d	-	5	0.2	×
3	Pd/SiO ₂	-	4	97	Yes
4	Pd/Celite 521	-	2	100	Yes
5	Pd/Celite 521	-	4	100	Yes
6	Pd/HOOC-propyl-SiO ₂	0.35	3.7	30	Yes
7	Pd/HOOC-butyl-SiO ₂	1.2	2.1	22	Yes
8	Pd/ Amberlite	10.0	2.5	2(70)	×
9	Pd/Dowex	9.5	2.5	9(70)	×
10	Pd/copolymer	0.5	2.1	50	No
11	Pd/copolymer	2.0	2.1	17	No

^a 383 K, $p(O_2) = 0.8$ MPa.

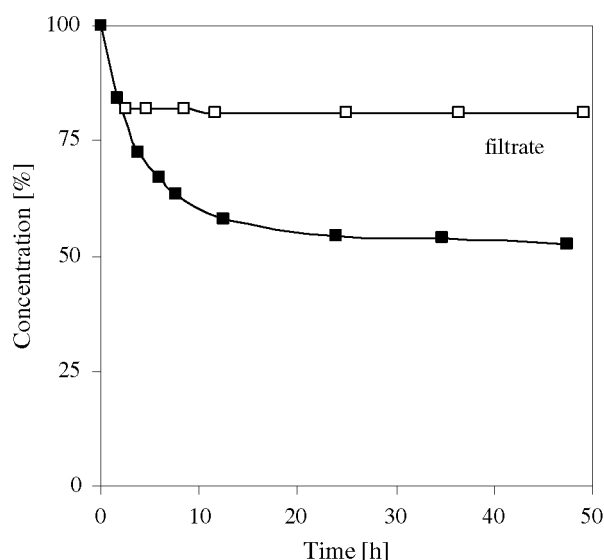
^b Conversion of cinnamate after 24 h (other values indicated in parentheses).

^c Not tested.

^d 0.6 mmol benzoic acid.

In a further refinement, a tailor-made polymeric support with lower concentration of acid groups was tested. Under the standard reaction conditions conversions around 50% (TON = 50) were easily achieved (entry 10). Additionally, the reactions carried out in the absence of the Pd catalyst supported on the acid-modified copolymer indicate heterogeneous character of the reaction. The typical reaction courses in the presence and in the absence of the catalyst (split test) are shown in Fig. 1.

Fig. 1. Split test (383 K, 1.2 MPa of O₂) with 2.1 wt% Pd/polymer. Closed squares indicate typical reaction course, open ones show cinnamate concentration after the catalyst was filtered out.



After the catalysts was filtered out the conversion in the clear filtrate remained constant, while in the presence of the catalyst further reaction progress was observed. Besides this practical test, AAS analyses of the liquid-phase (Varian's SpectrAA 20) confirmed the conclusion on heterogeneity of polymer supported catalysts providing an evidence for negligible leaching of Pd. The measured average Pd concentrations in the liquid-phase ranged between 10-15 ppm corresponding to less than 2 wt% of the total Pd content in the catalyst.

To establish operational window and the basic catalytic properties of the polymer supported catalyst, the principal reaction parameters were varied (Table 2).

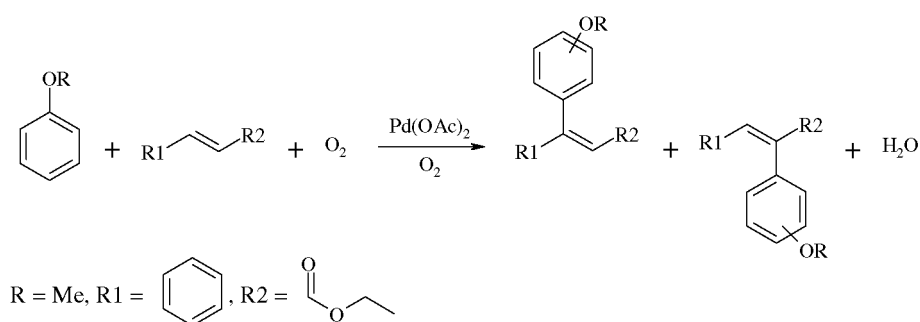
Table 2 : Pressure and temperature effects on the conversion of ethyl *trans*-cinnamate over 2.1 wt% Pd/polymer catalyst^a

T[K]	$p(O_2)$ [MPa]	X [%] ^b	TON (96 h)
343	1.2	8	23
363	1.2	24	32
383	0.4	34	37
383	0.8	50	53
383	1.2	47	51
403	1.2	51	57
423	1.2	19	26

^a Standard conditions (0.03 mmol Pd, 3 mmol ethyl *trans*-cinnamate). ^b Conversion of cinnamate after 24 h.

The effects of reaction temperature and oxygen pressure given in Table 2 point to the decrease of the TON at the temperature of 423 K and a positive reaction order in oxygen. Regarding the reaction mechanism, during oxidative alkenylations all the aromatic C-H bonds are activated, leading to simultaneous formation of different isomers. The Scheme 2 depicts the general reaction scheme for coupling of anisole with ethyl *trans*-cinnamate.

Scheme 2. Oxidative coupling of anisole with ethyl *trans*-cinnamate.



Given by the mechanism, mixtures of isomers were expected. In line with the formation of the two most abundant products: ethyl 3-(*p*-methoxyphenyl)-3-phenyl-propanoate ($\approx 45\%$) and ethyl 3-(*o*-methoxyphenyl)-3-phenylpropanoate ($\approx 25\%$), the reaction proceeded mainly at the β -position of the cinnamate, whereas the substitution in anisole took part at *para* and *ortho* positions. The selectivity towards the remaining four derivatives was considerably lower compared to the two main compounds.

The reaction selectivity was almost independent of the conditions. The oxygen pressure apparently did not influence product distribution, while slightly more *meta* isomers were formed at higher temperatures.

The immobilization of Pd alkenylation catalyst and the achievement of an active heterogeneous catalyst was difficult task particularly challenging since the reaction was carried out under oxygen. Compared to conventional the current approach did considerably simplify the reaction environment establishing a system in which the oxidative coupling is carried out in a standard three-phase system. The complexity of the task is well demonstrated by the data in Table 1. Only the designed polymeric catalyst exhibited reasonable activity along with the desired heterogeneous character.

Under the reaction conditions the highest TON around 60 were obtained (Table 2). Further activity improvement of the heterogeneous catalyst can be realised by fine tuning the composition of the support and changing some of the experimental parameters. For instance, controlled catalyst pretreatment was found to extend the catalyst lifetime to more than 100 turnovers. In the homogeneous reactions using various oxidants the turnover values vary between 3 and 280 with an average turnover of 83 [10, 11]. Using a co-catalyst (HPMO₁₂ + HPMo₁₁V₁) the highest TON under O₂ was 121 [15]. In previous work, in the presence of benzoic acid, TON of 780 was reached [23].

The oxidative coupling reaction is generally applicable to almost any combination of aromatic compound and alkene. The present catalytic system was also active with alkenes bearing a nitro group (ethyl nitrocinnamate). The alkenylation of *p*-hydroxyanisole yielded exclusively conjugated oxidative addition products. The results follow very well the common trends described in the introduction, the tested heterogeneous catalyst is hence expected to be generally active in the oxidative coupling.

4. Conclusions

A polymeric support modified by vinylbenzoic acid and impregnated with palladium(II) acetate gives heterogeneous catalyst active in the direct oxidative alkenylation of arenes under dioxygen. The highest TON reached about 100. The product distribution was almost independent on reaction conditions and closely resembled the selectivity of the homogeneous reaction. In contrast to conventional alkenylations that use complex environments the presented catalytic system is simple. Although the oxidative coupling of anisole with ethyl *trans*-cinnamate is investigated in more details, the heterogeneous catalyst is applicable to other aromatics and alkenes.

Acknowledgements

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