



Pd(OAc)₂/M(NO₃)_n (M = Cu(II), Fe(III); n = 2, 3): Kinetic investigations of an alternative Wacker system for the oxidation of natural olefins

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ABSTRACT

Pd-catalyzed oxidative coupling of camphene by dioxygen afforded mainly a diene, which subsequently underwent oxidation to a ring-expanded β,γ -unsaturated ketone with LiNO₃ as reoxidant. However, the instability of LiNO₃ results to the decomposition of NO₃⁻ ions which subsequently deactivates the catalyst. The present investigation describes the oxidation of terpenes catalyzed by Pd(OAc)₂/M(NO₃)_n (M = Cu(II), Fe(III); n = 2 or 3), using dioxygen as final oxidant. Fe(III) and Cu(II) effectively stabilize the nitrate reoxidant as determined by the significant increase of both catalytic activity and stability of the system. Turnover frequency suggests that Fe(III) is the most efficient co-catalyst. Moreover, it is established that the co-catalysts NO₃⁻, Cu(II) and especially Fe(III) ions, change the product distribution (diene/ketone) remarkably. Their involvement in the rate-determining step was investigated and the results of the kinetic investigations clarified important aspects of Pd(II)-catalyzed oxidation reactions. The described protocol offers an alternative to the traditional Wacker system which uses CuCl₂ as co-catalyst and is not effective in promoting the oxidation of bicycle olefins.

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1. Introduction

Terpenes represent a large and structurally diverse group of natural products. They are a source of valuable compounds that has been used by pharmaceutical companies as synthetic useful intermediates, beyond chiral building blocks [1,2]. In particular, oxygenated monoterpenes are among a very big range of fine chemicals produced throughout the world for the perfume, cosmetic and food industries [3]. Unfortunately, most of the industrial oxidative processes that are employed to produce oxygenated terpenes are unacceptable from the environmental standpoint due to the amount of waste generated and the use of toxic metals, such as Cr, and Os as stoichiometric oxidants [4].

As consequence of these drawbacks, the development of environment-friendly catalytic systems is highly desirable [5]. Within this framework, the use of dioxygen, a readily available and environmentally benign stoichiometric oxidant is especially attractive due to its low cost and the generation of water as the only byproduct [6]. However, the employment of this oxidant requires an activation step normally promoted by a transition metal, which must be recovered by a reversible reoxidant [7]. Among the various transition metals capable of activating dioxygen, palladium is the most frequently utilized, as in the well-established Wacker oxidation reaction [8–11]. This process that produces acetaldehyde from eth-

ylene is based on a PdCl₂/CuCl₂/O₂ redox coupling system [12,13]. Despite the potential utility of the Wacker oxidation, either in organic synthesis or for industrial purposes, there are significant limitations associated with this oxidative process [14]. For instance, because of the corrosive nature of both copper (II) and chloride ions, which are fundamental for the reaction, the CuCl₂ reoxidant is not always an innocent bystander [15]. Besides that the formation of chlorinated products compromises the selectivity and raises the overall cost of the process. Another important limitation of the Wacker reaction is the inefficiency in the oxidation of monoterpenes [16]. In this case, the high Lewis acidity of Cu(II) promotes rearrangement side reactions of the carbon skeleton, accompanied by isomerization of double bonds and nucleophilic addition of the solvent. These competitive reactions diminish the selectivity of the oxidation products [16]. In view of the aforementioned problems, oxidative process alternative to Wacker using dioxygen has been described in the literature, especially Pd(II)-catalyzed reactions [17–19].

Reoxidants for the palladium catalyst such as benzoquinone, heteropolyacids and alkyl hydroperoxides, have been extensively investigated [5,20,21]. A remarkable feature of the Pd(II)-catalyzed oxidation reactions is that the co-catalyst can mediate the two key steps in the catalytic cycle namely the olefin oxidation by the oxidized catalyst and the dioxygen-coupled reoxidation of the reduced catalyst [22]. A good example is the Pd(II)/NO_n⁻ catalytic system based on palladium–nitro–nitrosyl–redox couple, first described by Heumann and co-workers [23]. The evidence provided

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by NMR and FTIR investigations of the propylene oxidation, promoted by Pd(II)–nitro complexes clarified important aspects of the mechanism of these reactions [24].

We have been involved in the oxidation of monoterpenes by dioxygen in both homogeneous and heterogeneous catalytic systems based on metal catalysts such as cobalt, iron and especially palladium [25–27]. In this context and prior investigation of the camphene oxidation catalyzed by Pd(OAc)₂/LiNO₃, we have developed a new process consisting of an intermolecular oxidative coupling which afforded a diene, followed by its oxidation to a β,γ-unsaturated ketone [27,28]. However, the major disadvantage of the Pd(OAc)₂/LiNO₃ system is the fast deactivation of the catalyst promoted by the decomposition of NO₃⁻ ions.

The present investigation describes the results of terpenes oxidation (limonene, β-pinene, and particularly camphene) by dioxygen in a modified Wacker system, i.e. Pd(OAc)₂/M(NO₃)_n (M = Cu(II), Fe(III); n = 2 or 3). Kinetic aspects such as the dependence of the rate-determining step on substrate, palladium, and co-catalyst concentrations are also discussed.

2. Experimental

All reagents were purchased from commercial sources and used without further purification, unless otherwise stated. Hexane, chloroform and acetic acid (99% w/w) were purchased from Vetec (São Paulo, Brazil). Racemic camphene (distilled prior to use), Pd(OAc)₂, Fe(NO₃)₃·9H₂O, LiClO₄, and Cu(NO₃)₂·2H₂O were purchased from Sigma–Aldrich (Milwaukee, WI). The products obtained from limonene and β-pinene oxidations were identified by co-injection with authentic samples in a Shimadzu GC17A gas chromatograph, equipped with FID detector, and with DB5 capillary column (30 m length, 0.25 mm i.d., 0.25 mm film thickness). The temperature profile used was as follows: 80 °C for 3 min, 10 °C/min up to 260 °C, hold time of 5 min. The products obtained from oxidation of camphene, i.e. diene and ketone, were isolated by silica column chromatography and fully characterized by FTIR (Mattson FTIR 3000/Galaxy Series), ¹H and ¹³C NMR (Bruker DRX-400, tetramethylsilane, CDCl₃) spectroscopy and mass spectrometry. The mass spectrometry analyses were carried in a GC/MS Shimadzu GC17A gas chromatograph fitted with a DB5 capillary column (30 m length, 0.25 mm i.d., 0.25 mm film thickness) coupled with a MS-QP 5050A mass spectrometer Shimadzu. The chromatographic conditions were as follows: helium as the carrier gas at 2 mL/min; the temperature profile was 80 °C for 1 min,

10 °C/min up to 260 °C, hold time of 5 min; the GC injector and MS ion source temperatures were kept at 260–270 °C, respectively; the MS detector operated in the EI mode at 70 eV, with a scanning range of m/z 50–500.

2.1. Kinetic investigations

Oxidation reactions were carried out in a stirred 50 mL three-necked glass reactor fitted with a sampling septum and coupled to a system for monitoring the dioxygen uptake. The reactor was pressurized to 0.10 MPa with dioxygen and the temperature adjusted to 60 °C using a water bath. Careful optimization of the stirring rate excluded the possibility of controlling by diffusion. The ionic strength of the medium was kept constant by adding LiClO₄. The reaction progress was monitored by measurements of the dioxygen uptake and GC analysis of aliquots of the reaction mixture taken at regular time intervals. In a typical run, catalyst and reoxidants were dissolved in a reactor containing acetic acid (HOAc, ca. 10 mL). The system was then pressurized at 0.10 MPa with dioxygen and the temperature adjusted to 60 °C. The t₀ of each kinetic run corresponded to the substrate addition. All experiments were performed in triplicate.

3. Results and discussion

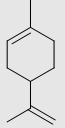


3.1. General discussion

The oxidation reactions of limonene, β-pinene and camphene, by molecular oxygen, catalyzed by Pd(II)/NO₃⁻, were carried out in HOAc solutions, and the results are presented in Table 1. Two main compounds were obtained from the reaction with limonene (Fig. 1). The allylic oxidation of this substrate afforded carvoyl acetate **1**. The undesirable product α-terpenyl acetate **2**, resulting from a competitive transformation involving carbon skeletal rearrangement and solvent addition, was also formed (Entry 1, Table 1).

Similarly, the reaction of β-pinene afforded both products but with α-terpenyl acetate **2** in almost quantitative yield (Entry 2, Table 1). This side reaction is favored in HOAc solutions and decreases the selectivity of oxidation products [29].

Camphene, on the other hand, is not prone to these competitive transformations. Comparatively to works that described the oxidation type-Wacker of terpenes in acetic acids, the selectivity of oxidation products of camphene is remarkably higher when the

Table 1
Oxidation of monoterpenes catalyzed by Pd(OAc)₂/LiNO₃ in HOAc solutions.^a

Entry	Monoterpene	Structure	Time (h)	Conversion ^b (%)	Product distribution ^c (%)			
					1	2	3	4
1	Limonene		4	45	60	40		
			4	48	4	96		
2	β-Pinene		4	38			46	54
3 ^d	Camphene		8.5	60			8	92

^a Reaction conditions: [monoterpene] = 10.00 mmol; Pd(OAc)₂ = 0.10 mmol; [LiNO₃] = 4.00 mmol; 60 °C; O₂ (0.10 MPa).

^b Quantified by GC based on substrate consumption.

^c Selectivity determined by GC analyses.

^d [Camphene] = 5.00 mmol.

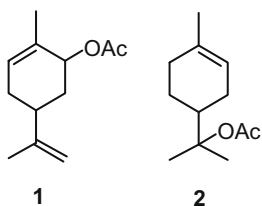


Fig. 1. Products of allylic oxidation (**1**) and skeletal rearrangement/solvent addition (**2**).

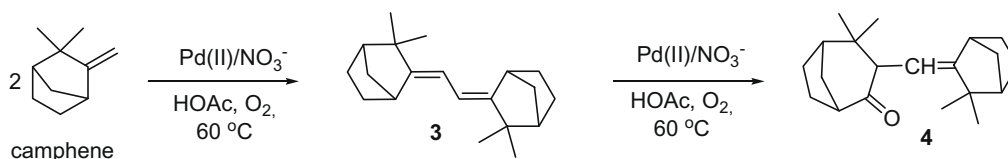
reaction is catalyzed by both $\text{Pd}(\text{OAc})_2/\text{Fe}(\text{NO}_3)_3$ or $\text{Pd}(\text{OAc})_2/\text{Cu}(\text{NO}_3)_2$ [30]. In fact, a chemoselective palladium-catalyzed oxidative coupling gave the diene **3** (Scheme 1), which was selectively converted into the corresponding β,γ -unsaturated ketone **4** with high selectivity (ca. 92% after 8.5 h, Entry 3, Table 1).

The structural elucidation of the diterpene derivatives **3** and **4**, using a combination of FTIR, NMR (one- and two-dimensional ^1H and ^{13}C), and MS techniques, has been previously described in the literature [28]. It was demonstrated that the palladium-catalyzed oxidative coupling of camphene is highly stereoselective, and results mainly in the formation of the (*E,E*)-isomer of **3**. The two atropoisomers of **3**, arising from the restricted rotation around the C–C bond, were consecutively oxidized into two isomers of ketone **4** [28]. It should be mentioned that mechanistic aspects of the stoichiometric oxidation reactions of camphene, promoted by Pd(II)–nitro complexes, has been investigated by NMR spectroscopy [31]. The oxidative ring expansion process of one of the isocamphane units to bicyclic ketone fragment of **3** (Scheme 1) has been unambiguously proven by NMR experiments [28]. Hence, one of the trisubstituted double bonds of **3** in the Pd(II)/ NO_3^- system is oxidized, and then one of its isocamphanic units expand resulting into **4**. It should be pointed out that the ability of palladium to promote oxidative ring expansion of disubstituted olefins was reported by Pavares and Grigg who achieved the ring expansion of camphene into methylenecamphor using the Wacker system in isopropyl alcohol solutions [32].

In order to improve the efficiency of the catalytic system, co-catalysts can be introduced to promote the reaction between the reduced nitrogen species and dioxygen [33]. Kinetic investigation of the effect of the addition of metal ions Cu(II) and Fe(III) to the catalytic system is described below (Fig. 2).

The kinetic curves presented in Fig. 2 reveal that Cu(II), and more remarkably Fe(III), increased the initial reaction rate of oxidative coupling/oxidative ring expansion of camphene compared to Li(I). Moreover, a higher catalytic conversion was achieved in a shorter reaction time. The selectivity and conversion results of these reactions are shown in Table 2.

Initially, a reaction in absence of nitrate reoxidant was performed, and no formation of oxidation products was achieved (Entry 1, Table 2). Conversely, palladium-catalyzed isomerization of carbon skeletal of camphene resulted in a complex mixture of minority products identified by GC–MS analyses as tricyclene and fenchene. Besides, products resulting from skeletal rearrangement allowed of solvent addition, i.e. borneol, fenchyl and bornyl acetates were also detected. No formation of palladium black spe-



Scheme 1. Tandem oxidative coupling/ring oxidative expansion reactions of camphene catalyzed by $\text{Pd}(\text{OAc})_2/\text{LiNO}_3$.

Table 2

Effect of the metal co-catalyst on the activity of palladium and in the product distribution of camphene oxidation.^a

Entry	Catalytic system	Conversion ^b (%)	TON ^c	Selectivity ^b (%)		
				3	4	Others ^d
1	$\text{Pd}(\text{OAc})_2$	14	–	–	–	14
2	$\text{Pd}(\text{OAc})_2/\text{LiNO}_3$	38	19	52	40	8
3	$\text{Pd}(\text{OAc})_2/\text{Cu}(\text{NO}_3)_2$	58	29	7	70	23
4	$\text{Pd}(\text{OAc})_2/\text{Fe}(\text{NO}_3)_3$	79	40	12	83	5

^a Reaction conditions: [camphene] = 5.00 mmol; $[\text{Pd}(\text{OAc})_2]$ = 0.10 mmol; $[\text{LiNO}_3]$ = 1.80 mmol; $[\text{Cu}(\text{NO}_3)_2]$ = 0.90 mmol; $[\text{Fe}(\text{NO}_3)_3]$ = 0.60 mmol; O_2 (0.10 MPa); 60 °C; 1 h.

^b Conversion and selectivity determined by GC analyses.

^c TON: turnover number calculated as mol of camphene converted by mol of Pd(II).

^d Products resulting from carbon skeletal isomerization such as tricyclene and fenchene, and rearrangement allowed of solvent addition, i.e. borneol, fenchyl and bornyl acetates.

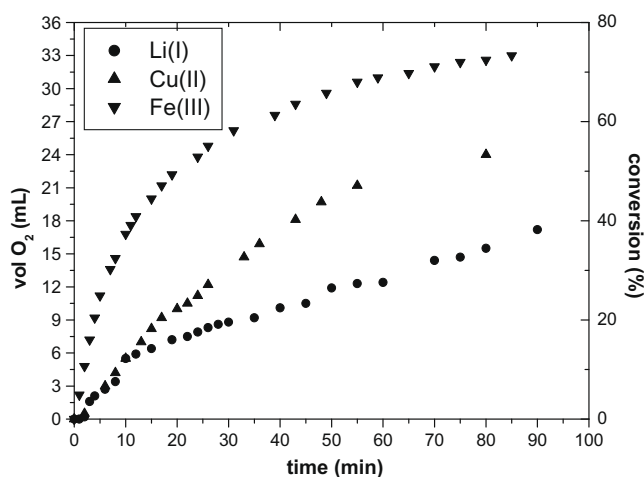


Fig. 2. Kinetic curves of the camphene oxidation catalyzed by $\text{Pd}(\text{OAc})_2/\text{M}(\text{NO}_3)_n$; (M = Li(I), Cu(II) or Fe(III); $n = 1, 2$ or 3). Reaction conditions: [camphene] = 7.50 mmol; $[\text{Pd}(\text{OAc})_2]$ = 0.10 mmol; $[\text{Fe}(\text{NO}_3)_3]$ = 0.60 mmol; $[\text{LiNO}_3]$ = 1.80 mmol; $[\text{Cu}(\text{NO}_3)_2]$ = 0.90 mmol; HOAc (10 mL); 60 °C; 0.1 MPa (O_2).

cies was observed. The replacement of Li(I) by Cu(II) and especially Fe(III) in the catalytic system led to a significant increase in the turnover numbers (TON), i.e. the number of mmol of substrate converted by 1 mmol of palladium catalyst (see Entries 2–4, Table 2). It is important to mention that in the formation of ketone **4**, more than 1 mol of Pd(II) is required. The nature of the co-catalyst clearly changed the distribution of the products. In the presence of $\text{Pd}(\text{OAc})_2/\text{LiNO}_3$, the camphene oxidation resulted in nearly equimolar formation of diene **3**/ketone **4** (Entry 2, Table 2). On the contrary, the camphene oxidation reactions carried out in the presence of $\text{Pd}(\text{OAc})_2/\text{Fe}(\text{NO}_3)_3$ or $\text{Pd}(\text{OAc})_2/\text{Cu}(\text{NO}_3)_2$ gave mainly ketone **4** (Entries 3 and 4, Table 2). Although Cu(II) was less efficient than Fe(III) in terms of increasing the reaction rate (Fig. 2), to be important for the selectivity of the reaction (Entry 2, Table 2).

It should be highlighted that the performance of Fe(III) cations is remarkable not only in terms of higher longevity for the catalyst but also for the selectivity of the reaction. It also deserves comment that several investigations have demonstrated the ability of Fe(III) to activate O₂ under mild conditions via non free radical processes [34]. In addition, Fe(III) ions are able to form bridged palladium complexes, with NO₃⁻ or OAc⁻ ligands, in HOAc solutions [35]. Probably, the higher hardness of Fe(III) cation can make the coordination to oxygen more favorable. It seems that Fe(III) cations assist in the stabilization of nitrogen species during the reaction, avoiding its decomposition into nitrous oxides [36]. However, to the best of our knowledge, there are no reports on the effective participation of Fe(III) in palladium-catalyzed oxidation reactions involving dioxygen.

Another peculiarity of the camphene oxidation in the presence of Pd(II)/NO₃⁻ system is that the selectivity of the reaction was also strongly affected by the substrate concentration. This effect was also evaluated and the results are shown in Table 3.

The diene **3** and the ketone **4** were obtained in almost equimolar proportion when the initial camphene concentration was equal to 5.00 mmol, in the presence of LiNO₃ as reoxidant (Entry 2, Table 2). However, at a higher camphene concentration (ca. 12.5 mmol) and with the same reoxidant, it showed a preference for the diene formation (Entry 1, Table 3). Probably, one or more steps of the oxidative coupling reaction would involve two molecules of camphene being thus favored at higher concentration of substrate. Conversely, the formation of the ketone **4** seems to be more favorable in the presence of Cu(II) and Fe(III) reoxidants, and at lower camphene concentration (Table 2). Using a camphene concentration equal to 5.00 mmol, ketone **4** was obtained in 70% and 83% yield in the presence of Cu(II) and Fe(III), respectively (Entries 3 and 4, Table 2). On the other hand, at a higher camphene concentration (12.5 mmol), the yields were lower at 17% and 46% for Cu(II) and Fe(III) ions, respectively (Entries 2 and 3, Table 3).

3.2. Kinetic investigations on camphene oxidation catalyzed by Pd(OAc)₂/Fe(NO₃)₃ system

3.2.1. Choice of the kinetic parameter: oxygen consumption

Kinetic data are obtained by measuring the decrease of reagent concentrations [37]. In the camphene oxidation, three main reagents are involved: terpene (camphene or diene), nitrate (or nitrite) and dioxygen. The camphene concentration was initially chosen as the kinetic parameter but we realized that there were some potential problems associated with this approach that could complicate the interpretation of the results. The camphene and the nitrate ions do not react in the absence of the palladium catalyst. However, in the presence of this catalyst, the camphene concentration is reduced firstly by *stoichiometric* reaction with the nitrate ions and secondly, via catalytic reactions which involving nitrate

Table 3
Effect of the camphene concentration on products distribution.^a

Entry	Catalytic system	Conversion ^b (%)	Selectivity ^b (%)		
			3	4	Others ^c
1	Pd(OAc) ₂ /LiNO ₃	45	77	4	6
2	Pd(OAc) ₂ /Cu(NO ₃) ₂	54	47	17	7
3	Pd(OAc) ₂ /Fe(NO ₃) ₃	72	64	46	5

^a Reaction conditions: [camphene] = 12.5 mmol; [Pd(OAc)₂] = 0.10 mmol; [LiNO₃] = 1.80 mmol; [Cu(NO₃)₂] = 0.90 mmol; [Fe(NO₃)₃] = 0.60 mmol; O₂ (0.10 MPa); 60 °C; 1 h.

^b Conversion and selectivity determined by GC analyses.

^c Products arising from rearrangement and solvent addition, i.e. borneol, fenchyl and bornyl acetates.

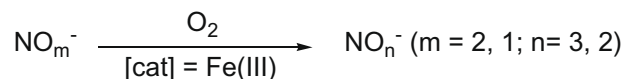


Fig. 3. Reoxidation of reduced nitrogen species.

and dioxygen [27]. Since we were only interested in the *catalytic* transformations that involve the palladium, camphene and dioxygen, it was concluded that the measurement of the camphene concentration was not appropriate for the kinetic investigations. For these reasons, the measurement of the dioxygen consumption seemed to be more adequate in proving the kinetic aspects of the Pd(II)–camphene interactions. It was verified that the results of conversion obtained from measuring the uptake of oxygen were satisfactorily reproducible and were in agreement with the conversion obtained by GC analyses.

An additional problem is that besides to substrates oxidation reaction, i.e. camphene and diene, the dioxygen is involved in a third reaction, i.e. the reoxidant recovery (see Fig. 3). Since this transformation does not involve the palladium catalyst, we excluded the possibility of the total reaction rate to be limited by reoxidation of nitrate, employing a high concentration of nitrate. This procedure becomes this step sufficiently fast.

3.2.2. Reactions involved in the catalytic palladium/nitrate system: rate-determining step

Provided that the possibility of nitrate reoxidation limiting the reaction rate was excluded, we turned our attention to the reactions associated with camphene oxidation (V₁) and diene oxidation (V₂). Since the diene/ketone ratio is reoxidant dependent (see Tables 2 and 3), it was assumed that in the Pd(OAc)₂/LiNO₃ system V₁ is at least comparable to V₂ (see Table 2). The opposite is true in the Pd(OAc)₂/Fe(NO₃)₃ system, where V₂ ≫ V₁ and virtually all diene formed is converted to ketone. These observations are sufficient to support the hypothesis that under the given conditions, the rate-determining step in the camphene oxidation is the oxidative coupling.

3.2.3. Effect of the camphene concentration

In these experiments, the concentration of all the reagents was kept invariable except the initial camphene concentration, which was varied from 2.50 to 12.50 mmol. As can be noted, the interval

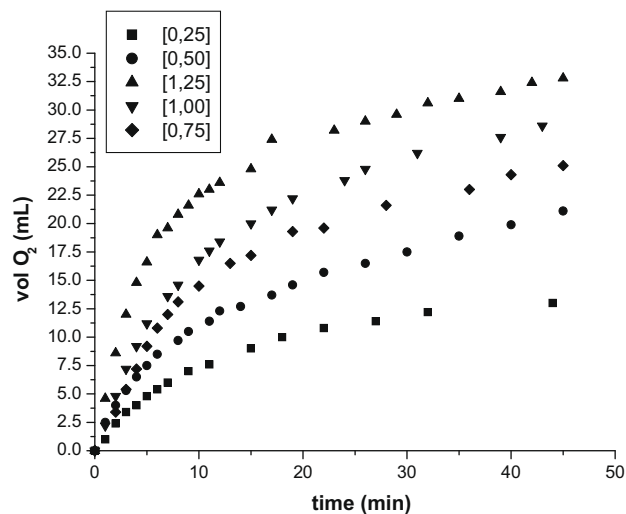


Fig. 4. Effect of substrate concentration on the camphene oxidation catalyzed by Pd(OAc)₂/Fe(NO₃)₃. Reaction conditions: [Pd(OAc)₂] = 0.10 mmol; [Fe(NO₃)₃] = 0.70 mmol; 60 °C; O₂ (0.10 MPa).

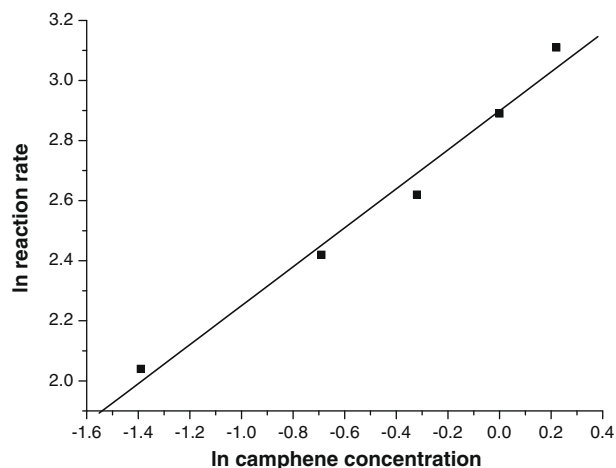


Fig. 5. Reaction rate linear plot of the camphene oxidation catalyzed by Pd(OAc)₂/Fe(NO₃)₃.

in which the reaction rate depends on the *initial camphene concentration* is short (ca. 10 min, Fig. 4). Consequently after this time, the substrate concentration diminished with concomitant decrease in the oxygen consumption. For this reason, the evaluated kinetic effect, i.e. the influence of the initial concentration on the reaction rate, is masked and thus attention should be focused only at the initial time period. Indeed, since the values of dioxygen uptake selected for the calculations referred to the initial period of the oxidation, the reaction is far away from its equilibrium position, which is a crucial requisite for the attainment of consistent data.

The slope of the initial reaction rate versus concentration plot is approximately 0.7 ($R^2 = 0.982$), and a linear dependence on the camphene concentration can be considered (Fig. 5). It is a surprising fact since the oxidative coupling involves two molecules of the substrate. However, this observation is in agreement with the proposed σ -vinyl-organopalladium intermediate previously detected by NMR spectroscopy of the camphene oxidation by Pd(II)-nitro complexes [31].

3.2.4. Effect of the Pd(II) concentration

The order of reaction for palladium was acquired by keeping all reaction variables constant, except the palladium concentration

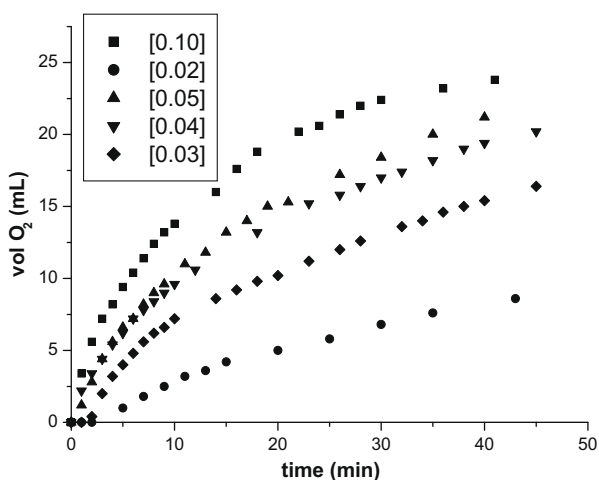


Fig. 6. Effect of palladium concentration on the reaction rate of camphene oxidation catalyzed by Pd(OAc)₂/Fe(NO₃)₃. Reaction conditions: [Fe(NO₃)₃] = 0.70 mmol; [camphene] = 5.00 mmol; [Pd(OAc)₂] = 0.02; 0.03; 0.04; 0.05 and 0.10 mmol; HOAc (10 mL); 60 °C; O₂ (0.10 MPa).

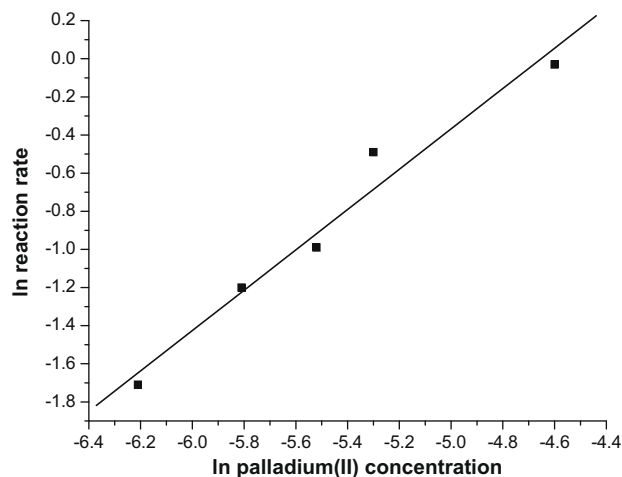


Fig. 7. Reaction order of Pd(OAc)₂ in the camphene catalyzed oxidation.

Table 4

Reaction orders of palladium in the camphene catalyzed oxidation with different reoxidants.^a

Catalytic system	Reaction order ^b
Pd(OAc) ₂ /LiNO ₃	0.9
Pd(OAc) ₂ /Cu(NO ₃) ₂	1.1
Pd(OAc) ₂ /Fe(NO ₃) ₃	1.1

^a Reaction conditions: [camphene] = 5.00 mmol; [LiNO₃] = 2.10 mmol; [Cu(NO₃)₂] = 1.05 mmol; [Fe(NO₃)₃] = 0.70 mmol; [Pd(OAc)₂] = 0.02; 0.03; 0.04; 0.05 and 0.10 mmol; HOAc (5.0 mL); 60 °C; O₂ (0.10 MPa).

^b Obtained measuring the reaction rate in mL (O₂) as time function (min).

that was varied from 0.02 to 0.10 mmol. The kinetic curves obtained in the case of Pd(OAc)₂/Fe(NO₃)₃ system are depicted in Fig. 6.

A slope of 1.06 ($R^2 = 0.984$) was obtained consistent with a first order behavior in relation to the palladium concentration in the Pd(OAc)₂/Fe(NO₃)₃ catalytic system (Fig. 7).

As depicted in Table 4, a first order behavior was also observed for the other reoxidants with regards to the dependence on oxygen consumption rate of the Pd(II) concentration. These results suggest that the Pd(II) is involved in the rate-determining step, consistent with the mechanism of most Pd(II)-catalyzed reactions [38].

3.2.5. Effect of the nitrate ions

The effect of nitrate ion concentration in the camphene oxidation revealed some interesting features. Apparently, they are not only involved in the recovery of the palladium catalyst. Literature data from the oxidation of olefins with isotopically labeled oxygen in Pd(II)/NO_n⁻ suggested a catalytic transfer of oxygen atoms from the NO_n⁻ groups to the substrate molecule [38,39]. This observation seems to be also true for the Pd(OAc)₂/NO₃⁻ catalyzed camph-

Table 5

Reaction orders of NO₃⁻ ions in the camphene oxidation by dioxygen in the presence of Pd(OAc)₂/LiNO₃, Pd(OAc)₂/Cu(NO₃)₂ and Pd(OAc)₂/Fe(NO₃)₃ catalytic systems.^a

Catalytic system	Order
Pd(OAc) ₂ /LiNO ₃	1.0
Pd(OAc) ₂ /Cu(NO ₃) ₂	1.1
Pd(OAc) ₂ /Fe(NO ₃) ₃ ^b	>1

^a Reaction conditions: [camphene] = 5.00 mmol; [Pd(OAc)₂] = 0.10 mmol; [Fe(III)] = 0.50 mmol; HOAc (5.0 mL); 60 °C; O₂ (0.10 MPa); [NO₃⁻]_{total} = 1.50; 2.00; 2.50 and 3.00 mmol.

^b In the Fe(NO₃)₃ system, the nitrate was added as LiNO₃.

ene oxidation. As previously described in the literature, the camphene oxidation under N_2 atmosphere by the $PdClNO_2(CH_3CN)_2$ complex resulted in a mixture of diene/ketone (3:1), indicating that the nitro group was the oxygen source [35]. A summary of the effect of the nitrate concentration is detailed in Table 5. For the systems with $LiNO_3$ or $Cu(NO_3)_2$ as reoxidants where the reaction rates are lower, it was verified that the dependence on the nitrate concentration is approximately linear. However, at the range of nitrate concentration used, and with the $Fe(NO_3)_3$ as reoxidant, it was not possible to determine the reaction order accurately, although it is visibly higher than the other two systems (see Fig. 2).

Thus, in view of these experimental data, it is plausible to assume that nitrate ions are involved in the rate-determining step, i.e. the oxidative coupling of the camphene.

It is important to emphasize that the ions nitrate/nitrite can participate in both steps of camphene oxidation. In other words, they can favor either the substrate coordination to palladium during the oxidative coupling or the diene oxidation transferring oxygen atoms from dioxygen to the diene, affording the rearranged ketone. The effectiveness of NO_n^- ions should be ascribed to the electron-withdrawing effect of these ligands that increases the electrophilicity of palladium. Thus, the coordination of the bulk terpenic substrate to palladium, generating the complex $Pd(II)-L$ ($L = NO_n^-$), becomes more favorable than in the presence of $Pd(II)$ with bridged ligand ($L = OAc^-$) [35].

3.2.6. Effect of Fe(III) concentration

As presented in Table 3, the Fe(III) co-catalyst significantly altered both the conversion and the selectivity of camphene oxidation. The effect of this co-catalyst on the oxidation reaction was further investigated and the results are shown in Fig. 8. As can be seen, a significant increase in the reaction rate was observed for concentration values above 0.70 mmol.

At lower concentration values, the effect observed on the reaction rate was small and could not be quantified. However, the analysis of the product distribution provided important insights about the involvement of Fe(III) on the rate-determining step. Since the Fe(III) ion efficiently co-catalyzed the diene formation (see Tables 1–3), this is presumably involved in the rate-determining step of the reaction. From our standpoint, the harness of the Fe(III) cation can be encourage the dioxygen coordination, however, this effect is better detectable at higher concentrations. In addition, since the Fe(III) cation also stabilize more efficiently the nitrate and nitrite

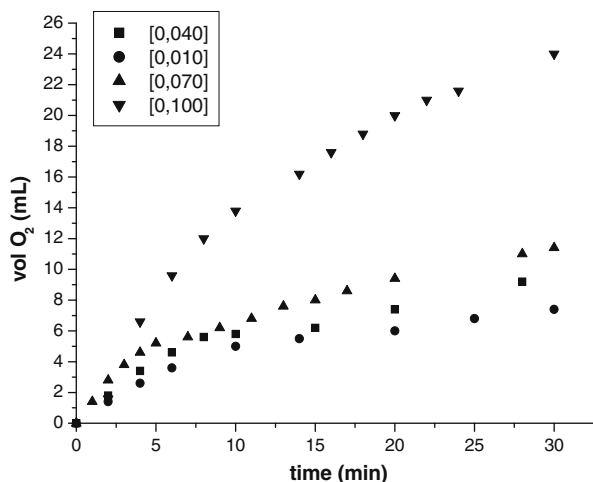


Fig. 8. Effect of the Fe(III) concentration on the reaction rate of camphene oxidation catalyzed by $Pd(OAc)_2/Fe(NO_3)_3$. Reaction conditions: [camphene] = 5.00 mmol; $[NO_3^-]_{total} = 3.0$ mmol; $[Pd(OAc)_2] = 0.10$ mmol; $[Fe(III)] = 0.10; 0.40; 0.70$ and 1.00 mmol; HOAc (10.0 mL); $60^\circ C$; O_2 (0.10 MPa).

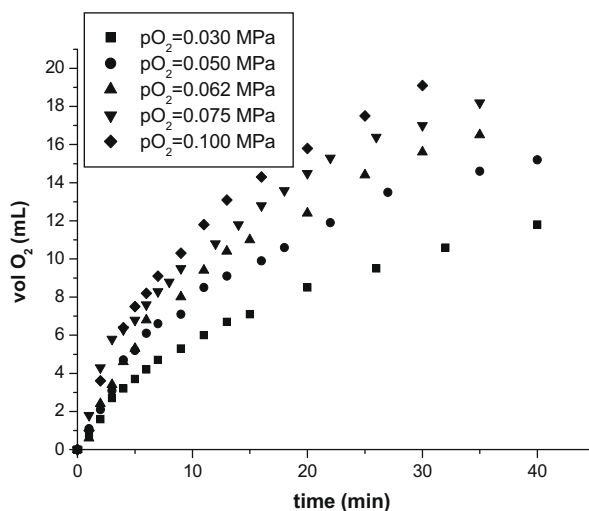


Fig. 9. Effect of the dioxygen partial pressure on the reaction rate of camphene oxidation catalyzed by $Pd(OAc)_2/Fe(NO_3)_3$. Reaction conditions: [camphene] = 5.00 mmol; $[Pd(OAc)_2] = 0.10$ mmol; $[Fe(NO_3)_3] = 0.70$ mmol; HOAc (10.0 mL); $60^\circ C$; $pO_2 = 0.030; 0.050; 0.062; 0.075$ and 0.10 MPa.

species, this fact may contribute for the electron withdrawn effect on palladium.

3.2.7. Effect of partial pressure of oxygen

The effect of the partial pressure of oxygen in the catalytic system was investigated within the pressure range 0.025–0.100 MPa. It was established that the partial pressure of oxygen influence the initial rate of the $Pd(OAc)_2/Fe(NO_3)_3$ camphene catalyzed oxidation (Fig. 9).

This observation can be interpreted in terms of the participation of oxygen in the first step of the reaction (oxidative coupling). In fact, a noticeable dependence on the metal co-catalyst Fe(III) concentration was established in the $Pd(OAc)_2/Fe(NO_3)_3$ -catalyzed reactions. The literature describes the ability of this cation to form the complex $Fe(III)-O_2$ in oxidative process [40,41]. However, in the range of pressures evaluated, it was not possible clearly quantify the reaction dependence on the partial pressure of dioxygen.

3.2.8. Mechanistic insights about the palladium-catalyzed oxidative coupling of camphene

The literature describes two possible mechanisms for oxidative coupling of alkenes. The first corresponds to an oxypalladation of the olefinic bond (e.g., palladium acetate addition) forming a σ -alkyl palladium intermediate. The second would involve the generation of a σ -vinyl palladium intermediate via palladation at a vinylic carbon [35,38]. Based on our kinetic data and on NMR experiments previously reported we assumed that the second mechanism is more likely to be involved in the oxidation of camphene catalyzed by the palladium–nitrate–iron system [35].

The dependence of the rate-determining step on Fe(III) concentration can be attributed to its participation in an organopalladium

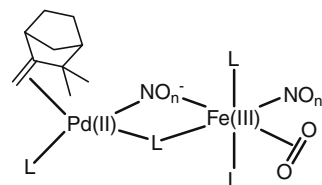
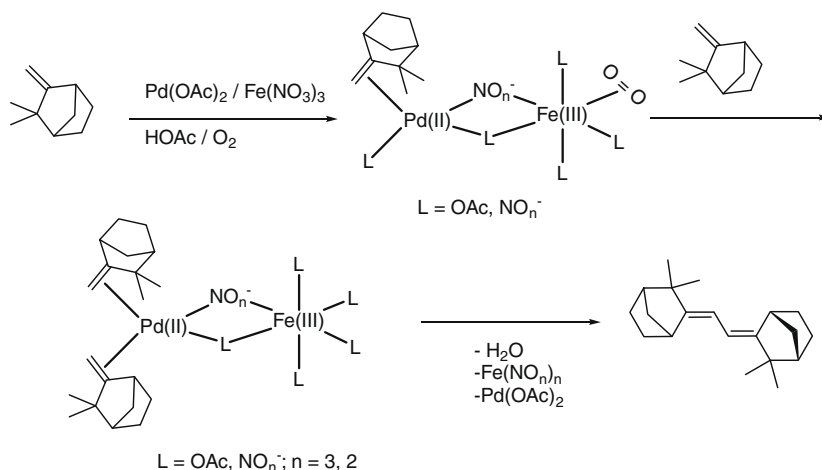


Fig. 10. Proposal of a possible intermediate involved in the rate-determining step of the $Pd(OAc)_2/Fe(NO_3)_3$ -catalyzed camphene oxidation.



Scheme 2. Proposal of the main steps involved in Pd(OAc)₂/Fe(NO₃)₃-catalyzed oxidative coupling of camphene.

intermediate formed on the slow stage of the reaction. We propose that a possible intermediate in the slow step or reaction could include the dioxygen coordinated to the Fe(III), which in turn could be coordinated to the Pd(II), via a nitro/and or acetate ligands, while simultaneously coordinated to camphene, as shown in the Fig. 10 [40,41].

Thus, once this key intermediate is formed, the Fe(III) could act decreasing the electronic density around the Pd(II), via electron-withdrawing NO₃⁻ ligands, favoring the coordination of the camphene to palladium (Fig. 10). Such interaction probably involves Fe(III) bonding to Pd(II) via bridging ligands, and seems to be responsible for the increased effect of Fe(NO₃)₃ in the palladium-catalyzed oxidation of the camphene. Simultaneously, the Fe(III) also could coordinate to dioxygen promoting the recovery of the reduced nitrogen species. The direct activation of dioxygen by an Fe(III) metallic center in a coordination compound, has been previously documented. This synergic effect, resulting from cooperation between Pd(II) and Fe(III) species, was recently described by Potemkin on the investigation of alcohol oxidations catalyzed by palladium (II) tetraqua complexes and Fe(II)–Fe(III) aqua ions [42].

Thus, based on kinetic experiments performed we thinking that the palladium-catalyzed oxidative coupling can be rationalized by the reaction sequence described in Scheme 2.

Recently, we have reported an oxidative system based on palladium where high selectivities and yields were also reached on terpenes oxidation [43]. However, the final oxidant employed was hydrogen peroxide in acetonitrile solutions. Since the hydrogen peroxide is able of active the palladium, that system no need metal reoxidant. Nevertheless, despites the nice results obtained, long time reactions were requiring for achieve high conversion.

4. Conclusions

The catalytic performance of the Pd(OAc)₂/M(NO₃)_n (M = Cu(II), Fe(III); n = 2, 3) multicomponent system in the oxidation of terpenes, especially camphene, was evaluated. The nature of the co-catalyst affects both product distribution and reaction rate. Among the catalytic systems evaluated, the Pd(OAc)₂/Fe(NO₃)₃ combination present the highest stability/activity besides being the most efficient nitrate reoxidant. Moreover, Fe(III) is capable of increasing the rate of both steps (oxidative coupling of camphene into diene and oxidation of the diene into ketone) in the camphene catalyzed oxidation. The dependence of the rate-determining step on camphene, palladium, nitrate and Fe(III) is another important feature of

this alternative Wacker-type catalytic system. Additional mechanism studies will be presented in due course.

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