# A Highly Selective Pd(OAc)<sub>2</sub>/Pyridine/K<sub>2</sub>CO<sub>3</sub> System for Oxidation of Terpenic Alcohols by Dioxygen

Danieli M. Carari · Márcio J. da Silva

Received: 6 June 2011/Accepted: 3 December 2011/Published online: 15 December 2011 © Springer Science+Business Media, LLC 2011

**Abstract** Molecular sieves, complex organic bases and radical oxidants are commonly used in alcohols oxidation reactions. In this work, we have evaluated the beneficial effects of addition of  $K_2CO_3$  to Pd(II)-catalyzed oxidation alcohols, which resulted in a remarkable increase in the oxidation reaction rates without selectivity losses. Herein, in a metallic reoxidant-free system, terpenic alcohols ( $\beta$ -citronellol, nerol and geraniol) were selectively converted into respective aldehydes from Pd(II)-catalyzed oxidation reactions in presence of dioxygen. High conversions and selectivities (greater than 90%) were achieved in the presence of the Pd(OAc)<sub>2</sub>/K<sub>2</sub>CO<sub>3</sub> catalyst and pyridine excess. The exogenous role of others auxiliary anionic and nitrogen compounds was appraised.

**Keywords** Palladium · Terpenic alcohol · Nitrogen ligand · Dioxygen

### 1 Introduction

Monoterpenes are renewable, abundant and inexpensive naturally occurring compounds, and for these reasons are attractive feedstocks in several fine chemical industries [1]. Oxygenated terpenes are predominantly used as ingredients in the flavor and fragrance industries [2, 3]. For instance, (R)-citronellal which is known be an active insecticide, is also an important raw material in the synthesis of pharmacos [4]. A total of 2000 tons per year of (R)-citronellal are produced by Takasago International Co. (Takasago

D. M. Carari (🖂) · M. J. da Silva

Departamento de Química, Universidade Federal de Viçosa, Viçosa, Minas Gerais 35690-000, Brazil e-mail: silvamj2003@ufv.br process), which is a Rh/phosphine-catalyzed multi-step process under low temperatures and inert atmosphere, using myrcene as a raw material [5]. Because the direct synthesis of terpenic aldehydes from monoterpenes is difficult due the differences in reactivity of the double bonds, which may vary significantly in electron density and steric accessibility [6], an interesting approach may be its synthesis from respective terpenic alcohols, which are also abundant feedstocks.

The development of oxidative processes based on an abundant non-toxic green oxidant such as dioxygen, is an important and challenging goal in oxidation chemistry [7]. There is an urgent demand for greener catalytic processes that employ clean oxidants such as dioxygen [8, 9]. A typical example is the Wacker system, (PdCl<sub>2</sub>/CuCl<sub>2</sub>/O<sub>2</sub>) which is used in olefins oxidation [10]. On the other hand, in palladium-catalyzed alcohol oxidation, metal reoxidantfree systems have been proposed. Larock and co-workers described the oxidation of benzylic alcohols by dioxygen catalyzed by Pd(OAc)<sub>2</sub>/K<sub>2</sub>CO<sub>3</sub> in DMSO solutions [11]. However, this catalyst showed a very low activity, requiring a reaction time as long as 24-72 h for oxidation of others alcohols. Alternatively, several researchers have proposed catalysts based on palladium/nitrogen compounds, such as sparteine [12], bathophenantroline [13] and triethylamine [14]. Both catalytic systems based on alkaline or nitrogen bases allowed the direct oxidation of Pd(0)by dioxygen, without a reoxidant. However, among the most successful and versatile oxidative catalysts described, Pd(OAc)<sub>2</sub>/pyridine/MS3A system (Uemura catalyst) deserves highlights [15]. Uemura system efficiently catalyze the aerobic oxidation of different types of alcohols: a variety of aldehydes was obtained in 86-95% yield from alicyclic [16], benzylic, saturated primary alcohols using Pd(OAc)<sub>2</sub>/pyridine/MS3A in toluene, at 80 °C for 2 h, under 1 oxygen atmosphere [17]. However, Uemura system is less effective when the substrates used are unsaturated or sterically hindered alcohols. For instance, a longer reaction time or a higher pyridine load was required in oxidation of  $\beta$ -citronellol by dioxygen using a Pd(OAc)<sub>2</sub>: pyridine molar ratio of 1:4; 75% isolated yield was achieved after 15 h reaction. Conversely, with a Pd(OAc)<sub>2</sub>: pyridine molar ratio equal to 1:100, it was achieved an isolated yield of 81% after 6 h of reaction [18]. Recently, Kumpulainen and Koskinen described the use of a modified copper-TEMPO catalyst (Cu(OTf)<sub>3</sub>/N-methylimidazol)/bipy/1,8diazabicyclo[5.4.0]undec-7-ene) in aerobic oxidation of  $\beta$ -citronellol, obtaining high yields and conversions [19].

In this paper, significantly enhanced activity of the Pd(OAc)<sub>2</sub>/pyridine system was achieved with the addition of  $K_2CO_3$  to the system. In toluene solutions containing a excess pyridine (100-fold in relation to palladium), Pd(OAc)<sub>2</sub>/K<sub>2</sub>CO<sub>3</sub> catalyst promoted an efficient and selective oxidation of terpenic alcohols ( $\beta$ -citronellol, nerol and geraniol) by dioxygen into respective aldehydes. Noticeably, Pd(OAc)<sub>2</sub>/pyridine/K<sub>2</sub>CO<sub>3</sub> system was as effective as the Pd(OAc)<sub>2</sub>/pyridine/MS3A system. This simple and environmentally friendly catalyst proposed herein does not requires molecular sieves or metal reoxidant, and uses oxygen as stoichiometric oxidant. Moreover, Pd(OAc)<sub>2</sub>/ K<sub>2</sub>CO<sub>3</sub> catalyst require smaller loads of both palladium and pyridine than Uemura system. The role of the main reaction variables, including temperature and nature of others anionic and nitrogen bases, were also assessed.

#### **2** Experimental Procedures

#### 2.1 Materials

All chemicals were purchased from commercial sources. Pd(OAc)<sub>2</sub> was acquired from Sigma-Aldrich (99% w/w). Molecular sieves (MS3A; Merck) were used after thermal activation at 400 °C.  $\beta$ -citronellol (racemic mixture 90–95% w/w, Sigma Aldrich), nerol (Sigma Aldrich, 97% w/w) and geraniol (Sigma Aldrich, 98% w/w) were used as received. Toluene (99%, w/w, Merck) was used without treatment. Carbonate salts were acquired from Sigma-Aldrich (99% w/w) and were dried at 100 °C before use. Pyridine and sparteine (99% w/w, Sigma-Aldrich), and triethylamine (99% w/w, Merck) were also used as received.

# 2.2 Catalytic Tests

Reactions were carried out in a glass reactor (50 mL) equipped with a magnetic stirrer, with sampling system and connected to a gas burette to monitor dioxygen uptake. In a typical run, the  $Pd(OAc)_2$  catalyst (0.05 mmol), nitrogen

base (pyridine, sparteine or triethylamine) were dissolved in toluene solution (10.0 mL) under dioxygen pressure (0.10 MPa). Furthermore, after addition of the terpenic alcohol (2.75 mmol) to the reaction solution, it was heated to 60 °C and magnetically stirred for 8–12 h. When appropriate, before initiating the reaction, 2.5 mmol of the auxiliary anionic base was added. Blank reactions were carried out in the same conditions cited in the absence of the catalyst.

#### 2.3 Reaction Monitoring

Reactions were monitored by analyzing aliquots taken at regular time intervals by gas chromatography (Varian 450 instrument), equipped with a flame ionization detector and fitted with a Carbowax 20 M capillary column (30 m length, 0.25 mm i.d., 0.25 mm film thickness). Gas chromatography conditions were as follows: 80 °C (3 min); rate of temperature increase: 10 °C/min; final temperature: 260 °C; injector temperature: 250 °C; and detector temperature: 280 °C. Conversion was estimated from the corresponding chromatographic peak areas in comparison with the corresponding calibrating curve. Dodecane was used as an internal standard.

#### 2.4 Products Chromatographic Analysis

Compounds were identified by GC/MS analyses (Shimadzu MS-QP 5050A mass spectrometer instrument operating at 70 eV electronic impact mode coupled with a Shimadzu 17A GC). Additionally, the aldehydes were also identified by co-injection with the authentic samples in GC as described in the Sect. 2.3.

# 2.5 Synthesis of Pd(OAc)<sub>2</sub> Catalyst Supported on K<sub>2</sub>CO<sub>3</sub>

The Pd(OAc)<sub>2</sub> catalyst supported on K<sub>2</sub>CO<sub>3</sub> was obtained via impregnation. Palladium acetate (125.0 mg; 0.557 mmol), was dissolved in toluene (30 mL) and magnetically stirred at 80 °C temperature. Then, potassium carbonate (3.338 g) was added and the suspension resulting maintained under stirring by 2 h at 80 °C temperature. After decantation, the solid catalyst was filtered and washed with toluene and three times with a minimal of ethyl ether. After evaporation solvent under air, the catalyst solid was dried at 100 °C temperature by 2 h, resulting in a brown solid.

#### **3** Results and Discussion

#### 3.1 General Aspects

The terpenic alcohols oxidation reactions are normally complicated by the presence double bonds that may also be oxidized or undergoes isomerization along reaction. Although Pd(II) catalysts are well explored in oxidation reactions, to develop oxidative processes in which the Pd(0) is directly recovered by dioxygen is the goal of several researchers [20]. Herein, a combination of the catalysts proposed separately by Larock [11] and Uemura [15–18] was considered, and after an investigation of role of several anionic and nitrogen bases, an oxidative system can be obtained:  $Pd(OAc)_2/pyridine/K_2CO_3$  system.

3.2 Effects of the Nitrogen Compounds on the Pd(OAc)<sub>2</sub>-Catalyzed Oxidation Reaction of β-Citronellol by Dioxygen

Oxidatively stable ligands such as nitrogen bases play a crucial role in oxidation reactions by minimizing catalyst deactivation, promoting the direct reaction between palladium reduced species and dioxygen, as well as modulating substrate reactivity [21]. Moreover, the exogenous action of nitrogen bases is also a key-factor in both oxidation reactions and oxidative kinetic resolution of alcohols [12, 22].

Firstly, we have investigated the effect of the nature of nitrogen compounds on the Pd(OAc)<sub>2</sub>-catalyzed  $\beta$ -citronellol oxidation reaction by dioxygen (Fig. 1). In this step,  $\beta$ -citronellol was the substrate and pyridine, sparteine and triethylamine were the bases selected. When mixtures of  $Pd(OAc)_2$  and nitrogen compounds are used, the number maximum of ligands (L) (L = triethylamine, sparteine or pyridine) coordinated to palladium is two, leading to Pd(OAc)<sub>2</sub>L<sub>2</sub> catalyst. Herein, were used four equivalents of L; consequently, the action of nitrogen compounds is both as ligand and exogenous base. In Table 1 are showed conversion results obtained in reactions of  $\beta$ -citronellol oxidation by dioxygen in Pd(OAc)<sub>2</sub>/nitrogen compound system. Reactions were performed using excess of nitrogen compound in relation to palladium (1:4 and 1:100 molar ratio). Under these reaction conditions the nitrogen compound acts as ligand and as exogenous base.

GC and GC–MS analyses showed that  $\beta$ -citronellal was the principal product formed in all reactions (greater than 90% selectivity). When the palladium: nitrogen compound molar ratio used was equal to 1:4, triethylamine and pyridine were the most efficient nitrogen compounds. In



Fig. 1 Pd(OAc)<sub>2</sub>/nitrogen compound-catalyzed oxidation reaction of the  $\beta$ -citronellol by dioxygen

**Table 1** Effect of Pd(OAc)<sub>2</sub>/nitrogen compound on  $\beta$ -citronellol oxidation by dioxygen

Run	Nitrogen compound	Pd(OAc) <sub>2</sub> : nitrogen compound molar ratio	Time (h)	Yields (%) <sup>b</sup>
1	Pyridine	1:4	8	9
2	Pyridine	1:100	8	22
3 <sup>c</sup>	Triethylamine	1:4	4	8
4	Triethylamine	1:100	8	36
5 <sup>c</sup>	Sparteine	1:4	2	<3
6	Sparteine	1:100	8	13

Reaction conditions:  $\beta$ -citronellol (2.75 mmol); Pd(OAc)<sub>2</sub> (0.05 mmol); nitrogen compound (0.20 or 5.0 mmol); O<sub>2</sub> (0.10 MPa); 60 °C

<sup>b</sup> Determined by GC

<sup>c</sup> Reaction was stopped due to palladium black formation

addition, these catalysts remained stables for a minimum of 4 h reaction (Table 1). Contrarily, under similar reaction conditions, palladium/sparteine system quickly was converted into Pd(0) species after time reaction lower than 2 h. This is suggestive that if a low concentration of nitrogen compound is used, less electron donating ligands and with steric hindrance (e.g. sparteine) results in a catalyst palladium less stable. On the other hand, a large excess of the nitrogen compound may be unfavorable, because it may occupy a palladium coordination site required for  $\beta$ -hydride elimination, which is normally the rate-limiting step in most of these reactions [23]. Nevertheless, pyridine may also prevent the decomposition of the catalyst into the inactive bulk metal (palladium black), preventing its aggregation as well as enhancing the oxidation reaction rate between reduced palladium and dioxygen [24, 25]. Here, when a large excess of nitrogen compound was employed, highest yield was achieved in the reaction performed in Pd(OAc)<sub>2</sub>/triethylamine system. According to Fig. 2, the reaction yield is higher with Pd(OAc)<sub>2</sub>/triethylamine than with Pd(OAc)<sub>2</sub>/pyridine system. In contrast, it seems that the stability of the Pd(OAc)<sub>2</sub>/pyridine system is higher than the stability of Pd(OAc)<sub>2</sub>/triethylamine (see results after 8 h).

Highlighted, in all catalytic runs performed with excess of nitrogen compound a non formation of palladium-black was observed. However, despites yields have been higher than those obtained at palladium: nitrogen compound molar ratio equal to 1:4 (Table 1), after an 8 h the reaction rate remain almost constant. Thus, this suggestive that the inhibitory effect caused by excess of nitrogen compounds is more pronounced when the olefin concentration is lower.

Kinetic curves (Fig. 2) reveal that although in the same concentrations (i.e. 1:100 Pd:L molar ratio), nitrogen compounds affected differently the reaction rate. Noticeably, the



**Fig. 2** Kinetic curves obtained from Pd(OAc)<sub>2</sub>-catalyzed β-citronellol oxidation by dioxygen in presence of different nitrogen compounds. Reaction conditions: β-citronellol (2.75 mmol); Pd(OAc)<sub>2</sub> (0.05 mmol); nitrogen base (5.0 mmol); toluene (10 mL); O<sub>2</sub> (0. 10 MPa); 60 °C

triethylamine caused a higher increase on initial rate of reaction than others nitrogen compounds; consequently, a high yield was reached after a 2 h reaction. A nitrogen compound may participate in the deprotonation step of a key-intermediate of these reactions (i.e. palladium-alkoxide), which normally is involved in rate-determining step [25].

If this nitrogen compound is not sufficiently basic, deprotonation of the palladium-alkoxide intermediated will be highly disfavored and reduce the catalyst activity. This principle has been detected in the PdCl<sub>2</sub>/sparteine-catalyzed reactions where the anionic ligand, chloride, is sufficiently nonbasic that an exogenous base is required to achieve even stoichiometric alcohol oxidation [25]. Thus, is possible that exogenous effect is directly related to ligand basicity. Literature reports the allowable pkb values for bases: sparteine (>11.8) [26], pyridine (8.75) and triethylamine (3.35) [27]. Reaction in the presence of an excess stronger nitrogen base (i.e. triethylamine) was that which greatest yield was achieved (ca. 37%). A similar result has been observed in benzylic alcohol oxidation at room temperature, where triethylamine was more effective than other nitrogen bases [28]. Although  $PdX_2$  catalyst may reacts with tertiary amines to form Pd(0) species [23], we verified that under studied reaction conditions (i.e. excess of triethylamine) this did not happen. According to literature, triethylamine can reduce Pd(II) into Pd(0), but their coordination to key Pd(II) species could be also involved [29]. Indeed, literature also report that this reduction is absent when triethylamine is dried [30]. Thus, we can conclude that the role of the added nitrogen compound, towards the efficiency of palladium (II)-catalyzed reactions, should be more subtle than normally considered.

Conversely, due to higher electrodonating character of triethylamine when compared to others nitrogen compounds studied, palladium was more efficient regenerated by dioxygen and high yields were then reached (ca. 36% after 6 h reaction, Fig. 2). Contrarily, in Pd(OAc)<sub>2</sub>/sparteine-catalyzed reactions the maximum yield achieved was 15%, after 6 h of reaction. The cyclohexyl groups in sparteine may hamper substrate complexation to Pd(II), resulting in a lower catalytic activity. This result is in agreement with the fact that the bipyridine, another bulky ligand, significantly inhibits catalytic turnover of palladium-catalyzed oxidation reactions of benzylic alcohol [31]. Moreover, due sparteine is the weakest base, its exogenous action was drastically compromised. Conversely, although steric hindrance effect is almost absent on pyridine, its role as exogenous base is also affected by its lower basicity, resulting in a less active catalyst than the Pd(OAc)<sub>2</sub>/triethylamine catalyst.

# 3.3 Effects of Molecular Sieves in the Pd(OAc)<sub>2</sub>/ Nitrogen Compound-Catalyzed Oxidation Reaction of β-Citronellol by Dioxygen

The effects of molecular sieves on these reactions were investigated and the results are displayed in Fig. 3. Remarkably, in contrast to what was observed in the absence of MS3A (Fig. 2), the Pd(OAc)<sub>2</sub>/pyridine system was more efficient than the Pd(OAc)<sub>2</sub>/triethylamine system.



**Fig. 3** Effect of MS3A on the Pd(OAc)<sub>2</sub>-catalyzed  $\beta$ -citronellol oxidation by O<sub>2</sub>. Reaction conditions:  $\beta$ -citronellol (2.75 mmol); Pd(OAc)<sub>2</sub> (0.05 mmol); nitrogen compound (5.0 mmol); toluene (10 mL); O<sub>2</sub> (0. 10 MPa); MS3A (0.5 g) 60 °C

Although the beneficial role of MS3A in these reactions is not yet fully understood, an important work explored the effects of MS on the Pd(OAc)<sub>2</sub>/pyridine catalyst systems by performing kinetic studies of benzylic alcohol oxidation [32]. Those authors found that molecular sieves molecular sieves enhance the rate of the Pd(OAc)<sub>2</sub>/pyridine-catalyzed oxidation of alcohols This effect was attributed to the ability of molecular sieves to serve as a Brønsted base to enhance the reaction.

Thus, greater conversion of  $\beta$ -citronellol into citronellal was obtained with the Pd(OAc)<sub>2</sub>/pyridine catalyst (ca. 78%). Although this result is in agreement with literature [33], it must be mentioned that in the present study a lower concentration of palladium was used (1.8 mol% compared to 5 mol %) and the reaction temperature was also lower (60 °C instead of 80 °C).

# 3.4 Effects of an Anionic Base in the $Pd(OAc)_2$ -Catalyzed Oxidation Reaction of $\beta$ -Citronellol by Dioxygen in Presence of Pyridine Excess

The kinetic curves shown in Fig. 4 reveal that only  $Cs_2CO_3$ , and more remarkably  $K_2CO_3$ , improved performance of the Pd(OAc)<sub>2</sub>/pyridine system.

The efficiency of  $Cs_2CO_3$  and  $K_2CO_3$  salts was previously reported by Stoltz and co-workers while investigating the Pd(nbd)Cl<sub>2</sub>/sparteine-catalyzed aerobic oxidative kinetic resolution of secondary alcohols [34]. The authors found that  $Cs_2CO_3$  and  $K_2CO_3$  were that salts that dramatically accelerated those reactions.



**Fig. 4** Effect of an anionic base in  $\beta$ -citronellol oxidation by dioxygen performed in Pd(OAc)<sub>2</sub>/pyridine system. Reaction conditions:  $\beta$ -citronellol (2.75 mmol); Pd(OAc)<sub>2</sub> (0.05 mmol); pyridine (5.0 mmol); anionic bases (2.5 mmol); toluene (10 mL); O<sub>2</sub> (0. 10 MPa); 60 °C

It is also possible that both solid potassium and cesium carbonates act as a water scavenger. Apparently, most bulk cations such as  $K^+$  and  $Cs^+$  favor its reaction. Because an improvement in catalytic activity was obtained in presence of carbonate ions, it can be assumed that this proves that anionic ligands facilitate Pd(0) species oxidation. We believe that similarly to the acetate ion coordinate to palladium, carbonate ions may participate directly on disprotonation step of the  $\beta$ -citronellol and favor the formation of the palladium-alkoxide intermediate [23, 35].

In Fig. 5, a comparison of catalytic systems based on palladium used on  $\beta$ -citronellol by dioxygen is displayed. Remarkably, the addition of K<sub>2</sub>CO<sub>3</sub> to Pd(OAc)<sub>2</sub>/pyridine system became this system as effective as Pd(OAc)<sub>2</sub>/pyridine/MS3A.

Enhanced activity obtained by the addition of  $K_2CO_3$  (or  $Cs_2CO_3$ ) to the Pd(OAc)<sub>2</sub>/pyridine system may be attributed to fact of the insoluble K<sub>2</sub>CO<sub>3</sub> can act as a heterogeneous support for the reaction; the active catalyst appears to be heterogeneous and was adsorbed by the insoluble  $K_2CO_3$ . Moreover, besides its role as a solid support, the carbonate anion may act as a Brønsted base in a key step of reaction, such as deprotonation of a palladium-alkoxide intermediate, commonly formed in alcohol oxidation reactions [36]. This step should occur on the solid surface. We believe that if a minimal number of carbonate ions are in the solution they would react with HOAc generated along reaction and consequently, the regeneration of active Pd would not occur through this way. Is important note that the HOAc role did not affected by the presence of pyridine in excess.

For these reasons, was evaluated the catalytic activity of  $Pd(OAc)_2$  supported on  $K_2CO_3$ . The results obtained with



Fig. 5 Comparison of systems used in Pd(OAc)<sub>2</sub>-catayzed oxidation of  $\beta$ -citronellol by dioxygen. Reaction conditions:  $\beta$ -citronellol (2.75 mmol); Pd(OAc)<sub>2</sub> (0.05 mmol); pyridine (5.0 mmol); K<sub>2</sub>CO<sub>3</sub> (2.5 mmol); toluene (10 mL); MS3A (0.5 g); O<sub>2</sub> (0. 10 MPa); 60 °C

**Table 2** Oxidation of  $\beta$ -citronellol by dioxygen in Pd(OAc)<sub>2</sub>/pyridine/K<sub>2</sub>CO<sub>3</sub> system in homogeneous and heterogeneous conditions

Exp.	Pd(OAc) <sub>2</sub> /K <sub>2</sub> CO <sub>3</sub> system	Pyridine (mmol)	Conversion (%)	Palladium black formation
1	Homogeneous	6.0	87	Yes
$2^{\mathrm{a}}$	Heterogeneous	6.0	38	Yes
3	Homogeneous	12.0	90	No
4 <sup>a</sup>	Heterogeneous	12.0	45	Yes
5	Homogeneous	18.0	90	No
6 <sup>a</sup>	Heterogeneous	18.0	55	Yes

Reaction conditions:  $\beta$ -citronellol (2.75 mmol); Pd(OAc)<sub>2</sub> (0.05 mmol); pyridine (6–18.0 mmol); K<sub>2</sub>CO<sub>3</sub> (2.5 mmol); toluene (10 mL); O<sub>2</sub> (0. 10 MPa); 60 °C

<sup>a</sup> The supported catalyst was used containing a palladium carbonate molar ratio equal to homogeneous system

supported catalyst via impregnation and the palladium catalyst homogeneous are shown in Table 2.

The supported palladium catalyst on potassium carbonate was less stable than homogeneous palladium catalyst. In all catalytic runs, the formation of palladium black species formation was observed at reaction initial step. Lower conversions were obtained if compared to run performed with palladium homogeneous catalyst. Moreover, yet under a large pyridine excess, the heterogeneous catalyst was deactivated and reduced palladium species were formed.

3.5 Effects of the Simultaneous Addition of an Anionic Base and MS3A in the Pd(OAc)<sub>2</sub>-Catalyzed Oxidation Reaction of β-Citronellol by Dioxygen in Presence of Pyridine Excess

The possibility of synergism between molecular sieves and anionic bases was investigated and the results are displayed in Fig. 6.

While the addition of MS3A to  $Pd(OAc)_2/pyridine/K_2CO_3$  or  $Pd(OAc)_2/pyridine/Cs_2CO_3$  systems does not enhance their activities, a slight increase in conversion was observed for the other salts, especially in the case of  $Na_2CO_3$ . However, the observed conversion was lower than that achieved by  $Pd(OAc)_2/pyridine/MS3A$  without carbonate ions.

3.6 Effects of Temperature on Oxidation Reaction of β-Citronellol by Dioxygen in Pd(OAc)<sub>2</sub>/ Pyridine/K<sub>2</sub>CO<sub>3</sub> System

An increase in reaction temperature resulted in a consequential increase in the initial rate of reaction. Indeed, high aldehyde selectivity was obtained from the initial period of reaction (Fig. 7).



**Fig. 6** Effect of anionic bases on Pd(OAc)<sub>2</sub>-catalyzed  $\beta$ -citronellol oxidation with dioxygen in presence of pyridine excess and MS3A. Reaction conditions:  $\beta$ -citronellol (2.75 mmol); Pd(OAc)<sub>2</sub> (0.05 mmol); pyridine (5.0 mmol); anionic base (2.5 mmol); toluene (10 mL); MS3A (0.5 g); O<sub>2</sub> (0.10 MPa); 60 °C



**Fig. 7** Effects of the temperature on oxidation reaction of βcitronellol by dioxygen in Pd(OAc)<sub>2</sub>/pyridine/K<sub>2</sub>CO<sub>3</sub> system Reaction conditions: β-citronellol (2.75 mmol); Pd(OAc)<sub>2</sub> (0.05 mmol); pyridine (5.0 mmol); K<sub>2</sub>CO<sub>3</sub> (2.5 mmol); toluene (10 mL); O<sub>2</sub> (0.10 MPa); 60 °C

Is important to note that in reactions performed at 80 °C temperature the system showed less stable, and consequently Pd(0) species were formed. However, it did not occur with pyridine loadings up to 12.0 mmol, as will be described in the next section.

#### 3.7 Effects of Pyridine Concentration

Literature suggests that an excess of pyridine may inhibit palladium catalytic activity. However, in all pyridine concentration ranges studied (ca. 3.0–18.0 mmol), high



**Fig. 8** Effect of the pyridine loading on Pd(OAc)<sub>2</sub>/K<sub>2</sub>CO<sub>3</sub>-catalyzed  $\beta$ -citronellol oxidation by O<sub>2</sub><sup>a-d</sup> <sup>a</sup>Reaction conditions:  $\beta$ -citronellol (2.75 mmol); Pd(OAc)<sub>2</sub> (0.050 mmol); K<sub>2</sub>CO<sub>3</sub> (2.5 mmol) toluene (10 mL); 80 °C temperature; O<sub>2</sub> (0.10 MPa); 12 h. <sup>b</sup>Conversion and selectivity determined by GC. In all catalytic runs the aldehyde selectivity was greater than 90% (not shown in Fig. 9 for simplification). <sup>c</sup>Formation of Pd(0) species after 5 min of reaction. <sup>d</sup>In catalytic runs with low pyridine concentration (ca. 3.0 and 6.0 mmol), the formation of Pd(0) species begins after 30 min of reaction

values of conversion of  $\beta$ -citronellol were obtained (Fig. 8).

Although with pyridine concentrations between 3.0 and 6.0 mmol, the formation of Pd(0) species begins after 30 min of reaction, it did not affected the final conversion. Moreover, when a pyridine excess was employed no inhibitor effect was verified and palladium catalyst remains active.

# 3.8 Oxidation of Geraniol and Nerol by Dioxygen in Pd(OAc)<sub>2</sub>/Pyridine/K<sub>2</sub>CO<sub>3</sub> System

Heartened by the observation of selective oxidation of the  $\beta$ -citronellol by dioxygen using Pd(OAc)<sub>2</sub>/pyridine/K<sub>2</sub>CO<sub>3</sub> system, we investigated the oxidation of two others terpene alcohols (i.e. geraniol and nerol) as examples of alcohols that could be oxidized, or react in other ways. The palladium-catalyzed oxidation reactions by dioxygen of geraniol and nerol were performed at 60 and 80 °C temperature (Fig. 9).

Expectedly, an increase in reaction temperature resulted in a consequential increase in the conversion of the terpenic alcohols into respective aldehydes.

However, in all catalytic runs no decreases on aldehyde selectivity it was found verified; selectivities higher than 90% were reached in all cases, as showed GC analysis (no displayed in Fig. 9 by simplification). The oxidation of both allylic terpenic alcohols by dioxygen in Pd(OAc)<sub>2</sub>/



**Fig. 9** Effect of temperature on oxidation reaction of geraniol and nerol by dioxygen in Pd(OAc)<sub>2</sub>/pyridine/K<sub>2</sub>CO<sub>3</sub> system. Reaction conditions: substrate (2.75 mmol); Pd(OAc)<sub>2</sub> (0.05 mmol); pyridine (5.0 mmol); K<sub>2</sub>CO<sub>3</sub> (2.5 mmol); toluene (10 mL); O<sub>2</sub> (0.10 MPa)



Fig. 10 Oxidation of geraniol and nerol by dioxygen in  $Pd(OAc)_2/$  pyridine/K<sub>2</sub>CO<sub>3</sub> system

pyridine/ $K_2CO_3$  system proved highly selective and the aldehydes (i.e. *trans*-citral an *cis*-citral (neral)) were obtained with selectivity upper of 90%, independently of the reaction temperature (Fig. 10).

#### 4 Conclusions

In summary, the  $Pd(OAc)_2/K_2CO_3/pyridine$  system was highly efficient in promoting selective oxidation by dioxygen of terpenic alcohols (i.e.  $\beta$ -citronellol, nerol and geraniol) into aldehydes in toluene solutions. Noticeably, the Pd(OAc)<sub>2</sub>/K<sub>2</sub>CO<sub>3</sub>/pyridine system was as effective as Pd(OAc)<sub>2</sub>/pyridine/MS3A system (Uemura system). As described in this work, selection of the nitrogen compound and the auxiliary anionic base is crucial in developing robust and active aerobic alcohol oxidation catalysts. The results obtained with palladium in homogeneous phase suggested that their action may be promoted by solid K<sub>2</sub>CO<sub>3</sub>, which may act as a heterogeneous support for the reaction and as a Brønsted base. However, Pd(OAc)<sub>2</sub> supported on K<sub>2</sub>CO<sub>3</sub> catalyst showed unstable even at presence of pyridine excess. This protocol is a straightforward synthesis method of terpenic aldehydes in metal reoxidant-free catalytic system for palladium and which use molecular oxygen as stoichiometric oxidant.

Acknowledgements The authors are grateful for the financial support from CAPES, CNPq, FAPEMIG and FUNARBE (Brazil). They also wish to thank Prof. Luis Claudio Barbosa for the GC–MS analyses.

#### References

- 1. Muzart J (2003) Tetrahedron 59:5789
- 2. Gallezot P (2007) Catal Today 121:76
- 3. Pybus DH, Sell CS (2001) The chemistry of fragrances. RSC Paperbacks, Cambridge
- Lenardão EJ, Botteselle GV, Azambuja F, Perin G, Jacob RG (2007) Tetrahedron 63:6671
- Yoji H, Takeshi I, Yoshiki O (2002) European Patent EP122516, 2002
- 6. Brennfhrer A, Neumann H, Beller M (2009) ChemCatChem 1:28
- 7. da Silva MJ, Teixeira RR, Carari DM (2009) J Organomet Chem 694:3254
- da Silva MJ, de Oliveira AA, da Silva ML (2009) Catal Lett 130:424

- 9. da Silva MJ, Gusevskaya EV (2001) J Mol Catal A 176:23
- 10. Bäckvall JE, Gogoll AJ (1987) J Chem Soc Chem Commun 1236
- 11. Peterson KP, Larock RC (1998) J Org Chem 63:3185
- 12. Bagdanoff JT, Ferreira EM, Stoltz BM (2003) Org Lett 5:835
- 13. Stoltz BM (2004) Chem Lett 33:362
- Schultz MJ, Park CC, Sigman MS (2002) Chem Commun 3034
  Nishimura T, Onoue T, Ohe K, Uemura S (1998) Tetrahedron Lett 39:6011
- Nishimura T, Kakiuchi N, Onoue T, Ohe K, Uemura S (2000) J Chem Soc. Perkin Trans 1:1915
- 17. Nishimura T, Onoue T, Ohe K, Uemura S (1999) J Org Chem 64:6750
- Nishimura T, Maeda Y, Kakiuchi N, Uemura S (2000) J Chem Soc. Perkin Trans 1:4301
- 19. Kumpulainen ETT, Koskinen AMP (2009) Chem Eur J 15:10901
- 20. Beccalli EM, Broggini G, Martinelli M, Sottocornola S (2007) Chem Rev 5318
- 21. Milstein D (2010) Top Catal 53:915
- 22. Mandal SK, Jensen DR, Pugsley JS, Sigman MS (2003) J Org Chem 68:4600
- 23. Steinhoff BA, Guzei IA, Stahl SS (2004) J Am Chem Soc 126:11268
- 24. Gligorich KM, Sigman MS (2009) Chem Commun 3854
- 25. Cornell CN, Sigman MS (2006) Org Lett 8:4117
- 26. Neumann D, Krauss G, Hieke M, Groger D (1983) Plant Med 48:20
- Lide DR (ed) (1999) CRC handbook of chemistry and physics, 80th edn. CRC Press, Boca Raton
- 28. Muzart J (2009) J Mol Catal A 308:15
- Ringsdoff H, Schlarb B, Venzmer J (1988) Angew Chem Int Ed 27:113
- 30. Grushin VV, Alper H (1993) Organometallics 12:1890
- Schultz MJ, Hamilton SS, Jensen DR, Sigman MS (2005) J Org Chem 70:3343
- 32. Steinhoff BA, King AE, Stahl SS (2006) J Org Chem 71:1861
- 33. Nishimura T, Uemura S (2000) Catal Surv Jpn 4:31
- 34. Ferreira EM, Stoltz BM (2001) J Am Chem Soc 123:7725
- 35. Popp BV, Stahl SS (2007) J Am Chem Soc 129:4410
- 36. Popp BV, Stahl SS (2009) Chem Eur J 15:2915