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Transformation of Unsaturated Fatty Acids/Esters to Corresponding Keto Fatty Acids/Esters by Aerobic Oxidation with Pd(II)/Lewis Acid (LA) Catalyst

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ABSTRACT: Utilization of renewable biomass to partly replace the fossil resources in industrial applications has attracted attention due to the limited fossil feedstock with the increased environmental concerns. This work introduced a modified Wacker-type oxidation for transformation of unsaturated fatty acids/esters to the corresponding keto fatty acids/esters, in which Cu^{2+} cation was replaced with common non-redox metal ions, that is, a novel Pd(II)/Lewis acid (LA) catalyst. It was found that adding non-redox metal ions can effectively promote Pd(II)-catalyzed oxidation of unsaturated fatty acids/esters to the corresponding keto fatty acids/esters, even much better than Cu^{2+}, and the promotional effect is highly dependent on the Lewis acidity of added non-redox metal ions. The improved catalytic efficiency is attributed to the formation of hetero-bimetallic Pd(II)/LA species, and the oxidation mechanism of this Pd(II)/LA catalyst is also briefly discussed.

KEYWORDS: *biomass valorization; unsaturated fatty acid; oxidation; Lewis acid; palladium(II)*

INTRODUCTION

With the rapid depletion of fossil feedstock, the exploitation of renewable biomass to partly replace the fossil resources as the carbon source for chemical industry has attracted much attention.[1,2] One classic example is the extensive addition of biofuel in gasoline, in which biofuel is produced through transesterification of plant oils with methanol to the corresponding methyl esters.[3] Because of the renewable availability and biodegradability, not only utilization as biofuel, these plant oils, for example, vegetable oils have also been employed in the preparation of drying oils for paints and coatings after transformation to conjugated derivatives,[4-6] and employed as the monomer of biopolymers after epoxidation.[7-10] Because of the unsaturated C=C bond in plant oils, utilization of unmodified vegetable oils as lubricants generally faces the aging challenge. Accordingly, elimination of the C=C double bond through ketonization or formation of chloro alkyoxy derivatives was reported to improve the quality of vegetable oil based lubricants.[11,12]

While transesterification, isomerization and epoxidation of versatile vegetable oils have been widely investigated and partly applied in industry, the studies on ketonization of unsaturated fatty acids and their derivatives are very limited until now. In literature, Sels and coworkers [13] reported a nitrous oxide based oxidation of unsaturated fatty acid esters and triacylglycerol mixtures to the keto fatty esters in the absence of solvent and metal ion catalyst; Knothe [14] also developed the synthesis of long-chain 1,2-dioxo methyl esters of monounsaturated fatty acid with potassium permanganate as oxidant. As a well-known protocol for olefin oxidation, Wacker-type oxidation with Pd(II) catalysts has also been reported in oxidizing unsaturated fatty acid and its derivatives to the keto fatty acid and other derivatives with CuCl, or benzoquinone as co-catalysts.[15-17]

For the Wacker-type oxidations, Hosokawa et al. [18,19] even isolated a few palladium-copper hetero-bimetallic complexes which are active for olefin oxidations. Most recently, we unexpectedly found that adding certain non-redox metal ions like Sc^{3+} as Lewis acid can significantly accelerate Pd(II)-catalyzed olefin oxidation even better than that using Cu^{2+} as co-catalyst.[20] Similar promotional effects were also observed in Pd(II)-catalyzed olefin isomerization, olefin oxidative coupling, alkane oxidative dehydrogenation, and nitrile hydration.[21-24] The promotional effect was attributed to the formation of hetero-bimetallic Pd(II)/LA species which serves as the key active species in above-mentioned reactions, and binding of Lewis acid to the Pd(II) species may have increased its positive net charge, thus improving its redox potential for oxidation reactions.[25] This Pd(II)/LA based catalyst strategy has offered a new opportunity for versatile Pd(II)-catalyzed reactions, including traditional Wacker-type oxidations, [26,27] and related applications in biomass utilizations. Here, we report the application of this Pd(II)/LA catalyst for the valorization of vegetable oils through oxidation of unsaturated fatty acids/esters to the corresponding keto fatty acids/esters with oxygen as oxidant, and it was found that the promotional effect of Lewis acids like Sc^{3+} is much better than that of Cu^{2+} as co-catalyst in this Pd(II)-catalyzed vegetable oil oxidation.

MATERIALS AND METHODS

Materials. All chemical reagents were commercially available and used without further purification. $Sc(OTf)_3$: (Accela Chembio Co., Ltd., Shanghai, China). $Pd(OAc)_2$: (Stream Chemicals Inc., Newburyport, MA). $Cu(OTf)_2$: (Alfa Aesar, Stoughton, MA). NaOTf, $Mg(OTf)_2$, $Fe(OTf)_2$ and octadecane: (TCI (Shanghai) Development Co., Ltd., Shanghai, China). $Ca(OTf)_2$, $Zn(OTf)_2$, $Al(OTf)_3$, $Y(OTf)_3$, and $Yb(OTf)_3$: (Shanghai Dibai Chemical Co. Ltd., Shanghai, China). Methyl palmitoleate, methyl oleate, methyl linoleate, oleic acid, linoleic acid and 1,3,5-tri-chlorobenzene: (Aladdin Ltd., Shanghai, China). Dimethyl sulfoxide (DMSO), *N*,*N*′-dimethylacetamide (DMA), *N*,*N*′-dimethylformamide (DMF), acetonitrile (CH_3CN), toluene, *n*-octane, cyclohexane and 1,4-dioxane: (Sinopharm Chemical Reagent Co.,Ltd, Shanghai, China). Nuclear magnetic resonance (NMR) was performed on an AV400 400MHz instrument (Bruker, Beijing, China). Ultraviolet visible (UV/Vis) spectra were recorded on a specord 205 Plus spectrophotometer (Analytik Jena, Jena, Germany) and gas chromatography-mass spectrometry (GC-MS) analysis was performed on a 7890A GC/5975C mass spectrometer (Agilent, Philadelphia, PA) using the following column and temperature program. HP-5: 30 m × 0.25 mm, i.d., 0.25 μm (Agilent, Philadelphia, PA); the initial temperature of 150 °C was held for 3 min, then raised at 5 °C/min to 200 °C, and again raised at 20 °C/min to 300 °C, finally held for 2 min. Mass spectra were recorded at 70 eV in the electron ionization mode (EI-MS).

Internal standard method. Firstly, a series of calibration solutions (at least five) were prepared, which contain the analytes that we need to find the response factors to the standard (*n*-octadecane in this study) in GC analysis. These calibration solutions should cover the concentrations of the analytes for which the concentrations of future practical samples will fall in. These calibration solutions were next injected one by one into GC for analysis, and the detector responses (peak areas) to all of the analytes were recorded. The response factor of each analyte in one calibration solution was calculated as the value of the weight ratio of the analyte/*n*-octadecane timing the peak area ratio of *n*-octadecane/the analyte. The average response factor of each analyte in five calibration solutions was employed as the GC response factor of the analyte in coming practical analysis.

General procedure for catalytic oxidation of methyl oleate, 1, to a mixture of methyl oxo-octadecanoate, 2, by $Pd(OAc)_2/Sc(OTf)_3$

In a typical procedure, $Pd(OAc)_2$ (1.34 mg, 0.006 mmol) and $Sc(OTf)_3$ (5.9 mg, 0.012 mmol) were dissolved in 2.7 mL of acetonitrile in a glass tube, next **1** (88.9 mg, 0.3 mmol) and 0.3 mL of water were then added. The glass tube was placed into a 50 mL stainless autoclave which was then charged with oxygen to 20 atm. (*Caution: 20 atm of oxygen possesses potential explosion, and can aid combustion of flammable materials; the reactions need to be carried out in a well-ventilated fumehood, free from any source of ignition*). Next, the reaction mixture was stirred at 80 °C in an oil bath for 18 h. After the reaction, the autoclave was cooled to room temperature and carefully depressurized to normal pressure. Control experiments including using $Pd(OAc)_2$ or $Sc(OTf)_3$ alone as catalyst were carried out in parallel. After GC analysis of **2** using the internal standard method, the solvent was removed by rotary evaporation and the residue was purified by silica gel column chromatography (20 cm × 1.5 cm) using *n*-hexane/ethyl acetate (10:1, v/v, 500 mL) as eluent to afford the products as white solid in 92% yield. ^1H NMR (400 MHz, $CDCl_3$) δ 3.60 (s, 3H, -COOCH_3), 2.31 (t, J = 7.4 Hz, 4H, -CH_2-C(O)-CH_2-), 2.23 (t, J = 7.6 Hz, 2H, CH_2-$COOCH_3$), 1.61 – 1.42 (m, 6H, 3× -CH_2-), 1.26-1.15 (m, 18H, 9× -CH_2-), 0.81 (t, J = 6.3 Hz, 3H, CH_2-CH_3).

Catalytic oxidation of oleic acid to a mixture of oxo-octadecanoic acid: General oxidation procedures were followed for this reaction except using oleic acid (84.4 mg, 0.3 mmol). Purification of the products by column chromatography (20 cm × 1.5 cm) using *n*-hexane/ethyl acetate/acetic acid (90:30:1, v/v/v) afforded the product as a pale yellow solid in 50% yield. ^1H NMR (400 MHz, $CDCl_3$) δ 2.46 – 2.25 (m, 6H, -CH_2-C(O)-CH_2-, CH_2-COOH), 1.73 – 1.46 (m, 6H, 3× -CH_2-), 1.26 (s, 18H, 9× -CH_2-), 0.88 (t, J = 6.5 Hz, 3H, CH_2-CH_3).

Catalytic oxidation of methyl palmitoleate to a mixture of methyl oxo-hexadecanoate: General oxidation procedures were followed except using methyl palmitoleate (80.5 mg, 0.3

mmol). The products were determined by ^1H NMR analysis in 91% yield with internal standard method. ^1H NMR (400 MHz, CD_3CN), δ 3.62 (s, 3H, -COOC*H*$_3$), 2.39 (t, J = 7.4 Hz, 4H, -C*H*$_2$-C(O)-C*H*$_2$-), 2.29 (t, J = 7.4 Hz, 2H, C*H*$_2$-$COOCH_3$), 1.60 – 1.48 (m, 6H, 3× -C*H*$_2$-), 1.35-1.23 (m, 14H, 7× -C*H*$_2$-), 0.90 (t, J = 6.8 Hz, 3H, CH_2-C*H*$_3$).

Catalytic oxidation of methyl linoleate to a mixture of methyl dioxo-octadecanoate: General oxidation procedures were followed except using methyl linoleate (88.8 mg, 0.3 mmol). Purification of the products by column chromatography using *n*-hexane/ethyl acetate (10:1, v/v) afforded the product as a light yellow solid in 83% yield. ^1H NMR (400 MHz, $CDCl_3$) δ 3.67 (s, 3H, -COOC*H*$_3$), 2.53 – 2.14 (m, 4H, -C*H*$_2$-C(O)-C(O)-C*H*$_2$-), 2.13 – 1.84 (m, 2H, C*H*$_2$-$COOCH_3$), 1.72 – 1.52 (m, 6H, 3× -C*H*$_2$-), 1.46 – 1.10 (m, 16H, 8× -C*H*$_2$-), 0.97 – 0.80 (m, 3H, CH_2-C*H*$_3$).

Catalytic oxidation of linoleic acid to a mixture of dioxo-octadecanoic acid: General oxidation procedures were followed except using linoleic acid (84.2 mg, 0.3 mmol). Purification of the product by column chromatography using *n*-hexane/ethyl acetate/acetic acid (90:30:1, v/v/v) afforded the products as a light yellow solid in 47% yield. ^1H NMR (400 MHz, $CDCl_3$) δ 2.48 – 2.20 (m, 4H, -C*H*$_2$-C(O)-C*H*$_2$-), 2.17 – 1.92 (m, 2H, C*H*$_2$-COOH), 1.78 – 1.48 (m, 6H, 3× -C*H*$_2$-), 1.45 – 1.05 (m, 16H, 8× -C*H*$_2$-), 1.06 – 0.73 (m, 3H, CH_2-C*H*$_3$).

Catalytic kinetics of methyl oleate oxidation by $Pd(OAc)_2/Sc(OTf)_3$: General oxidation procedures were followed using **1** (88.9 mg, 0.3 mmol) in the designed interval period, and the yields of isomerization and oxidation products were analyzed by ^1H NMR and GC using the internal standard method, respectively.

RESULTS AND DISCUSSION

To investigate the oxidations of unsaturated fatty acids and their ester derivatives by Pd(II)/LA catalyst, methyl oleate, **1**, was initially employed as a model compound using $Pd(OAc)_2$ as catalyst, Sc(OTf)$_3$ as Lewis acid additives, and oxygen as oxidant. First, the effects of solvents on this reaction were investigated and the results are summarized in Table 1. It was found that the CH_3CN/H_2O mixture (90:10, v/v) provided the best catalytic efficiency for the oxidation of **1** to the keto fatty esters, a mixture of methyl oxo-octadecanoate, **2**. After reaction at 80 ˚C for 18 h under 20 atm of oxygen, 62% conversion with 39% yield of **2** was achieved by GC analysis with 1% equiv. of Pd(OAc)$_2$ and 2% equiv. of Sc(OTf)$_3$ as Pd(II)/LA catalyst; extending the reaction time to 40 h further offered 96% conversion with 88% yield of **2** (Table 1, entries 1 and 2). The remaining byproducts were the mixtures of isomerization products, **3**, as identified by ^{1}H NMR analysis. Similar isomerizations of common olefins by Pd(II)/LA catalyst were also observed previously in our laboratory.[21] Increasing the Pd(OAc)$_2$ loading from 1% to 2% equiv. with Sc(OTf)$_3$ to 4% equiv. improved the conversion up to 100% with 98% yield of **2** after 18 h reaction, and an isolated yield of 92% was achieved under current conditions (Table 1, entry 3). Further increasing the catalyst loading to 4% equiv. completed the oxidation in 4.5 h, giving 98% yield of **2** (Table 1, entry 4). In another test, keeping the concentration of the Pd(II)/LA unchanged, increasing the methyl oleate from 100 mM to 200 mM, corresponding to 1% equiv. Pd(OAc)$_2$ loading, achieved 98% conversion of substrate with 95% GC yield or 90% isolated yield of **2** in 40 h (Table 1, entry 5), clearly indicating the high activity of this Pd(II)/LA catalyst in vegetable oil oxidation. However, in the case of using oxygen balloon as the oxidant source, the activity of this Pd(II)/LA system is very sluggish, giving only 87% of conversion with 2% yield of **2** (Table 1, entry 6), suggesting that the pressurized oxygen is essential for the regeneration of the active Pd(II)/LA catalyst in the catalytic cycle. In another control experiment, using acetonitrile alone as the solvent (in the absence of water), also provided 100% conversion of methyl oleate under air, however, there were no **2** detected, only giving the isomerization products **3** (Table 1, entry 7). In nonpolar solvents like THF, toluene, *n*-octane and cyclohexane, extremely low yields were obtained with noticeable palladium black formation after the reactions (Table 1, entries 8-11), implicating the inefficient re-oxidation of palladium(0) by dioxygen under these conditions. In addition, these solvents except THF are immiscible with water, which apparently block the formation of the active Pd(II)/LA species for oxidation. On the other side, the low catalytic efficiency in polar aprotic solvents like DMA, DMF and DMSO without palladium black formation can be attributed to their coordination to the Pd(II) species (Table 1, entries 12-14), leading to the reduced oxidizing power of the Pd(II) species for olefin oxidation. Taken together, a reasonable polarity of solvent like that of acetonitrile is essential for efficient unsaturated fatty acid oxidation by the Pd(II)/LA catalyst as well as those for common olefin oxidations.[20]

The identification of **2** was conducted by ^{1}H NMR analysis, which disclosed that the methylene groups nearby the oxidized carbonyl group of **2** have the chemical shift around 2.4 ppm (Figure 1A), while **3** have the chemical shifts of the olefinic C=C bond between 5.3 and 5.5 ppm (Figure 1B), as previously reported.[6,13] Further identification of **2** by GC-MS analysis disclosed a series of products including methyl 5-oxo-octadecanoate, methyl 10-oxo-octadecanoate, methyl 9-oxo-octadecanoate, methyl 8-oxo-octadecanoate, and methyl 17-oxo-octadecanoate with the relative contents of 7%, 70%, 8%, 11% and 3%, respectively.

Next, using CH_3CN/H_2O (v/v, 90/10) as solvent, various non-redox metal salts as Lewis acids were investigated to promote $Pd(OAc)_2$-catalyzed methyl oleate oxidation, and the results are summarized in Table 2. In the absence of Lewis acid, using $Pd(OAc)_2$ alone as catalyst was ineffective for methyl oleate transformation (Table 2, entry 1). The promotional effects of Ba^{2+} and Ca^{2+} were very limited, giving only 4% and 8% yield of **2** (Table 2, entries 2 and 3), while other divalent metal ions like Fe^{2+} and Zn^{2+} apparently improved the catalytic efficiency of $Pd(OAc)_2$ catalyst, providing 28% and 46% yield of **2**, respectively (Table 2, entries 4 and 5). Pd(II)/Cu(II) system is the classic Wacker-type catalyst for olefin oxidation;[27] however adding $Cu(OTf)_2$ provided only a slightly higher yield (56%) of **2** than that (46%) of adding Zn^{2+} as Lewis acid (Table 2, entry 6), while adding $Cu(OAc)_2$ did not generate any promotional effect. Significantly, adding trivalent, non-redox metal ions like Al^{3+}, Y^{3+}, and Sc^{3+} greatly improved the yield up to 75%, 94% and 98%, respectively (Table 2, entries 7-9), much higher than that of adding Cu^{2+}. As mentioned, Cu(II) salts were popularly employed as co-catalyst for regenerating the active Pd(II) species from reduced Pd(0) in Wacker-type oxidations;[27] here, attempting to further improve the catalytic efficiency of this Pd(II)/Sc(III) system, additional $Cu(OAc)_2$, $Cu(TFA)_2$, $CuCl_2$, $CuBr_2$ or $Cu(OTf)_2$ were added to the system using 1 mol% $Pd(OAc)_2$ with 2 mol% $Sc(OTf)_3$ catalyst loading, however, a sharply decreased yield was obtained in each case, giving only 2-12% yield of **2**. Even adding BQ or DMA to this Pd(II)/Sc(III) system in acetonitrile also caused the yields dropping to 38% or 32%, respectively. Similar inhibitory effect of $CuCl_2$ were observed by Kaneda in their $PdCl_2$-catalyzed internal olefin oxidations in DMA, in contrast to its acceleratory role in terminal alkene oxidations.[28] In that case, the inhibitory effect of $CuCl_2$ was attributed to inhibit π-coordination of an olefin to the Pd species through the complexation of Cu with Pd.

In another test in Table 1, 12% equiv. of NaOTf were employed as Lewis acid, which contains the identical amount of OTf^- anion as those in 4% equiv. of $Sc(OTf)_3$, however, it was inactive for methyl oleate transformation (Table 2, entry 12). Clearly, the promotional effect originated from the added metal ions as Lewis acid rather than the OTf^- anion. Consistent with this, the stronger the Lewis acid employed and the larger the promotional effect generally observed. In particular, the much higher yield of **2** (94% or 98%) obtained by adding Al^{3+} or Y^{3+} than that (56%) by adding Cu^{2+} in this study clearly highlighted the Lewis acid properties of added non-redox metal ions rather than their redox properties in this Pd(II)-catalyzed vegetable oil oxidation. In the textbook mechanism of Wacker-type oxidation, the role of the Cu^{2+} cation is assigned to re-oxidize the reduced Pd(0) back to the active Pd(II) species to achieve the catalytic cycle, thus highlighted its redox properties.[29] Together with previous studies,[20] the results demonstrated here further support that the Lewis acid properties of the Cu^{2+} cation may have played significant roles in Wacker-type oxidations, even though it is not distinguishable from its redox properties in Pd(II)/Cu(II) system.

Catalytic kinetics further displayed the high activity of this Pd(II)/LA catalyst in oxidation of methyl oleate, and it also provided fruitful mechanistic information. As shown in Figure 2, in 4 h reaction at 80 ˚C, using 2% equiv. $Pd(OAc)_2$ loading with 4% equiv. of $Sc(OTf)_3$ achieved 56% conversion of **1**, however, the isomerization products **3** were obtained as the main products in 34% yield, and the yield of **2** was only 21%. With the reaction proceeding, the yield of **3** dropped gradually, meanwhile the yield of **2** increased gradually up to 98% in 18 h with 100% conversion of **1**. Clearly, the isomerization reaction is competitive with the oxidation, and it proceeds faster than oxidation. Remarkably, with the reaction proceeding, the resulting isomerization products **3** can be eventually oxidized to **2** as the terminal products, thus leads to the high selectivity of the keto fatty esters. It is worth mentioning that as shown in Figure 2, in the absence of Lewis acid, $Pd(OAc)_2$ alone as catalyst is very sluggish for both isomerization and oxidation reactions.

Figure 3 displays the influence of the Sc(III)/Pd(II) ratio on the Pd(II)/LA catalyzed methyl oleate oxidation. In the absence of $Sc(OTf)_3$, $Pd(OAc)_2$ alone as the catalyst is almost inactive for methyl oleate transformation in 18 h at 80 ˚C, whether for isomerization or oxidation. The 1:1

ratio of Sc(III)/Pd(II) provided 41% conversion of **1** with dominant **2** (30% yield) and minor **3** (5% yield). Increasing the ratio of Sc(III)/Pd(II) to 3:1 improved the conversion up to 62% with 45% yield of **2** and 13% yield of **3**. However, as displayed in Figure 3, further increasing the ratio of Sc(III)/Pd(II) caused the yield of **2** to decrease, whereas the yield of **3** increased linearly, even though it still improved the conversion of **1**. For example, at the ratio of 8:1, after 18 h reaction, it provided 76% conversion of **1** with only 31% yield of **2** but 28% yield of **3**. The selectivity of the keto fatty esters **2** also revealed a decreased trend with further increase of the Sc(III)/Pd(II) ratio after 3:1.

Table 3 shows the oxidations of different unsaturated fatty acids/esters to the corresponding keto fatty acids/esters by this Pd(II)/LA catalyst. As described above, oxidation of **1** provided 92% isolated yield of **2** under 20 atm of oxygen at 80 ˚C in 18 h. Under the current conditions, oxidation of methyl palmitoleate and methyl linoleate gave the corresponding keto fatty esters, a mixture of methyl oxo-hexadecanoate in 83% yield and a mixture of methyl dioxo-octadecanoate in 91% yield, respectively, which were determined by ^{1}H NMR analysis. Not only the unsaturated fatty esters, but also oleic acid and linoleic acid can be oxidized by this Pd(II)/LA system to afford a mixture of oxo-octadecanoic acid in 50% yield and a mixture of dioxo-octadecanoic acid in 47% yield, respectively. The relatively low activity of this Pd(II)/LA catalyst in oxidizing unsaturated fatty acids is possibly related to the interaction of the carboxylic acid with the Pd(II) and/or Lewis acid, which may block the formation of the active Pd(II)/LA species for oxidation.

As presented above, adding non-redox metal ions like Sc^{3+} can sharply promote the oxidations of different unsaturated fatty acids/esters by $Pd(OAc)_2$ catalyst to the corresponding keto fatty acids/esters, which is similar to previous reports for common olefin oxidations.[17] In previous studies, through UV-Vis, ^{1}H and ^{13}C NMR characterizations, it was found that, in acetonitrile, adding non-redox metal ions to Pd(OAc)$_2$ leads to the formation of hetero-bimetallic Pd(II)/LA species having two acetate bridges.[20-22] As a result, binding of Lewis acid to the Pd(II) species makes it more positively charged as observed by the downshift of the chemical shift of the acetate bridge in ^{1}H and ^{13}C NMR spectra, which leads to its improved catalytic efficiency in olefin oxidations. In addition, similar hetero-bimetallic Pd(II)/LA salts with acetate bridges were widely reported, including LA = Ba^{2+}, Sr^{2+}, Ca^{2+}, Mn^{2+}, Co^{2+}, Ni^{2+}, Cd^{2+}, Nd^{2+}, Zn^{2+} and Ce^{4+}, and some of those were successfully identified by X-ray single crystal characterizations.[30-33] Here, in the identical CH_3CN/H_2O solvent, formation of the Pd(II)/LA species, for example, Pd(II)/Sc(III) species, should happen as well as those in previous studies, and is responsible for vegetable oil oxidations. It is worth mentioning that, a few hetero-bimetallic Pd(II)/Cu(II) complexes were isolated by Hosokawa and Murahashi, and they are active catalyst for olefin oxidations.[18,19]

Accordingly, a similar Pd(II)/Sc(III) species catalyzed oxidation can be proposed for this unsaturated fatty acids/esters oxidation as shown in Figure 4. By taking **1** for example, in the first step, **1** is ligated to the Pd(II)/Sc(III) species to generate the intermediate **4**. Next, a water molecule attacks on the ligated C=C bond of the vegetable oil followed by β-hydride elimination.[34-36] Then, the keto fatty esters **2** are released with the formation of the H-Pd(II)/Sc(III) intermediate **5**. This intermediate may interact with the second Sc^{3+} cation to stabilize the Pd(II) hydride to form the Sc(III)•••H-Pd(II)/Sc(III) intermediate **6**; otherwise, the intermediate **5** may be feasibly reduced to the inactive palladium(0).[37,38] Dioxygen insertion of the intermediate **6** leads to the formation of the HOO-Pd(II)/Sc(III) intermediate **7**.[39-44] After releasing the HOO^- anion, the Pd(II)/Sc(III) species is regenerated to achieve the catalytic cycle.[20,22] Since the formation of the Pd(II)/Sc(III) species sharply promotes the vegetable oil oxidation, two plausible roles of Sc^{3+} can be expected in this Pd(II)/LA species: 1) ligation of the Sc^{3+} cation to the Pd(II) species may increase the positive charge of the Pd^{2+} cation as indicated by the chemical shift of acetate bridge, making it more electrophilic, thus facilitating the C=C bond coordination of the vegetable oil on the Pd^{2+} cation; and 2) because of the enhanced electron transfer from the C=C bond of the unsaturated fatty esters to the Pd(II)/Sc(III) species, it further promotes the water molecule attacking on the ligated C=C bond, thus accelerating the oxidation of the vegetable oil. As shown in Figure 3, not only the 1:1 ratio of Sc(III)/Pd(II) improved the vegetable oil oxidation, the ratio of 2:1 still obviously improved the oxidation efficiency, and the ratio of 3:1 also slightly improved the efficiency, indicating the extra Sc^{3+} cation still benefited the Pd(II)-catalyzed oxidation. Accordingly, a third role of the Sc^{3+} cation was proposed to stabilize the H-Pd(II)/Sc(III) species through the formation of the Sc(III)•••H-Pd(II)/Sc(III) intermediate **III**, which inhibits the reductive elimination of the H-Pd(II) bond to form the inactive Pd(0), and promotes the oxygen insertion into the H-Pd(II) bond because of its weakness through Sc^{3+} binding. Indeed, in the case of using a 1:1 ratio of the Sc(III)/Pd(II) catalyst, there still was palladium black observed after the vegetable oil oxidation, while with 2:1 ratio of the Sc(III)/Pd(II) catalyst, there was no palladium black formation observed.

This work introduces the Pd(II)/LA catalyst for oxidation of renewable unsaturated fatty acids/esters to the corresponding keto fatty acids/esters which can be applied as lubricants in industry. It was found that adding non-redox metal ions like Sc^{3+} to simple $Pd(OAc)_2$ as the Pd(II)/LA catalyst can sharply promote its oxidation efficiency, even much better than the classic Pd(II)/Cu(II) catalyst, which highlights the Lewis acid properties of Cu^{2+} cation in this Pd(II)-catalyzed oxidation of unsaturated fatty acids/esters. The observed promotional effects are obviously Lewis acidity dependent on the added non-redox metal ions, and generally, a stronger Lewis acid provided a better efficiency. As well as in previous studies, the promotional effect of Lewis acid is attributed to the formation of the hetero-bimetallic Pd(II)/LA species which is responsible for oxidations. The demonstrated Pd(II)/LA catalyst may offer new opportunities for transforming versatile plant oils to the corresponding keto fatty acids, esters or other derivatives in their industrial utilizations through catalytic oxidations.

SUPPORTING INFORMATION

Detailed NMR and GC-MS data for different vegetable oil oxidations. This material is available free of charge via the Internet at http://pubs.acs.org.

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REFERENCES

1. Chaudhari, R. V.; Torres, A.; Jin, X.; Subramaniam, B. Multiphase catalytic hydrogenolysis/hydrodeoxygenation processes for chemicals from renewable feedstocks: kinetics, mechanism, and reaction engineering. *Ind. Eng. Chem. Res.* **2013**, *52*, 15226-15243.

2. Ding, L.; Wang, A.; Zheng, M.; Zhang, T. Selective transformation of cellulose into sorbitol by using a bifunctional nickel phosphide catalyst. *ChemSusChem* **2010**, *3*, 818-821.

3. Tariq, M.; Ali, S.; Khalid, N. Activity of homogeneous and heterogeneous catalysts, spectroscopic and chromatographic characterization of biodiesel: A review. *Renew. & Sust. Energ. Rev*. **2012**, *16*, 6303-6316.

4. Philippaerts, A.; Joost, V. A.; Bert, S. Conjugated linoleic acids and conjugated vegetable oils: From nutraceutical to bio‐polymer. *J. Eur. Lipid Sci. Tech.* **2013**, *115*, 717-720.

5. Larock, R. C.; Dong, X.; Chung, S.; Reddy, C. K.; Ehlers, L. E. Preparation of conjugated soybean oil and other natural oils and fatty acids by homogeneous transition metal catalysis. *J. Am. Oil Chem. Soc.* **2001**, *78*, 447-453.

6. Andjelkovic, D. D.; Min, B.; Ahn, D.; Larock, R. C. Elucidation of structural isomers from the homogeneous Rhodium-catalyzed isomerization of vegetable oils. *J. Agric. Food Chem.* **2006**, *54*, 9535-9543.

7. Poli, E.; Bion, N.; Barraulta, J.; Casciato, S.; Dubois, V.; Pouilloux, Y.; Clacens, J. Selective epoxidation of unsaturated fatty esters over peroxophosphotungstic catalysts (POW) under solvent free conditions: Study of the POW catalyst's mechanism. *Catal. Today*, **2010**, *157*, 371-377.

8. Kozhevnikov, V.; Mulder, G. P.; Steverink-de Zoete, M. C.; Oostwal M. G. Epoxidation of oleic acid catalyzed by peroxo phosphotungstate in a two-phase system. *J. Mol. Catal. A Chem.* **1998**, *134*, 223-228.

9. Sepulveda, J.; Teixeira, S.; Schuchardt, U. Alumina-catalyzed epoxidation of unsaturated fatty esters with hydrogen peroxide. *Appl. Catal. A Gen.* **2007**, *318*, 213-217.

10. Du, G.; Tekin, A.; Hammond, E. G.; Woo, L. K. Catalytic epoxidation of methyl linoleate. *J. Am. Oil Chem. Soc.* **2004**, *81*, 477-480.

11. Kökritz, A.; Martin, A. Oxidation of unsaturated fatty acid derivatives and vegetable oils. *Eur. J. Lipid Sci. Technol*. **2008**, *110,* 812-824.

12. Lowery, B. A.; Andersh, B.; Isbell, T. A. Synthesis of chloro alkoxy and alkoxy derivatives of methyl oleate. *J. Am. Oil Chem. Soc.* **2013**, *90*, 911-917.

13. Hermans, I.; Janssen, K.; Moens, B.; Philippaerts, A.; Van Berlo, B.; Peeters, J.; Jacobs, P. A.; Sels, B. F. Solvent‐and metal‐free ketonization of fatty acid methyl esters and triacylglycerols with nitrous oxide. *Adv. Synth. Catal.* **2007**, *349*, 1604-1608.

14. Knothe, G. Synthesis and characterization of long-chain 1,2-dioxo compounds. *Chem. Phys. Lipids.* **2002**, *115*, 85-91.

15. Warwel, S.; Pompetzki, W.; Deckwirth, E. A. Transition-metal catalyzed oxidation of unsaturated fatty acids—synthesis of ketocarboxylic acids and dicarboxylic acids. *Eur. J. Lipid Sci. Technol.* **1991**, *93*, 210-215.

16. Marcel, S. F.; Jie, L. K.; Lam, C. K. Regiospecific oxidation of unsaturated fatty esters with palladium(II) chloride/p-benzoquinone: a sonochemical approach. *Chem. Phys. Lipids.* **1996**, *81*, 55-61.

17. Morandi, B.; Wickens, Z. K.; Grubbs, R. H. Practical and general palladium-catalyzed synthesis of ketones from internal olefins. *Angew. Chem. Int. Ed.* **2013**, *52*, 2944-2948.

18. Hosokawa, T.; Takano, M.; Murahashi, S. I. The first isolation and characterization of a palladium-copper heterometallic complex bearing μ_4-oxo atom derived from molecular oxygen. *J.Am. Chem. Soc.* **1996**, *118*, 3990-3991.

19. Hosokawa, T.; Nomura, T.; Murahashi, S. I. Palladium-copper-DMF complexes involved in the oxidation of alkenes. *J. Organomet. chem.* **1998**, *551*, 387-389.

20. Qin, S.; Dong, L.; Chen, Z.; Zhang, S.; Yin, G. Non-redox metal ions can promote Wacker-type oxidations even better than copper (II): a new opportunity in catalyst design. *Dalton Trans.* **2015**, *44*, 17508-17515.

21. Senan, A. M.; Qin, S.; Zhang, S.; Lou, C.; Chen, Z.; Liao, R.-Z.; Yin, G. Nonredox metal-ion-accelerated olefin isomerization by palladium (II) catalysts: Density functional theory (DFT) calculations supporting the experimental data. *ACS Catal.* **2016**, *6*, 4144-4148.

22. Zhang, S.; Chen, Z.; Qin, S.; Lou, C.; Senan, A. M.; Liao, R.-Z.; Yin, Non-redox metal ion promoted oxidative coupling of indoles with olefins by the palladium (II) acetate catalyst through dioxygen activation: experimental results with DFT calculations. G. *Org. Biomol. Chem.* **2016**, *14*, 4146-4157.

23. Lou, C.; Qin, S.; Zhang, S.; Lv, Z.; Senan, A. M.; Chen, Z.; Yin, G. Non-redox metal ions promoted oxidative dehydrogenation of saturated C-C bond by simple $Pd(OAc)_2$ catalyst. *Catal. Commun*. **2017**, *90*, 5-9.

24. Zhang, S.; Xu, H.; Lou, C.; Senan, A. M.; Chen, Z.; Yin, G. Efficient Bimetallic Catalysis of Nitrile Hydration to Amides with a Simple $Pd(OAc)_2$/Lewis Acid Catalyst at Ambient Temperature. *Eur. J. Org. Chem.* **2017**, 1870–1875.

25. Guo, H.; Chen, Z.; Mei, F.; Zhu, D.; Xiong, H.; Yin, G. Redox inactive metal ion promoted C-H activation of benzene to phenol with Pd(II)(bpym): Demonstrating new strategies in catalyst designs. *Chem. Asian J.* **2013**, *8*, 888-891.

26. Keith, J. A.; Henry, P. M. The mechanism of the Wacker reaction: a tale of two hydroxypalladations. *Angew. Chem. Int. Ed.* **2009**, *48*, 9038-9049.

27. Tsuji, J. Oxidation of olefins to ketones in combination with electrooxidation. *Syntheses*, **1987**, *28*, 3683-3686.

28. Mitsudome, T.; Mizumoto, K.; Mizugaki, T.; Jitsukawa, K.; Kaneda, K. Wacker-type oxidation of internal olefins using a $PdCl_2$/N,N-dimethylacetamide catalyst system under copper-free reaction conditions. *Angew. Chem. Int. Ed.* **2010**, *49*, 1238-1240.

29. van Leeuwen, P. W. N. M. Oxidation with dioxygen. in *Homogeneous catalysis,* edition 1; Kluwer academic publishers: Netherlands, 2004; pp. 320.

30. Kozitsyna, N. Y.; Nefedov, S. E.; Dolgushin, F. M.; Cherkashina, N. V.; Vargaftik, M. N.; Moiseev, I. I. Heterodimetallic Pd^{II}-based carboxylate-bridged complexes: Synthesis and structure of single-crystalline Pd^{II}–M (M = Mn^{II}, Co^{II}, Ni^{II}, Cu^{II}, Zn^{II}, Nd^{III}, Eu^{III}, Ce^{IV}) acetates. *Inorg. Chim. Acta,* **2006**, *359*, 2072-2086.

31. Akhmadullina, N. S.; Cherkashina, N. V.; Kozitsyna, N. Y.; Gekhman, A. E.; Vargaftik, M. N. Unexpected participation of nucleophiles in the reaction of palladium(II) acetate with divalent 3*d* metals. *Kinet. Catal.,* **2009**, *50,* 396-400.

32. Brando, R. W.; Claridge, D. V. Heteronuclear acetate-bridged complexes; reaction of palladium(II) acetate with bivalent metal acetates. *Chem. Commun.*, **1968**, 677-678.

33. Pandey, R. N.; Henry, P. M. Interaction of palladium(II) acetate with sodium and lithium acetate in acetic acid. *Can. J. Chem*. **1974**, 1241-1247.

34. Bäckvall, J. E.; Ǻkermark, B.; Ljunggren, S. O. Stereochemistry and mechanism for the Palladium(II)-catalyzed oxidation of ethene in water (the Wacker process). *J. Am. Chem. Soc.* **1979**, *101*, 2411-2416.

35. Grushin, V. V. Hydrido complexes of palladium. *Chem. Rev.***1996**, *96*, 2011-2034.

36. Sigman, M. S.; Schultz, M. The renaissance of palladium (II)-catalyzed oxidation chemistry. *J. Org. Biomol. Chem*. **2004**, *2*, 2551-2554.

37. Bäckvall, J. E.; Hopkins, R. B. Multi-step catalysis for the oxidation of oleftns to ketones by molecular oxygen in chloride free media. *Tetrahedron lett.* **1988**, *29*, 2885-2888.

38. Zhang, G.; Xie, X.; Wang, Y.; Wen, X.; Zhao, Y.; Ding, C. Highly selective Wacker reaction of styrene derivatives: a green and efficient aerobic oxidative process promoted by benzoquinone/$NaNO_2$/$HClO_4$ under mild conditions. *Org. Biomol. Chem.* **2013**, *11*, 2947-2950.

39. Hosokawa, T.; Murahashi, S. New aspects of oxypalladation of alkenes. *Acc. Chem. Res.* **1990**, *23*, 49-54.

40. Hosokawa, T.; Miyagi, S.; Murahashi, S.; Sonoda, A. Oxidative cyclization of 2-allylphenols by palladium(II) acetate. Changes in product distribution. *J. Org. Chem.* **1978**, *43*, 2752-2757.

41. Harakat, D.; Muzart, J.; Bras, J. L. ESI-MS mechanistic studies of Wacker oxidation of alkenes: dinuclear species as catalytic active intermediates. *RSC Adv.* **2012**, *2*, 3094–3099.

42. Konnick, M. M.; Gandhi, B. A.; Guzei, I. A.; Stahl, S. S. Reaction of molecular oxygen with a Pd^{II}-hydride to produce a Pd^{II}-hydroperoxide: acid catalysis and implications for Pd-catalyzed aerobic oxidation reactions. *Angew. Chem., Int. Ed.* **2006**, *45*, 2904-2907.

43. Konnick, M. M.; Stahl, S. S. Reaction of molecular oxygen with a Pd^{II}-hydride to produce a Pd^{II}-hydroperoxide: experimental evidence for an HX-reductive-elimination pathway. *J. Am. Chem. Soc.* **2008**, *130*, 5753 -5762.

44. Denney, M. C.; Smythe, N. A.; Cetto, K. L.; Kemp, R. A.; Goldberg, K. I. Insertion of molecular oxygen into a palladium(II) hydride bond. *J. Am. Chem. Soc.* **2006**, *128*, 2508-2509.

FIGURE CAPTIONS

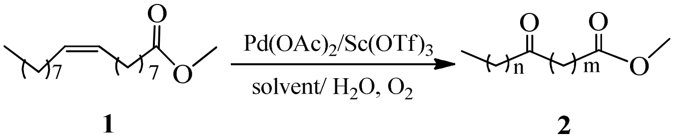
Figure 1. ^{1}H NMR identifications of products from methyl oleate oxidation by Pd(II)/LA catalyst. (A) oxidation products, (B) isomerization products, and (C) original methyl oleate substrate, in $CDCl_3$.

Figure 2. Catalytic kinetics for oxidation of **1** to **2** by Pd(II)/Sc(III) catalyst. Reaction conditions: CH_3CN/H_2O (v/v, 2.7 mL/0.3 mL), $Pd(OAc)_2$ (2 mM), $Sc(OTf)_3$ (4 mM), **1** (100 mM), O_2 (20 atm), 80 ˚C.

Figure 3. The influence of the Sc(III)/Pd(II) ratio on the Pd(II)-catalyzed oxidation of **1**. Reaction condition: $Pd(OAc)_2$ (1 mM), CH_3CN/H_2O (v/v, 2.7 mL/0.3 mL), O_2 (20 atm), 18 h, 80 ˚C.

Figure 4. Proposed mechanism for Pd(II)/LA catalyzed oxidation of unsaturated fatty acids/esters.

Table 1. Pd(II)/Sc(III) Catalyzed Methyl Oleate, **1**, Oxidation to a Mixture of Methyl Oxo-octadecanoate, **2**, in Different Solvents.[a]

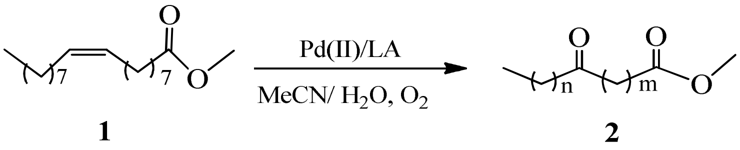


1 **2**

Entry	Pd(II)/Sc(III) (mM/ mM)	Solvent	Time /h	Conv. /%	Yield %
1	1/ 2	CH_3CN/ H_2O	18	53	39
2	1/ 2	CH_3CN/ H_2O	40	96	88
3	2/ 4	CH_3CN/ H_2O	18	100	98 (92)
4	4/ 8	CH_3CN/ H_2O	4.5	100	98
5[b]	2/ 4	CH_3CN/ H_2O	40	98	95 (90)
6[c]	2/ 4	CH_3CN/ H_2O	18	88	2
7[d]	2/ 4	CH_3CN	18	100	N.D.
8[c]	2/ 4	THF/ H_2O	18	28	10
9	2/ 4	Toluene/ H_2O	18	12	3
10	2/ 4	*n*-Octane/ H_2O	18	15	1
11[b]	2/ 4	Cyclohexane/ H_2O	18	10	6
12	2/ 4	DMA/ H_2O	18	9	4
13	2/ 4	DMF/ H_2O	18	24	8
14	2/ 4	DMSO / H_2O	18	23	13

[a] Conditions: organic solvent/water (v/v, 2.7 mL/0.3 mL), **1** (100 mM), O_2 (20 atm), 80 ˚C, yield was determined by GC analysis and the data in parentheses represent isolated yield. [b] **1** (200 mM). [c] O_2 balloon at 70 ˚C. [d] CH_3CN alone as solvent under air. N.D. = Not detected.

Table 2. Pd(II)-Catalyzed Oxidation of **1** in the Presence of Different Non-Redox Metal Ions. [a]



Entry	Lewis acid	Conv.%	Yield%
1	-	3.1	N.D.
2	$Ba(OTf)_2$	7	4
3	$Ca(OTf)_2$	23	8
4	$Fe(OTf)_2$	37	28
5	$Zn(OTf)_2$	50	46
6	$Cu(OTf)_2$	80	56
7	$Al(OTf)_3$	92	75
8	$Y(OTf)_3$	100	94
9	$Sc(OTf)_3$	100	98 (92)
10	$Yb(OTf)_3$	53	49
11	$In(OTf)_3$	68	28
12[b]	NaOTf	3	trace

[a] Conditions: CH_3CN/H_2O (v/v, 2.7 mL/0.3 mL), Pd $(OAc)_2$ (2 mM), Lewis acid (4 mM), **1** (100 mM), O_2 (20 atm), 80 °C, 18 h. Yield was determined by GC and the data in parentheses represent isolated yield. [b] NaOTf 12 mM. N.D. = Not detected.

Table 3. Wacker-Type Oxidation of Different Unsaturated Fatty Acids/Esters by $Pd(OAc)_2$ with the $Sc(OTf)_3$ in CH_3CN/H_2O.[a]

Entry	Substrate	Time	Yield %
1[b]	Methyl oleate	18 h	92
2[b]	Oleic acid	18 h	50
3[c]	Methyl palmitoleate	18 h	91
4[b]	Methyl linoleate	24 h	83
5[b]	Linoleic acid	24 h	47

[a] Reaction Conditions: CH_3CN/H_2O (v/v, 2.7 mL/0.3 mL), $Pd(OAc)_2$ (2 mM), $Sc(OTf)_3$ (4 mM), unsaturated fatty acids or esters (100 mM), O_2 (20 atm), 80 ˚C. [b] Isolated yield. [c] Yield determined by ^1H NMR analysis with internal standard.

Figure 1

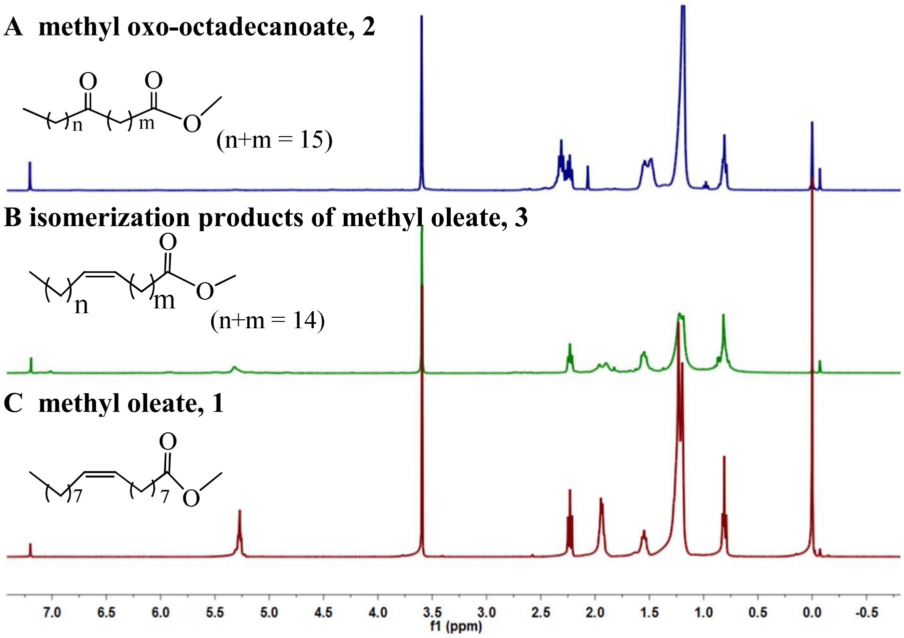

A methyl oxo-octadecanoate, 2
O
O
n
m
O
(n+m = 15)
B isomerization products of methyl oleate, 3
O
n
m
O
(n+m = 14)
C methyl oleate, 1
O
7
7
O
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
f1 (ppm)

Figure 2

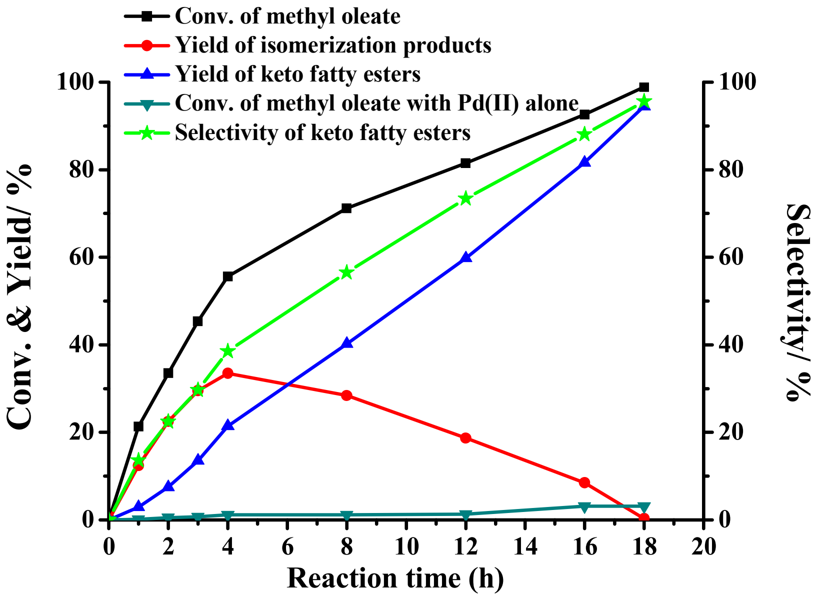

Conv. of methyl oleate
Yield of isomerization products
Yield of keto fatty esters
Conv. of methyl oleate with Pd(II) alone
Selectivity of keto fatty esters
Conv. & Yield/ %
Selectivity/ %
Reaction time (h)
0
20
40
60
80
100
0
2
4
6
8
10
12
14
16
18
20

Figure 3

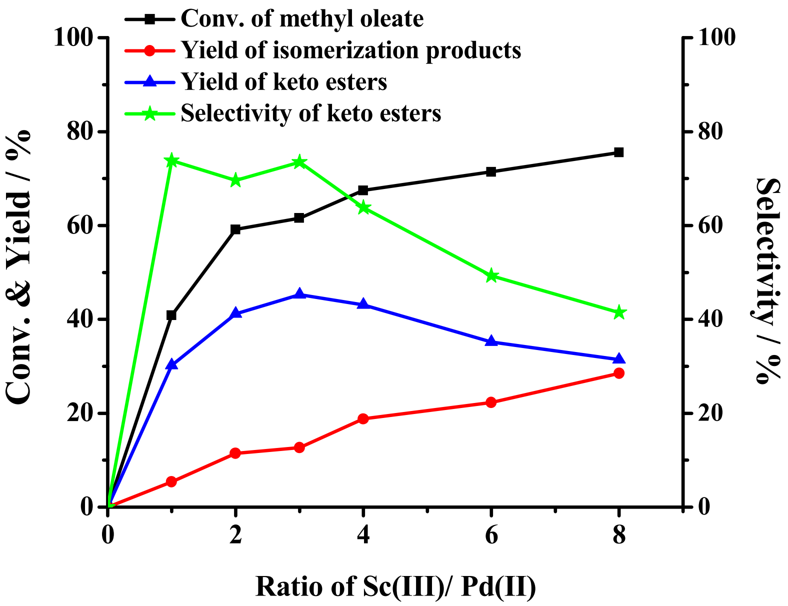
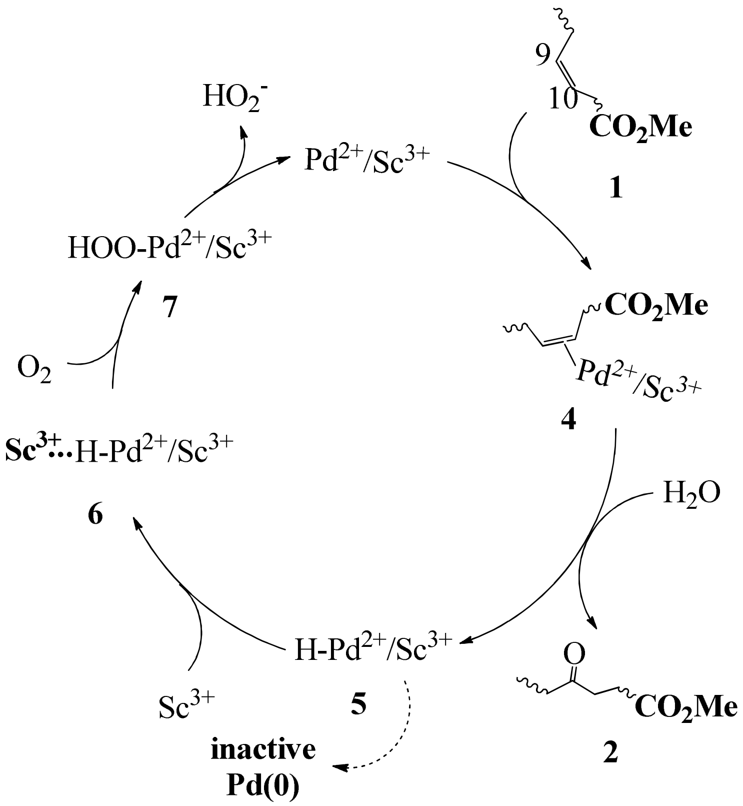

Conv. of methyl oleate
Yield of isomerization products
Yield of keto esters
Selectivity of keto esters
Conv. & Yield / %
Selectivity / %
Ratio of Sc(III)/ Pd(II)
0
20
40
60
80
100
0
2
4
6
8

Figure 4


9
10
CO2Me
1
HO2-
Pd2+/Sc3+
HOO-Pd2+/Sc3+
7
CO2Me
Pd2+/Sc3+
4
O2
Sc3+···H-Pd2+/Sc3+
6
H2O
H-Pd2+/Sc3+
5
O
CO2Me
2
Sc3+
inactive
Pd(0)

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