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Hydrogenolysis of hydroxymatairesinol over carbon-supported palladium catalysts

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The natural lignan hydroxymatairesinol was hydrogenolysed to a potential anticarcinogenic substance matairesinol over different carbon-supported palladium catalysts. The reaction was conducted in 2-propanol at 70 °C under hydrogen flow in a stirred glass reactor. The catalysts were characterised by N_2-physisorption, CO pulse chemisorption and pH measurement of aqueous catalyst slurries. The most active catalyst (Degussa-Hüls) gave yields of matairesinol over 90% in 4 h. It was concluded that the acidity of the catalyst had a profound influence on the reaction rate.

KEY WORDS: lignans; hydroxymatairesinol; matairesinol; hydrogenolysis; carbon-supported palladium catalyst.

1. Introduction

Lignans, a group of plant phenols consisting of two β-β-linked cinnamic acid residues [1], can be found in many different plant parts, such as the wooden parts, roots, leaves, flowers, fruits, and seeds. Most plants contain only small amounts of lignans as glycosidic conjugates associated with fibre components, which makes the isolation process difficult [2]. Coniferous trees, on the other hand, contain exceptionally large amounts of lignans in unconjugated forms, which makes it easier to isolate them. Norway spruce (*Picea abies*) knots, i.e., the part of a branch that is embedded in the stem, contain large quantities of lignans, 6–24 wt.%, out of which hydroxymatairesinol is the most abundant, constituting 65–85 wt.% of the lignans [3]. There are two diastereomers of hydroxymatairesinol, (7*R*,8*R*,8′*R*)-(–)-7-allo-hydroxymatairesinol (HMR 1) and (7*S*,8*R*,8′*R*)-(–)-7-hydroxymatairesinol (HMR 2), of which the latter is the major isomer [4].

Many different plant lignans are converted by the mammalian gut microflora to the mammalian lignans enterolactone and enterodiol [5]. In the beginning of the 1980s it was suggested that lignans may prevent breast cancer [6]. Several studies were made and the results showed that women who have breast cancer excrete smaller amounts of enterolactone than healthy women do, and that the urinary enterolactone excretion can be associated with the grain-fibre intake. It has also been proposed that besides breast cancer, lignans may prevent prostate and colon cancer. In addition to the anticarcinogenic effects, lignans also have antioxidative effects [7].

Matairesinol (MAT) can be found in small amounts in different plants, for example in flaxseed and rye [5]. MAT can be produced through hydrogenolysis of HMR, which as indicated above could be extracted in larger quantities from Norway spruce knots. Hydrogenolyses of benzyl alcohol derivatives have earlier been performed over carbon-supported palladium catalysts in ethanol [8]. The hydroxyl is a poor leaving group, but the reaction rate can be clearly enhanced by addition of an acid, which produces a protonated alcohol making water the leaving group [8,9]. There are several benefits with activated carbons as support materials: they have high surface area, are inexpensive and inert in corrosive environments, and the precious metals supported on them can easily be recovered [10]. Moreover, their pore structure and surface area can be varied relatively easily. However, commercial carbon-supported metal catalysts sometimes exhibit large batch-to-batch variations in performance which is, at least partially, due to natural variations in the starting materials [10]. Eklund *et al.* [11] demonstrated the possibility to hydrogenolyse HMR under hydrogen pressure over Pd/C in dichloroethane and the K-acetate adduct of HMR was hydrogenolysed with Raney-Nickel and Pd/C catalysts in ethanol (hydrogen pressure). In this work, a mixture of hydroxymatairesinol isomers (HMR 1 and HMR 2) extracted from Norway spruce was hydrogenolysed to

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MAT over 5 wt.% palladium on carbon catalysts provided by different suppliers. The influence of the initial ratio between isomers was also investigated. The hydrogenolysis was performed in 2-propanol at 70 °C under hydrogen atmosphere in a stirred glass reactor. The reaction scheme is shown in figure 1a and the difference between the two diastereomers of HMR is shown in figure 1b. The catalysts were characterised by N_2-physisorption (surface area), CO pulse chemisorption (dispersion, metal particle size), and pH measurement of the catalyst dispersed in water (acidity).

2. Experimental

2.1. Materials

Hydroxymatairesinol was isolated from Norway spruce knots: the knots were ground and extracted in acetone–water mixture (90:1 v/v). The extract was concentrated in a rotary evaporator and then purified by flash chromatography on silica (eluent dichlormethane:ethanol, 97.5:2.5 v/v) to yield a pure hydroxymatairesinol solution, which was evaporated in a rotary evaporator. The purity of the material was

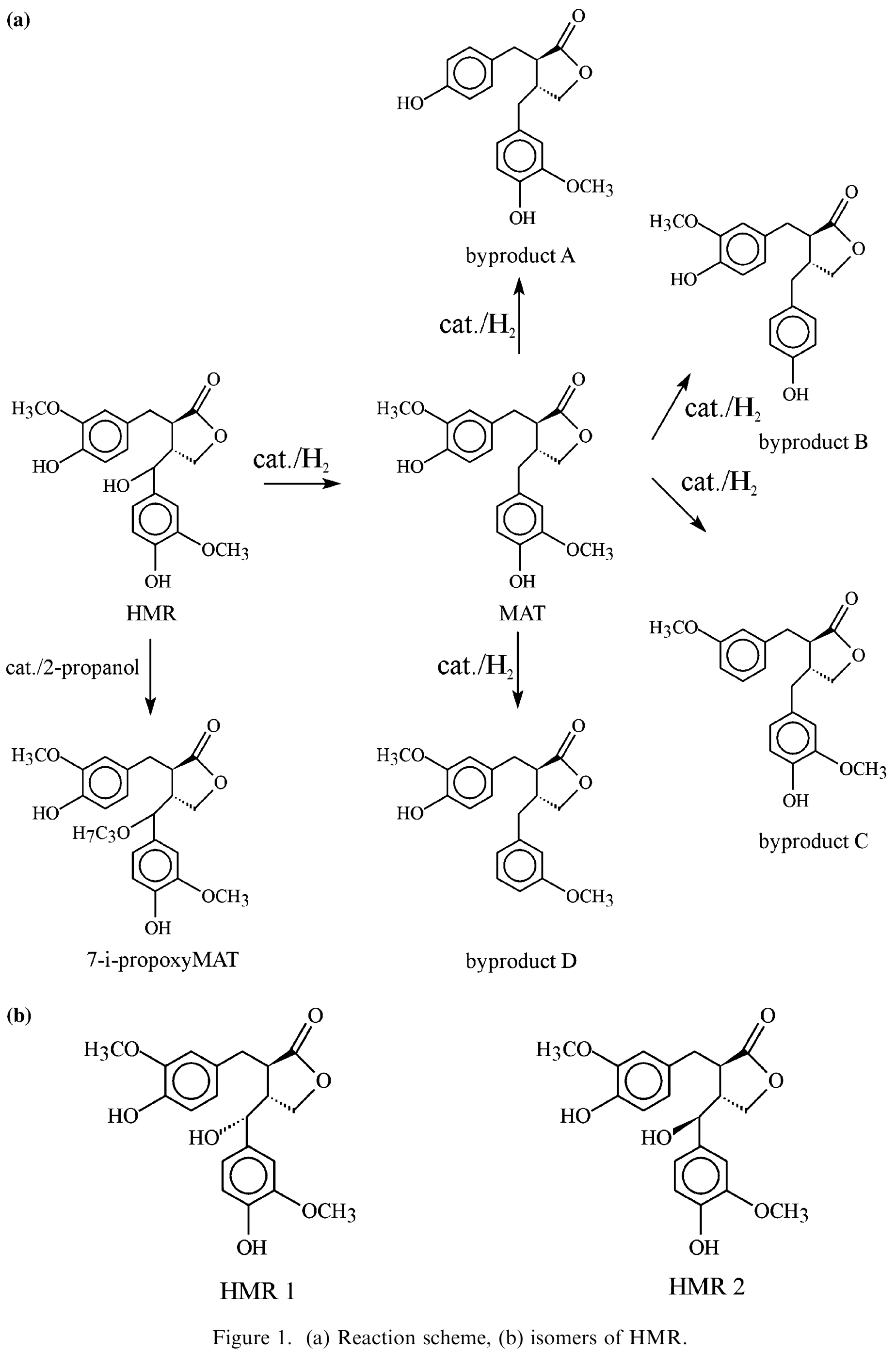

Figure 1. (a) Reaction scheme, (b) isomers of HMR.

determined by gas chromatography to be 93%. The major impurity was the lignan conidendrin. The ratio between HMR 1 and HMR 2 was approximately 1:3.

The catalysts were 5 wt.% Pd/C supplied by Degussa-Hüls AG, Germany (E 105 Y/W 5%, year 1999, 54.2% water, dried in oven at 100 °C over night), Degussa AG, Germany (E 105 Y/W 5%, year 2004, 53.3% water, dried in oven at 100 °C over night), and Sigma-Aldrich, Germany. Furthermore, a 5 wt.% Pd/C was synthesised in the following way: activated carbon (birch), some water to cover the support, and $PdCl_2$ were added. The palladium salt was added in form of a solution. While monitoring the pH (acidic), the solution was neutralised by sodium carbonate for formation of hydroxides precipitated on the support, which are then more easily reduced. The catalyst was reduced chemically using formic acid. Sodium acetate, which prevents peptisation (coagulation) of the metal according to [12], and the reducing agent formic acid were added dropwise under stirring at 90 °C. After stirring the mixture for 1 h, the solution was cooled down and a sample was withdrawn for a qualitative reaction to confirm that there were no chloride ions in the solution after the impregnation.

2.2. Hydrogenolysis of hydroxymatairesinol

Experiments were performed under atmospheric pressure in a 200 mL glass reactor equipped with a heating jacket (using silicon oil as the heat transfer fluid), a re-flux condenser (cooling medium set to −20 °C), oil lock, pitched-blade turbine and stirring baffles. In a typical experiment, 100 mg of the catalyst was charged into the reactor. The catalyst was pre-activated *in situ* by hydrogen gas flow (100 mL/min) at 100 °C [13] in 1 h, after which the reactor was cooled down to the reaction temperature 70 °C under nitrogen gas flow (100 mL/min). The reactant solution, consisting of 100 mg hydroxymatairesinol dissolved in 78 g 2-propanol (Lab-Scan, 99.7%), was deoxygenated by nitrogen gas flow (100 mL/min) for 10 min in a glass tube. The experiment started when pouring the reactant solution into the reactor, the reaction time was set to zero, the stirring was started, the gas flow was changed to hydrogen (100 mL/min) and the first sample was withdrawn. The stirring rate was 1000 rpm, ensuring efficient external mass transfer. The duration of the experiments was 4 h.

Samples were taken at different time intervals and analysed by a gas chromatograph (GC) equipped with a HP-1 column (length 25 m, inner diameter 0.20 mm, film thickness. 0.11 μm) and a flame ionisation detector (FID) operating at 300 °C. The samples were silylated prior to analysis: 100 μL of the samples and 2 mL of methyl *tert*-butyl ether (MTBE) containing 40 μg each of the internal standards heneicosanoic acid and betulinol were added to glass tubes. The solvents were evaporated in a stream of nitrogen gas (3 bar) and further dried in a vacuum desiccator at 40 °C for 15 min. To the residue 80 μL *N*,*O*-bis(trimethylsilyl)trifluoro-acetamide (BSTFA, 98%, Fluka), 20 μL trimethylchlorosilane (TMCS, 98%, Acros Organics) and 20 μL pyridine (99.0%, J.T. Baker) were added. The solutions were kept in an oven at 70 °C for 30 min and after that transferred to vials and analysed by GC. 1 μL of the silylated samples was injected with an auto-sampler. The injection temperature was 260 °C and the split ratio 1:20. Hydrogen served as carrier gas. The initial temperature of the column was 120 °C (for 1 min) and the temperature increased with a rate of 6 °C/min to 300 °C (for 10 min). The peaks were identified by analysis with a gas chromatograph-mass spectrometer (GC-MS) operating at the same GC conditions.

2.3. Characterisation of the catalysts

The specific surface areas of the Pd/C catalysts were measured with a physisorption–chemisorption apparatus (Sorptometer 1900, Carlo Erba Instruments). Both BET and Dubinin methods were used for the calculation of the surface areas.

To determine the metal particle size and dispersion, samples were analysed by CO pulse chemisorption (Autochem 2910, Micrometrics). Hundred milligram of the sample was placed into a quartz U-tube containing silica wool, the tube was inserted to the system and the sample was treated in a stream of helium gas at 50 °C for 30 min. After that, the sample was pre-treated at 100 °C for 1 h in hydrogen, using helium as carrier gas, after which it was flushed with helium (still at 100 °C) for 1 h, cooled to room temperature, placed on water bath, and subsequently the CO pulses were introduced (10% CO in helium, helium as carrier gas) until adsorption was complete. The dispersion was calculated from the amount of CO consumed, assuming the CO:Pd stoichiometry to be unity [13].

The acidity of the catalysts was measured with a pH-electrode (Metrohm). Fifty mg of the catalyst was dispersed in 50 mL de-ionised water. The slurry was mixed by a magnetic stirrer during the measurement. A computer was collecting the data and pH versus time was plotted, until a constant pH was reached.

3. Results and discussion

3.1. Characterisation results

The carbon-supported palladium catalysts were characterised by nitrogen-physisorption, CO pulse chemisorption, and pH measurements of aqueous catalyst slurries. Table 1 shows the results of characterisation of Pd/C; surface area (both BET and Dubinin methods), dispersion, metal particle size, and pH. Catalysts I–III (Table 1) had all surface areas exceeding

Table 1
Catalyst properties

Catalyst	BET surface area (m^2/g)	Dubinin surface area (m^2/g)	Dispersion (%)	Metal particle diameter (nm)	pH
I (Degussa-Hüls)	916	1154	16	7	4.4
II (Degussa)	715	915	29	4	7.3
III (Sigma-Aldrich)	936	1214	42	3	7.4
IV (Self-prepared)	399	599	23	5	5.9

700 m^2/g (BET method), while catalyst IV had only around 400 m^2/g. The dispersions varied between 16 and 42% and increased in the following order: catalyst I < IV < II < III. Catalyst I had the largest particles, 7 nm, while the other catalysts had equal or smaller than 5 nm. It is well known that the CO/Pd ratio can vary between 0.5 (large Pd particles, CO adsorbed in bridged form) and 1 (small Pd particles, CO adsorbed in linear from). An increasing fraction of CO is adsorbed linearly when the particle size decreases. For particles smaller than 5 nm [13, 14] linearly bonded CO is in excess and the CO/Pd ratio can be assumed 1. In our case it is justified to assume the adsorption stoichiometry to be 1, although this means that for catalyst I the particle size could be a little bit overestimated. The pH of the catalysts varied between acidic (4.4) and neutral (7.4); the pH increased in the same order as the dispersion.

3.2. Catalyst testing results

In figure 2a, the conversion versus time and in figure 2b the selectivity versus conversion are visualised, while Table 2 displays the turnover frequencies (TOF) and initial rates. The conversion and selectivity were calculated as

$$\text{conversion} = \frac{c_{\mathrm{HMR,tot,0}} - c_{\mathrm{HMR,tot}}}{c_{\mathrm{HMR,tot,0}}} \qquad (1)$$

$$\text{selectivity} = \frac{c_{\mathrm{MAT}}/c_{\mathrm{HMR,tot,0}}}{\text{conversion}} \qquad (2)$$

In equations (1) and (2), $c_{\mathrm{HMR,tot,0}}$ is the initial concentration of total HMR, c_{MAT} and $c_{\mathrm{HMR,tot}}$ the concentration of MAT and total HMR.

The catalyst supplied by Degussa-Hüls (I, Table 1) gave the highest conversion and TOF. All catalysts showed high selectivity to MAT, but the selectivity decreased when the conversion increased (figure 2b). The result from the experiment with the self-prepared Pd/C catalyst (IV, Table 1) is visualised in figure 3. HMR 2 was the major and HMR 1 the minor isomer. In the beginning, the fraction of HMR 1 increased, which suggests isomerisation between HMR 2 and HMR 1 (see differences between the isomers in figure 1b). By-products were 7-isopropoxymatairesinol (7-i-propoxyMAT, two isomers), resulting from interaction with the solvent, as well as four products formed through hydrogenolysis of the functional-groups on the benzene-rings of matairesinol (see reaction scheme in figure 1a). The concentration of HMR 1 obtained its maximum around 40 min in the case of catalyst IV, while for the most active catalyst (I, Degussa-Hüls) the maximum was achieved already at 10 min.

Hydrogenolysis reactions can be enhanced by addition of acids [8, 9]. In the present case, addition of an acid should be avoided since HMR is converted to conidendrin through cyclisation in acid [15]. No increase in the concentration of conidendrin was noticed in the experiments with palladium on acidic support materials. Activated carbons contain acidic surface groups and they can be determined by temperature programmed desorption (TPD) measuring the evolved CO and CO_2, titration of the surface groups (Boehm titration) by different bases, FTIR measurement, and pH of an immersion of carbons in water [16,17]. These methods

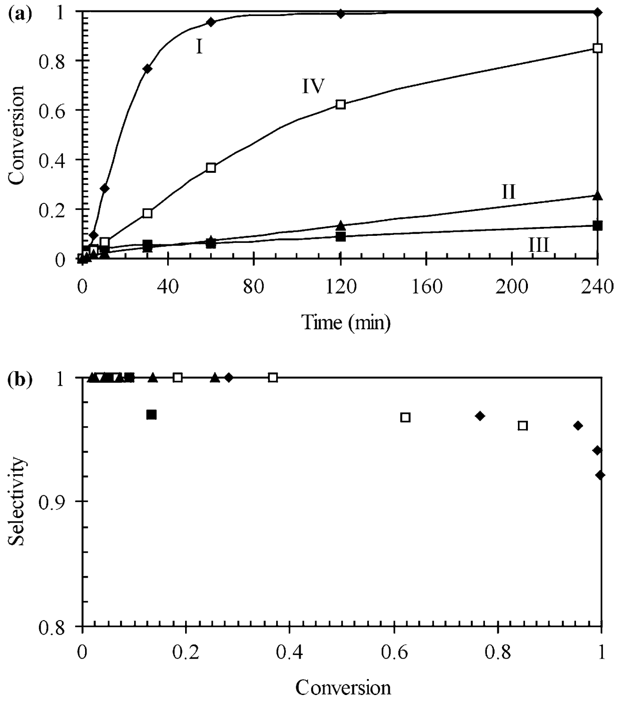

Figure 2. Hydrogenolysis of HMR over Pd/C catalysts: ◆, I (Degussa-Hüls); ▲, II (Degussa); ■, III (Sigma-Aldrich); and □, IV (self-prepared). (a) Conversion versus time (b) selectivity versus conversion. Conditions: 70 °C, 100 mL/min hydrogen gas flow, 2-propanol.

Table 2
Turnover frequencies and initial rates

Catalyst	TOF (s^{-1})[a]	Initial rate[b] (10^{-6} mol s^{-1} g^{-1})
I (Degussa-Hüls)	0.01512	22.74
II (Degussa)	0.00047	1.29
III (Sigma-Aldrich)	0.00043	1.68
IV (Self-prepared)	0.00253	5.46

[a] Moles of HMR converted after 30 min/(moles of surface metal ×1800 s).
[b] Moles of HMR converted after 30 min/(mass of metal ×1800 s).

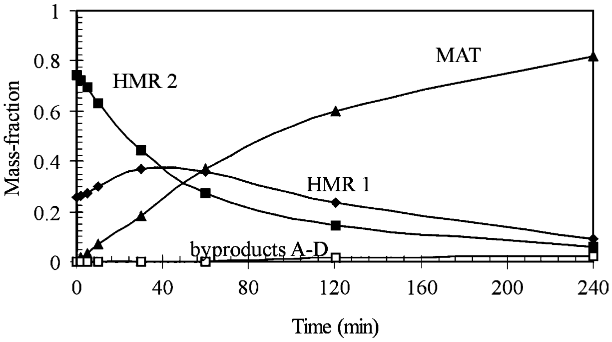

Figure 3. Hydrogenolysis of HMR over Pd/C catalyst IV (Table 1) at the same conditions as in figure 2: ◆, HMR 1; ■, HMR 2; ▲, MAT; and □, byproducts A–D are in the figure. Trace amount of 7-i-propoxyMAT was also obtained.

have been used previously for carbons without any loaded metal [16, 17]. In the present study the pH of the Pd/C catalysts dispersed in water was measured, as in [18, 19] for determination of the acidity of the carbon. The relation between the turnover frequencies and the pH of the catalysts in water can be seen in figure 4. The reaction is very sensitive to variations in pH of the support, proceeding much faster for a material with lower pH. Two of the catalysts tested, I (Degussa-Hüls, 1999) and II (Degussa, 2004), displayed very large differences in pH, 4.4 and 7.3 (Table 1), respectively. TOF was much higher for catalyst I (Table 2), while the dispersion was higher for the catalyst II. Although the two catalysts which were most active had the biggest metal particles, the differences in activities cannot be attributed to structure sensitivity effects. The dispersions of the catalysts II and IV (Table 1) were approximately the same, while the pH of the slurries were dissimilar, giving rise to different catalytic activities, leading to a conclusion that the activity is significantly influenced by the acidity. The acidic groups present on carbon surfaces are carboxylic, anhydride, lactone, and phenolic groups [16]. Only carboxylic and anhydride groups are strictly acidic in water, with the anhydride hydrolysing to two carboxylic acid functions. Lactone groups, on the other hand, need to undergo ring opening in a basic medium. Phenolic groups are supposed to be frequently present on the surface, but their acidity in water is limited and will be strongly dependent on neighbouring functional groups. It is clear from the experimental results that acidity enhances the reaction rate. Since the TOF can be correlated with the pH of the catalyst slurry, the activity would mainly depend on the concentration of carboxylic groups on the surface. As mentioned earlier, the hydrogenolysis reaction can be enhanced by the presence of acid through protonation of the hydroxyl group making water the leaving group. The plausible reaction mechanism can be envisaged as presented in figure 5. The benzene ring and oxygen in the hydroxyl group adsorb to the metal (R_2 denotes the rest of the molecule; the lactone ring and the other benzene ring). A proton (H^+ coming from the support) adds to the hydroxyl group. The carbon–oxygen bond breaks and water leaves the molecule, after which the carbenium ion is attacked by a hydride ion and MAT is formed.

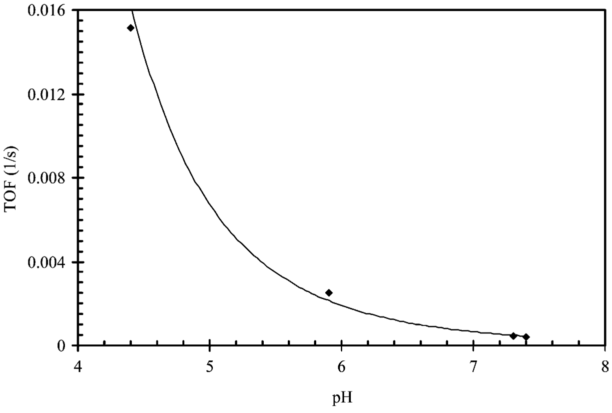

Figure 4. Turnover frequency versus pH of the catalyst slurries in aqueous solutions.

The initial ratio between the isomers HMR 2 and HMR 1 in the experiments described above was 3:1. It was visible from figure 3 that there was isomerisation from HMR 2 to HMR 1. In order to see how the isomers were reacting separately, further isolation of the isomers was performed. Mixtures with different ratios of the isomers were obtained, where always one isomer was in large excess and the other in minor amount, since it was not possible to separate the two isomers completely. Experiments with catalyst I and mixtures of the different isomers were performed (figure 6), demonstrating that HMR 1 (figure 6a) was reacting slower than HMR 2 (figure 6b). There was also isomerisation to the minor isomer in both cases. From the dependence of the HMR 2/HMR 1 ratio on conversion (figure 7), it can be seen that this ratio was decreasing faster for less active (less acidic) catalysts than for more active (figure 7a). It implies that on a less active catalyst more isomerisation of the isomer HMR 2 (which is reacting faster in hydrogenolysis) to the isomer HMR 1 (which is reacting slower) took place. On the most acidic catalyst, the hydrogenolysis was in fact much faster than the isomerisation. The final value for the HMR 2/HMR 1 ratio

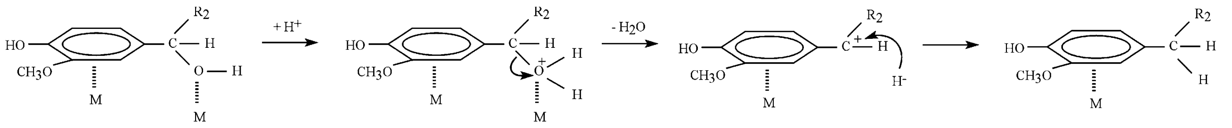

Figure 5. Reaction mechanism for the hydrogenolysis of HMR to MAT.

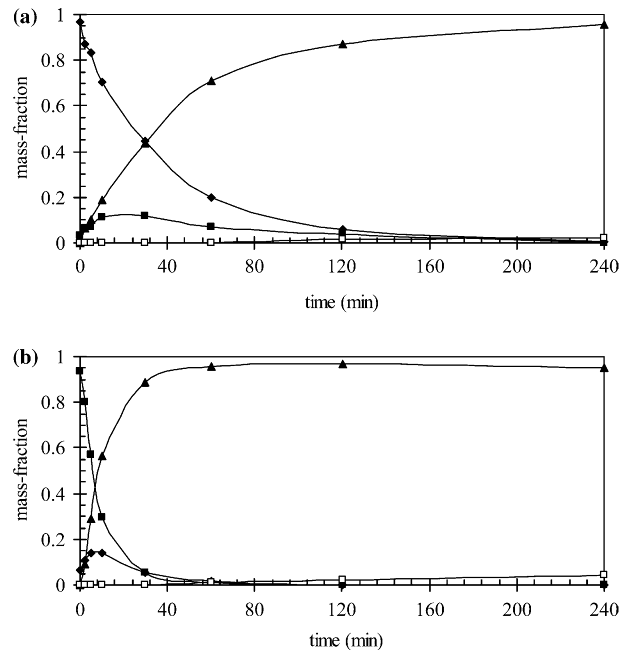

Figure 6. Hydrogenolysis of HMR over Pd/C catalyst I (Table 1) at the same conditions as in figure 2: ◆, HMR 1; ■, HMR 2; ▲, MAT; and □, byproducts A–D are in the figure. Trace amount of 7-i-propoxyMAT was also obtained. (a) HMR 1 isomer in excess and (b) HMR 2 isomer in excess.

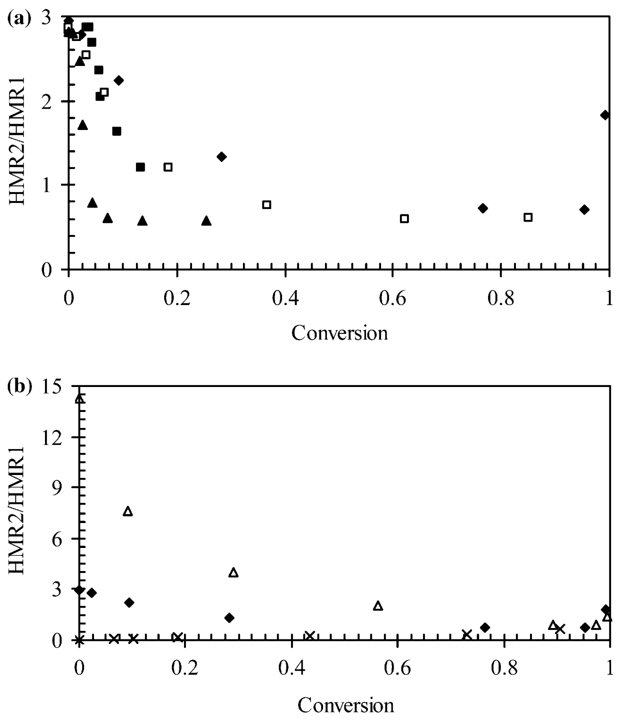

Figure 7. Ratio HMR 2/HMR 1 versus conversion: (a) Initial ratio HMR 2/HMR 1 was 3. ◆, I (Degussa-Hüls); ▲, II (Degussa); ■, III (Sigma-Aldrich); □, IV (self-prepared), (b) Catalyst I (Degussa-Hüls), different initial ratios of HMR 2/HMR 1.

was always close to 0.6–0.7, even when mixtures with different initial isomer ratios were used (figure 7b). This indicates that besides hydrogenolysis of both HMR isomers to MAT, also isomerisation between these isomers occurred.

4. Conclusions

The hydrogenolysis of hydroxymatairesinol to MAT was successfully accomplished over several carbon-supported palladium catalysts, giving in particular for Pd/C (Degussa-Hüls) yields over 90%. The acidity of the support material, quantified through the pH of the catalyst slurries in aqueous solutions, is important for the reaction; higher activities were achieved over palladium catalysts on more acidic supports.

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