Accepted Manuscript

Title: Aerobic oxidation of α -pinene catalyzed by homogeneous and MOF-based Mn catalysts

Authors: Yasmin S. Raupp, Ceylan Yildiz, Wolfgang Kleist, Michael A.R. Meier



PII:S0926-860X(17)30367-8DOI:http://dx.doi.org/doi:10.1016/j.apcata.2017.07.047Reference:APCATA 16352To appear in:Applied Catalysis A: General

 Received date:
 20-6-2017

 Revised date:
 26-7-2017

 Accepted date:
 28-7-2017

article as: Please cite this Yasmin S.Raupp, Ceylan Yildiz, Wolfgang Kleist, Michael A.R.Meier, Aerobic oxidation of α -pinene catalyzed MOF-based by homogeneous and Mn catalysts, Applied Catalysis A, Generalhttp://dx.doi.org/10.1016/j.apcata.2017.07.047

This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

Aerobic oxidation of α -pinene catalyzed by homogeneous and MOF-based Mn catalysts

Yasmin S. Raupp,¹ Ceylan Yildiz,² Wolfgang Kleist,^{2,3,4*} Michael A. R. Meier^{1,*}

- Karlsruhe Institute of Technology (KIT), Institute of Organic Chemistry (IOC), Laboratory of Applied Chemistry, Straße am Forum 7, 76131 Karlsruhe, Germany; E-mail: <u>m.a.r.meier@kit.edu</u>
- 2) Karlsruhe Institute of Technology (KIT), Institute for Chemical Technology and Polymer Chemistry (ITCP), Engesserstraße 20, 76131 Karlsruhe, Germany
- 3) Karlsruhe Institute of Technology (KIT), Institute of Catalysis Research and Technology (IKFT), Herrmann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen, Germany
- 4) Present address: Ruhr-University Bochum, Laboratory of Industrial Chemistry, Universitätsstraße 150, 44801 Bochum, Germany; Email: <u>wolfgang.kleist@rub.de</u>

Graphical abstract



Highlights

- homogeneous and heterogenous catalysts for aerobic alpha-pinene oxidation were compeared to one another

- environmentally benign reaction conditions for the aerobic oxidation of alpha-pinene were developed

- reaction parameters were optimized, resulting in a robust and applicable direct oxidation procedure

Abstract

Manganese catalysts were investigated for the liquid-phase aerobic oxidation of α -pinene. First, the influence of reaction parameters such as time, solvent, temperature, oxidant flow rate and catalyst concentration on conversion, yield and selectivity were evaluated using Mn(III) acetate as homogeneous catalyst. Mn(III) acetate afforded pinene oxide as the main product along with small amounts of verbenol and verbenone. The optimized reaction conditions were likewise applied to a novel mixed-linker metal-organic framework (MOF) based on MIL-53NH₂(Al), which was successfully synthesized and modified in a two-step post-synthetic reaction using maleic anhydride

and Mn(III) acetate. The performance of the Mn-containing MOF catalyst was directly compared to its homogeneous counterpart Mn(III) acetate, showing very similar activity in a mixture of diethyl carbonate/dimethylformamide (DEC/DMF) as solvent. In both cases, a conversion of 31% and the formation of 17% pinene oxide (55% selectivity) were observed after 6 h. The heterogeneous MOF catalyst was easily removed from the reaction mixture by filtration and reused for at least five catalytic cycles without significant loss of activity. A hot filtration test showed that the catalysis mainly proceeded heterogeneously, although minor contributions of homogeneous species could not completely be excluded.

Keywords: terpenes, pinene, pinene oxide, aerobic oxidation, homogeneous catalysis, heterogeneous catalysis, manganese, metal-organic framework

Introduction

The selective oxyfunctionalization of olefins is an important step in the chemical value chain, as cheap and readily available substances can be converted into a wide variety of valuable products [1-3]. In times of depleting fossil reserves and an ever increasing emission of greenhouse gases, the development of catalytic and sustainable processes for the chemical modification of renewable raw materials has become a major focus, especially for the synthesis of oxygen-containing compounds [4]. Among the available renewable raw materials, terpenes constitute an abundant and versatile supply of building blocks for the fine chemical industry [5-7]. Especially monoterpenes like α - and β -pinene, which are the main components of gum turpentine, a by-product obtained from the pulp and paper industry, represent inexpensive starting materials for the synthesis of various flavors, fragrances, agrochemicals and therapeutically active substances. The autoxidation of α -pinene proved to be radical-propagated and produces fine chemicals such as pinene oxide, verbenol and verbenone [8]. These oxygenated derivatives can be used as precursors for citral, menthol, sandalwood fragrance or taxol as well as for the vitamins A and E [9-11].

Anastas and Warner recommend solvent-free procedures in their 12 principles of Green Chemistry [12]. However, since this is often not possible, the use of a solvent becomes inevitable. As reviewed by Mallat and Baiker, the involvement of organic solvents in redox reactions is rarely considered, although the 'sacrificial' solvent may take over the role of the actual oxidizing agent leading to false mechanistic interpretations of the results [13]. Moreover, the formation of solvent related by-products that do not belong to the actual oxidation mechanism effects the atom economy and increases the E factor. In particular, sulfoxides (e.g. DMSO), nitriles (e.g. acetonitrile) and amides (e.g. DMF) are known to act as sacrificial solvents. Caps *et al.* also identified methylcyclohexane as an active part in the epoxidation mechanism of *trans*-stilbene [14]. Considering these studies, the choice of an appropriate reaction medium constitutes a demanding task.

Recently, a lot of effort has been made to replace conventional homogeneous catalytic systems by their heterogeneous equivalents to benefit from the possibility of catalyst regeneration. This substitution contributes to reduce problems concerning waste disposal and to avoid or simplify steps, such as catalyst separation, etc. [5, 15]. For this purpose, various strategies for immobilizing redox-active elements in a solid matrix have been investigated. For instance, the isomorphous substitution in the crystallographic positions of an inorganic framework, the impregnation of metal compounds onto a surface, tethering metal complexes to the surface *via* a spacer ligand, the encapsulation into a solid matrix, etc. proved to be suitable approaches [16]. More recently, metal-organic frameworks have been considered as promising and effective catalysts for various types of oxidations in the liquid phase (e.g., alcohol oxidation [17-19], epoxidation [20-23], hydrocarbon oxidation [24], etc.).

Advantageously, the well-distributed and well-defined isolated metal centers of MOFs enable them to potentially combine the advantages of heterogeneous and the efficiency of homogeneous catalysts [25, 26]. In this regard, this work demonstrates the development of a novel Mn-containing MOF catalyst and its implementation for a more sustainable catalytic process.

In the literature, numerous catalytic systems for the oxidation of terpenes have been reported. However, a direct comparison of the catalytic performance is rarely possible, since these systems differ in many aspects such as oxidizing agent (e.g. molecular oxygen, hydrogen peroxide (H₂O₂), tertbutyl hydroperoxide (TBHP)), homogeneous or heterogeneous catalysis as well as reaction conditions. Nardello-Rataj et al. applied eco-friendly solvents (cyclopentyl methyl ether and 2-methyl tetrahydrofuran) and reusable amphiphilic polyoxometalate nanoparticles for the epoxidation of various terpenes using H_2O_2 [27]. In some other studies, catalytic systems for the oxidation of terpenes, which do not require the use of any solvent, were developed. Lajunen and coworkers demonstrated the aerobic oxidation of olefins under solvent-free conditions using a Co(II) pyridine complex as catalyst and, in contrast to several previous papers [28], without co-oxidant [29]. Gusevskaya et al. also performed the reaction under solvent-free conditions with molecular oxygen, but promoted by heterogeneous chromium containing mesoporous molecular sieves MCM-41 [30]. Additionally, no metal leaching of the catalyst was observed, making recovering easy. Kholdeeva and colleagues explored the potential of Fe- and Cr-containing MOFs (MIL-100 and MIL-101) for the solvent-free oxidation of alkenes [24, 31]. The applied reaction conditions were rather mild and afforded mainly the allylic oxidation products. The authors also investigated the heterogeneous nature of the catalysis and discovered that Fe-MIL-101 leached iron into the solution at temperatures higher than 50 °C [32].

In the last twenty years, various Mn(III) acetate mediated oxidative free-radical reaction protocols have been developed for inter- or intramolecular reactions [33, 34]: Usually, Mn(III) acetate is used for oxidative free-radical cyclizations [3] and for α -keto-acetoxylations [35]. Some studies also utilized Mn(III) acetate for allylic oxidation reactions. One example is given by Bégué *et al.*, who applied Mn(III) acetate as a catalyst for the aerobic epoxidation of various olefins including limonene

with pivalaldehyde as sacrificial aldehyde in fluorous solvents [36]. Likewise, Shing *et al.* applied Mn(III) acetate for allylic oxidations of simple and complex olefins applying pure oxygen and TBHP in decane as co-oxidant [37]. Mn has also been employed for the heterogeneously catalyzed epoxidation of alkenes with air as oxidant. For instance, Raja *et al.* designed redox molecular sieve catalysts for the selective oxidation of α -pinene among other alkenes using benzaldehyde as sacrificial aldehyde [38]. To the best of our knowledge, the aerobic oxidation of α -pinene by a Mn-containing MOF catalyst has not been reported before.

In this study, Mn(III) acetate was investigated as homogeneous catalyst for the oxidation of α -pinene and compared to the performance of a novel Mn-containing MOF catalyst. We focused on a more benign reaction procedure by, i.e., avoiding the use of stoichiometric reagents such as organic hydroperoxides, which are generally toxic, hazardous and produce serious amounts of waste and directly using oxygen from air as the sole oxidant. The influence of different reaction conditions on the conversion and selectivity was studied in detail for the homogeneous model catalyst. Regarding sustainability, the choice of appropriate reaction conditions for the catalytic reaction was considered throughout. For this purpose, diethyl carbonate was employed as solvent, since organic carbonates are considered to be more sustainable alternatives to volatile organic compounds or fluorinated solvents. Furthermore, we report on a new strategy for the immobilization of Mn complexes via post-synthetic modification of MIXMIL-53-NH₂(50) [39, 40] with maleic anhydride and Mn(III) acetate. The efficiency of the Mn-containing MOF MIXMIL-53-NH₂(50)-Mal-Mn as heterogeneous catalyst was explored for the liquid-phase oxidation of α -pinene using the reaction conditions developed for the homogenous model system, allowing for a direct comparison. Moreover, the heterogeneous nature of the catalytic system was assessed by a hot filtration test and the recyclability of the catalyst as well as its stability were investigated.

Results and Discussion

We started our investigations on the manganese-catalyzed aerobic oxidation of α -pinene by determining optimal reaction conditions for Mn(III) acetate as a homogeneous counterpart to the metal-organic framework MIXMIL-53-NH₂(50)-Mal-Mn MOF that was subsequently applied as heterogeneous oxidation catalyst (Figure 1). Conversion, yield and selectivity were optimized by variation of one reaction parameter at a time (reaction time, solvent composition, catalyst concentration, temperature, oxidant flow rate). Reaction products were identified using GC-MS by comparison with authentic samples and quantified by GC techniques (for details see experimental part). In the first set of experiments, the oxidation of α -pinene was monitored at 130 °C for 24 h with continuous air flow through the solution (50 mL/min) and a 50:50 mixture of DMF/toluene as solvent (Figure 2). The solvent mixture DMF/toluene was chosen on the basis of reports on aerobic

epoxidations of olefins without radical initiators or sacrificial aldehydes using DMF as solvent [41-46]. In these reports, the use of DMF was essential for the progress of the catalytic reaction and the following mechanism was suggested: a metal-DMF complex is produced, which coordinates molecular oxygen to form a superoxo species, which then transfers the molecular oxygen to the olefin. On that account, first, the suitability of DMF was tested. For practical reasons, the addition of a lower boiling solvent was required to achieve adequate reflux conditions. Since toluene has been widely used for the aerobic oxidation of alcohols at least 50% toluene were added as solvent [13]. Applying the above-mentioned conditions, the reaction gave pinene oxide as the main product together with verbenone and verbenol as minor side-products.

First, the impact of the reaction time was studied. An increase in reaction time from 6 to 24 h improved the α -pinene conversion from 30 to 51%. In contrast, only a slight increase of pinene oxide yield was observed, resulting in a remarkable decrease of the selectivity from 60 to 36%. This observation is in accordance with the studies of Jasra *et al.* [42] and Yu *et al.* [47], who explained this observation by the high reactivity of epoxides and thus the conversion of pinene oxide into isomeric products. Therefore, longer reaction times were not favorable for the formation pinene oxide.

Next, the influence of the solvent was subject of investigation. Therefore, the DMF/toluene ratio was varied (50:50, 40:60, 30:70, 20:80, 10:90), proving the 10:90 mixture to be the most efficient solvent system. This observation might be explained by a lower concentration of amines, formed by DMF decomposition at high temperature, which can block the free metal sites of the catalyst and thus limit the oxidation reaction. However, a certain amount of DMF seems to have a positive impact on the conversion and yield of pinene oxide, as the latter dropped if only toluene was used. This observation was also made in earlier studies when we discovered that the STA-12(Co)-catalyzed epoxidation of (E)-stilbene did not occur in toluene, whereas mixtures of toluene and DMF permitted some catalytic activity [23], most likely due to a solvent co-oxidation mechanism. A strong indication for this theory was the detection of N-formyl-N-methylformamide (FMF) as a by-product by GC-MS, which was also found in this study. This is in accordance with the studies of Baiker et al., who reported that olefin transformation can be accompanied by significant DMF oxidation, leading to FMF formation [13, 48]. In this case, the intermediate N-(hydroperoxymethyl)-N-methylformamide derived from DMF can act as an oxygen-transfer agent, forming FMF as result. The autoxidation of amides is accelerated by transition metal ions and thus by the presence of the catalyst [49]. However, also the oxidation of the olefin mediated by a transition metal peroxo species and the following regeneration of the catalyst through oxidation of the solvent could explain the strong influence of the solvent and its oxidation [23].

Ensuing investigations were focused on the effect of five different catalyst concentrations on the conversion and selectivity. The results of the performed reactions with catalyst amounts varying between 2.00 and 0.25 mol% are summarized in Table 1. A reaction without catalyst was performed as blank test (Table 1, entry 6). The blank test gave 5% conversion with only 2% product formation,

conforming that the successful formation of pinene oxide in the other reactions was truly induced by the catalyst.

Interestingly, the best conversion (62%) and pinene oxide yield (40%) were achieved by the lowest catalyst amount (0.25 mol%). Conversion, yield and selectivity observed for the reactions containing 1.50, 1.00 and 0.50 mol% catalyst were in a similar range but slightly lower. The reaction with the highest amount of catalyst (2.00 mol%) resulted in only 46% conversion. These findings are in accordance with the study of Lajunen *et al.*, who applied Co(II) complexes for the aerobic oxidation of α -pinene. The authors also reported that the oxidation with the largest catalyst amount was slower and produced fewer product than the reactions with less catalyst [29].

In further experiments, the dependency of conversion and yield on the reaction temperature was investigated (Figure 3). α -Pinene conversion and pinene oxide yield increased at higher temperatures. By increasing the temperature from 100 to 130 °C, conversion and pinene oxide yield almost tripled from 19 and 13% to 53 and 36%, respectively. As expected, the increase of the reaction temperature led to an increased reaction rate, but did not result in a significant difference in selectivity, as only a marginal decrease from 69 to 67% was detected for the pinene oxide selectivity [50].

Next, the applied air flow rates were varied from 25 to 100 mL/min (Figure 4). The analysis showed that high flow rates were advantageous for the overall conversion. By doubling the oxidant flow rate from 25 to 50 mL/min, the conversion increased from 36 to 54% and also the yield of pinene oxide increased to 35%. However, an increase in flow rate from 50 to 100 mL/min did not result in further enhancement of conversion, yield and selectivity to pinene oxide. The selectivity, which amounted almost 70% in all three experiments, did not depend on the flow rate. It can thus be concluded that a high oxygen availability is crucial to this reaction, although an upper limit for the positive impact was discovered. Another cause of the benefits from high oxidant flow rates might be assigned to the faster removal of volatile catalyst poisons, such as amines, that could be produced by DMF degradation.

Combining the findings of the performed screening reactions, a reaction time of 6 h, DMF/toluene (10:90) as solvent mixture, 130 °C, 0.25 mol% catalyst concentration and an air flow of 50 mL min⁻¹ gave the best result for the aerobic α -pinene oxidation catalyzed by Mn(III) acetate. With the optimized reaction conditions, a α -pinene conversion of 62% and a pinene oxide yield of 40% were achieved, resulting in a turnover number (TON = [n_{product}/n_{catalyst}]) of 160 and a selectivity of 65%. However, both DMF and toluene are not ideal solvents for this reaction (considering sustainability aspects), although DMF turned out to be an essential component for the epoxidation mechanism. In addition to the by-product formed by DMF oxidation, GC-MS analysis of the reaction mixture also revealed that toluene was not an inert solvent under the applied reaction conditions, leading to considerable amounts of benzyl alcohol and benzaldehyde as by-products. To find a more sustainable alternative for toluene, dimethyl carbonate and diethyl carbonate were evaluated as co-solvents under the same reaction conditions (Table 2). The 10:90 mixture of DMF and dimethyl carbonate resulted in

the lowest conversion (7%) and yield of pinene oxide (1%), which might be caused by the lower boiling point (90 °C) compared to toluene (111 °C) and diethyl carbonate (126 °C). The 90:10 mixture of diethyl carbonate and DMF gave an α -pinene conversion of 38% and a pinene oxide yield of 23%. This mixture should be preferred over toluene/DMF for sustainability reasons (see general discussion above and safety (S), health (H) and environment (E) scores by CHEM21 selection guide: toluene: S = 5, H = 6, E = 3, overall ranking = problematic; dimethyl carbonate: S = 4, H = 1, E = 3, overall ranking = recommended [51]), even if the conversion was slightly lower (compare Table 2, entries 1 and 3). Although these data are for dimethyl carbonate (data for diethyl carbonate is not available), they suggest a better sustainability for the latter. Moreover, no additional by-products related to solvent oxidation were produced (i.e. carbonates were inert solvents under these conditions). However, as already experienced for toluene as the sole solvent, diethyl carbonate without addition of DMF gave poor conversion and yield. Moreover, if only a stoichiometric amount of DMF (Table 2, entry 4) was used (in relation to α -pinene), both conversion (20%) and pinene oxide yield (9%) were low compared to the reaction using DMF (Table 2, entry 3).

For those reasons, it should be noted that, from an environmental point of view, diethyl carbonate as a co-solvent is the better choice, since no additional side products are formed and the solvent has sustainability advantages. The reaction employing the above-mentioned conditions with diethyl carbonate resulted in a conversion of 38% (TON = 23) and 59% selectivity for pinene oxide.

After having investigated appropriate reaction conditions for the aerobic α -pinene oxidation with Mn(III) acetate as homogeneous catalyst, these reaction conditions were subsequently applied for the reaction using the novel Mn-containing MOF MIXMIL-53-NH₂(50)-Mal-Mn as heterogeneous catalyst to enable direct comparison of the catalyst performances.

For this purpose, a mixed linker metal-organic framework with MIL-53(Al) structure containing equal amounts of terephthalate and 2-aminoterephthalate linkers was synthesized in a modified two-step post-synthetic modification (PSM) that has been previously reported for the generation of MOF-based single-site Pd catalysts [26]. First, the amine groups of the organic linker molecules were covalently modified using maleic anhydride, resulting in a chelating side group at the linkers that was subsequently used for the immobilization of manganese complexes. The XRD pattern (Figure 5) of the resulting catalyst revealed a crystalline structure that is very similar to the simulated diffractogram for MIL-53(Al) with minor deviations that can be explained by a breathing behavior of the pores after the introduction of the immobilized guest species in the pore structure [39]. Attenuated total reflection (ATR) IR spectra (Figure S2) were recorded to exclude residual free acid (C=O band expected around 1685 cm⁻¹) or solvent molecules (DMF; C=O band expected around 1650 cm⁻¹) in the pores of the frameworks. The N-H stretching vibrations of the amine functionalities (around 3500 cm⁻¹ and 3389 cm⁻¹), the OH stretching vibrations of the Al-OH-chains (around 3621 cm⁻¹) and the OH

stretching vibrations of the maleate side group (around 3692 cm⁻¹) were observed. ¹H-NMR spectra of the MOF before and after immobilization of the Mn species (Table 3 and Figure S3-S5) proved the presence of the two linker molecules in the desired ration (1:1) and revealed a modification degree of $\approx 6\%$ of the amine groups. Results from physisorption experiments (Table 3) proved that the catalyst still featured a high specific surface area and accessible micropore volume after the PSM reaction. The manganese content of the catalyst was determined by atomic absorption spectroscopy (AAS), resulting in a loading of 0.9 wt% (Table 3).

In a first attempt, the Mn-containing MOF catalyst showed notable activity for the aerobic oxidation of α -pinene in a solvent mixture of DMF and DEC with a continuous feed of air into the reaction mixture for 6 h at 130 C. Pinene oxide, verbenone and verbenol were detected as the major products by GC-MS and comparison with authentic samples (Figure 1). Additionally, the formation of the sideproducts verbenone and verbenol was also observed. Subsequently, the catalytic performance of the MOF based catalyst was compared to the homogeneously dissolved Mn salt (Figure 6). The heterogeneous catalyst exhibited a good activity and showed similar results as achieved by 0.5 mol/% Mn(III) acetate under the same conditions. Indeed, after 6 h, the conversion was 31% with the homogeneous system as well as with the MOF-containing catalyst. The selectivities of Mn(III) acetate and the MOF-containing catalyst to pinene oxide (55% and 54%, respectively), verbenone (7% and 8%, respectively) and verbenol (6% and 3%, respectively) were also similar. The mass balances accounted for 68% and 65%, respectively. The remainder of the converted α -pinene can be assigned to pinene oxide isomerization products since the GC chromatogram showed several additional, very small peaks in the same region as the main oxidation products pinene oxide, verbenol and verbenone. GC-MS analysis was performed to analyze these additional side products. In consistence with the mass spectra campholenic aldehyde, pinocarvone and carveol were detected.

To benefit from the main advantages of heterogeneous catalysis, the Mn-containing MOF must be easily recoverable from the reaction medium and allow for a straightforward regeneration. If these criteria are fulfilled, heterogeneous catalysis facilitates waste prevention and conservation of resources. Therefore, the stability of the catalyst under the applied reaction conditions has to be ensured. For the assessment of its stability, the present catalyst's reusability was tested by using it in five successive catalytic reactions. After each catalytic reaction, the catalyst was filtered from the reaction mixture, washed, dried at room temperature and reused in another α -pinene oxidation reaction under the same conditions. The results of the recycling test show that the catalyst was active for at least five reaction cycles without significant loss of activity (Figure 7).

The successful reuse of MIXMIL-53- $NH_2(50)$ -Mal-Mn may be interpreted as a first indication that the catalytic active sites of the catalyst neither became inactive during the reaction nor that significant amounts of Mn leached out of the catalyst. However, a truly heterogeneous reaction pathway can only

be asserted by a heterogeneity test as proposed by Sheldon and Schuchardt *et al.* [32]. Therefore, a hot filtration test was carried out by filtering the catalyst from the hot reaction mixture after 3 h and continuing the reaction for another 5 h. At the same time, a control experiment was conducted in which the catalyst remained in the reaction mixture. In the case of exclusive heterogeneous catalysis, conversion and yield should remain constant after catalyst removal. In our experiments, the conversion and yield of pinene oxide further increased slightly after removal of the MIXMIL-53-NH₂(50)-Mal-Mn catalyst (Figure 8). However, in comparison to the control experiment, the reaction rate was remarkably lower, indicating that the reaction was mainly catalyzed heterogeneously. The observed activity despite catalyst filtration might arise from solid catalyst particles that were too small to be removed by the filter, although minor amounts of homogeneous species cannot be completely ruled out as an additional catalyst and the advantages of a heterogeneous system. In the five consecutive runs, an overall TON of 166 was obtained.

Conclusion

Mn(III) acetate was investigated for the liquid-phase aerobic α-pinene oxidation and the influence of reaction time, solvent, temperature, oxidant flow rate and catalyst concentration on conversion, yield, and selectivity were evaluated. High temperatures (130 °C) and oxidant flow rates (50 mL min⁻¹), low catalyst concentrations (0.25 mol%) and a DMF/toluene solvent mixture emerged as the most favorable reaction conditions. Longer reaction times did not enhance the formation of pinene oxide, since epoxides tend towards isomerization processes at high temperatures. Toluene was exchanged by diethyl carbonate, which did not undergo any side reaction under the applied conditions and is regarded as a more sustainable solvent. Furthermore, the novel mixed-linker metal-organic framework MIXMIL-53-NH₂(50)-Mal-Mn was successfully synthesized and structurally characterized. NMR spectroscopy confirmed that the detected linker ratio of terephthalate and 2-aminotherephtalate matched to the applied 1:1 ratio, which proved that both linker molecules were incorporated into the framework with the same preference. As shown by physisorption experiments the high specific surface area was maintained after the post-synthetic modification reactions leading to a potentially highly active catalytic material. We could show that the framework with its immobilized and well-defined manganese(III) complexes featured notable catalytic activity for the oxidation of α -pinene with molecular oxygen in DEC/DMF applying the aforementioned reaction conditions. The reaction resulted in high selectivity for pinene oxide as the main product, along with smaller amounts of verbenol and verbenone. The novel MOF catalyst gave good results, which were comparable to the conversion and yield achieved by Mn(III) acetate. The accumulated TON of the MOF catalyst (166) was considerably higher compared to the homogeneous catalyst system (23). A hot filtration test indicated that the reaction mainly proceeded through a heterogeneous pathway, but an involvement of

homogeneous species could not be completely excluded. Moreover, the Mn-containing MOF showed constant activity over at least five catalytic cycles, proving its recyclability and underlining the stability of the MOF under the applied reaction conditions.

Despite significant constraints due to the necessity of DMF, as a sacrificial reductant, this work provides evidence that the Mn-containing MOF MIXMIL-53- $NH_2(50)$ -Mal-Mn can be considered a promising solid catalyst for aerobic oxidations.

References

- [1] A.E. Shilov, G.B. Shul'pin, Chem. Rev., 97 (1997) 2879-2932.
- [2] R. Sheldon, J. Kochi, Metal-catalyzed oxidations of organic compounds: mechanistic principles and synthetic methodology including biochemical processes, Academic Press, New York, 1981.
- [3] B.B. Snider, Chem. Rev., 96 (1996) 339-364.
- [4] M.A. Meier, J.O. Metzger, U.S. Schubert, Chem. Soc. Rev., 36 (2007) 1788-1802.
- [5] J.L.F. Monteiro, C.O. Veloso, Top. Catal., 27 (2004) 169-180.
- [6] K.A. Swift, Top. Catal., 27 (2004) 143-155.
- [7] A. Corma, S. Iborra, A. Velty, Chem. Rev., 107 (2007) 2411-2502.
- [8] U. Neuenschwander, F. Guignard, I. Hermans, ChemSusChem, 3 (2010) 75-84.
- [9] K. Bauer, D. Garbe, H. Surburg, Common fragrance and flavor materials: preparation, properties and uses, Wiley-VCH, Weinheim, 1997.
- [10] P.A. Wender, T.P. Mucciaro, J. Am. Chem. Soc., 114 (1992) 5878-5879.
- [11] H. Mimoun, Chimia, 50 (1996) 620-625.
- [12] P. Anastas, N. Eghbali, Chem. Soc. Rev., 39 (2010) 301-312.
- [13] T. Mallat, A. Baiker, Catal. Sci. Technol., 1 (2011) 1572-1583.
- [14] K. Guillois, S. Mangematin, A. Tuel, V. Caps, Catal. Today, 203 (2013) 111-115.
- [15] L. Menini, M.J. da Silva, M.F. Lelis, J.D. Fabris, R.M. Lago, E.V. Gusevskaya, Appl. Catal., A, 269 (2004) 117-121.
- [16] I. Arends, R. Sheldon, Appl. Catal., A, 212 (2001) 175-187.
- [17] S. Proch, J. Herrmannsdörfer, R. Kempe, C. Kern, A. Jess, L. Seyfarth, J. Senker, Chem. Eur. J., 14 (2008) 8204-8212.
- [18] F. Carson, S. Agrawal, M. Gustafsson, A. Bartoszewicz, F. Moraga, X. Zou, B. Martín- Matute, Chem. Eur. J., 18 (2012) 15337-15344.
- [19] F.X.L. i Xamena, A. Abad, A. Corma, H. Garcia, J. Catal., 250 (2007) 294-298.
- [20] K. Brown, S. Zolezzi, P. Aguirre, D. Venegas-Yazigi, V. Paredes-García, R. Baggio, M.A.
- Novak, E. Spodine, Dalton Trans., (2009) 1422-1427.
- [21] K. Leus, I. Muylaert, M. Vandichel, G.B. Marin, M. Waroquier, V. Van Speybroeck, P. Van Der Voort, Chem. Commun., 46 (2010) 5085-5087.
- [22] N.V. Maksimchuk, K.A. Kovalenko, S.S. Arzumanov, Y.A. Chesalov, M.S. Melgunov, A.G. Stepanov, V.P. Fedin, O.A. Kholdeeva, Inorg. Chem., 49 (2010) 2920-2930.
- [23] M.J. Beier, W. Kleist, M.T. Wharmby, R. Kissner, B. Kimmerle, P.A. Wright, J.D. Grunwaldt, A. Baiker, Chem. Eur. J., 18 (2012) 887-898.
- [24] O.A. Kholdeeva, I.Y. Skobelev, I.D. Ivanchikova, K.A. Kovalenko, V.P. Fedin, A.B. Sorokin, Catal. Today, 238 (2014) 54-61.
- [25] M.A. Gotthardt, A. Beilmann, R. Schoch, J. Engelke, W. Kleist, RSC Advances, 3 (2013) 10676-10679.
- [26] M.A. Gotthardt, R. Schoch, T.S. Brunner, M. Bauer, W. Kleist, ChemPlusChem, 80 (2015) 188-195.
- [27] A. Mouret, L. Leclercq, A. Mühlbauer, V. Nardello-Rataj, Green Chem., 16 (2014) 269-278.
- [28] T. Mukaiyama, T. Yamada, Bull. Chem. Soc. Jpn., 68 (1995) 17-35.
- [29] M.K. Lajunen, T. Maunula, A.M. Koskinen, Tetrahedron, 56 (2000) 8167-8171.
- [30] P.A. Robles-Dutenhefner, B.B. Brandão, L.F. De Sousa, E.V. Gusevskaya, Appl. Catal., A, 399 (2011) 172-178.
- [31] I.Y. Skobelev, A.B. Sorokin, K.A. Kovalenko, V.P. Fedin, O.A. Kholdeeva, J. Catal., 298 (2013) 61-69.
- [32] R.A. Sheldon, M. Wallau, I.W. Arends, U. Schuchardt, Acc. Chem. Res., 31 (1998) 485-493.
- [33] A.S. Demir, M. Emrullahoglu, Curr. Org. Synth., 4 (2007) 321-350.
- [34] J. Gilmore, J. Mellor, J. Chem. Soc. C, (1971) 2355-2357.
- [35] B.B. Snider, L. Han, C. Xie, J. Org. Chem., 62 (1997) 6978-6984.
- [36] K. Ravikumar, F. Barbier, J.-P. Bégué, D. Bonnet-Delpon, Tetrahedron, 54 (1998) 7457-7464.
- [37] T.K. Shing, Y.-Y. Yeung, P.L. Su, Org. Lett., 8 (2006) 3149-3151.

[38] R. Raja, G. Sankar, J.M. Thomas, Chem. Commun., (1999) 829-830.

[39] T. Loiseau, C. Serre, C. Huguenard, G. Fink, F. Taulelle, M. Henry, T. Bataille, G. Férey, Chem. - Eur. J., 10 (2004) 1373-1382.

[40] T. Ahnfeldt, D. Gunzelmann, T. Loiseau, D. Hirsemann, J.r. Senker, G. Férey, N. Stock, Inorg. Chem., 48 (2009) 3057-3064.

- [41] M. Salavati-Niasari, S. Abdolmohammadi, M. Oftadeh, J. Coord. Chem., 61 (2008) 2837-2851.
- [42] M.V. Patil, M.K. Yadav, R.V. Jasra, J. Mol. Catal. A: Chem., 277 (2007) 72-80.
- [43] M.L. Kantam, B.P.C. Rao, R.S. Reddy, N. Sekhar, B. Sreedhar, B. Choudary, J. Mol. Catal. A: Chem., 272 (2007) 1-5.
- [44] Q. Tang, Q. Zhang, H. Wu, Y. Wang, J. Catal., 230 (2005) 384-397.
- [45] Q. Tang, Y. Wang, J. Liang, P. Wang, Q. Zhang, H. Wan, Chem. Commun., (2004) 440-441.
- [46] K.M. Jinka, J. Sebastian, R.V. Jasra, J. Mol. Catal. A: Chem., 274 (2007) 33-41.
- [47] Y. Cao, Y. Li, H. Yu, F. Peng, H. Wang, Catal. Sci. Technol., 5 (2015) 3935-3944.
- [48] Z. Opre, T. Mallat, A. Baiker, J. Catal., 245 (2007) 482-486.
- [49] P. Timmanagoudar, G. Hiremath, S. Nandibewoor, J. Indian Chem. Soc., 74 (1997) 296-298.
- [50] A. Bhunia, M.A. Gotthardt, M. Yadav, M.T. Gamer, A. Eichhöfer, W. Kleist, P.W. Roesky,
- Chem. Eur. J., 19 (2013) 1986-1995.
- [51] D. Prat, A. Wells, J. Hayler, H. Sneddon, C.R. McElroy, S. Abou-Shehada, P.J. Dunn, Green Chem., 18 (2016) 288-296.



Figure 1. Catalytic oxidation of α -pinene by MIXMIL-53-NH₂(50)-Mal-Mn resulting in pinene oxide, verbenone and verbenol as main products. (conversion: 31%, selectivities: 54, 8 and 3%, respectively). Reaction conditions: α -pinene (1.0 mmol), MIXMIL-53-NH₂(50)-Mal-Mn (0.5 mol% Mn), DMF/diethyl carbonate (10:90, 30 mL), compressed air (50 mL min⁻¹), 130 °C, 6 h.



Figure 2. Conversion, yield and selectivity of aerobic α -pinene oxidation catalyzed by Mn(III) acetate. Reaction conditions: α -pinene (1.0 mmol), catalyst (1.0 mol% Mn), DMF/toluene (50:50, 30 mL), compressed air (50 mL min⁻¹), 130 °C.



Figure 3. Dependency of reaction temperature on conversion and yield. Reaction conditions: α -pinene (1.0 mmol), Mn(III) acetate (1.0 mol%), DMF/toluene (10:90, 30 mL), compressed air (50 mL min⁻¹).



Figure 4. Influence of air flow rate on conversion and yield for the catalytic oxidation of α -pinene. Reaction conditions: α -pinene (1.0 mmol), catalyst (0.5 mol% Mn), DMF/toluene (10:90, 30 mL), compressed air (flow as indicated), 130 °C, 6 h.



Figure 5. XRD patterns of simulated MIL-53(Al) and MIXMIL-53(Al)-NH₂(50)-Mal-Mn.



Figure 6. Conversion and yield of aerobic α -pinene oxidation catalyzed by MIXMIL-53-NH₂(50)-Mal-Mn and homogeneous Mn(III) acetate, respectively. Reaction conditions: α -pinene (1.0 mmol), catalyst (0.5 mol% Mn), DMF/DEC (10:90, 30 mL), compressed air (50 mL min⁻¹), 130 °C.



*Figure 7. Catalytic performance of MIXMIL-53-NH*₂(50)-Mal-Mn in five cycles of α-pinene epoxidation. Reaction conditions: α-pinene (1.0 mmol), MIXMIL-53-NH₂(50)-Mal-Mn (0.5 mol% Mn), DMF/diethyl carbonate (10:90, 30 mL), compressed air (50 mL min⁻¹), 130 °C, 6 h.



Figure 8. Comparison of conversion and yield of α -pinene epoxidation with and without catalyst removal after 3 h (as indicated by vertical line). Reaction conditions: α -pinene (1.0 mmol), MIXMIL-53-NH₂(50)-Mal-Mn (0.5 mol% Mn), DMF/diethyl carbonate (10:90, 30 mL), compressed air (50 mL min⁻¹), 130 °C.

| Entry | Catalyst conc. | Conversion [%] | Selectivity (yield) [%] | | |
|-------|----------------|----------------|-------------------------|-----------|----------|
| | [mol%] | | Pinene oxide | Verbenone | Verbenol |
| 1 | 2.00 | 46 | 67 (31) | 4 (2) | 5 (2) |
| 2 | 1.50 | 53 | 67 (35) | 8 (4) | 6 (3) |
| 3 | 1.00 | 53 | 66 (35) | 5 (3) | 4 (2) |
| 4 | 0.50 | 52 | 66 (34) | 7 (3) | 5 (3) |
| 5 | 0.25 | 62 | 65 (40) | 7 (4) | 5 (3) |
| 6 | 0 (blank test) | 5 | 52 (2) | 8 (0,4) | 6 (0,3) |

Table 1. Effect of catalyst concentration on conversion and selectivity. Reaction conditions: α -pinene (1.0 mmol), Mn(III) acetate (as indicated), DMF/toluene (10:90, 30 mL), compressed air (50 mL min⁻¹), 130 °C, 6 h.

Table 2. Solvent effect in the aerobic epoxidation of α -pinene. Reaction conditions: α -pinene (1.0 mmol), Mn(III) acetate (1.0 mol%), solvent (30 mL), compressed air (50 mL min⁻¹), 130 °C, 6 h.

| Entry | Solvent | Conversion | Selectivity (yield) [%] | | |
|-------|-----------------------|------------|-------------------------|-----------|----------|
| | | [%] | Pinene oxide | Verbenone | Verbenol |
| 1 | Toluene/DMF (90:10) | 53 | 66 (35) | 5 (3) | 4 (2) |
| 2 | Dimethyl | 7 | 14 (1) | 6 (0.4) | 5 (0.3) |
| | carbonate/DMF (90:10) | | | | |
| 3 | Diethyl carbonate/DMF | 38 | 59 (23) | 5 (2) | 4 (1) |
| | (90:10) | | | | |
| 4 | Diethyl carbonate/DMF | 20 | 43 (9) | 7 (1) | 8 (2) |
| | (99.5:0.5) | | | | |
| 5 | Diethyl carbonate | 11 | 14 (2) | 4 (0.4) | 5 (0.3) |

Table 3. Specific surface areas and micropore volumes of modified MIL-53(Al) materials obtained from nitrogen physisorption measurements. Mn content of MIXMIL-53-NH₂(50)-Mal-Mn determined by AAS measurements.

| Entry | | S _{BET} (m ² g ⁻¹) | Micropore volume [cm ³ g ⁻¹] | Mn content [wt%] |
|-------|---------------------------------------|--|--|------------------|
| 1 | MIXMIL-53-NH ₂ (50) | 840 | 0.23 | - |
| 2 | MIXMIL-53-NH ₂ (50)-Mal | 480 | 0.21 | - |
| 3 | MIXMIL-53-NH ₂ (50)-Mal-Mn | 380 | 0.15 | 0.9 |