Synthesis of high-value tricarballylate plasticizers directly from citric acid esters on bifunctional $Pd/Nb_2O_5.nH_2O$ catalysts

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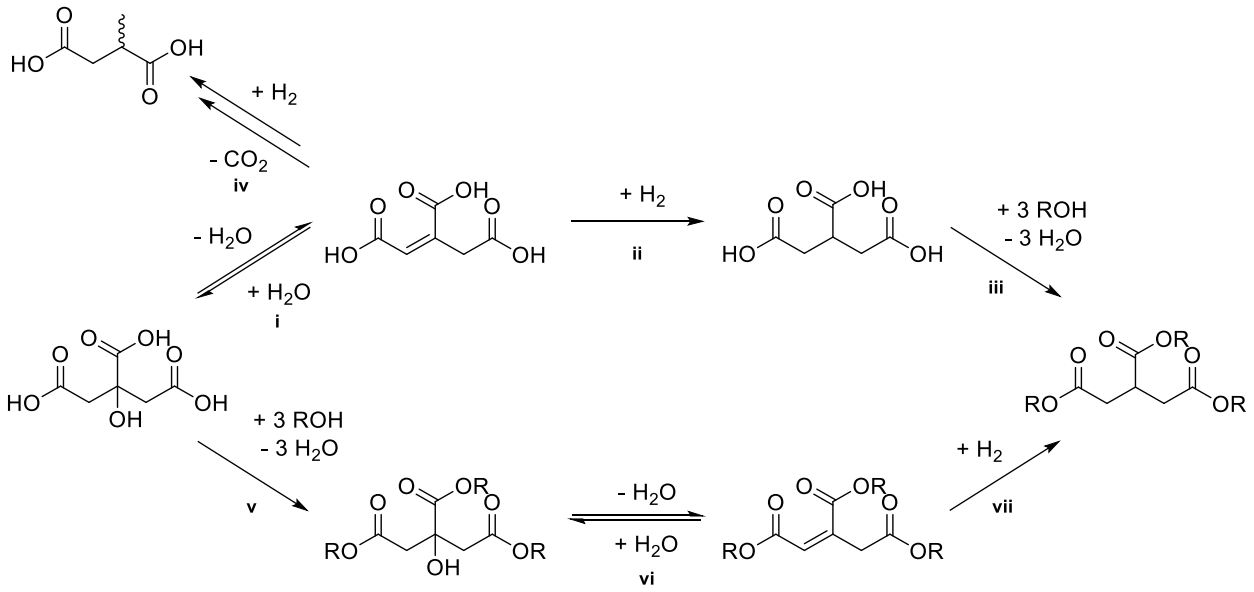
Abstract

Tricarballylate esters are considered as an appealing class of biobased plasticizers. This work focusses on the production of tricarballylate esters from citrate esters through a one-pot sequential dehydration-hydrogenation process, in order to circumvent the undesired decarboxylation side reaction in the synthesis of tricarballylic acid directly from citric acid. High yields up to 93% of different tricarballylate esters were obtained with a self-synthesised bifunctional 0.2 wt% $Pd/Nb_2O_5.nH_2O$ catalyst employed in methylcyclohexane as inert solvent.

Introduction

Strong health concerns about phthalate plasticizers in polyvinyl chloride plastics[1-3] have pressed the search for safe alternatives,[4-6] often focusing on the development of plasticizers from natural resources.[7-29] Tricarballylate plasticizers are considered as such an appealing alternative, since they possess excellent plasticizing properties[30,31] and can be obtained from a cheap and renewable resource, namely citric acid. However, an efficient and high-yielding valorisation route was not available until a one-pot sequential dehydration-hydrogenation of citric acid to tricarballylic acid was recently developed (Scheme 1, **i-ii**).[32-34] This tricarballylic acid precursor can subsequently be esterified (**iii**) via well-known processes[35] to obtain the desired tricarballylate plasticizers. Although high yields of tricarballylic acid were obtained over multiple runs in the abovementioned works, the loss of carbon through the spontaneous decarboxylation of the generated aconitic acid intermediate (**iv**) remains a potential threat to the robustness and scalability of this procedure.[36-40] To counteract this issue, the two synthesis steps of tricarballylate plasticizers can be reversed (Scheme 1, bottom pathway). As such, the esterification (**v**) is performed *prior* to the sequential dehydration-hydrogenation reaction (**vi**-**vii**), which leaves the carboxylic acid protected as an ester, hence drastically lowering the risk for decarboxylation. In this way, the most challenging step of the synthesis route comprises the dehydration-hydrogenation of the citrate ester (**vi**-**vii**), as the esterification of citric acid (**v**) is well-investigated, even in presence of heterogeneous and recyclable catalysts.[41-45]

Only one preceding patent describes the production of triethyl propane-1,2,3-tricarboxylate (TEPTC) from triethyl citrate (TEC), in which a yield of 54% TEPTC is obtained in the presence of a 56 wt% CuO/Al_2O_3 catalyst, employed in ethanol, at 175 °C under 10 bar H_2.[46] However, no information on reaction times, side products, nor the recyclability of the catalyst is provided. In this work, the route to tricarballylate esters from citrate esters is explored meticulously, with a particular emphasis on a controlled dehydration reaction using a solid acid catalyst in a stable organic solvent. Furthermore, the applicability of the system is expanded to citrate esters other than triethyl citrate.

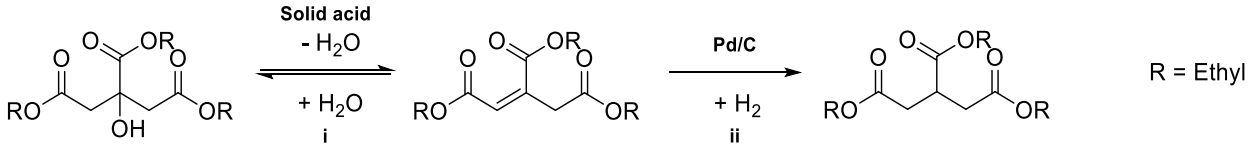


Scheme 1. Possible pathways towards tricarballylate plasticizers from citric acid: *Top pathway:* (**i**) dehydration of citric acid to aconitic acid, (**ii**) hydrogenation of aconitic acid to tricarballylic acid, (**iii**) esterification of tricarballylic acid to tricarballylate esters, (**iv**) undesired decarboxylation and subsequent hydrogenation of aconitic acid to methylsuccinic acid. *Bottom pathway:* (**v**) esterification of citric acid to citrate ester, (**vi**) dehydration of citrate ester to aconitate ester, (**vii**) hydrogenation of aconitate ester to tricarballylate ester.

Results and Discussion

Two-catalyst one-pot system in a green solvent

To produce tricarballylate esters directly from citrate esters, a net removal of the hydroxyl group from the respective citrate ester has to take place. In this work, this is approached via a dehydration of the citrate ester to the aconitate ester (Scheme 2, **i**) followed by a hydrogenation of the generated aconitate ester to the tricarballylate ester (**ii**). The dehydration is an equilibrium reaction and must be accelerated by adding an acid catalyst, since citrate esters do not possess the intrinsic acidity of citric acid.[32,33] For the subsequent hydrogenation of the aconitate ester to the corresponding tricarballylate ester, a Pd/C hydrogenation catalyst was used. As the sequential dehydration-hydrogenation of the citrate esters proceeds, water is generated, which might undesirably hydrolyse the ester groups of the substrate and/or product molecules to carboxylic acids. Therefore, ethanol was initially selected as the solvent in order to shift the equilibrium towards the esters.



Scheme 2. Reaction pathway in the sequential dehydration-hydrogenation of triethyl citrate (TEC): Dehydration of triethyl citrate to triethyl aconitate (**i**) followed by the hydrogenation of triethyl aconitate to triethyl tricarballylate (**ii**).

In absence of an acid catalyst, no conversion of triethyl citrate (TEC) was observed under the studied conditions (Table 1, entry 1; 0.1 M TEC in ethanol, 10 bar H_2 for 20 h at 150 °C). Adding a homogeneous Brønsted acid (tosylic acid; TsOH) did not result in an improved conversion rate (entry 2), but in the presence of heterogeneous acid catalysts some conversion of TEC and formation of triethyl tricarballylate (triethyl 1,2,3-propanetricarboxylate, TEPTC) were detected (entries 3-7). TEPTC was the only detected product, illustrating that the formed aconitate esters were smoothly hydrogenated and that no other side reactions occurred. However, the ^{1}H-NMR signals of the citrate or tricarballylate backbone displayed some extra splitting, indicating some hydrolysis of ester groups to the

corresponding carboxylic acid groups (ESI 1.2). Water involved in this hydrolysis can originate from the dehydration of TEC to its aconitate ester; however, it is more likely that the water molecules arise from the etherification of two ethanol molecules, since a large amount of diethyl ether was observed in each of the reaction mixtures (up to 20% of ethanol is converted to diethyl ether). This indicates that ethanol is unsuitable as solvent under current conditions, as it competes with TEC for the acid sites of the solid acid catalyst and it has an adverse effect on preserving the ester groups.

Therefore, the less reactive, but still green and environmentally friendly cyclopentyl methyl ether (CPME) was selected as solvent in which the acid catalysts were re-evaluated.[47-52] Again, no formation of TEPTC was observed in the presence of tosylic acid (entry 8). Discoloration of the reaction mixture was observed when zeolite or sulphated zirconia catalysts were applied (entries 9-12), indicating that CPME is unstable to these acid catalysts. Nevertheless, niobium solid acids gave rise to a considerable increase in TEPTC yield (entries 13-16), with a maximum of 25% in presence of the self-synthesized $Nb_2O_5.nH_2O$.[53,54] The yield of TEPTC correlates well with the total amount of acid sites for the niobium oxide materials (ESI Table S1), indicating that both Brønsted and Lewis acid sites can catalyze the dehydration of TEC.[33,53] This statement is supported by the 15% yield of TEPTC that is obtained in presence of a Lewis acidic γ-Al_2O_3 catalyst (entry 17). In order to further increase the yield of TEPTC, an effort was made to increase the number of Brønsted acid sites of $Nb_2O_5.nH_2O$ by a phosphoric acid treatment.[53] However, in presence of this $H_3PO_4/Nb_2O_5.nH_2O$ catalyst, the yield of TEPTC did not increase (entry 18).

Interestingly, the ^{1}H-NMR spectra of the reaction mixtures displayed multiplet instead of doublet signals, corresponding to the protons of the TEC and TEPTC backbones (Figure S1). Through thorough 2D ^{1}H,^{13}C-NMR analysis (ESI 1.3.2.), it was concluded that these multiplets solely belong to citrate or tricarballylate molecules and that the extra splitting is caused by different R-groups that are attached to the ester positions of both molecules. In addition to ethyl esters, also some methyl esters were observed, indicating that small amounts of CPME degrade under the reaction conditions, forming methyl esters. As such, CPME proved not to be as stable as initially anticipated, still, CPME outperformed other green reaction solvents in terms of TEPTC yield (entry 19-22), making it the solvent of choice for further optimization. Noteworthily, for other ether solvents, like 2-methyltetrahydrofuran (entry 19) and tert-amyl methyl ether (entry 20), similar solvent degradation was observed as for CPME.

Furthermore, lower mole balances are observed when niobium solid acids are applied, especially when using $Nb_2O_5.nH_2O$ in combination with CPME (56%; Table 1, entry 16). This most probably originates from a strong adsorption of citrate molecules on the $Nb_2O_5.nH_2O$ surface through a strong interaction with its hydroxyl group; a similar adsorption effect was observed for citric acid in presence of $Nb_2O_5.nH_2O$ in our previous work.[33] This strong adsorption of citrate on the catalyst surface is also perceived in the time profiles of the sequential dehydration-hydrogenation of TEC (ESI, Figure S6), where the low mole balance is already observed after 2 h of reaction time and is maintained over the complete course of the reaction. To validate this hypothesis, a desorption experiment with CD_3OD was carried out on the used catalysts from entry 16, which revealed that the adsorbed molecules were indeed of a citrate based origin (ESI Section 3.2).

Table 1. Sequential dehydration - hydrogenation of triethyl citrate [a]

Entry	Acid Catalyst	Amount	Solvent	Y_{TEPTC} [b] [%]	M. B. [c] [%]
1	-	-	Ethanol	-	> 99
2	TsOH	2 eq.	Ethanol	-	> 99
3	H-Beta (10.8) [d]	0.1 g	Ethanol	2	> 99
4	H-Y (2.7) [d]	0.1 g	Ethanol	6	> 99
5	H-MCM 22 (14) [d]	0.1 g	Ethanol	1	> 99
6	*Ortho*-Nb_2O_5 [e]	0.1 g	Ethanol	4	80
7	$Nb_2O_5.nH_2O$ [e]	0.1 g	Ethanol	2	92
8	TsOH	2 eq.	Cyclopentyl methyl ether	-	> 99
9	H-Beta (10.8) [d]	0.1 g	Cyclopentyl methyl ether	n.d.	n.d.
10	H-Y (2.7) [d]	0.1 g	Cyclopentyl methyl ether	n.d.	n.d.
11	H-MCM 22 (14) [d]	0.1 g	Cyclopentyl methyl ether	n.d.	n.d.
12	SO_4^{2-}/ZrO_2 [e]	0.1 g	Cyclopentyl methyl ether	n.d.	n.d.
13	*Ortho*-Nb_2O_5 [e]	0.1 g	Cyclopentyl methyl ether	8	92
14	$NbOPO_4.nH_2O$ [f]	0.1 g	Cyclopentyl methyl ether	12	94
15	$Nb_2O_5.nH_2O$ [f]	0.1 g	Cyclopentyl methyl ether	15	81
16	$Nb_2O_5.nH_2O$ [e]	0.1 g	Cyclopentyl methyl ether	25	56
17	γ-Al_2O_3 [f]	0.1 g	Cyclopentyl methyl ether	15	61
18	$H_3PO_4/Nb_2O_5.nH_2O$ [e]	0.1 g	Cyclopentyl methyl ether	18	86
19	$Nb_2O_5.nH_2O$ [e]	0.1 g	2-Methyltetrahydrofuran	23	74
20	$Nb_2O_5.nH_2O$ [e]	0.1 g	tert-Amyl methyl ether	21	70
21	$Nb_2O_5.nH_2O$ [e]	0.1 g	Methyl isobutyl ketone	14	49
22	$Nb_2O_5.nH_2O$ [e]	0.1 g	Ethyl acetate	15	97

[a] Reaction conditions: 0.1 M TEC in solvent (2 mL), 0.5 mol% hydrogenation catalyst, 150 °C, 10 bar H_2, 20 h. [b] Yield of triethyl 1,2,3-propanetricarboxylate. [c] Mole balance. [d] Si/Al ratio in between brackets. [e] Self-synthesized catalysts (See ESI). [f] Commercial catalyst. n.d.: not detected.

Next, the reaction parameters were optimized in order to increase the tricarballylate yield. First, the amount of $Nb_2O_5.nH_2O$ was varied: a smaller amount of $Nb_2O_5.nH_2O$ resulted in a lower tricarballylate yield (Table 2, entry 2), while an increased amount did not have a substantial effect (entry 3). Notably, the mole balance is inversely related to the amount of $Nb_2O_5.nH_2O$ present in the reaction mixture, confirming strong adsorption of triethyl citrate on the $Nb_2O_5.nH_2O$ surface. Secondly, the influence of the Pd amount was investigated: In absence of the hydrogenation catalyst, no tricarballylate products were observed, however, trace amounts of aconitate esters were detected (entry 4). This indicates that a hydrogenation catalyst is required for the conversion of the formed aconitate esters into tricarballylate esters, but even small amounts suffice; in presence of 0.1 mol% Pd, no aconitate esters were detected (entry 5) and in presence of 1.0 mol% Pd the tricarballylate yield increased to 37% (entry 6). A further increase to 2.0 mol% Pd had no additional benefit (entry 7). Varying the hydrogen pressure showed that a higher pressure resulted in a slightly higher tricarballylate yield (entry 8-10). From these results, it can be concluded that the hydrogenation of the generated aconitate esters proceeds smoothly on a standard Pd/C catalyst. However, since the dehydration of triethyl citrate is reversible (Scheme 2, **i**), the aconitate esters can also be hydrated again to form citrate esters on the $Nb_2O_5.nH_2O$ catalyst. Increasing the hydrogenation capacity of the system, either through more Pd or an increased hydrogen pressure, clearly leads to a faster hydrogenation of the dehydrated aconitate ester and thus in a faster irreversible conversion of these intermediates from the dehydration-hydration equilibrium, resulting in a higher tricarballylate yield. Increasing the reaction temperature resulted in a significant increase in tricarballylate yield, with a maximum of 58% at 170 °C (entry 11-14). However, at these elevated temperatures, the formation of methyl succinate esters was observed, through the decarboxylation of a hydrolyzed aconitate ester intermediate (Figure S8). When both the Pd content and the hydrogen pressure were increased at these elevated reaction temperatures, the reaction was again steered towards the desired tricarballylate products, producing a maximum yield of 63%, and only a 2% yield of methyl succinates with an associated mole balance of 65% (entry 15).

Direct recycling of both catalysts in a new catalytic experiment led to a considerable increase of the mole balance to 87%, indicating that the surface of $Nb_2O_5.nH_2O$ became saturated with citrate molecules in the first run (entry 16). Importantly, this strong interaction between the citrate molecules and the $Nb_2O_5.nH_2O$ surface does not hamper the efficiency of the reaction, since the yield of tricarballylates simultaneously increased to 82%, while only 5% of methyl succinates were observed. This proves that the surface-adsorbed esters remain available for exchange with fresh incoming ester reactants. Although methyl succinates are not the desired products, it must be noted that a small fraction of these esters will not be a problem for the intended final application; succinate esters are known to be efficient plasticizers for PVC, although plasticizing properties of methyl succinates are not documented yet.[18-20]

Table 2. Parameter optimization for the sequential dehydration – hydrogenation of triethyl citrate in CPME [a]

Entry	$Nb_2O_5.nH_2O$ [g]	Pd [b] [mol%]	P_{H_2} [bar]	T [°C]	Y_{PTC} [c] [%]	Y_{MS} [d] [%]	M. B. [e] [%]
1	0.10	0.5	10	150	25	n.d.	56
2	**0.05**	0.5	10	150	11	n.d.	69
3	**0.15**	0.5	10	150	27	n.d.	38
4	0.10	**0**	10	150	n.d.	n.d.	32
5	0.10	**0.1**	10	150	19	n.d.	65
6	0.10	**1.0**	10	150	37	n.d.	58
7	0.10	**2.0**	10	150	36	n.d.	62
8	0.10	0.5	**5**	150	26	n.d.	60
9	0.10	0.5	**15**	150	31	n.d.	62
10	0.10	0.5	**20**	150	33	n.d.	75
11	0.10	0.5	10	**140**	9	n.d.	69
12	0.10	0.5	10	**160**	45	n.d.	56
13	0.10	0.5	10	**170**	58	4	62
14	0.10	0.5	10	**180**	49	15	64
15	0.10	**1.0**	**20**	**170**	63	2	65
16 [f]	0.10	**1.0**	**20**	**170**	82	5	87

[a] Standard reaction conditions: 0.1 M TEC in cyclopentyl methyl ether (2 mL), 0.1 g $Nb_2O_5.nH_2O$, 0.5 mol% Pd, 150 °C, 10 bar H_2, 20 h. Variations on these reaction conditions are indicated in bold. [b] 5 wt% Pd/C. [c] Tricarballylate yield. [d] Methyl succinate yield. [e] Mole balance. [f] Recycling experiment of entry 15, where the catalytic system is directly recycled after two washing steps with cyclopentyl methyl ether (See ESI). n.d.: not detected.

When a less (trimethyl citrate (TMC)) and more bulky (tributyl citrate (TBC)) trialkyl citrate were applied as substrate, surprisingly similar yields of tricarballylate esters were obtained (ESI Figure S9). This demonstrates that through transesterification of the ester chains with the generated methanol from CPME, the difference in bulkiness of the substrate molecules is levelled out. Although CPME is a preferred green and environmentally friendly solvent, it is not entirely stable under the reaction conditions; thus it becomes difficult to maintain the initial ester chains of the substrate molecules. As a result, a mixture of tricarballylate molecules with different alkyl chain lengths is obtained, which is not desirable regarding plasticizer properties, since especially the more bulky tricarballylate esters are expected to possess the best plasticizing properties, by analogy with citrate based plasticizers.[4,10]

Bifunctional Pd/$Nb_2O_5.nH_2O$ catalysts in an inert and stable solvent

To avoid the loss of longer ester chains through transesterification, two inert organic solvents were evaluated for the sequential dehydration-hydrogenation of TEC (Table 3). Both toluene and methylcyclohexane do not possess any heteroatoms in their structure; thus breakdown and subsequent side reactions are rather improbable. In presence of these solvents, not only were the ester functionalities maintained, but also similar and even higher yields of TEPTC were obtained in respectively dry toluene (entry 3) and methylcyclohexane (entry 4), compared to the reaction in CPME (entry 1).

With the loss of ester functionalities being resolved and with this active and selective two-catalyst, one-pot system in hand, an emphasis was made on the development of bifunctional Pd/$Nb_2O_5.nH_2O$ catalysts. By immobilizing Pd^0 nanoparticles on the $Nb_2O_5.nH_2O$ surface, the diffusion distance between the acidic and the metal sites can be

reduced. As a result, a dehydrated aconitate intermediate will encounter a hydrogenation site faster on a bifunctional catalyst; thus, the aconitate ester is more likely to be hydrogenated faster to the desired tricarballylate ester, instead of being hydrated again to the initial citrate ester. In addition, a bifunctional catalyst would also simplify the system and facilitate the recyclability by ensuring a constant ratio between acid and metal sites. Since the acidity of the $Nb_2O_5.nH_2O$ plays an important role in the dehydration of the citrate molecules, a thermochemical reduction in propylene carbonate was chosen to synthesize the $Pd/Nb_2O_5.nH_2O$ catalysts;[33,55,56] *via* this method, the amorphous character and acidity of the oxide support are well-preserved (Table S1). In-depth characterization of these catalysts is provided in previous work by our group.[33]

When these $Pd/Nb_2O_5.nH_2O$ catalysts are applied for the sequential dehydration-hydrogenation of triethyl citrate (TEC) in methylcyclohexane as solvent, a slight increase in the yield of triethyl tricarballylate is noticed for $Pd/Nb_2O_5.nH_2O$ with low metal loadings, with a maximum of 33% when the 0.2 wt% $Pd/Nb_2O_5.nH_2O$ catalyst is employed (entry 6). At higher loadings, the yield of TEPTC decreased as a result of the lower amount of Brønsted acid sites on the catalysts as observed by pyridine adsorption FTIR (Table S1). A smaller amount of acid sites leads to a slower dehydration and to a lower yield of triethyl tricarballylate (entry 7 & entry 8).

Table 3. Sequential dehydration - hydrogenation in presence of non-reactive solvents and bifunctional Pd/Nb2O5.nH_2O catalysts. [a]

Entry	Catalyst	Pd	Solvent	Y_{PTC} [b] [%]	Y_{MS} [c] [%]	Esters [d] [%]	M. B. [e] [%]
1	$Nb_2O_5.nH_2O$	0.5 mol% [f]	Cyclopentyl methyl ether	25	n.d.	64 [h]	56
2	$Nb_2O_5.nH_2O$	0.5 mol% [f]	Toluene	16	n.d.	> 99	85
3	$Nb_2O_5.nH_2O$	0.5 mol% [f]	Dry toluene	24	n.d.	> 99	83
4	$Nb_2O_5.nH_2O$	0.5 mol% [f]	Methylcyclohexane	30	n.d.	> 99	52
5	$Pd/Nb_2O_5.nH_2O$	0.1 wt% [g]	Methylcyclohexane	32	n.d.	> 99	34
6	$Pd/Nb_2O_5.nH_2O$	0.2 wt% [g]	Methylcyclohexane	33	n.d.	> 99	43
7	$Pd/Nb_2O_5.nH_2O$	0.6 wt% [g]	Methylcyclohexane	17	n.d.	> 99	41
8	$Pd/Nb_2O_5.nH_2O$	1.0 wt% [g]	Methylcyclohexane	11	1	> 99	41

[a] Reaction conditions: 0.1 M TEC in solvent (2 mL), 0.1 g $Nb_2O_5.nH_2O$ (entry 1-4) or 0.1 g $Pd/Nb_2O_5.nH_2O$ (entry 5-8), 150 °C, 10 bar H_2, 20 h. [b] Tricarballylate yield. [c] Methyl succinate yield. [d] Percentage of esters that is maintained after reaction. [e] Mole balance. [f] mol% of Pd (5 wt% Pd/C) with respect to citric acid. [g] wt% of Pd with respect to $Nb_2O_5.nH_2O$, where 0.1 wt% equals 0.5 mol%. [h] Also 24% of methyl esters were present. n.d.: not detected.

Finally, the sequential dehydration-hydrogenation of different trialkyl citrates was revisited in methylcyclohexane and the conditions were optimized to increase the yield of the respective tricarballylates. Whereas in presence of CPME similar tricarballylate yields were obtained for the sequential dehydration-hydrogenation of TMC, TEC and TBC (*vide supra* & Figure S9), clear differences were observed when methylcyclohexane was applied as solvent (Figure 1). In the case of TMC, a reaction temperature of 160 °C seems optimal, while for TEC and TBC 170 °C is preferred, although the formation of methyl succinate esters is more pronounced at 170 °C for these substrates. From the results at a reaction temperature of 150 °C, it appears that the tricarballylate yield is inversely correlated with the ester chain length: as the length of the ester chains increases, the interaction between the hydroxyl group of the substrate citrate molecule and the solid bifunctional catalysts becomes more difficult due to steric hindrance. However, at higher temperatures some peculiar trends are observed. While for TEC and TBC an increase in tricarballylate yield is observed, which is in accordance with previous findings on the endothermic citrate dehydration (Table 2), the yield of TMPTC did not increase at elevated temperatures. This can be explained by the differences in polarity between the different substrate and product molecules. Since methylcyclohexane is a very apolar solvent and TMC and TMPTC still possess a reasonable polarity as a result of their short methyl ester chains, they will both have a higher affinity for the oxophilic $Nb_2O_5.nH_2O$ than the apolar solvent. As a result, not only TMC remains well-adsorbed on the catalyst, but also TMPTC will be prone to stick onto the catalyst; hence the low mole balances for the experiments with TMC as a substrate. This affinity for the catalyst decreases as the polarity of the molecule lowers, and as the results confirmed, the mole balance increased concurrently with the length of the ester chains and is thus inversely correlated with the polarity of the substrate and product molecules.

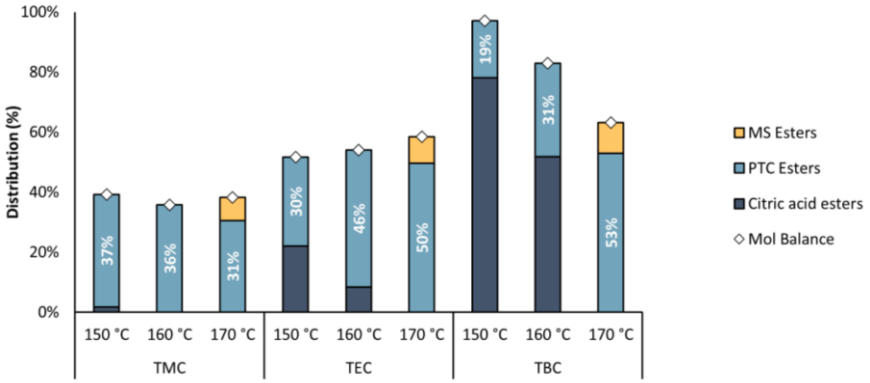


Figure 1. Temperature optimization for the dehydration-hydrogenation of different citric acid esters in presence of 0.2 wt% Pd/Nb_2O_5.*n*H_2O. The percentages denote the yield of PTC esters. Reaction conditions: 0.1 M citrate in methylcyclohexane (2 mL), 0.1 g 0.2 wt% Pd/Nb_2O_5.*n*H_2O, 10 bar H_2, 20 h.

To elucidate whether the catalytic surface becomes saturated and if the tricarballylate yield increases upon reuse, like in previous research on the dehydration-hydrogenation of citric acid,[33] recycling experiments were conducted (Figure 2). The dehydration-hydrogenation of TMC was performed at 160 °C, while the experiments with TEC and TBC were performed at 170 °C. The hydrogen pressure was increased to 20 bar for all experiments, which led to a low production of the undesired methyl succinates (≤ 4%) during all runs for each substrate.

When TMC is applied as substrate, a strong increase in TMPTC yield (93%) is observed in subsequent runs and the mole balance is almost completely restored (97%). This indicates that the surface is saturated after the first run; however, this saturation does not hamper the process in the following runs, since very similar results are obtained in run 2 and run 3. For TEC, the increase in TEPTC yield is less pronounced in the subsequent runs (2-4) and a plateau value is obtained. This yield could be further increased to 85% when the reaction time was prolonged to 30 h (run 5). Very similar trends as for TEC are observed for the dehydration-hydrogenation of TBC, with a maximal yield of 76% after 30 h (run 3). Thus, as the ester chains increase in length, the dehydration-hydrogenation sequence becomes more difficult due to steric hindrance around the central quaternary carbon, as was already observed in Figure 1 at 150 °C. In the case of TEC and TBC, the mole balance is not completely restored, not even after five consecutive runs with TEC as substrate. To further investigate this, the 0.2 wt% Pd/Nb_2O_5.*n*H_2O catalyst that was applied during the reusability experiments of TEC was collected after the 5th run, dried and subsequently stirred in CD_3OD at 60 °C for 20 h in an effort to desorb the remaining molecules from the surface of the bifunctional catalyst (ESI 3.6, Figure S11). It was observed that not only citrate molecules but also tricarballylate esters were still adsorbed on the catalyst surface. As such, the yields of tricarballylate esters, and thereby the performance of the catalytic system, are slightly underestimated. However, it was also observed that the ^{1}H-NMR peaks were split into broad multiplets, which indicates that some of the esters were hydrolyzed and that the adsorbed molecules are not only present as triesters but also as mono- and diesters, or even tricarboxylic acid. Since this splitting is not observed in the spectra of the crude reaction mixtures, the hydrolyzed esters appear less soluble in the apolar methylcyclohexane and possess a higher affinity for the oxophilic catalyst. On the other hand, this also means that our procedure in methylcyclohexane renders high amounts of pure tricarballylate esters with only a small fraction of methyl succinate esters and that these esters, after evaporation of the solvent, could be directly used as plasticizers in flexible PVC plastics.

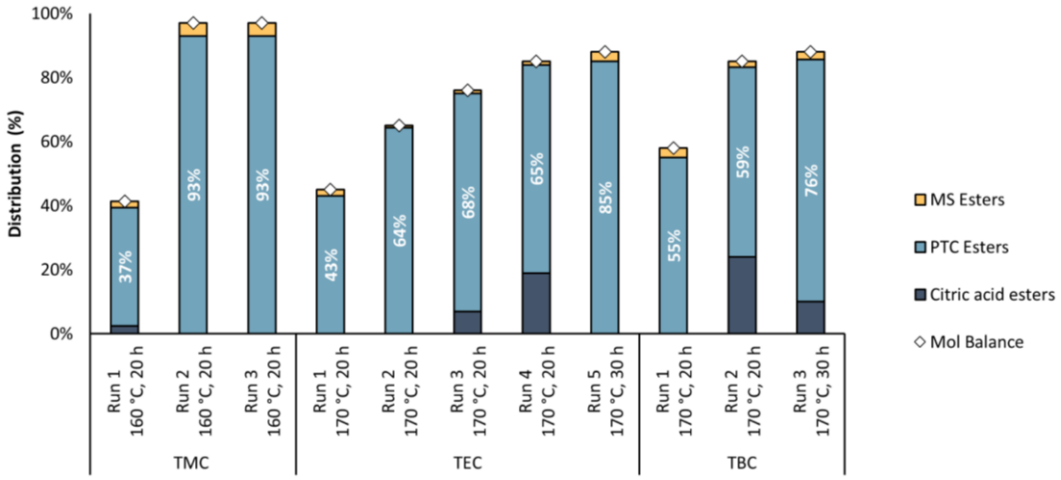


Figure 2. Direct reuse of 0.2 wt% Pd/Nb_2O_5.nH_2O for different citric acid ester substrate molecules. The percentages denote the yield of PTC esters. Reaction conditions: 0.1 M citrate in methylcyclohexane (2 mL), 0.1 g 0.2 wt% Pd/Nb_2O_5.nH_2O, 20 bar H_2, 20 h.

Conclusion

Summarizing, the synthesis of different trialkyl tricarballylate plasticizers directly from the respective citrate esters is presented through a one-step dehydration-hydrogenation process in presence of heterogeneous catalysts. The dehydration-hydrogenation of triethyl citrate was selected as model reaction for which Nb_2O_5.*n*H_2O together with a small amount of Pd/C proved to be the most efficient catalyst combination in cyclopentyl methyl ether as solvent. Although tricarballylate yields above 80% were obtained after 20 h at 160 °C with 20 bar H_2, cyclopentyl methyl ether turned out not to be entirely stable to the acidic Nb_2O_5.*n*H_2O catalyst, which led to undesired transesterification of the substrate and product esters by generated methanol. Switching to an inert methylcyclohexane solvent resolved this issue and the ester functionalities of the plasticizers were well preserved. Subsequent optimization of the dehydration-hydrogenation of triethyl citrate was performed in methyl cyclohexane in presence of Pd/Nb_2O_5.*n*H_2O bifunctional catalysts, where a low loading of 0.2 wt% proved to be optimal. Finally, the process was optimized with 0.2 wt% Pd/Nb_2O_5.*n*H_2O for the dehydration-hydrogenation of trimethyl, triethyl and tributyl citrate yielding 93%, 85% and 76% of the respective tricarballylate plasticizers under different optimized conditions, clearly surpassing previously developed systems.

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