

# Synthesis of hydroxyfatty esters by sequential epoxidation-hydrogenolysis: Solvent effects

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## ARTICLE INFO

### Keywords:

Tandem processes  
Hydrogenolysis  
Hydroxyfatty esters  
Fatty epoxides  
Solvent effects

## ABSTRACT

The tandem/sequential combination of epoxidation and hydrogenolysis for unsaturated fatty esters is not straightforward, due to incompatibility problems with the impurities present or generated in the used solvents. The chlorinated impurities in  $\alpha,\alpha,\alpha$ -trifluorotoluene leads to the formation of important amounts of chlorohydrins by HCl formation in the hydrogenolysis step. The use of trifluoroethanol (TFE) in the epoxidation step produces trifluoroacetic acid traces by oxidation, responsible for the opening of the epoxide with water and TFE. The solvent of choice was finally isobutyl acetate, which gathers the required physicochemical properties, with 85 % yield of hydroxystearates from methyl oleate in a sequential process.

## 1. Introduction

The transformation of renewable raw materials using catalytic methods fulfills two important principles of Green Chemistry [1,2] and the combination of several reactions in tandem/sequential<sup>1</sup> processes [3] should reduce the number of separation and purification steps, improving in this way the efficiency, and hence the sustainability, of those transformations. This strategy using homogeneous catalysts has been applied to the transformation of carbohydrates [4,5] and oleochemicals [6,7]. However, the use of heterogeneous catalysts for this purpose [8,9] should improve the applicability and sustainability of the processes. In fact, multistep transformations of polysaccharides [10,11] or sugar-derived polyols [12] with heterogeneous catalysts have been described, for example for the production of bisphenol A substitutes [13]. However, in spite of the industrial importance of oleochemistry [14–16], the examples of multistep transformations of oleochemicals with heterogeneous catalysts are more scarce [17,18]. In this context, we have recently reported the sequential epoxidation and Meinwald rearrangement of unsaturated fatty esters with two solid catalysts to obtain ketofatty esters [19].

The introduction of a hydroxyl group in the hydrocarbon chain of fatty acids opens the way to molecules with interesting properties [20] that may act as renewable monomers, able to form polyesters or

polyurethanes [21]. However, the direct hydration of a C=C double bond is a difficult task [22], and only some biocatalytic methods with hydratases of microbial origin have shown to be successful [23,24], although in many cases with productivity problems [25]. The classical indirect method included the addition of a carboxylic acid, formic or acetic, catalyzed by a strong Brønsted acid, and the saponification of the formed carboxylate [26]. This method produced a mixture of the position isomers of the addition products [27], leading even to the formation of lactones [28]. Recently, the hydroxylation of unsaturated fatty esters through hydroboration-oxidation has been described [29], although with the problems associated to the handling of borane. Alternatively, other authors described in the 60's the synthesis of hydroxyfatty acids or esters by hydrogenolysis of the corresponding epoxides catalyzed by Pd/C [30–32]. The system NaBH<sub>4</sub>/PEG showed to be unsuccessful for this purpose [33]. More recently, the hydrogenolysis has been described using sponge nickel catalyst, but it required harsher conditions of temperature and pressure [34]. Following our project for transformation of fatty esters with tandem/sequential heterogeneous catalysis [19], we present our results in the sequential epoxidation-hydrogenolysis process to obtain hydroxyfatty esters (Scheme 1). In this strategy, the catalyst for the first reaction is filtered before the addition of the catalyst and reagents for the second one. In this way, both catalysts can be recovered separately to be reused, with or without reactivation, to reach their

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<sup>1</sup> The term “tandem catalysis” is more suitable for processes in which both catalysts are present in the reaction medium from the beginning. As in this case the catalysts are not present simultaneously in the medium, the term “sequential” has been used along the manuscript.

<https://doi.org/10.1016/j.apcata.2021.118270>

Received 12 March 2021; Received in revised form 18 June 2021; Accepted 20 June 2021

Available online 24 June 2021

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maximum productivity [35,36].

## 2. Experimental

Pd/C (Acros, wet with 50 wt% water, 10 wt% Pd of the dry solid) and Pd(OH)<sub>2</sub>/C (Aldrich, wet with 50 wt% water, 20 wt% Pd of the dry solid) were kept in a glovebox and used as received. Ti-SiO<sub>2</sub> was prepared from Merck 60 silica (pretreated with 1 M HNO<sub>3</sub>, washed, dried and calcined) and titanocene dichloride (Cp<sub>2</sub>TiCl<sub>2</sub>) as previously described [19]. The epoxides of oleate (*cis*-9,10-epoxystearate), erucate (*cis*-13,14-epoxydocosanoate), elaidate (*trans*-9,10-epoxystearate), ricinoleate (*cis*-9,10-epoxy-12(*R*)-hydroxystearate) and the diepoxides of linoleate (*cis*, *cis*-9,10,12,13-diepoxystearates) were obtained by epoxidation with *tert*-butyl hydroperoxide catalyzed by Ti-SiO<sub>2</sub> in TFT [19]. The catalyst was filtered, washed with dichloromethane and the mixture of solvents were evaporated under reduced pressure. The epoxides were used in the hydrogenolysis reaction without further purification.

### 2.1. Hydrogenolysis general procedure

This general method was used with all the epoxides. A 10 ml Büchi reactor was charged with 500 mg of methyl *cis*-9,10-epoxystearate (1.6 mmol), 5 ml of 2,2,2-trifluoroethanol and 120 mg of catalyst (0.056 mmol Pd, 3.5 mol%). The reactor was filled with H<sub>2</sub> (5 bar) and the mixture was stirred at 65 °C. The reaction was monitored by GC until total conversion of the epoxystearate. The catalyst was filtered off and washed with dichloromethane. Methyl 9(10)-hydroxystearate was purified by column chromatography on silica with AcOEt/hexanes (1:9) as eluent and fully characterized by NMR.

### 2.2. Sequential epoxidation-hydrogenolysis

To a solution of methyl oleate (296.5 mg, 1 mmol) in isobutyl acetate (5 mL), the required amount of Ti-SiO<sub>2</sub> (15 μmol Ti) was added and the mixture was heated at 120 °C. TBHP (0.28 ml of 5.5 M solution in decane, 1.5 mmol) was added and the reaction was monitored by GC for 24 h (89 % conversion). After cooling to room temperature, the catalyst was filtered off and the solution was transferred to the Büchi reactor. Then, Pd/C (75 mg, 0.035 mmol Pd) was added, the reactor was filled with H<sub>2</sub> (5 bar) and the mixture was stirred at 65 °C. The reaction was monitored by GC.

## 3. Results and discussion

### 3.1. Hydrogenolysis of epoxystearate in TFT

Given that the optimal solvent in the epoxidation step was α,α,α-trifluorotoluene (TFT) [19], the hydrogenolysis of methyl *cis*-9,10-epoxystearate was tried with Pd/C in this solvent at 65 °C and 1 atm pressure of H<sub>2</sub>. After total conversion of the epoxide, the expected hydroxystearates were obtained with only 48 % selectivity. Surprisingly, the major by-products (29 % selectivity) were identified as methyl 9(10)-chloro-10(9)-hydroxystearate, the products of epoxide ring opening with HCl. The chlorine atom must come from the TFT solvent, which is industrially obtained from α,α,α-trichlorotoluene [37]. In this process,

the substitution of all the chlorine atoms must be incomplete, leading to the presence of PhCCl<sub>3</sub>, PhCCl<sub>2</sub>F and PhCClF<sub>2</sub> in small amounts (1% overall content). In fact, the chlorine content in TFT was determined by X-ray fluorescence (XRF), leading to a value of 0.2 wt%. The hydrogenolysis of those compounds must generate HCl (hydrodechlorination), which is added to the epoxystearate. This point was corroborated by carrying out the hydrogenolysis in chlorobenzene as solvent, leading to 100 % of chloro-hydroxystearates (Scheme 2). The attempts to perform the reaction in TFT with *N,N*-diisopropylamine to trap the HCl formed were unsuccessful due to the inhibition of the Pd catalyst.

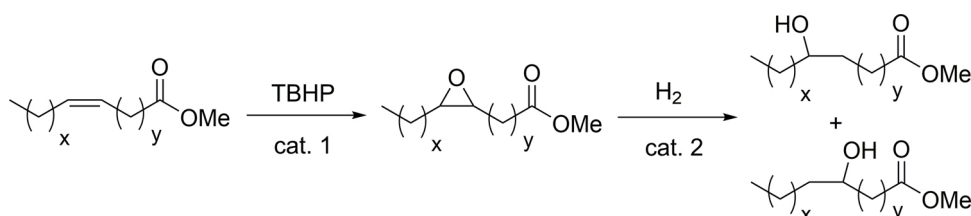
### 3.2. Solvent and H<sub>2</sub> pressure effects

Hence, a series of alternative solvents were tested in hydrogenolysis of methyl *cis*-9,10-epoxystearate at atmospheric pressure and the results are gathered in Table 1. The solvents described in the literature for this type of reaction are glacial acetic acid [31,32] and ethanol [30]. Both solvents were tested in this reaction but, three types of by-products were obtained in addition to the expected hydroxystearates (1) (Scheme 3). The ketostearates (2) are produced by a Meinwald rearrangement, which is catalyzed by acids. The presence of the two position isomers in 1 and 2 was confirmed by GC-MS. Methyl stearate (3) is the product of epoxide deoxygenation and subsequent hydrogenation of the formed C=C double bond. Both types of by-products, ketostearates (2) and stearate (3), had been already detected in the hydrogenolysis of 6,7-epoxystearic acid in ethanol [30], in around 40 % selectivity, and in the hydrogenolysis of methyl 9,10-epoxystearate in acetic acid [32], although in a non-defined amount. The last by-product detected was the product of epoxide ring opening with the solvent, either acetic acid (4a) or ethanol (4b). This ring opening was more important in the case of acetic acid (entry 1), which also promoted a partial esterification of the hydroxystearate to acetoxystearate. On the other hand, deoxygenation was more favorable in ethanol (entry 2), although less important than in previous results [30]. Thus, the selectivity to hydroxystearate was not higher than 71 % in any case.

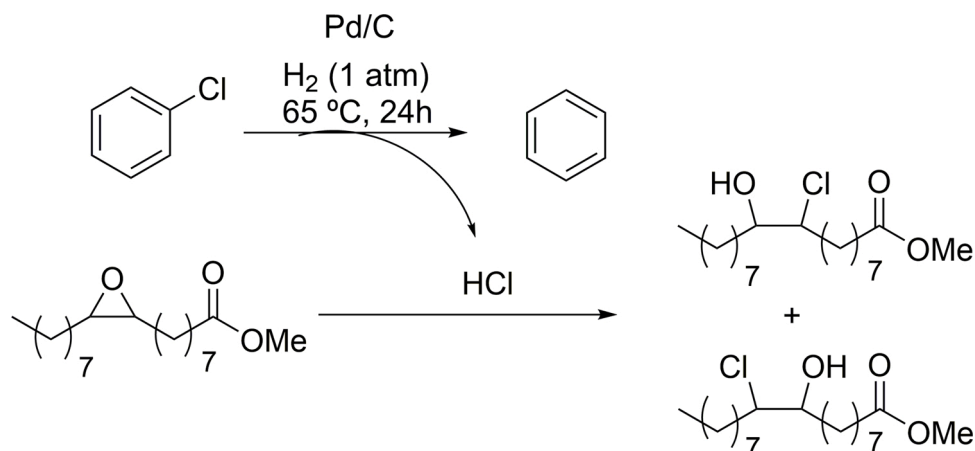
The epoxide ring opening should be avoided by using a less nucleophilic alcohol, such as *tert*-butanol. Unfortunately, deoxygenation was even more favorable (29 % selectivity) than in the case of ethanol, and selectivity to hydroxystearate decreased up to 58 % (entry 3). Thus, ethyl acetate was also chosen as an example of aprotic solvent and 2,2,2-trifluoroethanol (TFE) as an alcohol more acidic than ethanol but less sterically hindered than *tert*-butanol. The results with both solvents were similar (entries 4 and 5), with very low (in EtOAc) or null (in TFE) deoxygenation, and a constant rearrangement to ketostearate (2) (15 % selectivity), leading to a high selectivity to hydroxystearates (1) (82–85 %).

As the ketostearates (2) must be produced by the acidity of the catalyst [38], Pd(OH)<sub>2</sub>/C was tested (entries 6–8) in an attempt to decrease the acidity and then, the selectivity to ketostearate. The first observed effect was the significantly lower activity of the catalyst, with conversions in the range of 36–80 % after 24 h. The selectivity to ketostearate was not modified, but surprisingly *tert*-butanol was the best solvent (entry 6) with the highest conversion and almost no selectivity to stearate by deoxygenation.

Another way to favor kinetically the hydrogenolysis over the acid



Scheme 1. Catalytic sequential epoxidation-hydrogenolysis of unsaturated fatty esters.



**Scheme 2.** Pd/C catalysed reaction of methyl *cis*-9,10-epoxystearate with H<sub>2</sub> in chlorobenzene.

**Table 1**

Effect of solvent and catalyst on the hydrogenolysis of methyl *cis*-9,10-epoxystearate at atmospheric pressure.<sup>a</sup>

Entry	Catalyst <sup>b</sup>	Solvent	Conv. (%)	Selectivity (%)			
				1	2	3	4
1	Pd/C (10 %)	HOAc	98	61 <sup>c</sup>	14	4	21
2		EtOH	95	71	11	13	5
3		<i>t</i> BuOH	>99	58	13	29	0
4		EtOAc	>99	82	15	3	0
5		TFE <sup>d</sup>	>99	85	15	0	0
6	Pd(OH) <sub>2</sub> /C (20%)	<i>t</i> BuOH	80	85	13	2	0
7		EtOAc	36	78	17	5	0
8		TFE <sup>d</sup>	64	81	16	3	0

<sup>a</sup> Reactions were carried out in a round-bottom flask at 65 °C with a H<sub>2</sub> balloon. The scale was 0.8 mmol of epoxide in 3 ml solvent. Results after 24 h.

<sup>b</sup> Amount required for 3.5 mol% of Pd.

<sup>c</sup> 50 % hydroxystearate + 11 % acetoxystearate.

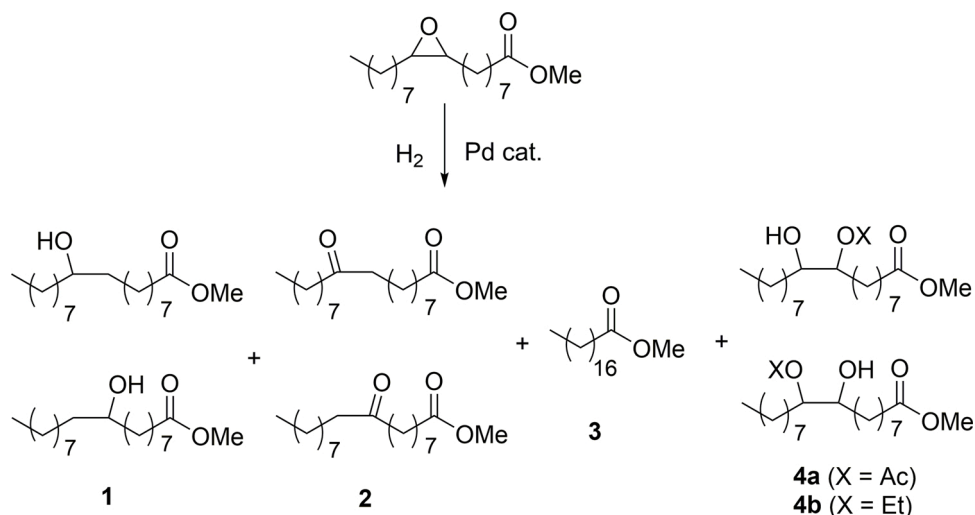
<sup>d</sup> TFE = 2,2,2-trifluoroethanol.

catalyzed reactions (Meinwald rearrangement and epoxide ring opening) would be the increase in hydrogen pressure. The results at 5 bar are gathered in Table 2. In most cases, conversion was complete after only 6 h. As expected, the result in HOAc was significantly better at higher pressure (entry 1), with 82 % selectivity to hydroxystearates, although a small part of them were obtained again in the form of acetates. The

selectivities to the acid-catalyzed reactions were reduced to 7% and 6% for Meinwald rearrangement and epoxide ring opening, respectively. However, in ethanol (entry 2) the increase in pressure improved the side deoxygenation reaction, with a significant reduction in the selectivity to hydroxystearates (only 57 %).

On the contrary, in *tert*-butanol (entry 3) the deoxygenation was somewhat reduced, although it remained still important, leading to 66 % selectivity to the hydroxystearates. The reactions in EtOAc (entry 4) and TFE (entry 5) showed a slight but significant improvement in the selectivity, up to 89 %. The similar results in both solvents, irrespective from the H<sub>2</sub> pressure, indicate that a protic solvent is not necessary to carry out the hydrogenolysis of the epoxide. Two additional fluorinated alcohols were tried as possible alternative to TFE. 1,1,1,3,3,3-Hexafluoroisopropanol (HFIP) is more acidic than TFE. It led to the same selectivity but the reaction was less efficient with regard to conversion (entry 6). 1,3-Bis(2,2,2-trifluoroethoxy)propan-2-ol (abbreviated as 3F03 F) is a solvent derived from glycerol [39,40], that has been already used in our group for different catalytic processes [41,42]. In this solvent (entry 7) the conversion of epoxystearate was complete after 6 h, but the selectivity to hydroxystearate was slightly lower (82 %) than in TFE (89 %). Thus, the use of Pd/C (10 %) in TFE or EtOAc under 5 bar pressure of H<sub>2</sub> was taken as the optimal conditions for this reaction.

As recoverability is one of the most interesting features of the heterogeneous catalysts, Pd/C was recovered and reused 8 times under the same conditions in TFE, with conversion and the same selectivity (87–89



**Scheme 3.** Hydrogenolysis of methyl *cis*-9,10-epoxystearate.

**Table 2**Effect of solvent on the hydrogenolysis of methyl *cis*-9,10-epoxystearate with 5 bar H<sub>2</sub>.<sup>a</sup>

Entry	Solvent	Conv. (%)	Selectivity (%)			
			1	2	3	4
1	HOAc	98	82 <sup>b</sup>	7	5	6
2	EtOH	98	57	6	32	5
3	<i>t</i> BuOH	>99	66	14	20	0
4	EtOAc	>99	89	8	3	0
5	TFE <sup>c</sup>	>99	89	11	0	0
6	HFIP <sup>d</sup>	65	88	12	0	0
7	3F03F <sup>e</sup>	>99	82	18	0	0
8	<sup>t</sup> BuOAc	>99	87	9	4	0

<sup>a</sup> In a scale of 1.6 mmol of epoxide in 5 ml solvent using Pd/C (10 %) as catalyst (3.5 mol% Pd) at 65 °C. Results after 6 h.

<sup>b</sup> 75 % hydroxystearate + 7% acetoxystearate.

<sup>c</sup> TFE = 2,2,2-trifluoroethanol.

<sup>d</sup> HFIP = 1,1,1,3,3,3-hexafluoroisopropanol.

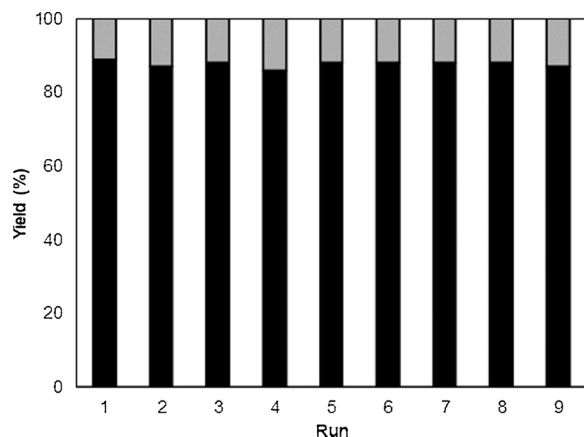
<sup>e</sup> 3F03 F = 1,3-bis(2,2,2-trifluoroethoxy)propan-2-ol.

%) to hydroxystearate in the 9 cycles (Fig. 1). Thus, no deactivation was detected under these optimal conditions.

### 3.3. Hydrogenolysis of other fatty epoxides

Two other simple epoxyfatty esters were made react under the optimal conditions (Scheme 4). The hydrogenolysis of the longer methyl *cis*-13,14-epoxydocosanoate (C22) proceeded in a similar way, with the same selectivity (88 %) to the hydroxyfatty esters, methyl 13(14)-hydroxydocosanoate. However, the methyl *trans*-9,10-epoxystearate was less reactive, with only 88 % conversion after 6 h (quantitative after 24 h), and less selective to hydroxystearates (79 %). None of those epoxides gave saturated fatty esters, with ketostearates as the only by-products.

The presence of an additional functional group was a source of side reactions, leading to more complicated mixtures of products. In the case of methyl *cis*-9,10-epoxy-12(*R*)-hydroxystearate (mixture of two diastereomeric epoxides of ricinoleate, Scheme 5), the reaction was not complete after 24 h, with only 86 % conversion. The expected hydrogenolysis products would be the 9,12-dihydroxystearates (5) and 10,12-dihydroxystearates (6), which in fact were obtained with 38 and 47 % selectivity, respectively. The 1,4 relative position is prone to the formation of furanic moieties [43,44]. The acidity of the catalyst, demonstrated by the contribution of the Meinwald rearrangement, would be responsible for the formation of the hydroxytetrahydrofuran (7) (9% selectivity) by attack of the 12-hydroxy group to the position 9 of the epoxide, as observed in our previous work [19]. The formation of the



**Fig. 1.** Reuse of Pd/C in the hydrogenolysis of methyl *cis*-9,10-epoxystearate in TFE. Yields of: (■) hydroxystearates (1) and (■) ketostearates (2).

unsubstituted tetrahydrofuran (8) (6% selectivity) can be envisaged through a dehydration-hydrogenation process from the hydroxytetrahydrofuran (7).

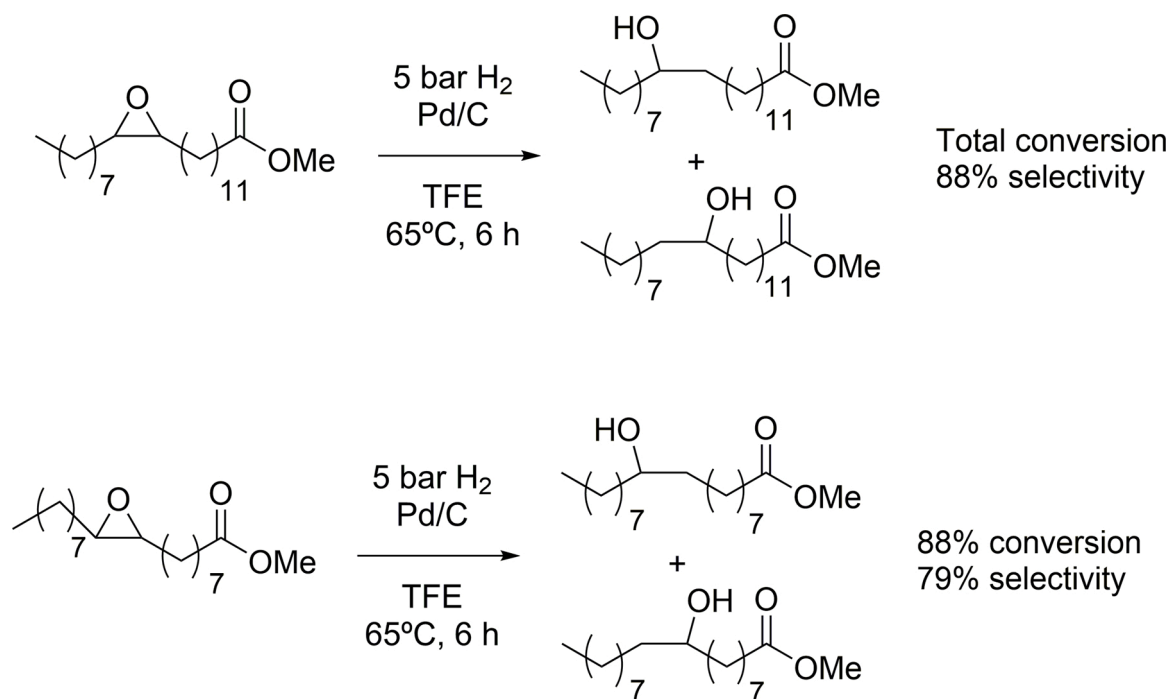
Finally, the hydrogenolysis of the methyl *cis,cis*-9,10:12,13-diepoxyestearate (mixture of diastereomers of linoleate diepoxide, Scheme 6) gave total conversion after 30 h, but an even more complicated reaction mixture was obtained. As expected, diols were the major products, with a selectivity of 59 %, but only 10,12-dihydroxystearate (6) (31 % selectivity) was unequivocally identified. The other 28 % corresponded to a single GC peak, with same retention time than 9,12-dihydroxystearate (5). However, in this case the other 1,4-diol, 10,13-dihydroxystearate (9), would be also obtained, and both the NMR and MS spectra of the 9,13-dihydroxystearate (10) and the mixture of (5) and (9) would be nearly indistinguishable. Additionally, several tetrahydrofuranic products were identified. Those with a hydroxyl group, either in the tetrahydrofuran ring (7 and 11) or in  $\alpha$  position (12 and 13), must come from the acid-promoted cyclization of the epoxyhydroxy intermediates generated in the first hydrogenolysis (Scheme 7). In fact, a similar result had been observed in the acid catalyzed ring-opening of this diepoxide [45]. Those hydroxytetrahydrofurans were obtained with 33 % selectivity. Finally, the unsubstituted tetrahydrofurans (8 and 13) were obtained with 8% selectivity.

### 3.4. Sequential epoxidation + hydrogenolysis

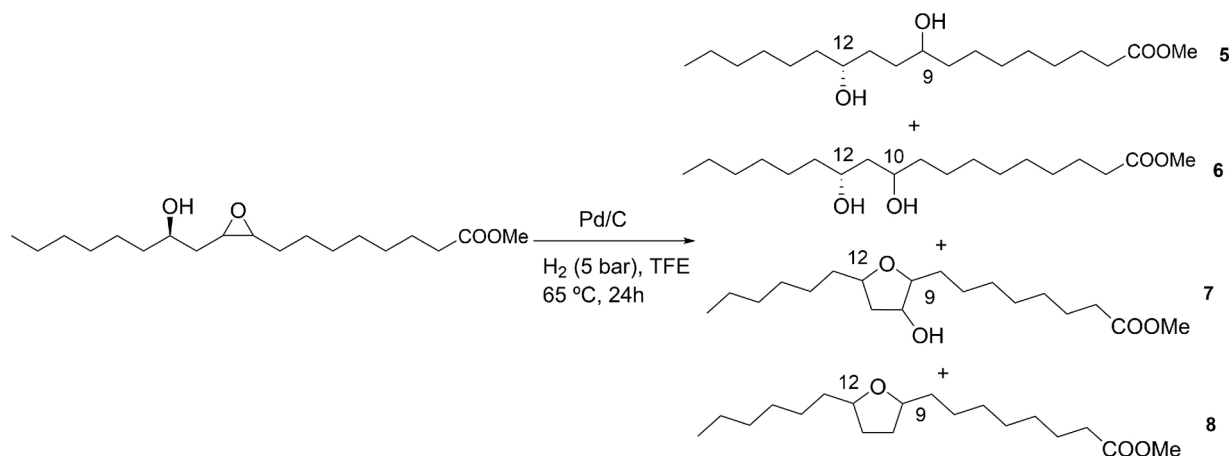
Thus, sequential epoxidation-hydrogenolysis process with methyl oleate was tried in the optimal solvents for hydrogenolysis. TFE was firstly chosen, as it had been shown good properties as solvent in other epoxidation reactions [46]. Under the optimal conditions of epoxidation [19], total conversion was obtained with *tert*-butyl hydroperoxide (TBHP) after 3 h and then the Ti-SiO<sub>2</sub> catalyst was filtered off, the Pd/C catalyst was added to the crude reaction mixture and 5 bar H<sub>2</sub> were introduced in the reactor. The analysis of the results (Table 3, entry 2) demonstrated that some additional side reactions took place (Scheme 8). The products of epoxide ring-opening with water and TFE were obtained with 7% and 11 % yield respectively, whereas yields of ketostearates and hydroxystearates were 12 % and 50 %. The total selectivity for products promoted by acid catalysis (diol, trifluoroethoxy-alcohol, and ketone) was 38 %, significantly higher than the selectivity observed in the single hydrogenolysis reaction (11 %, Table 2 entry 5). This seems to indicate the presence of an additional acid, probably traces of trifluoroacetic acid (TFA) obtained by oxidation of TFE under the epoxidation conditions. In fact, when the hydrogenolysis was repeated in TFE with a small amount of trifluoroacetic acid (TFA/epoxystearate molar ratio = 0.25) the result was quite similar, with yields of 42 % for hydroxystearates, and 58 % of products promoted by acid catalysis (9% of ketostearates, 36 % of trifluoroethoxy-hydroxystearates and 13 % of dihydroxystearate).

Thus, 3F03F was tried for the epoxidation reaction (entry 3), as it would not be able to produce an acid upon oxidation. However, the epoxidation was significantly slower, 76 % conversion after 6 h, and a substantial amount of Meinwald rearrangement was observed (20 % yield), so this solvent was not suitable either for a sequential process and the hydrogenolysis of the crude was not tried.

In the other optimal solvent for hydrogenolysis, ethyl acetate (entry 4), the epoxidation was significantly slower, but anyway, the crude of the epoxidation reaction (77 % epoxide + 23 % oleate) was submitted to hydrogenolysis. 95 % conversion was obtained after 24 h, although the final mixture contained only 60 % of hydroxystearate, together with 12 % of ketostearate, from Meinwald rearrangement, and 23 % of stearate obtained from the hydrogenation of the remaining oleate. The poor result in epoxidation may be due to the temperature limit (b.p. 77 °C) and hence isobutyl acetate (b.p. 116 °C) was considered as an alternative solvent with also good environmental parameters [47]. In a first test, the hydrogenolysis (Table 2, entry 8) performed in a similar way as ethyl acetate, and the sequential reaction was more efficient (Table 3, entry 5), with 93 % conversion in the epoxidation reaction and a final yield of



**Scheme 4.** Hydrogenolysis of methyl *cis*-13,14-epoxydocosanoate and methyl *trans*-9,10-epoxystearate.



**Scheme 5.** Hydrogenolysis of methyl *cis*-9,10-epoxy-12(*R*)-hydroxystearate.

hydroxystearates of 85 %.

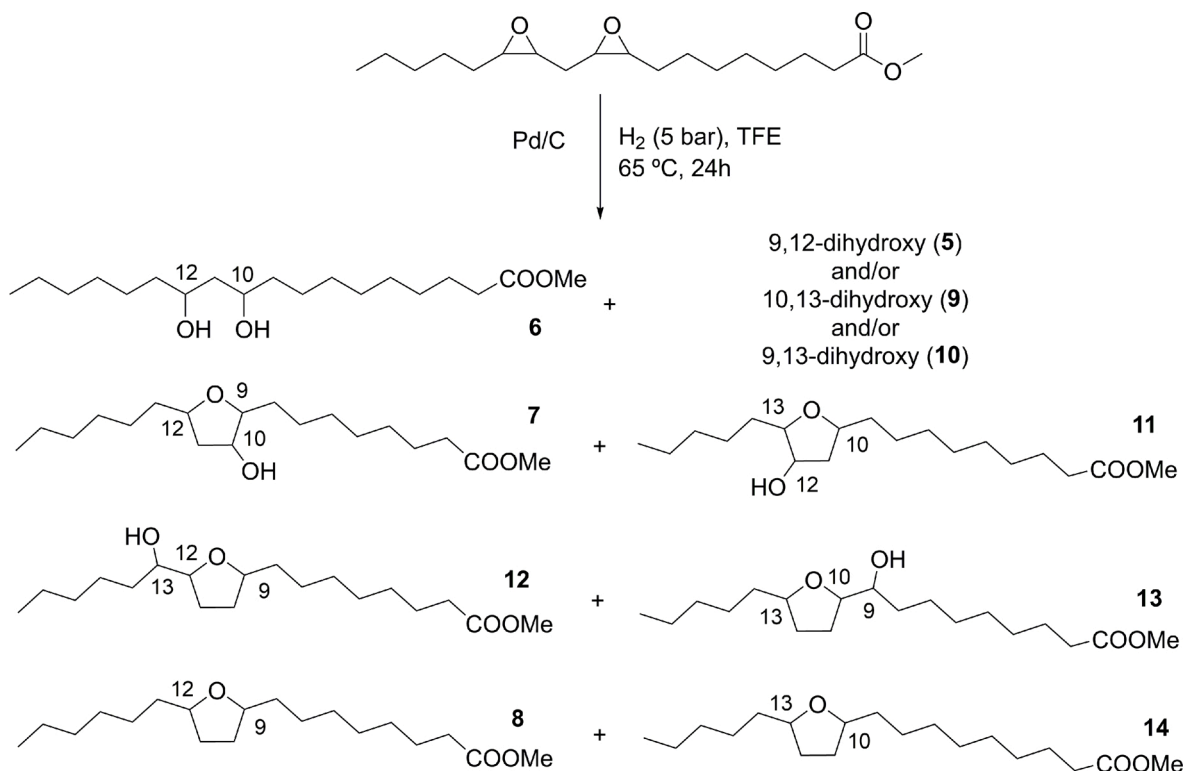
Finally, the recovery of the catalysts in this sequential process was tried. As shown in a previous work [19], the Ti-SiO<sub>2</sub> catalyst required additional calcination after recovery in several runs, and in this case the catalyst was calcined after each two runs. As can be seen in Fig. 2, the Ti catalyst was deactivated more quickly when isobutyl acetate was used as a solvent instead of TFT

Conversion to epoxide in the range of 83–88 % was obtained in runs 2–4, but the conversion decreased rapidly from run 5 and the activity was not recovered in spite of the calcination. However, Pd/C kept its activity and the yield of hydroxystearates was only dependent on the amount of epoxide in the crude of the first reaction, with a nearly constant amount of ketostearate (8–10 %) and an increasing amount of stearate coming from the unconverted oleate. Thus, the recovery of the Ti catalyst is less efficient in isobutyl acetate than in TFT. Hence, the sustainability of the single-solvent (isobutyl acetate) sequential process in comparison with the typical method in two different solvents must be fully evaluated, taking into account the energy consumption by the

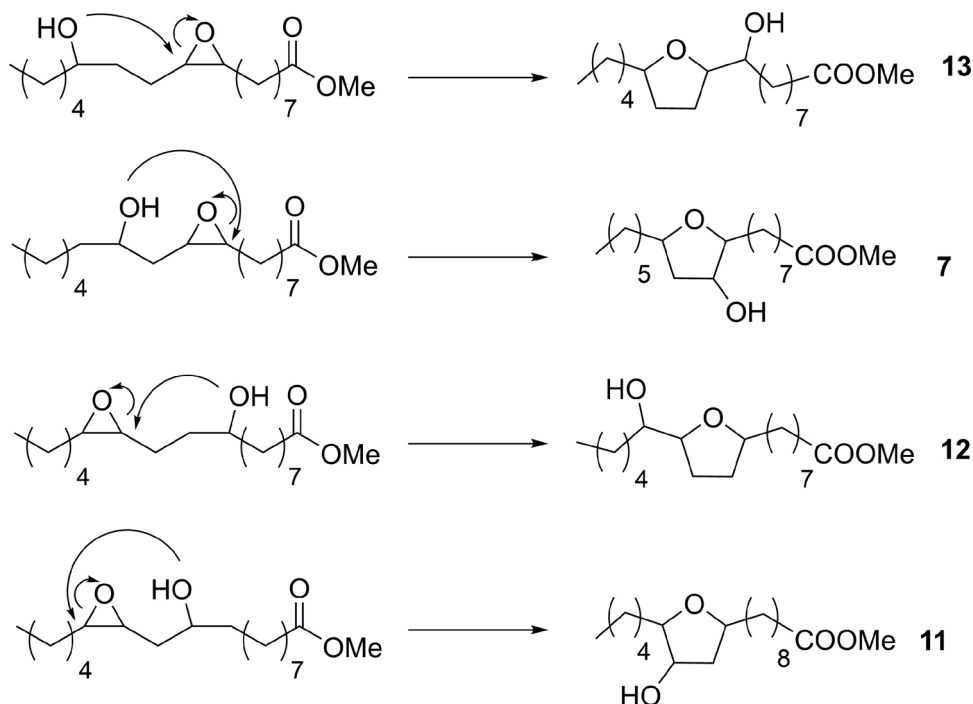
evaporation of the solvent in between the two reactions and the environmental concerns of the fluorinated TFT (NFPA 704 diamond: 3 3 1 [48]) used as a solvent in the epoxidation step in comparison with the environmentally more friendly isobutyl acetate (NFPA 704 diamond: 1 3 0 [49]).

#### 4. Conclusions

The Pd-catalyzed hydrogenolysis of epoxyfatty esters leads to the corresponding hydroxyfatty esters (mixtures of regioisomers). The activity and selectivity of the reaction are controlled by the solvent and the H<sub>2</sub> pressure, with a maximum of 89 % selectivity at total conversion of *cis*-epoxystearate under 5 bar H<sub>2</sub> pressure in either TFE or ethyl acetate, showing that a protic solvent is not required for this process. Moreover, the Pd/C catalyst can be used in 9 consecutive cycles without any loss of activity or selectivity. The presence of additional functionalities, such as a hydroxyl group or a second epoxide, produces cyclic by-products with tetrahydrofuran structure, although the alcohols (diols in those cases)



**Scheme 6.** Hydrogenolysis of methyl *cis,cis*-9,10:12,13-diepoxy stearate.



**Scheme 7.** Cyclization of partially hydrogenated methyl *cis,cis*-9,10:12,13-diepoxy stearate.

are still the main products of the reaction.

The attempts to carry out a sequential epoxidation-hydrogenolysis process have shown some incompatibilities of the solvents used in both reactions. In one case, the traces of chlorinated compounds in  $\alpha,\alpha,\alpha$ -trifluorotoluene leads to the formation of HCl by hydrodechlorination, which is responsible for the generation of chlorohydrins. In other case, the epoxidation medium (oxidant and catalyst) promotes

the oxidation of a small amount of TFE, leading to trifluoroacetic acid traces, which are able to catalyze side reactions such as the Meinwald rearrangement (to ketone), the hydrolysis (to diol) and the alcoholysis of the epoxide. Another efficient solvent for hydrogenolysis, the glycerol derivative 3F03 F, favors the Meinwald rearrangement as an important side reaction when used in the epoxidation reaction. Aprotic ethyl acetate is less efficient in epoxidation, due to the temperature limit, and

**Table 3**  
Solvent effect on the sequential epoxidation + hydrogenolysis of methyl oleate.<sup>a</sup>

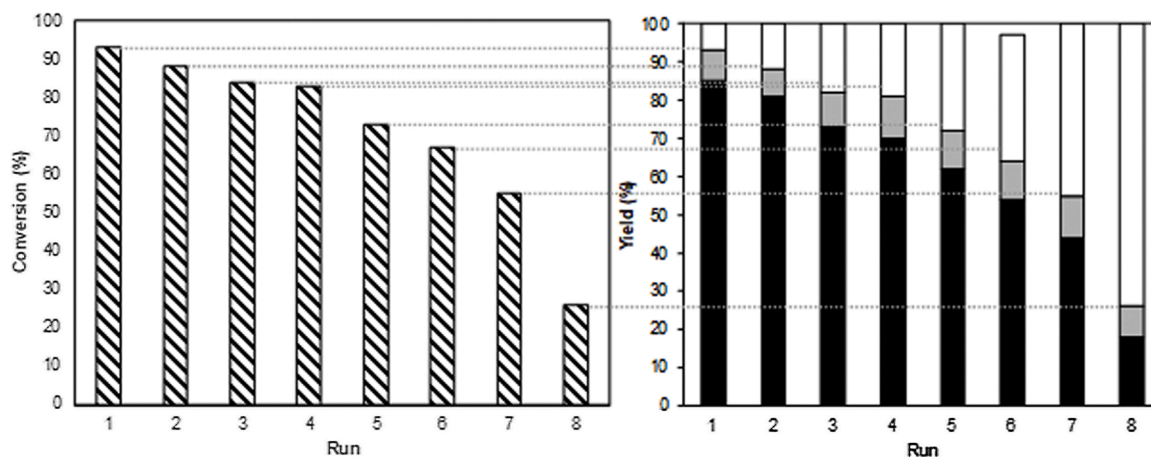
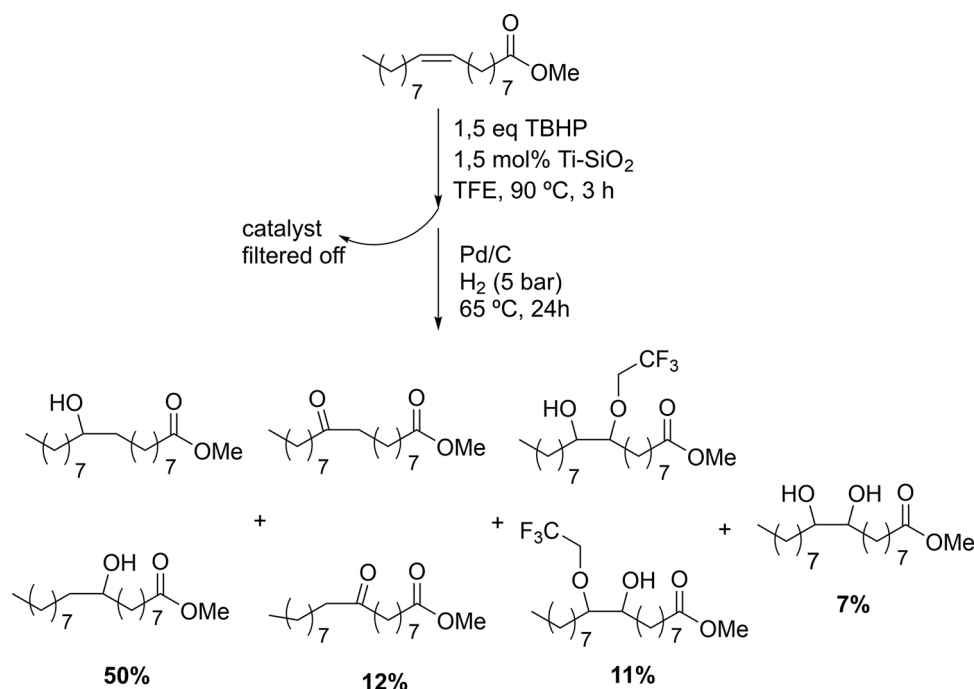
Entry	Solvent	Epoxidation		Hydrogenolysis (composition of the reaction mixture, %)				
		Time (h)	Conv. (%)	Time (h)	1	2	3	Others
1	TFT	1	>99	24 <sup>b</sup>	48	23	0	Chlorhydrin (29)
2	TFE	3 <sup>c</sup>	>99	24	50	12	0	Diol (7) Trifluoroethoxy-alcohol (11) Epoxide (20)
3	3F03F	6	76 <sup>d</sup>	–	–	–	–	–
4	EtOAc	24 <sup>c</sup>	77	24	60	12	23	Epoxide (5)
5	<sup>t</sup> BuOAc	8	93	24	85	8	7	–

<sup>a</sup> Reaction conditions: 1.0 mmol of oleate in 5 mL, Ti-SiO<sub>2</sub> (0.015 mmol Ti), 1.5 mmol TBHP (5.5 M in decane), 120 °C; after filtration of the Ti catalyst, 75 mg Pd/C (10 %) (3.5 mol% Pd) at 65 °C, 5 bar H<sub>2</sub>.

<sup>b</sup> Reaction at 1 atm H<sub>2</sub>.

<sup>c</sup> Epoxidation under reflux (≈ 78 °C).

<sup>d</sup> 56 % yield of epoxide +20 % yield of ketone (2).



**Fig. 2.** Reuse of the catalysts in the sequential epoxidation + hydrogenolysis. Left: recovery of Ti-SiO<sub>2</sub> in the epoxidation of methyl oleate in isobutyl acetate. Runs 1, 3, 5 and 7 performed after calcination of the catalyst. Right: recovery of Pd/C in the hydrogenolysis of the epoxidation crudes. Yields of: (■) hydroxystearates (1), (▒) ketostearates (2), and (□) stearate (3).

isobutyl acetate has shown to be the most suitable solvent for the sequential process, with a final yield of hydroxystearates of 85 %. The catalyst recovery in the sequential process have shown that the Ti-SiO<sub>2</sub> catalyst loses activity gradually, leading to an efficient process (>80 % yield of hydroxystearates) in four runs, although the recovery of Pd/C can be extended to at least 8 runs. Thus, the recovery efficiency of Ti-SiO<sub>2</sub> in isobutyl acetate is lower than in TFT, and the choice between single-solvent sequential or common two-solvents processes will depend on the full evaluation of the energy consumption and environmental risks associated with the fluorinated TFT.

#### CRedit authorship contribution statement

**Vicente Dorado:** Investigation, Methodology, Writing-Review & Editing. **Clara I. Herrerías:** Conceptualization, Supervision, Resources, Writing-Review & Editing. **José M. Fraile:** Conceptualization, Supervision, Project administration, Writing-Original Draft and Final Version.

#### Declaration of Competing Interest

The authors report no declarations of interest.

#### Acknowledgements

This work was financially supported by the Spanish Ministerio de Ciencia, Innovación y Universidades (project number RTI2018-093431-B-I00) and the Gobierno de Aragón (E37\_20R group, co-financed with Feder 2014-2020 “Construyendo Europa desde Aragón”).

#### Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:<https://doi.org/10.1016/j.apcata.2021.118270>.

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