

1 **Methanolysis of epoxidized soybean oil in continuous flow conditions**

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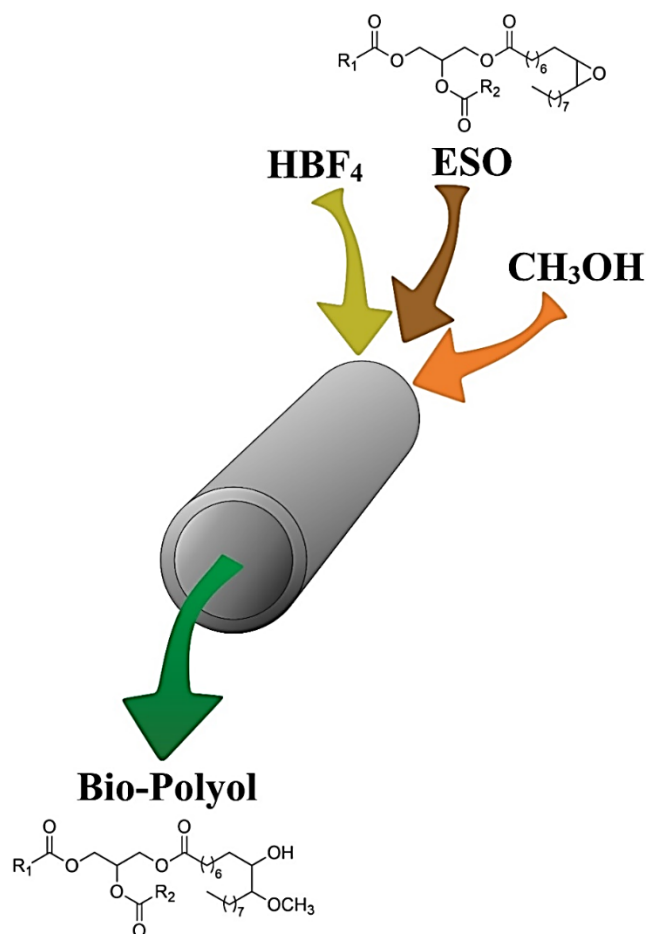
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9 10 **Abstract**

11 Bio-polyols synthesized from vegetables oils are a great alternative to petrochemical polyols for
12 polyurethanes industry. The simplest approach to bio-polyols synthesis involves epoxidation of
13 carbon-carbon double bond of unsaturated fatty ester moieties and subsequent epoxide ring-opening
14 by nucleophilic reagents. In order to improve the latter process by increasing both productivity and
15 product quality, the advantages of flow chemistry were exploited, such as facile automation,
16 reproducibility, improved safety and process reliability, investigating for the first time in the
17 literature the methanolysis reaction of epoxidized soybean oil (ESO) in a continuous flow mode.
18 Compared with batch reaction, flow mode allowed the cut of the reaction time from 30 min to 2
19 min, and the reduction of catalyst concentration by an order of magnitude, which brought
20 significant benefits in terms of cost efficiency and eco-sustainability, rendering the method suitable
21 for industrial applications.

22 **Graphical Abstract**

23

24 **Keywords:** ESO, Bio-based, Polyol, Soybean oil, Flow mode25 **1. Introduction**

26 Oil reserve depletion and increasing market prices have led researchers worldwide to seek
 27 renewable resources to replace petrochemical derivatives (Choi et al. 2015). New green
 28 technologies have to be developed assuring the use of renewable resources as an alternative to
 29 petrochemical products. Vegetable oils such as soybean (Changa et al. 2017), palm (Khatuna et al.
 30 2017), linseed (Calvo-Correas et al. 2015), castor (Mutlu and Meier 2010) etc., are promising
 31 alternatives since they are relatively inexpensive and renewable sources.

32 In this context, bio-polyols synthesized from unsaturated fatty esters are suitable substitutes of
 33 petrochemical polyols for polyurethanes industry (Desroches et al. 2012). Since from the pioneering
 34 work of Petrović on the synthesis of polyols from vegetable oils (Petrović 2008), there has been an
 35 explosion of interest on this topic (Petrović et al. 2008; Alagi et al. 2015; Tan et al. 2011; Datta and

36 Głowinska 2014; Bloise et al. 2012; Longobardi et al. 2013; Mele et al. 2014; Annese et al. 2014;
37 Dai et al. 2009; Annese et al. 2011; Pantone et al. 2017; Lozada et al. 2009). The simplest approach
38 involves epoxidation of carbon-carbon double bond of unsaturated fatty ester chains and subsequent
39 epoxide ring-opening reaction (hydroxylation) by nucleophilic reagents (Scheme 1).

40 The epoxidation of oils is a well-known technique used in the production of epoxidized soybean oil
41 (ESO), which is used as plasticizer, lubricant, cross-linking agent, stabilizer etc. (Fenollar et al.
42 2009). Petrović et al. patented the alcoholysis of epoxidized oils using tetrafluoroboric acid as a
43 catalyst with different hydroxylated molecules like water, monoalcohols (methanol, ethanol,
44 propanol and butanol) and their mixtures (Petrović et al. 2000; Petrović et al. U. S. Pat. 2002).

45 In order to improve the hydroxylation process and increase the productivity of the process itself, the
46 methanolysis reaction of epoxidized soybean oil (ESO) under continuous flow conditions was
47 investigated (Scheme 2).

48 In fact, while studies of the epoxidation of soybean oil in continuous mode have been reported (He
49 et al. 2013), the methanolysis of ESO under flow conditions remained totally unexplored (Almena
50 et al. 2013).

51 In the past two decades, flow chemistry has received a growing interest due to the several
52 advantages provided to synthetic processes such as facile automation, secured reproducibility,
53 improved safety and process reliability (Hartman et al. 2011; Elvira et al. 2013; Schwalbe et al.
54 2002; Mason et al. 2007; Razzaq and Kappe 2010; Wegner et al. 2011). Moreover, reaction
55 parameters such as temperature, concentration, composition of reactants established for the small
56 scale flow process can be transferred directly to larger flow reactors, without the need for chemical
57 assessments (Wegner et al. 2011).

58 Note of mention, the use of pressure-resistant reactors enables to work at temperatures much greater
59 than the boiling point of the solvent until reaching supercritical conditions, thus leading to very
60 short reaction times (Razzaq et al. 2010).

61 In this work, reaction conditions of methanolysis of ESO carried out in flow were optimized by
62 means of the response surface methodology (RSM), a strategy generally used for modeling and
63 optimizing the experimental parameters in physical and chemical processes. By using this approach,
64 relationship between the input variables temperature (T) and residence time (RT) and the response
65 data was determined, highlighting advantages obtained by the use of flow chemistry in this process
66 (Leardi et al. 2009; Bezerra et al. 2008).

67

68 **2. Experimental section**

69 *2.1 Materials and Methods*

70 A Vapourtec R-series flow reactor was used for flow chemistry experiments (Vapourtec.
71 <https://www.vapourtec.com/it/> (accessed May 20, 2017)). The reactor consists of a PFA tube having
72 a total volume of 10 mL, wrapped in spire and housed inside a quartz enclosure, which is connected
73 to the heating unit and to the temperature sensor for continuous monitoring of this parameter.

74 The “reagent in” port of the reactor coil was connected to the pump with a length of PFA tubing.
75 The “reagent out” port was then directly interfaced with a 8 bar back pressure regulator after which
76 there is a length of PFA tubing leading to a collection flask.

77 The instrument has several digital control displays for all variables. For example, it is possible to
78 control the flow rate from which the residence time of reagents is dependent on. The RT can be
79 varied in the range of 10 seconds - 200 minutes.

80 Temperature can be accurately controlled ($\pm 1^\circ\text{C}$), through a feedback system, in the range of room
81 temperature - 150°C .

82 ^1H -NMR spectra were recorded on a Agilent 500 MHz spectrometer, operating at 11.74 Tesla,
83 corresponding to the resonance frequency of 499.73 MHz for the ^1H nucleus. The NMR samples
84 were prepared by dissolving 0.2 mL oil in 0.7 mL CDCl_3 and analyzed in 5 mm NMR tubes. The
85 chemical shifts are reported in ppm referenced to residual isotopic impurity of CDCl_3 (7.26 ppm).

86 Typical parameters for $^1\text{H-NMR}$ spectra were: 45° pulse, 4 s acquisition time, 8.01 kHz spectral
87 window, 8 scans, 16 K data points. The FID was not processed prior to Fourier transformation.

88 Conversions of ESO in bio-polyol were evaluated based on the $^1\text{H-NMR}$ signal integral of residual
89 epoxide protons at 3.15-2.74 ppm (Fig. 1b). All integral values were determined assuming the
90 signal at 2.2 ppm as reference (with integral value equal to 6), being it assigned to protons of the α -
91 position of fatty acyl groups (-O-CO-CH₂-) that remain unvaried during methanolysis. On these
92 bases, the integral value of epoxide protons (at 3.15-2.74 ppm) in the spectrum of the starting
93 material (ESO) was found to be 7.94 (Fig 1a).

94 In a typical calculation, the conversion of epoxide in polyol was evaluated by equation (1):

$$95 \text{ Conversion}\% = \left(1 - \frac{I_{3.15-2.74}}{7.94}\right) \times 100 \quad (1)$$

96 where $I_{3.15-2.74}$ is the integral value of residual epoxide protons at 3.15-2.74 ppm in the spectrum of
97 reaction mixture (Fig. 1b).

98 A Viscometer Cannon-Fenske reverse flows YNT instrument was used to determine the viscosity
99 using the standard method ASTM D445 (Standard Test Methods for Kinematic Viscosity of
100 Transparent and Opaque Liquids). The determination of density was obtained with the pycnometer
101 method EN ISO 1675. Iodine number value, oxirane number (ON) and hydroxyl number were
102 determined by EN ISO 661, ASTM D 1652, and ASTM D4274 methods, respectively. (Dai et al.
103 2009, Pantone et al. 2017)

104 Commercial starting materials were purchased in highest purity available from scientific chemicals
105 suppliers (Aldrich) and were used without purification. ESO was provided by Greenswitch S.r.l.
106 (iodine number of 1.2 g I₂/100 g, oxirane number of 6.3 g O/100 g, mean Molecular Weight Mn of
107 943.80656 g/mol).

108

109 *2.2 General batch mode methanolysis of ESO*

110 Methanol 8.2 mL (0.2031 mol) and 34 μL ($2.7 \cdot 10^{-4}$ mol) of 48% aqueous solution of HBF_4 (or
111 other catalyst such as H_3PO_4 85%, p-toluenesulfonic acid monohydrate 98%, HCOOH and 1,8-
112 Diazabicyclo[5.4.0]undec-7-ene DBU) were added to a 50 mL, two-necked flask equipped with a
113 condenser, a stirrer, and a thermometer. (Dai et al. 2009, Pantone et al. 2017) To the refluxing
114 mixture, heated with a bath, 5 mL ($5.3 \cdot 10^{-3}$ mol) of ESO (oxirane oxygen 6.3 g O/100 g) were
115 added and left to react for 30 min.

116 Reactions performed in batch mode at a higher temperature than the boiling temperature of
117 methanol were carried out in a 55.6 mL stainless steel autoclave mounted in an electrical oven
118 having a magnetic stirrer on its base. Reagents were introduced in a glass vial (~ 20 mL) and placed
119 into the autoclave, in order to avoid any contact with metal walls. In a typical experiment the glass
120 vial was charged with methanol (8.2 mL, 0.2031 mol), ESO (5 mL, $5.3 \cdot 10^{-3}$ mol) and HBF_4 (or
121 other catalysts), the vial was introduced into the autoclave which was sealed (Casiello et al. 2015).
122 After cooling to room temperature, the reaction mixture was neutralized with small amounts of
123 aqueous ammonia (30%) and then washed into a separating funnel with water (to remove inorganic
124 by-product NH_4BF_4). The organic layer was subjected to heating at 98°C under a low vacuum on a
125 rotatory evaporator to remove the excess of methanol and the water residue. (Dai et al. 2009,
126 Pantone et al. 2017). The reaction progress was monitored by $^1\text{H-NMR}$ and by evaluating both the
127 hydroxyl and oxirane numbers.

128

129 *2.3 General Procedure for the methanolysis in flow conditions*

130 ESO (5 mL, $5.3 \cdot 10^{-3}$ mol) and methanol (4.4 mL, 0.1084 mol) were placed in a bottle labeled as
131 “Reagent A”. Tetrafluoroboric acid 48% (16 μL , $1.2 \cdot 10^{-4}$ mol) and methanol (4.4 mL, 0.1084 mol)
132 were placed in a bottle labeled as “Reagent B”. Two additional bottles containing methanol were
133 labeled as “solvent” (Scheme 3).

134 Two pumps were primed using the equipment manufacturer's suggested start-up sequence.
135 Methanol was pumped through the reactor coil heated at 100°C at the flow rate of 0.5 mL/min.
136 Then, by means of switches on the unit, both the Reagents “A and B” were flowed simultaneously
137 in a 1:0.45 volumetric ratio, at the overall flow rate of the reaction mixture of 0.388 mL/min, with a
138 calculated residence time of 25.8 min. When the set amount of reaction mixture had been processed,
139 the flow was switched back from reagent to solvent. The reaction mixture collected at the exit of the
140 reactor coil, was purified with the same procedure used for the reaction conducted in batch.
141 For reactions carried out with small amounts of methanol, the procedure was slightly modified to
142 circumvent the problem of high viscosity of ESO. In these cases (see Table 4), both the reagents
143 (ESO, CH₃OH) and catalyst HBF₄ were preliminary mixed in an unique bottle prior to be pumped
144 into the reactor (Negus et al. 2015).

145

146 *2.4 Experimental design and data analysis*

147 The two specific reaction parameters “temperature and residence time” were optimized by means of
148 experimental optimization design (DOE) method, using the central composite design (CCD)
149 elaborated by the Statgraphic® Centurion XV software.

150 A central composite design “2² + star” was created for studying the effects of 2 factors in 11 runs
151 (reported in Table 2). The drawing was executed in a single block and the order of the experiments
152 was completely randomized to have protection against the effects of latent variables.

153 DOE provided information on the influence of the temperature and residence time and any
154 interactions between the variables according to a quadratic polynomial model of general formula
155 (2):

156

$$157 \quad Y = \beta_0 + \beta_1x_1 + \beta_2x_2 + \beta_{12}x_1x_2 + \beta_{11}x_1^2 + \beta_{22}x_2^2 \quad (2)$$

158

159 where x_1 and x_2 are the experimental variables (T and RT), while $\beta_0, \beta_1, \beta_2, \beta_{11}, \beta_{12},$ and β_{22} are
160 the coefficients of polynomial model and Y is the response (reaction conversion).

161

162 **3. Results and discussion**

163 Preliminarily, starting from the literature protocol (Dai et al. 2009), the optimization of reaction
164 conditions for methanolysis of ESO carried out in the batch mode was performed. This refinement
165 of the operating procedure allowed us to set the best reaction conditions as follows: catalyst loading
166 (HBF_4) 1% (w/w with respect to ESO), hydroxyl/epoxide ratio 11:1, refluxing temperature of
167 methanol (65°C), and reaction time 30 minutes, shorter than that reported (1 hour). The bio-polyol
168 product displayed the same physicochemical properties as the one described in the literature (Dai et
169 al. 2009; Pantone et al. 2017): hydroxyl number 191 ± 15 (mg KOH/g), oxirane number 0.2 (g
170 O/100 g), viscosity 4550 (cP), and density 1.02 (kg/dm^3). Moreover, based on $^1\text{H-NMR}$ signals of
171 residual epoxide protons (3.15-2.74 ppm) the maximum conversion was estimated to be $86 \pm 6\%$
172 (Figure 1).

173 With the optimised conditions in hand, the methanolysis of ESO in continuous flow mode was
174 performed obtaining a bio-polyol with the identical physicochemical properties of that obtained in
175 batch mode, but in a much shorter reaction time (2 minutes).

176 Moreover, as expected from a process conducted in the flow mode, the reaction occurred with a
177 higher selectivity. Indeed, in this case the transesterification side-products formed in batch mode
178 (i.d. methyl esters of fatty acids, $\sim 7\%$), were totally absent, as evidenced by the disappearance of
179 singlet signals at 3.65 ppm due to $\text{CH}_3\text{OCO-}$ protons in the $^1\text{H-NMR}$ spectrum of the methanolysis
180 carried out in the flow mode (Figure 2).

181 Besides the above-mentioned advantages of higher selectivity and reaction rate, the pressure-
182 resistant reactor allowed us to adopt much harder reaction conditions. Indeed, based on the
183 resistance of back pressure valve (8 bar), the operating temperature was raised up to the value of

184 120°C, which is much greater than the boiling point of methanol (65°C). The higher temperature
185 conditions enabled the decrease of catalyst loading (HBF₄) maintaining unchanged the conversion
186 of the entire process (flow rate elevated).

187

188 *3.1 Study on the effect of catalyst (HBF₄) concentration in flow mode*

189 Due to the environmental issues given by tetrafluoroboric acid disposal, to improve eco-
190 sustainability of the process the influence of concentration of HBF₄ under flow conditions was
191 studied in deep attempting to minimize the catalyst loading without affecting conversion or
192 prolonging too much the reaction times.

193 Results, summarized in Table 1, showed that the minimum value of catalyst concentration required
194 to maintain unchanged conversion at 86% is 0.1% (w/w with respect to ESO, Table 1, run 4). Under
195 these conditions, residence time at 65°C was 60 min, but could be halved at 30 min operating at
196 120°C (Table 1, run 5).

197 Based on these data, the optimization of parameters was continued operating at the concentration of
198 HBF₄ of 0.1%, a value that can conjugate the maximum conversion of 85% with a relatively short
199 reaction time (Table 1, run 5).

200

201 *3.2 Temperature and residence time optimization with DOE method*

202 For the optimization of “Temperature” and “Residence time” a number of eleven reactions was
203 statistically required by DOE method (Table 2). Based on the instrumental limits and data in Table
204 1, the ranges of 100 - 120°C (for T) and 2 - 30 min (for RT) were chosen.

205 As control experiments, the hydroxyl number of polyol products was checked for reactions
206 occurring with highest conversions (runs 1, 4, 11). In all cases, the expected value of 191 ± 15 mg
207 KOH/g was obtained, which is consistent with that of the analogous polyol produced in the batch
208 mode reaction.

209 3.2.1 Statistical analysis of experimental design

210 Results of methanolysis experiments in Table 2 were analyzed by ANOVA to assess the “goodness
211 of fit” and statistical parameters were listed in Table 3 (Elsayed and Lacor 2012; Yuan et al. 2008).

212 From data in Table 3 clearly emerged that only the two parameters B and BB are statistically
213 significant at a confidence level of 95% (since they have a *P*-value less than 0.05). Therefore, the
214 only significant variable affecting the response is the residence time. The separate effect of the two
215 variables can be visualized graphically in Figure 3.

216 Another graphical and direct manner to appreciate the significance of variables and their
217 interactions in experimental designs was given by Pareto chart (Figure 4) (Ferreira et al. 2017).

218

219 Based on the preliminary variance analysis, the RT and conversion are related by a quadratic
220 relationship, while the temperature can be excluded from the optimization study as well as the
221 interaction between the two parameters.

222 The software also provided the surface response graph (Figure 5), according to equation (3),
223 together with the optimized RT, which resulted to be 25.8 min. As temperature did not have a
224 significant effect in the range studied, for the successive experiments the lowest value of 100°C was
225 used.

226

$$227 \quad Y = 30.2721 + 4.55884 x - 0.0891156 x^2 \quad (3)$$

228 (where x = residence time, Y = reaction conversion, $R^2 = 0.973021$)

229

230 The control experiment performed to validate the optimized conditions obtained with the DOE
231 method (HBF₄ 0.1% w/w with respect to ESO, temperature 100°C, reaction time 25.8 min,
232 hydroxyl/epoxide ratio 11:1) led to a bio-polyol product with a conversion of $89 \pm 7\%$
233 (evaluated by ¹H-NMR) and the expected hydroxyl number of 192 ± 12 mg KOH/g.

234 Under the same conditions, reaction carried out in batch mode resulted in a conversion of $70 \pm 5\%$.

235

236 3.3 Effect of hydroxyl/epoxide ratio

237 With the aim to enhance the cost efficiency of the process, the decrease of the excess amount of
238 methanol was attempted. At this end, the study on the influence of hydroxyl/epoxide ratio was
239 carried out by adopting the experimental conditions optimized above. For comparison, reactions in
240 batch mode were also investigated.

241 Results showed that the molar excess of methanol could be reduced from 11 to 2 without affecting
242 both conversion and selectivity. Note of mention, a similar trend was also observed for reactions in
243 batch, even if in these latter cases both conversions and selectivities were always inferior, thus
244 demonstrating the higher efficiency of the flow mode reactions (Table 4).

245

246 *3.4 Study of other catalysts*

247 As HBF_4 has been shown to be the most efficient catalyst for ESO alcoholysis reaction in batch
248 [Lozada et al. 2009; Razzaq and Kappe 2010], a comparison of its performances, under the
249 optimized flow conditions, with those of the other Brønsted acids commonly used for catalyzing
250 this process was conducted (e.g. H_3PO_4 85%, TsOH monohydrate 98%, and HCOOH 85%) and the
251 screening was also extended to the batch mode (Table 5).

252 Results confirmed the expected trend, in which performances were dependent on the acid strength
253 of catalysts according to the pKa values scale: HBF_4 (- 4.60) > TsOH (- 2.80) > H_3PO_4 (+ 2.15) >
254 HCOOH (+ 3.75).

255 From data in Table 5 emerged that HBF_4 is the best catalyst especially in flow mode, where
256 concentration required to give almost complete conversion is 0.1%, which is almost twenty times
257 smaller than of p-toluensulfonic acid (1.75%), the next catalyst in the acidity scale (Table 5, run 2).

258 The difference in catalytic activity between HBF_4 and the other acids is more evident in batch
259 mode, where the latter provided conversions lower than 43%, demonstrating once again the
260 superior efficiency of the flow mode reactions.

261 Finally, DBU was also investigated as basic catalyst [Lozada et al. 2009], but in this case the
262 transesterification was the sole process observed (Table 5, run 5).

263 **4. Conclusions**

264 In conclusion, the replacement of batch process by continuous flow synthesis in preparation of
265 polyols from methanolysis of ESO resulted in notable progress in terms of both process
266 intensification and product quality. Compared with batch reaction, flow mode could cut the reaction
267 time from 30 min to 2 min, which brought significant benefit for energy consumption. A further
268 advantage of this method concerns the catalyst loading. Indeed, HBF_4 catalyst can be reduced by an
269 order of magnitude respect to the batch experiments, passing from 1% to 0.1%, while maintaining
270 unchanged the process productivity.

271 Finally, as an additional benefit of these investigations, the large excess of methanol (11 equiv.) can
272 be eliminated in both batch and flow experiments until reaching the almost stoichiometric
273 conditions (2 equiv.). All these improvements indicate that this new procedure of methanolysis of
274 ESO in flow mode, which has no precedent in the literature, brings significant benefits in terms of
275 cost efficiency and eco-sustainability and has a good potential for industrial applications.

276

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285

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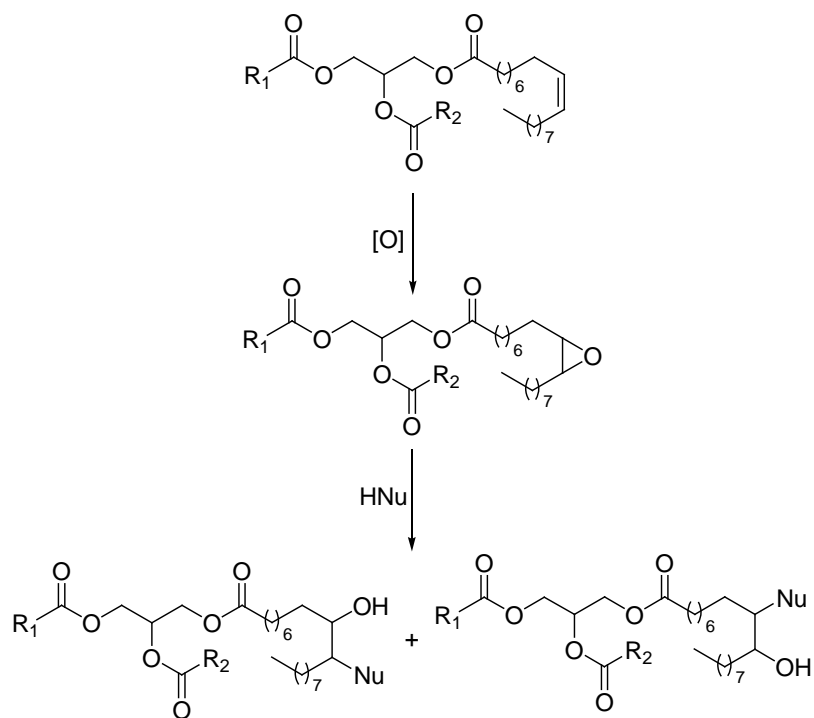
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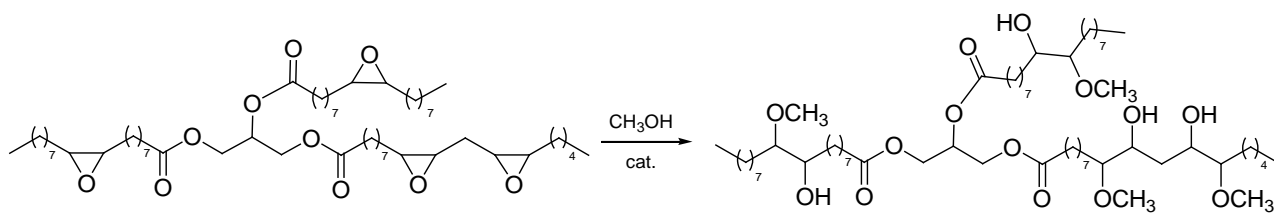


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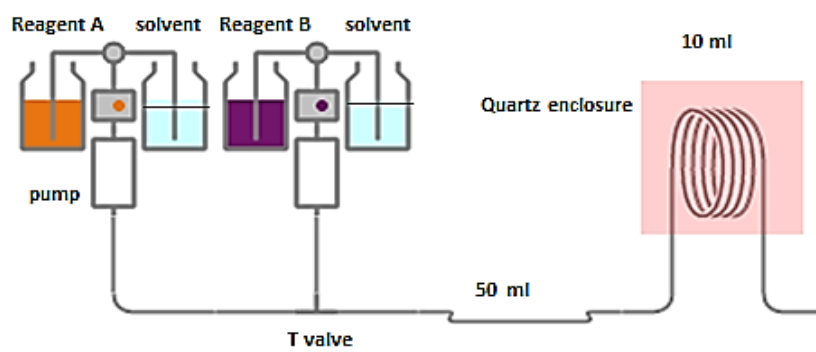
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Scheme 1. Representation of a typical chemical approach to the conversion of soybean oil into polyol.

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Scheme 2. Representation of ESO methanolysis reaction.

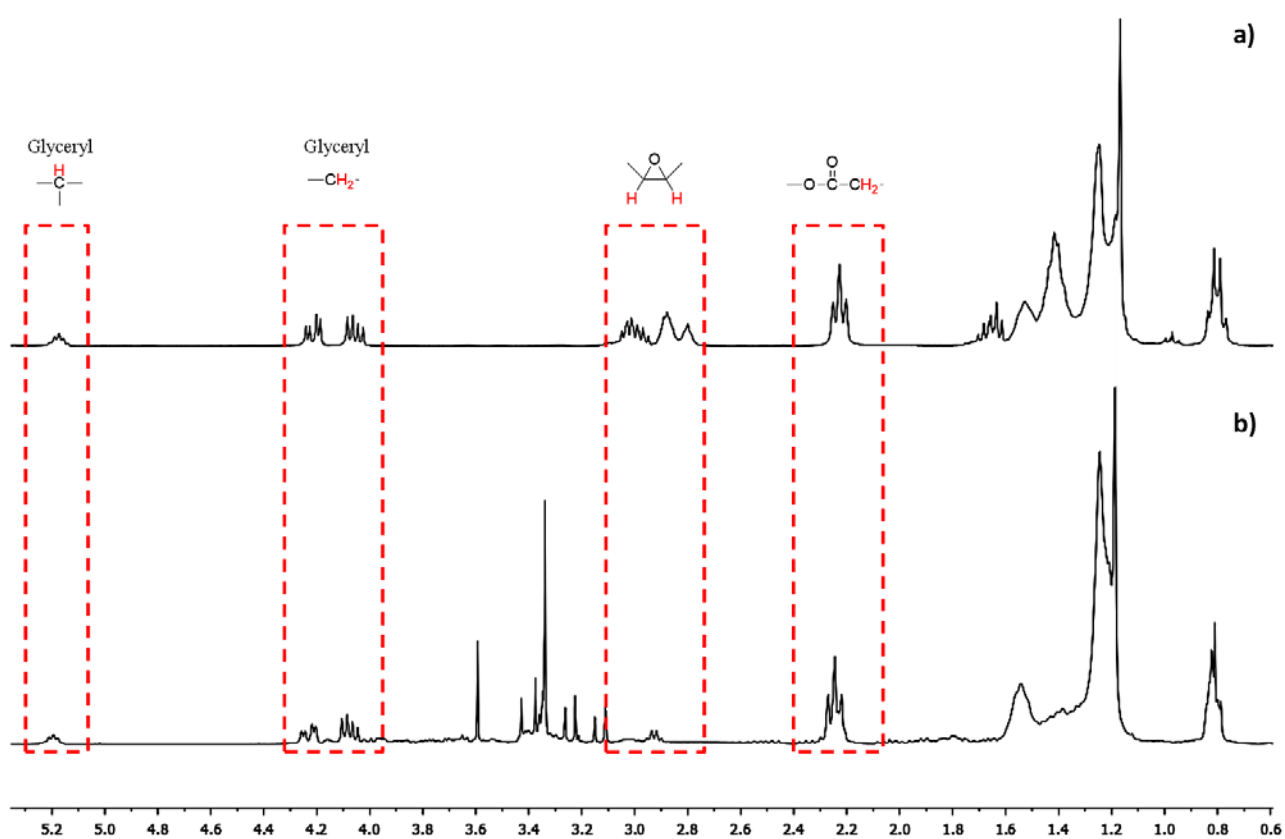


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Scheme 3. Representative scheme of the continuous flow reactor.

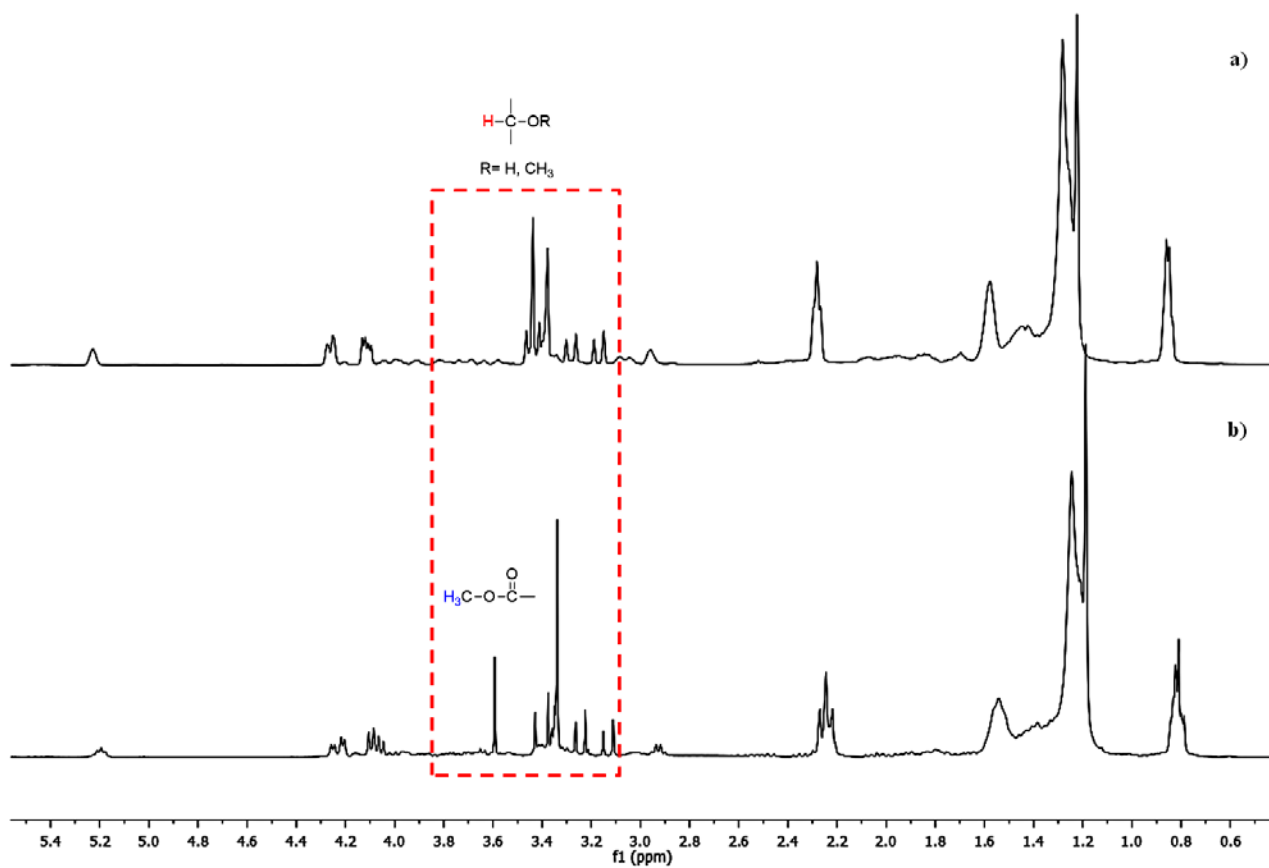
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388 **Figure 1.** ¹H-NMR (CDCl₃, 500 MHz) spectrum of (a) ESO; (b) bio-polyol from HBF₄-catalyzed (1% w/w
389 with respect to ESO) methanolysis of ESO in batch mode at 65°C with a reaction time of 30 min.

390



391

392 **Figure 2.** $^1\text{H-NMR}$ (CDCl_3 , 500 MHz) spectrum of reaction mixture of HBF_4 -catalyzed (1% w/w)
393 methanolysis of ESO carried out at 65°C in (a) continuous flow mode (reaction time 2 min), and (b) batch
394 mode (reaction time 30 min).

395

396

Table 1. Effect of catalyst loading on HBF₄-catalysed methanolysis of ESO in flow mode.^a

Run	HBF ₄ (%)	Temperature (°C)	Flow rate (mL/min)	Residence Time (min)	Conversion (%) ^b
1	1	65	5	2	87 ± 6
2	0.5	65	3.33	3	88 ± 5
3	0.25	65	0.33	30	89 ± 8
4	0.1	65	0.17	60	87 ± 6
5	0.1	120	0.33	30	85 ± 6
6	0.05	65	0.05	200	66 ± 7
7	0.05	120	0.05	200	69 ± 5

397

^a Reaction conditions: ESO (5 g), catalyst HBF₄ (% w/w with respect to ESO, as reported), hydroxyl/epoxide ratio of 11:1, flow rate (as reported), reaction temperature (as reported).

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^b Evaluated by ¹H-NMR. Values are means ± S.D. of three replicates.

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403**Table 2.** DOE experiments for evaluation of reaction parameters “Temperature and Residence Time” in methanolysis of ESO carried out in flow mode.^a

Run	Temperature (°C)	Residence Time (min)	Conversion (%)
1	110	30	90
2	110	2	38
3	120	16	87
4	120	30	88
5	110	16	85
6	120	2	41
7	100	16	70
8	100	2	38
9	110	16	84
10	110	16	76
11	100	30	88

404 ^a The 11 experiments were carried out according to the procedure described in section 2.2. Catalyst (HBF₄)
405 concentration was equal to 0.1% w/w with respect to ESO. Hydroxyl/epoxide ratio equal to 11:1.

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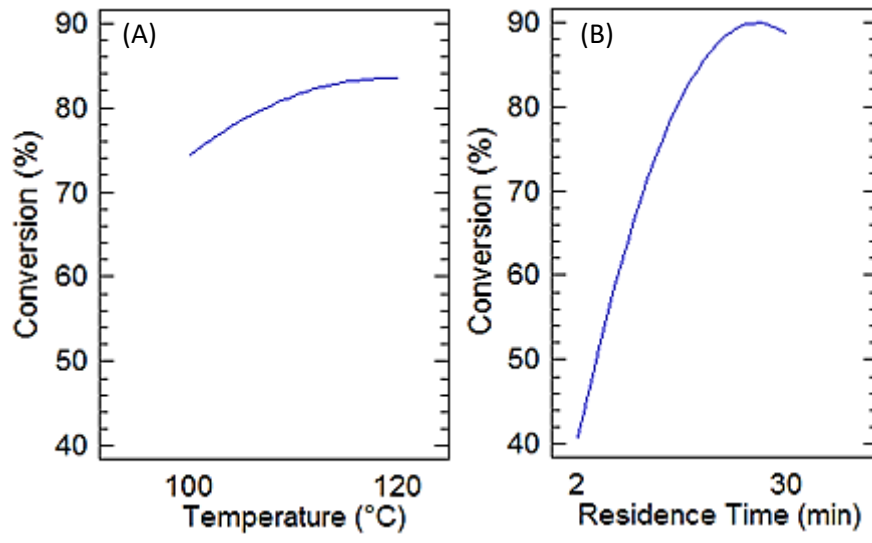
Table 3. Statistical parameters from ANOVA.

Source	Df	Mean Square	<i>P</i> -Value
A: Temperature	1	125.127	0.0730
B: Residence Time	1	3427.26	0.0001
AA	1	15.8333	0.4572
AB	1	1.5625	0.8103
BB	1	715.008	0.0029
Total error	5	24.4102	-
Total (corr.)	10	-	-

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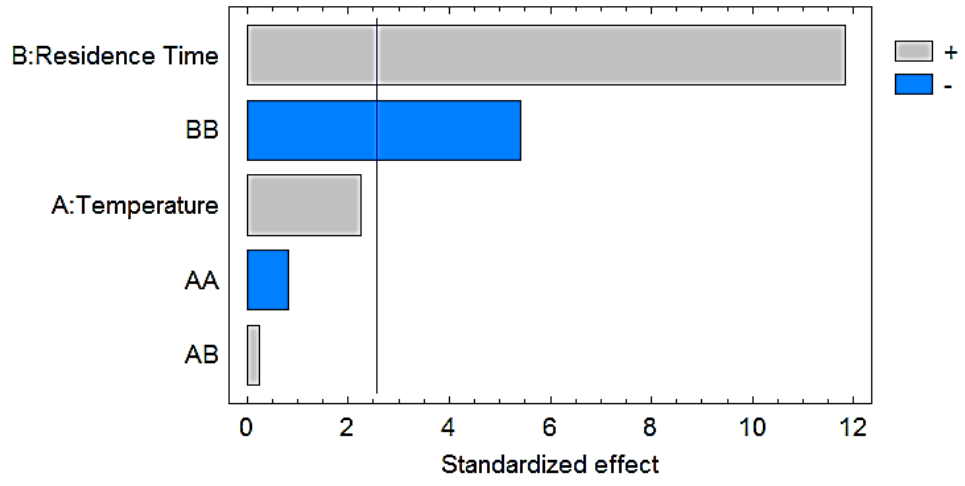
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Figure 3. Effects plot on conversion of (A) Temperature and (B) Residence Time.

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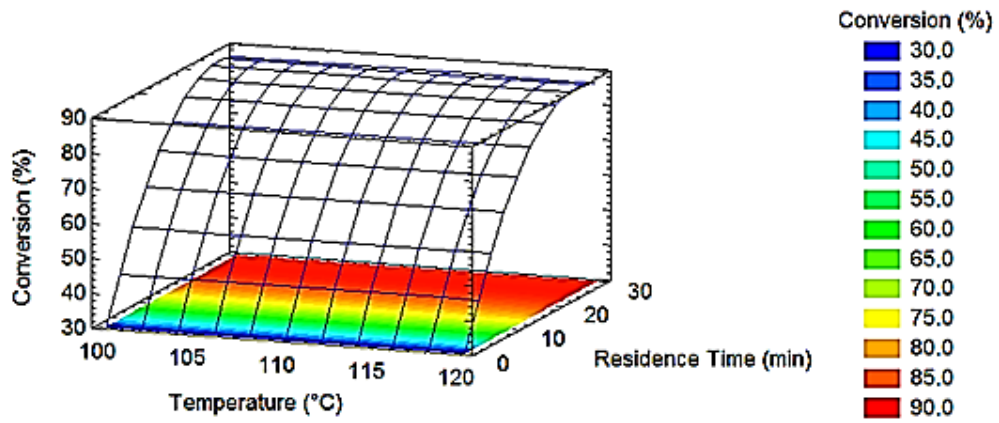
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Figure 4. Standardized Pareto Chart.

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Figure 5. Estimated Response Surface.

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422 **Table 4.** Effect of hydroxyl/epoxide ratio.^a

Run	Hydroxyl/epoxide ratio	Flow mode		Batch mode	
		Conversion ^b (%)	Selectivity ^b (%)	Conversion ^b (%)	Selectivity ^b (%)
1	11	89 ± 7	100 ^c	70 ± 5	93 ^d
2	6.5	87 ± 7	100 ^c	73 ± 5	93 ^d
3 ^e	2	88 ± 6	100 ^c	71 ± 5	94 ^d

423 ^a Reaction conditions (see section 2.2): ESO (5 g), catalyst HBF₄ (0.1% w/w with respect to ESO), hydroxyl/epoxide
 424 ratio (as reported), reaction time 25 min, reaction temperature 100°C.

425 ^b Evaluated by ¹H-NMR.

426 ^c Hydroxyl number of polyol product 191 ± 15 mg KOH/g.

427 ^d A 6 - 7% of transesterification products was observed.

428 ^e To circumvent the problem of high viscosity of ESO, all reagents (ESO, CH₃OH) and catalyst were preliminary mixed
 429 prior to be pumped into the reactor (see section 2.2).

430

Table 5. Catalyst effect on methanolysis of ESO.^a

Run	Catalyst	Catalyst concentration (%) ^b	Conversion (%) ^c	
			Flow mode	Batch mode
1	HF ₄	0.1	89 ± 7	70 ± 5
2	TsOH	1.75	85 ± 7	36 ± 5
3	H ₃ PO ₄	6.0	85 ± 5	43 ± 5
4	HCOOH	50.0	75 ± 5	34 ± 5
5	DBU ^e	0.5	100 ^d	-

^a Reaction conditions: ESO (5 g), hydroxyl/epoxide equal to 11:1, reaction time 25 min, temperature 100°C.

^b W/w with respect to ESO.

^c Evaluated by ¹H NMR.

^d ESO was completely transformed into the transesterification products.

^e DBU= 1, 8-Diazabicyclo[5.4.0]undec-7-ene.

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