Supplementary Information (SI) for Reaction Chemistry & Engineering.

Selective Transfer Hydrogenation of Furfural Under Continuous Flow Conditions Promoted by the Recoverable Homogeneous Shvo's Catalyst

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ELECTRONIC SUPPLEMENTARY INFORMATION

This section contains 15 pages including 1 Scheme, 2 Tables and 8 Figures.

EXPERIMENTAL SECTION

All chemicals were purchased from commercial sources and, with the exception of dichloromethane (dried and distilled prior to use), used without further purification.

Batch experiments were carried out under a nitrogen atmosphere in a 15 mL oven-dried Schlenk flask fitted with a Teflon plug valve. For run 1-3 (table S1) 7.2 mg (6.8 µmol, 1 mol%) of Shvo's catalyst and 54.5 µL (0.68 mmol) of furfural were dissolved in 2-MeTHF (2.73 mL, 0.25 mol/L) and 2-PrOH (50 µL, 1 mmol) solution. The system is then kept under magnetic stirring for 90 minutes and heated at the desired temperature (90 – 150°C) in an oil bath. The solution was then cooled down to room temperature and processed for GC analysis. In the case of ^{1}HNMR analysis, solvents were evaporated under vacuum, and the solid dissolved in $CDCl_3$ to record the ^{1}HNMR spectra.

Continuous Flow Reactions were conducted in a commercial flow ASIA® Flow Chemistry System (Syrris). A solution of 200 µL of furfural (2.4 mmol), 26.4 mg of Shvo's catalyst (0.024 mmol, 1 mol%), a desired amount of H-donor source (2-propanol, 2-butanol, 1 butanol, MeOH and EtOH) in 10 mL of 2-MeTHF was pumped at the desired flow rate (125- or 250- or 500- ml/min) with an ASIA Syringe Pump with Asia Red Syringes (2.5 mL / 5 mL) in an Asia Tube Reactor (Stainless - Steel, 4 mL) pre-heated at the reaction with a back-pressure of 10 bar of N_2 regulated by a Asia Pressure Controller (Scheme S1). The flow system was flushed with 10 mL of 2-MeTHF to clean the line. The output was collected at specific times on stream, and the liquid sample was processed for GC analysis.

During the recovery and reuse experiments, pure FAL was obtained with a 98% yield by distilling off the 2-MeTHF. Shvo's catalyst was precipitated using 2 mL of 2-PrOH, which was subsequently distilled for recovery. The recovered catalyst was successfully reused under optimised reaction conditions for five consecutive runs (Figure S2). NMR spectra and FT-IR (Figure S5, S6 and S7) of the pure FAL and the recovered Shvo's catalyst are provided.

Gas chromatographic analyses were performed on an Agilent 6890 gas chromatograph equipped with a wide-bore capillary column (CP-WAX 52CB, 60 m, i.d. 0.53 mm) and FID as detector. The carrier gas used was N_2, with a flow rate of 2 mL/min. The heating program began with a 5-minute isotherm at 50 °C, followed by a 5 °C/min increase to 230 °C, which was maintained for 2 minutes. The temperature was then increased to 250 °C at a rate of 15 °C/min and maintained for an additional 5 minutes.

^{1}H NMR and GC analysis determined all conversions reported in this study. With respect to GC-analysis, an internal standard method was used to quantify furfural (FUR) conversion and product selectivity, employing n-tetradecane as the internal standard. Calibration curves for both FUR and furfuryl alcohol (FAL) were constructed using standard solutions containing a fixed concentration of n-tetradecane, ensuring accurate and reproducible quantification. The resulting R^2 values for all calibration curves exceeded 0.999. Gas chromatography (GC) analysis confirmed the exclusive formation of FAL, with no detectable byproducts from etherification, acetalisation, or aldol condensation. The remaining material consisted solely of unreacted FUR, resulting in a complete carbon balance in the range of 98–100%. These findings were further supported by the isolated yields of FAL, which closely matched the measured conversions. All reactions were performed at least three times to ensure reproducibility, with experimental error remaining below 2%.

The Furfural (FUR) conversion, Furfuryl Alcohol (FAL) selectivity and Furfuryl Alcohol (FAL) yield were calculated as follows:

$$\text{FUR Conversion [\%]} = \frac{mol_{FUR\ initial} - mol_{FUR\ final}}{mol_{FUR\ initial}} \times 100 \qquad [1]$$

$$\text{FAL Selectivity [\%]} = \frac{mol_{FAL}}{mol_{all\ reaction\ PRODUCTS}} \times 100 \qquad [2]$$

$$\text{FAL Yield [\%]} = \frac{mol_{FAL}}{mol_{FUR\ initial}} \times 100 \qquad [3]$$

Productivity in reactions carried out under batch conditions was calculated as:

$$Batch\ \text{Productivity [µmol/hour]} = \frac{mol_{FAL}}{reaction\ time} \qquad [4]$$

Productivity in reactions carried out under continuous flow conditions was calculated as:

$$Flow\ Productivity = \frac{mol\ of\ product\ (mmol)}{volume\ of\ solvent\ eluted\ (mL)} \cdot flow\ rate\ (mL/min) \qquad [5]$$

with $$Flow\ rate = \frac{volume\ of\ solvent\ eluted\ (mL)}{elution\ time\ (min)} \qquad [6]$$

Two types of NMR analysis were carried out: one of the reaction crude (example shown in figure S4) and one post-filtration through a silica plug to remove the catalyst (example shown in figure S1). The latter, in particular, was done to calculate test performance: the integration value of the diagnostic protons of furfural and furfuryl alcohol was determined relative to the furfural C**H**O peak, which was arbitrarily assigned an integral value of 1.00. Furfural conversion, as well as furfuryl alcohol (FAL) yield and selectivity, were then calculated accordingly. The integral values were normalised to the number of protons for each considered integration, according to the following equation.

$$FAL\ yield\ [\%] = \frac{(integration\ FAL, CH/1H)}{(integration\ Furfural, CH + integration\ FAL, CH/1H)} \times 100 \qquad [7]$$

This equation is provided as an example, but the same reasoning was also employed to derive the conversion. The selectivity obtained is maximum, as evidenced by ^{1}H-NMR analysis, which indicates that this reaction yields only a single product.

The green metrics were calculated as follows:

$$AE = \frac{MW_{reactant}}{MW_{product}} \qquad [8]$$

$$SF = \frac{Actual\ Mass\ of\ Reagent}{Stoichiometric\ Mass\ of\ Reagents} \qquad [9]$$

$$MRP = \frac{RME \cdot SF}{AE \cdot Yield} \qquad [10]$$

$$RME = \frac{1}{(1 + EFactor)} \qquad [11]$$

$$VMR = \frac{\sqrt{AE^2 + Yield^2 + \left(\frac{1}{SF}\right)^2 + MRP^2 + RME^2 + SHI^2 + BI^2}}{\sqrt{7}} \qquad [12]$$

General procedure followed for the workup and E-Factor calculation: A solution of 200 µL of furfural (2.4 mmol), 26,4 mg of Shvo's catalyst (0.024 mmol, 1 mol%), 287 µL 2-PrOH (3.75 mmol) in 10 mL of 2-MeTHF was pumped at 250 µl/min with an ASIA Syringe Pump with Asia Red Syringes (2.5 mL / 5 mL) in an Asia Tube Reactor (Stainless - Steel, 4 mL) pre-heated at the reaction with a back-pressure of 10 bar of N_2 regulated by a Asia Pressure Controller. The flow system was flushed with 10 mL of 2-MeTHF to clean the line. The output was collected at specific times on stream, and the liquid sample was processed for GC analysis. 2-MeTHF was recovered by distillation from the reaction mixture, while Shvo's catalyst was precipitated from 2 mL of 2-PrOH and recovered with 98% efficiency. The 2-PrOH was subsequently distilled for reuse, and pure furfuryl alcohol (FAL) was obtained with an isolated yield of 97%

The E-Factor calculation was performed as follows:

E-Factor = $(m_{\text{2-MeTHF}} + m_{\text{washing 2-MeTHF}} + m_{\text{furfural}} + m_{\text{reagent 2-PrOH}} + m_{\text{Shvo's catalyst}} + m_{\text{purification 2-PrOH}}) - (m_{\text{FAL}} + m_{\text{recovered 2-MeTHF}} + m_{\text{recovered purification 2-PrOH}} + m_{\text{recovered Shvo's catalyst}}) / m_{\text{FAL}}$

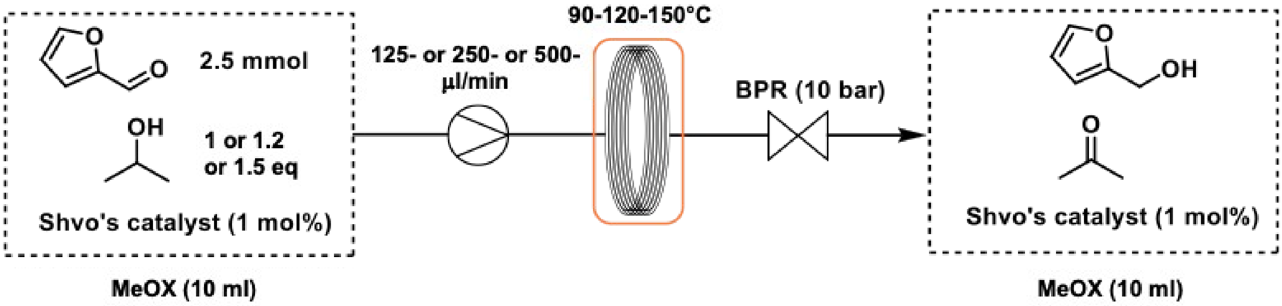
E-Factor = [(8.55 g (2-MeTHF) + 8.55 g (washing 2-MeTHF) + 0.23 g (furfural) + 0.22 g (reagent 2-PrOH) + 0.0264 g (Shvo's catalyst) + 1.572 (purification 2-PrOH) – 0.224 g (FAL) – 16.9 g (recovered 2-MeTHF) – 1.53 (recovered purification 2-PrOH) – 0.0259 (recovered Shvo's catalyst)]/ 0.224 (FAL) = 2

General procedure followed for the flow scale-up at **12 mmol**: A solution of 1 mL of furfural (12 mmol), 13.2 mg of Shvo's catalyst (0.12 mmol, 1 mol%), 1.4 mL 2-PrOH (3.75 mmol) in 8.6 mL of 2-MeTHF was pumped at 250 µl/min with an ASIA Syringe Pump with Asia Red Syringes (2.5 mL/5 mL) in an Asia Tube Reactor (Stainless - Steel, 4 mL) pre-heated at the reaction with a back-pressure of 10 bar of N_2 regulated by a Asia Pressure Controller. The flow system was flushed with 10 mL of 2-MeTHF to clean the line. The output was collected at specific times on stream, and the liquid sample was processed for GC analysis. 2-MeTHF was recovered by distillation from the reaction mixture, while Shvo's catalyst was precipitated from 4 mL of 2-PrOH and recovered with 98% efficiency. The 2-PrOH was subsequently distilled for reuse, and pure furfuryl alcohol (FAL) was obtained with an isolated yield of 98%

General procedure followed for the flow scale-up at 24 mmol: A solution of 2 mL of furfural (24 mmol), 264 mg of Shvo's catalyst (0.24 mmol, 1 mol%), 2.16 mL 2-PrOH (36.0 mmol) in 7.8 mL of 2-MeTHF was pumped at 250 µl/min with an ASIA Syringe Pump with Asia Red Syringes (2.5 mL / 5 mL) in an Asia Tube Reactor (Stainless - Steel, 4 mL) pre-heated at the reaction with a back-pressure of 10 bar of N_2 regulated by a Asia Pressure Controller. The flow system was flushed with 10 mL of 2-MeTHF to clean the line. The output was collected at specific times on stream, and the liquid sample was processed for GC analysis. 2-MeTHF was recovered by distillation from the reaction mixture, while Shvo's catalyst was precipitated from 4 mL of 2-PrOH and recovered with 98% efficiency. The 2-PrOH was subsequently distilled for reuse, and pure furfuryl alcohol (FAL) was obtained with an isolated yield of 98%

The E-Factor calculation was performed as follows:

E-Factor = [(6.67 g (2-MeTHF) + 8.55 g (washing 2-MeTHF) + 2.3 g (furfural) + 2.2 g (reagent 2-PrOH) + 0.264 g (Shvo's catalyst) + 3.144 (purification 2-PrOH) – 2.3 g (FAL) – 14.9 g (recovered 2-MeTHF) – 3.1 (recovered purification 2-PrOH) – 0.259 (recovered Shvo's catalyst)]/ 2.3 (FAL) = 1.1



Scheme S1. Schematic representation of the ASIA® Flow Chemistry System (Syrris).

Table S1. Comparison of productivity (mmol/h) and volumetric productivity (space-time yield, SPY, expressed in mmol/(h*L)) for protocols performed under batch conditions at various temperatures and reaction times.

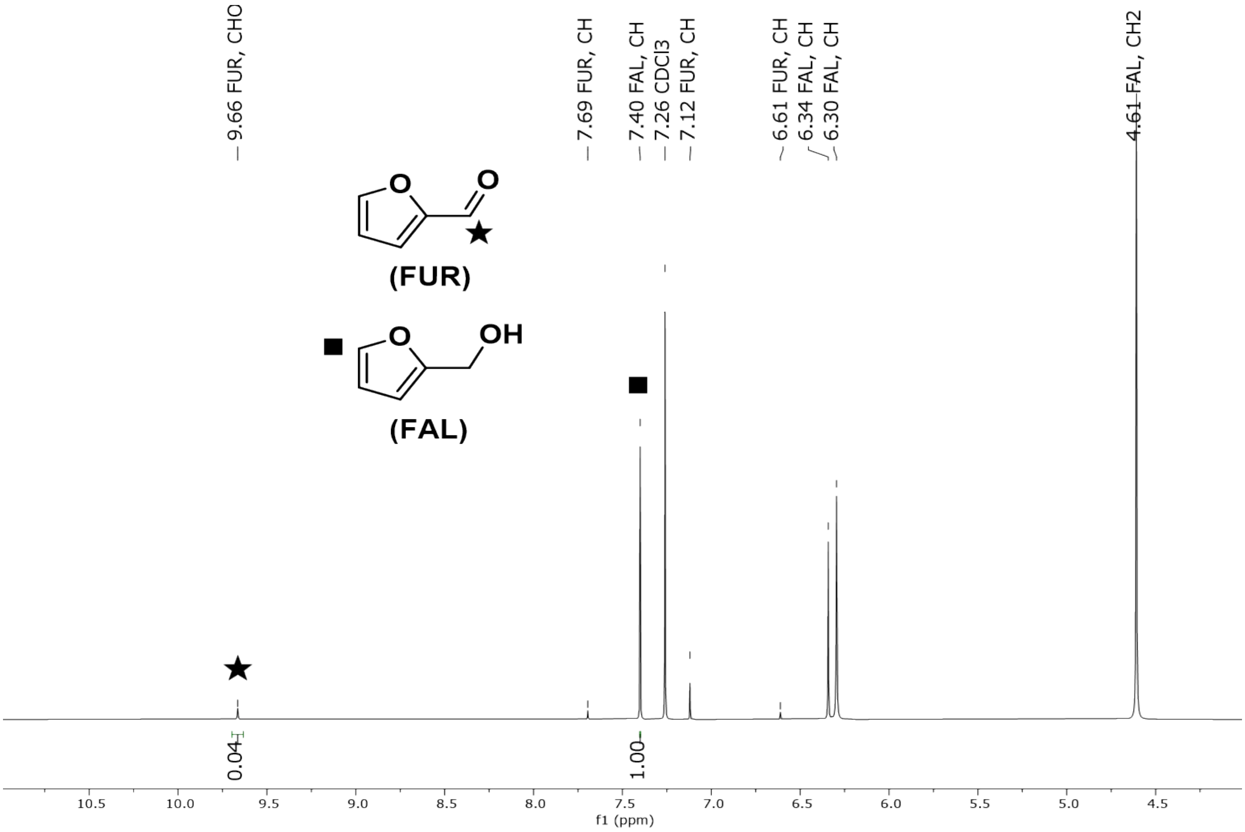
Entry	**T [°C]**	**Time [min]**	**FAL Yield* [%]**	**Productivity [mmol/h]**	**SPTY [mmol/(h*L)]**
1	90	30	83	1.08	71.9
2	90	60	89	0.57	37.7
3	90	90	92	0.40	26.6
4	120	30	87	1.16	77.1
5	120	60	93	0.61	40.3
6	120	90	94	0.41	27.2
7	150	30	96	1.20	79.7
8	150	60	98	0.61	40.7
9	150	90	99	0.43	28.6

Reaction condition: Shvo's catalyst (6.8 µmol, 1 mol%), furfural (0.68 mmol), 2-MeTHF (0.25 mol/L) and 2-PrOH (1 mmol). *Calculated *via* gas-liquid chromatography analyses using n-tetradecane as internal standard.

Table S2. Comparison of productivity (mmol/h) and volumetric productivity (space-time yield, SPY, expressed in mmol/(h*L)) for protocols performed under batch conditions at various equivalents of H-dono and temperatures at the optimised flow rate of 250 µL/min.

Entry	T [°C]	2-PrOH [equiv.]	Furfural [mmol]	FAL Yield* [%]	Productivity [mmol/h]	SPTY [mmol/(h*L)]
1	90	1	2.4	71	2.56	639.0
2	90	1.2	2.4	80	2.88	720.0
3	90	1.5	2.4	90	3.24	810.0
4	90	2	2.4	92	3.31	828.0
5	120	1	2.4	89	3.20	801.0
6	120	1.2	2.4	91	3.27	819.0
7	120	1.5	2.4	94	3.38	846.0
8	120	2	2.4	98	3.53	882.0
9	150	1	2.4	90	3.24	810.0
10	150	1.2	2.4	93	3.35	837.0
11	150	1.5	2.4	97	3.49	873.0
12	150	2	2.4	99	3.56	891.0
14[a]	150	1.5	12	98	17.64	4410.0
15[b]	150	1.5	24	98	35.28	8820.0

Reaction condition: Shvo’s catalyst (0.024 mmol; 1 mol%), furfural (2.4 mmol), 2-MeTHF (0.25 mol/L) under 10 bar of Ar. *Calculated *via* gas-liquid chromatography analyses using n-tetradecane as internal standard.[a]Shvo’s catalyst (0.12 mmol; 1 mol%), furfural (12 mmol), 2-MeTHF (1.4 mol/L) under 10 bar of Ar. [b]Shvo’s catalyst (0.24 mmol; 1 mol%), furfural (24 mmol), 2-MeTHF (3.1 mol/L) under 10 bar of Ar.



FigureS1. Example of a ^{1}H-NMR spectrum in $CDCl_3$ of the filtered crude reaction (run 1, table S1), zooming between 11 and 4.0 ppm. FAL yield =96%.

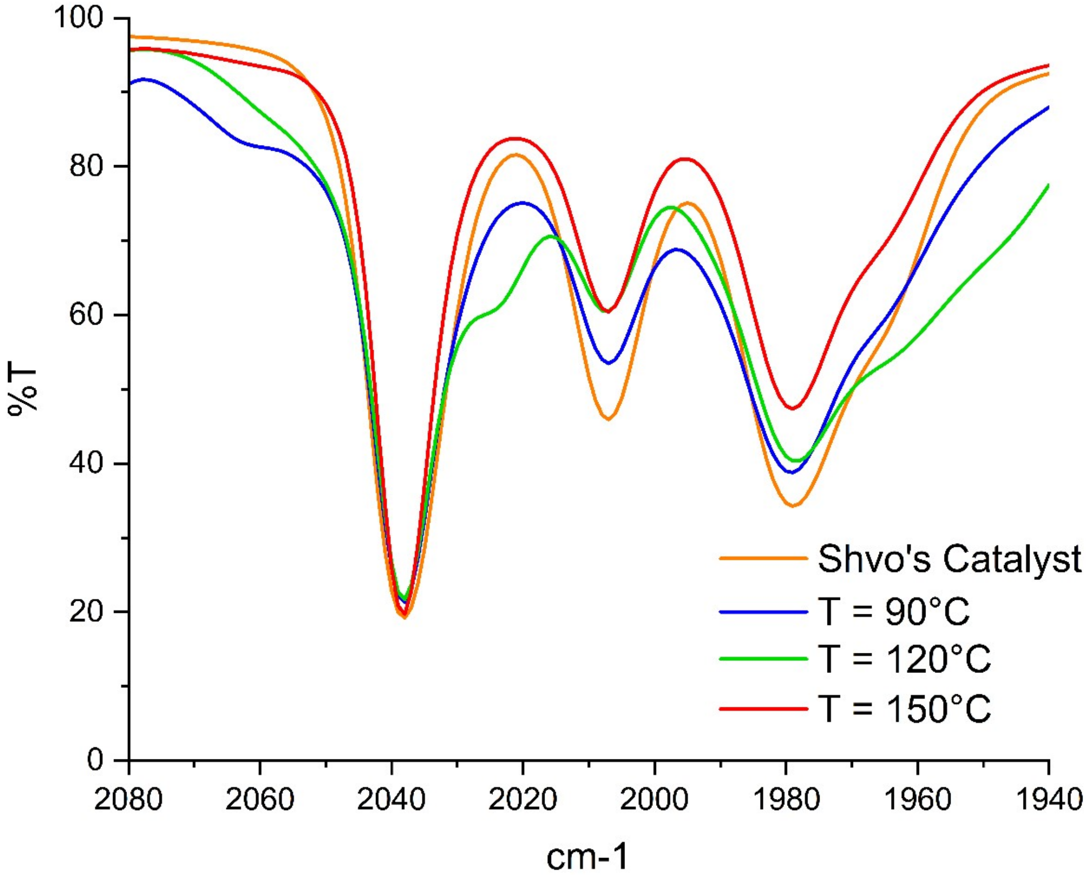
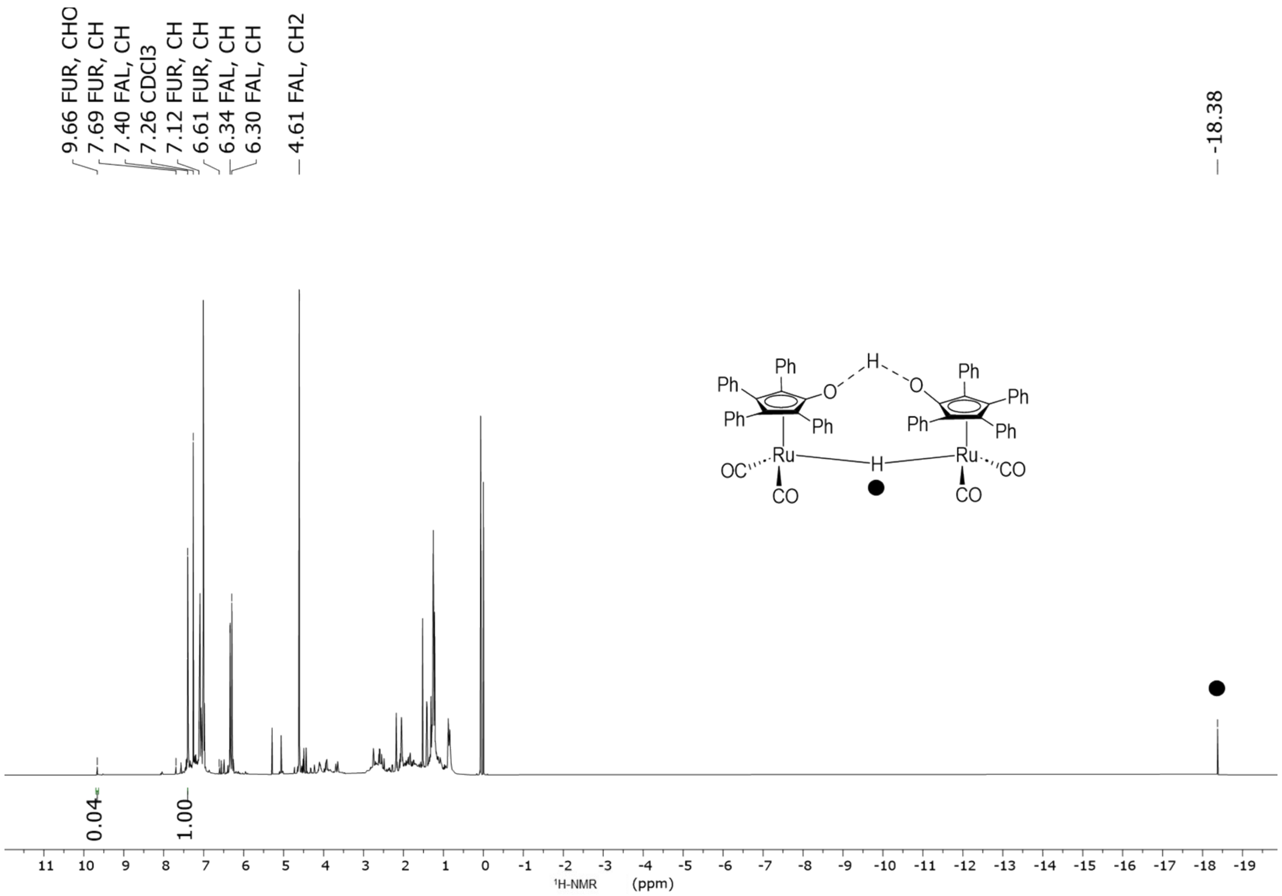
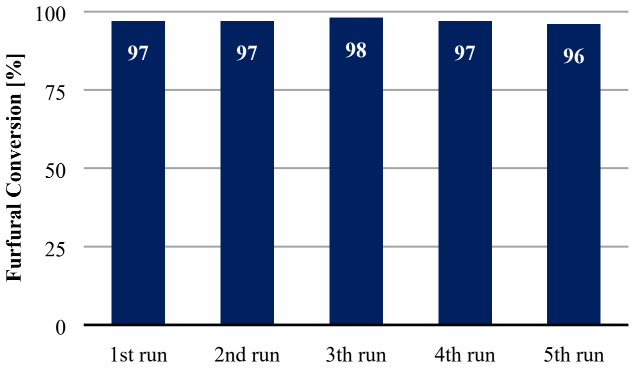


Figure S2. IR spectra comparison from run 1-3 (table S1), in CH_2Cl_2. Shvo's complex spectra is reported as reference.



FigureS3. Example of a ^{1}H-NMR spectrum in $CDCl_3$ of the crude reaction (run 1, table S1), zooming between 12 and -20 ppm. The other signals not highlighted are residues of iPrOH (H-donor), 2-MeTHF (solvent), in which there is BHT as its stabilizer, and grease.



FigureS4. Recycle of Shvo's catalyst for 5 consecutive runs at 150°C, 1.5 equivalents of 2-PrOH, flow rate of 250 µL/min

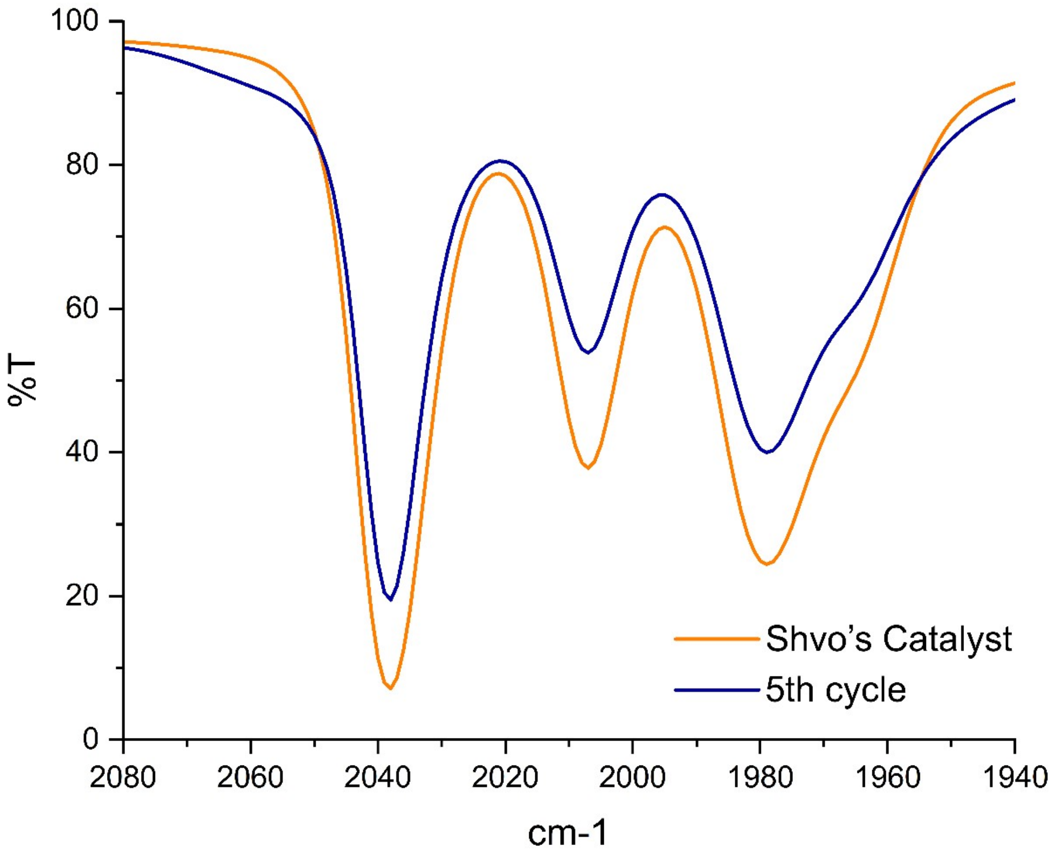
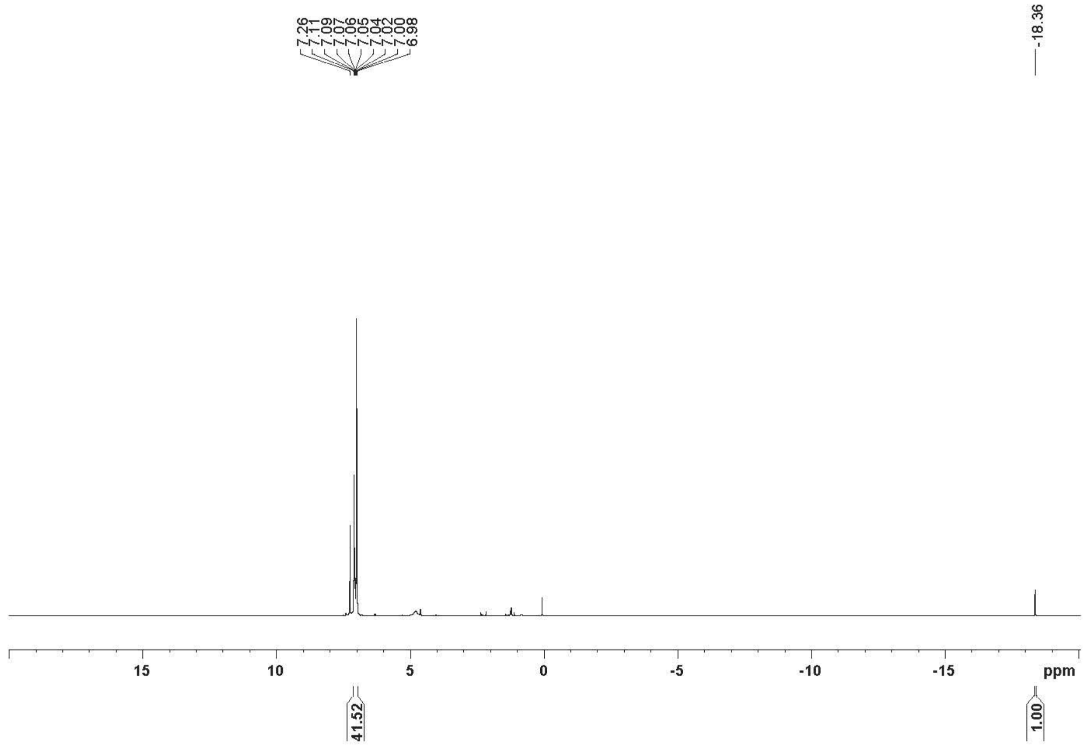
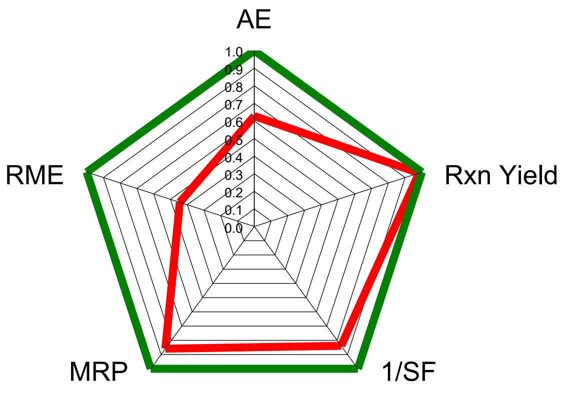
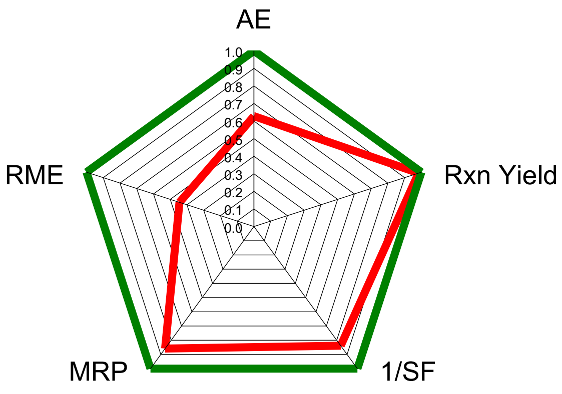


Figure S5. FT-IR of the fresh Shvo's catalyst (orange) and the crude solid after the 5th cycle in the flow reactor.



FigureS6. ^{1}H-NMR spectrum in $CDCl_3$ of the recovered Shvo's catalyst after the 5th cycle in the flow reactor.

FigureS7. ^{13}C-NMR spectrum in $CDCl_3$ of the recovered Shvo's catalyst the 5th cycle in the flow reactor.

12 mmol		**24 mmol**	
			
AE	0.63	**AE**	0.63
Rxn Yield	0.98	**Rxn Yield**	0.98
1/SF	0.84	**1/SF**	0.84
MRP	0.86	**MRP**	0.92
RME	0.44	**RME**	0.48
VMR: 0.77		**VMR:** 0.79	

FigureS8. Comparison of green metrics for the scale-up at 12 mmol and 24 mmol using 1 mol% of Shvo's catalyst, with 10 mL of reaction mixture flushed through the system.