Electronic Supplementary Material (ESI) for Catalysis Science & Technology.

Supporting information for

One-pot reductive amination of aldehydes with nitroarenes over Au/Al_2O_3 catalyst in a continuous flow reactor

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1. General

^1H and ^{13}C NMR spectra were recorded at 400 and 100 MHz on a Bruker AV400 spectrometer. GC analysis was carried out using Agilent 6890N equipped with HP 5-MS column (60.0 m × 320 μm × 0.25 μm) and the flame ionization detector. GC–MS analysis was performed with Agilent 7000B Triple Quad System equipped with HP 5-MS column. Atomic adsorption spectrum measurements were carried out with Hitachi Z-8000 instrument. Transmission electron microscopy (TEM) studies were carried out using a JEM-2010 (JEOL, Japan) electron microscope. XRD patterns of the samples were recorded on a Shimadzu XRD-7000 diffractometer using CuK_α radiation ($\lambda = 0.15418$ nm). The investigation of the catalytic properties of Au/Al_2O_3 catalyst in the one-pot reductive amination of aldehydes with nitroarenes was performed using commercially available continuous flow device H-Cube Pro^{TM} (Thalesnano, Hungary).

2. Chemicals

Hydrogen tetrachloroaurate $HAuCl_4{\cdot}aq$ (49.47 wt.% Au) was purchased from Aurat (Russia) and used without further purification. Nitrobenzene (99%), 4-nitrotoluene (99%), 3-nitrostyrene (97%), benzaldehyde (98+%), 4-tolualdehyde(99+%), 4-chlorobenzaldehyde (98.5+%), 4-anisaldehyde (99+%), heptaldehyde (95%), n-decane (99+%) from Acros Organics were used as supplied. Toluene (99.5%) from "ECOS" (Russia) and methanol (99.8%) from J.T.Baker were employed as solvents.

3. Catalyst preparation

The alumina support was prepared in the form of cylindrical garanules with the diameter of 1.5 mm by extrusion of paste, obtained by mixing of 30 wt% of alumina oxide (Puralox TH 100/150, Sasol), 70 wt% of alumina hydroxide (Disperal 20, Sasol) and water solution of nitric acid for peptization of alumina. After extrusion the alumina support was dried at 110°C overnight and then calcined in air flow at 550°C for 4 h. The obtained granules with S_{BET} of 151 $m^2\ g^{-1}$, total pore volume of 0.62 mL g^{-1} and mean pore diameter of 16.5 nm was crushed and sieved. The powder within the 250-500 μm range was used for the catalyst preparation.

The method for preparing of the Au/Al_2O_3 catalyst was similar to those previously described [S1]. 20 mL of a 2 mM $HAuCl_4$ solution was adjusted to pH 7 with 0.5M solution of NaOH. The solution was added with stirring to 1.0 g of Al_2O_3 suspended in 60 mL of distilled H_2O at 70°C. The resulting mixture was stirred in inclined rotating flask for two hours. The mixture was then suction filtered and washed by 50 mL of distilled water at room temperature. The final solid was dried at 100°C and then calcined in air at 350°C for one hour.

4. Characterization of the as-prepared and spent Au/Al_2O_3 catalysts

The transmission electron microscopy (TEM) studies were carried out using a JEM-2010 (JEOL, Japan) electron microscope with a lattice resolution of 0.14 nm and a 200 kV accelerating voltage. The mean diameters of gold particles for each catalyst sample were determined by counting of 250-300 particles in TEM images taken with a medium magnification. TEM data of the as-prepared and spent Au/Al_2O_3 catalyst are presented in Figures S1-S2. TEM study of the spent Au/Al_2O_3 catalyst (Figure S2) demonstrated that the mean diameter of metal particles didn’t increase after three cycles of the reductive amination of n-heptaldehyde with nitrobenzene in toluene under continuous flow conditions at 80°C.

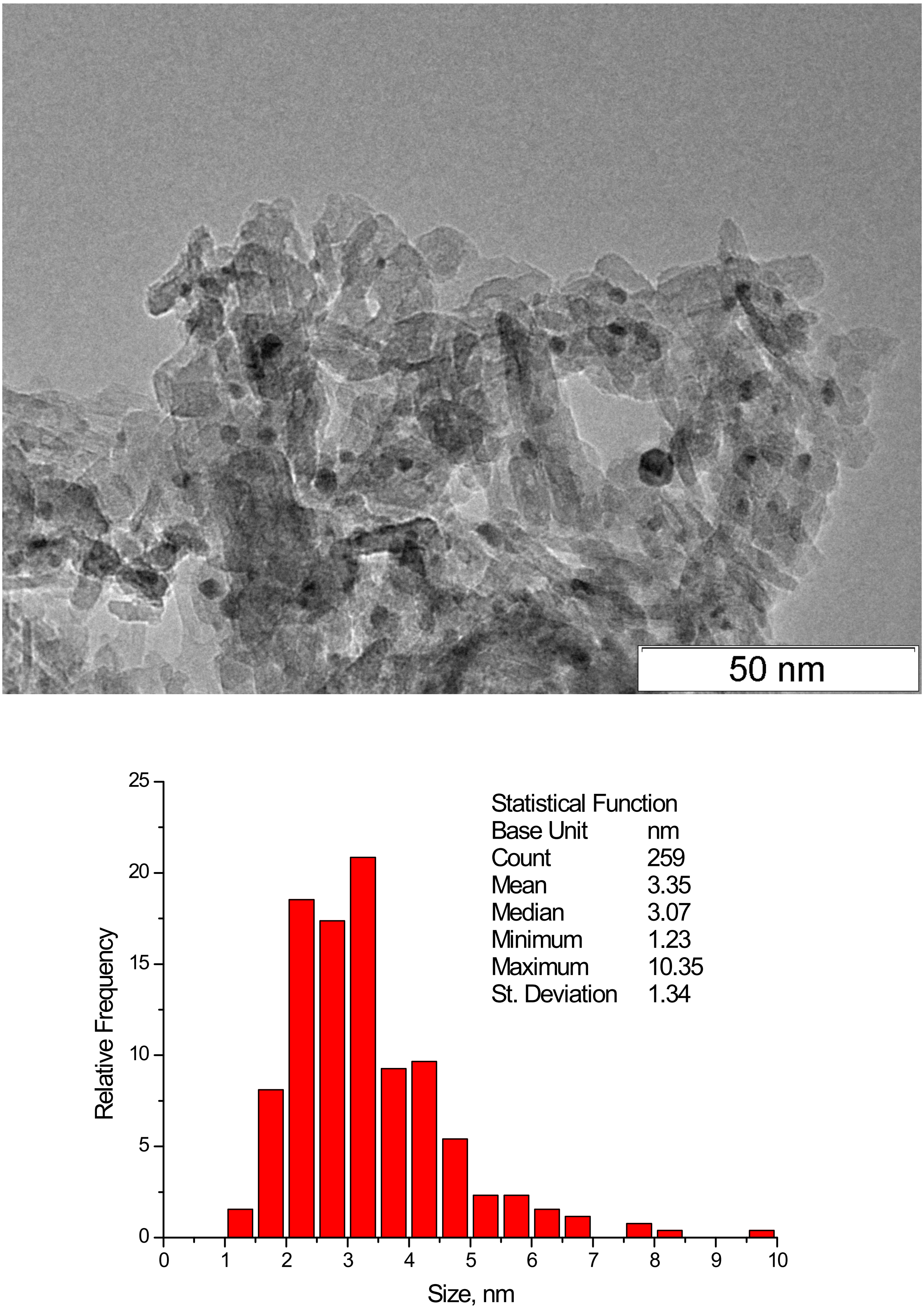
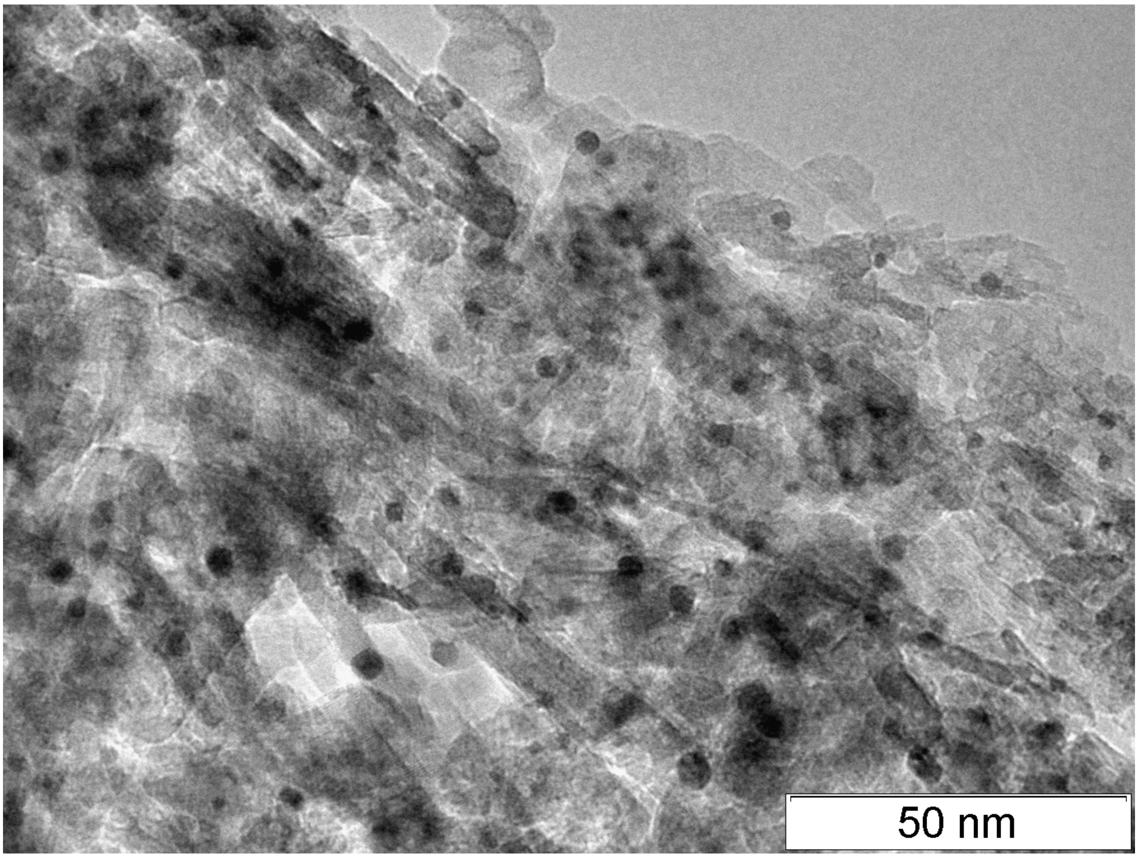


Figure S1. TEM images of the as-prepared Au/Al_2O_3 catalyst



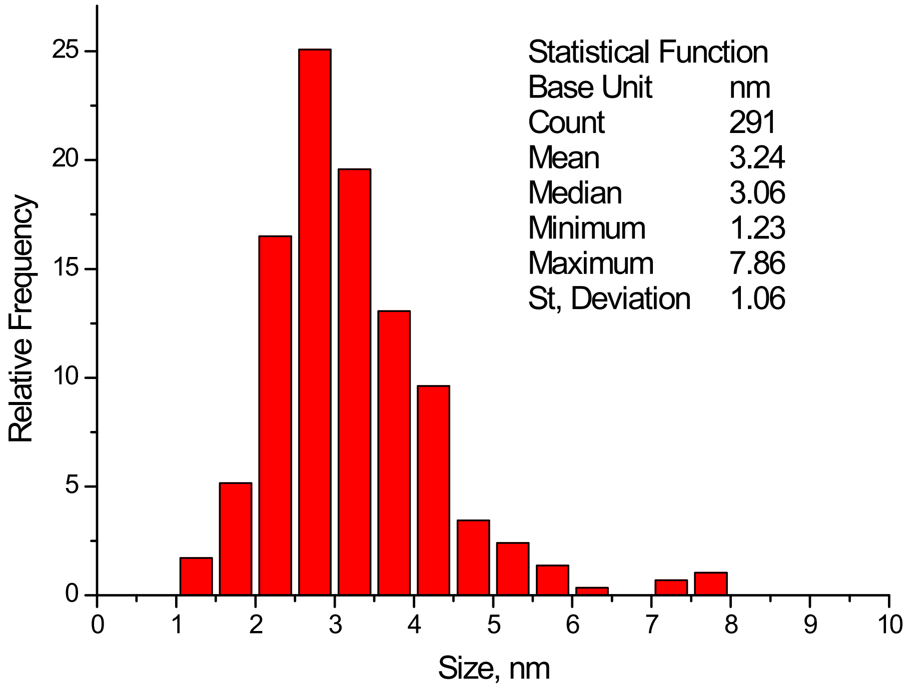


Figure S2. TEM images of the Au/Al_2O_3 catalyst after three cycles of the reductive amination of n-heptaldehyde with nitrobenzene in toluene under continuous flow conditions at 80°C and pressure = 50 bar.

XRD patterns of the as-prepared Au/γ-Al_2O_3 catalyst were recorded on a Shimadzu XRD-7000 diffractometer using CuK_α radiation ($\lambda = 0.15418$ nm) and Ni filter on the reflected beam. The data were collected for 50 s per step with a 0.1° step size in the 2Θ range between 30° and 90°. XRD data are presented in Figure S3. The volume-averaged crystallite sizes (D) of the face centred cubic structure of Au particles were determined from the value of the integral breadths of the (111), diffraction peak, using the Scherrer equation [S2] after subtraction of contribution of the γ-Al_2O_3 support. According to XRD data the volume-averaged crystallite sizes of the gold nanoparticles is less than 5 nm.

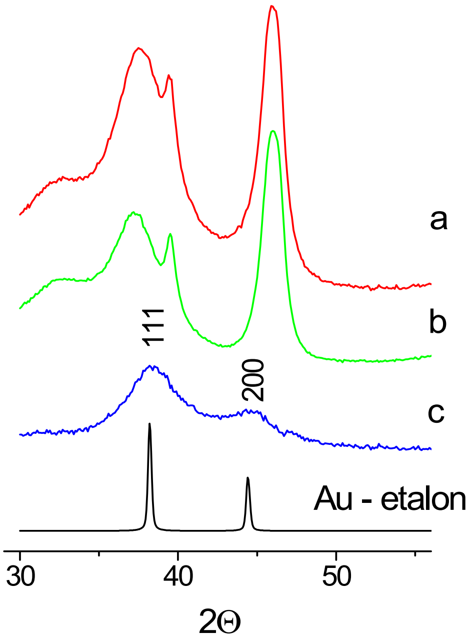


Figure S3. Fragments of X-ray diffraction patterns for Au/Al_2O_3 catalyst – (a), γ-Al_2O_3 support – (b) and difference curve – (c).

The Au contents of the as-prepared and spent catalyst's samples were measured by Atomic absorption spectroscopy on Hitachi Z-8000 instrument.

Thermal analysis of the as-prepared and spent catalysts was performed on a NETZSCH STA 449C Jupiter instrument. The sample (40 mg) in a corundum crucible placed on a thermo balance was heated from 25 to 600°C under air flow (heating rate of 10°C min^{-1}). As a reference sample, calcined silica was used.

The differential thermogravimetric (DTG) curve of the as-prepared catalyst exhibit the broad peak with a maximum at 86°C, which is related to removal of adsorbed water (the loss of the sample weight in the 25-250°C range is 5.8%) (Figure S4). Additionally, the weight loss of

1.2% is observed in the 250-540°C range, probably due to elimination of hydroxyl groups from the alumina surface or water removal from micro pores. The DTG curve of spent Au/Al_2O_3 exhibited two weight loss regions: the first (25-250°C) was caused by the removal of adsorbed water (the weight loss in this temperature range is 4.5%) and the second (250-540°C) could be explained by combustion of carbonaceous species deposited onto the catalyst surface, that was confirmed by the exothermic peak on DTA curve in this region with maxima at 371°C (Figure S5). The weight loss in this temperature region was 3.8% and estimated amount of carbon deposition in spent Au/Al_2O_3 catalyst was approximately 2.6 wt.%.

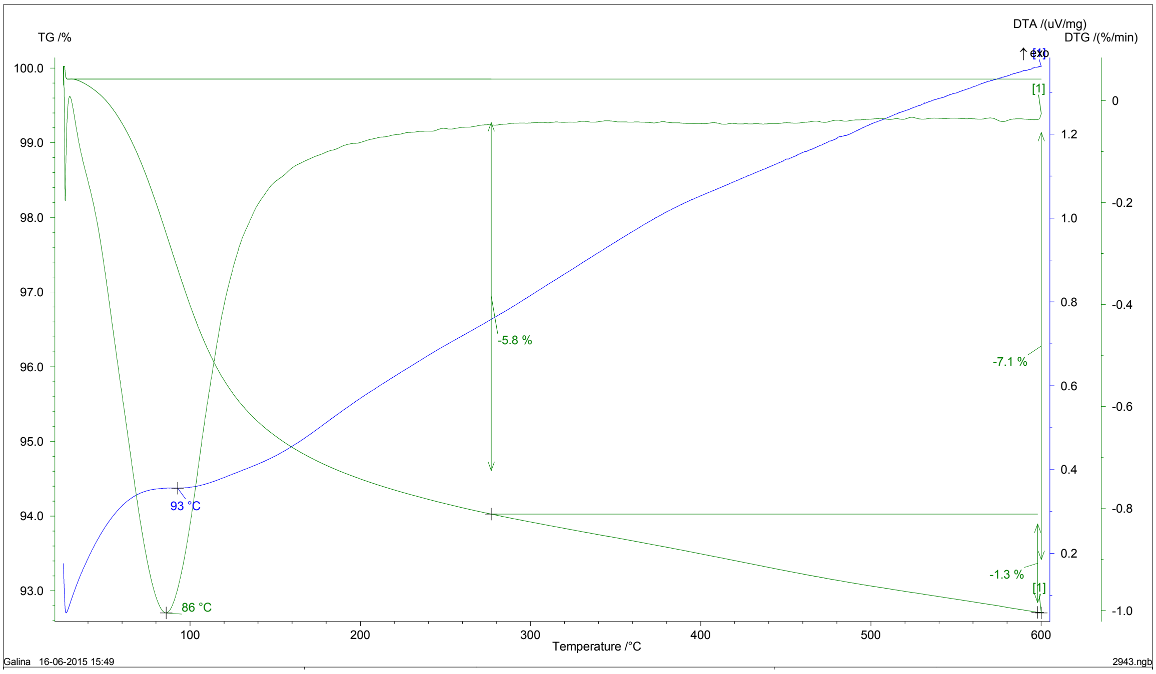


Figure S4. Thermal analysis curves for the as-prepared Au/Al_2O_3 catalyst.

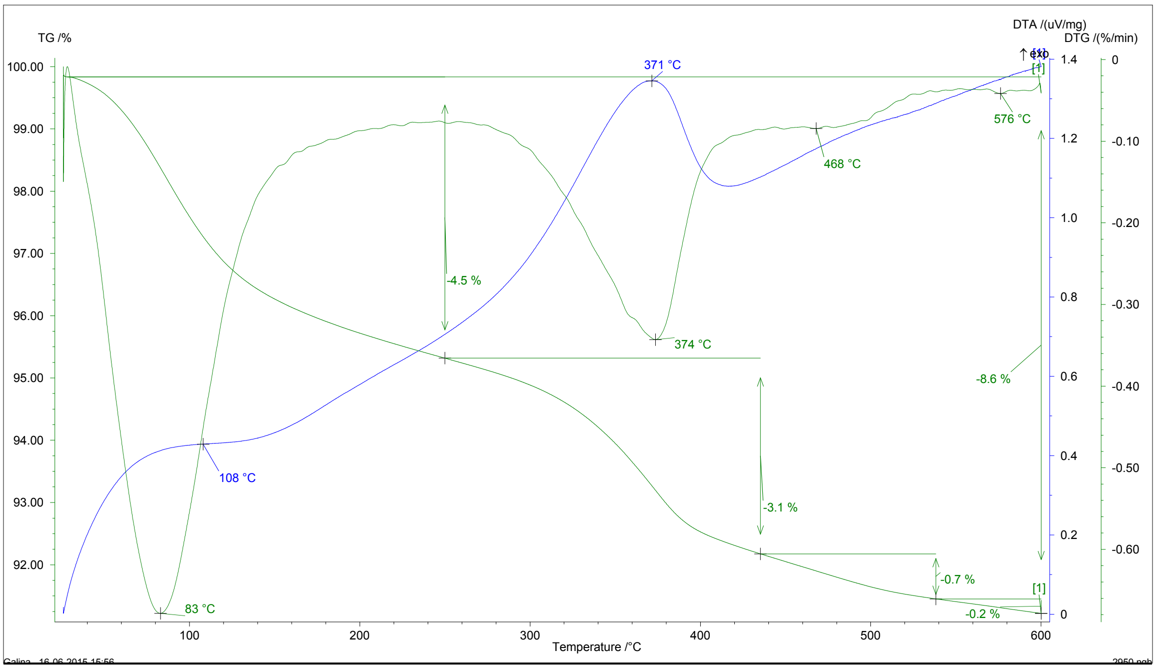


Figure S5. Thermal analysis curves for the Au/Al_2O_3 catalyst after three cycles of the reductive amination of n-heptaldehyde with nitrobenzene in toluene under continuous flow conditions at 80°C and pressure = 50 bar.

Table S1 shows the main characteristics of as-prepared Au/Al_2O_3 catalyst and catalyst used in three cycles of reductive amination of n-heptaldehyde with nitrobenzene (reaction conditions: 0.025 mol L^{-1} nitrobenzene, 0.0375 mol L^{-1} n-heptaldehyde, 80°C, 50 bar H_2).

Table S1 Main characteristics of as-prepared and spent Au/Al_2O_3 catalyst

Au/Al_2O_3 catalyst	Content of Au, wt.%	Average Au particle size, nm	Content of carbon deposition, wt.%
As-prepared	2.5±0.1	3.4	-
Spent	2.4±0.1	3.2	2.6

5. Typical procedure for reductive amination of aldehydes with nitroarenes over Au/Al_2O_3 catalyst

The investigation of the catalytic properties of Au/Al_2O_3 catalyst in the one-pot reductive amination of aldehydes with nitroarenes was performed using commercially available continuous flow device H-Cube Pro^{TM} (Thalesnano, Hungary), equipped with system for the automatic control of operation parameters (temperature, pressure, flow rate of substrate and hydrogen). The liquid feed was introduced in the reactor by HPLC pump in up-flow mode after the mixing with the hydrogen flow, generated by built-in electrolytic cell. The hydrogen pressure was maintained at the set-point level by means of automated back pressure regulator.

The packed bed cartridge-like reactors CatCart®30 with the inner diameter of 4.0 mm and length 30 mm (volume 0.38 mL) were used in the experiments. More detailed description of technical characteristics of the system has been published elsewhere [S3-S5].

Before the experiment the cartridge was filled with the catalyst (0.200 g of particles with the size of 250-500 μm) and was installed in the heated block controlled via Peltier system. The desired reaction parameters (temperature, pressure, hydrogen and reactant flow) were chosen and the process was started. The pure solvent was fed to the reactor with the rate of 0.5 ml/min until the required parameters were reached; afterwards the inlet was switched to the flask with the substrate's solution and the reaction was started. The solution of nitroarene (0.025M) and aldehyde (0.025M or 0.0375M) in toluene was used in the experiments with *n*-decane as the internal standard. In the standard experiment the reaction was carried out at 50 bar of hydrogen pressure, 0.5 mL min^{-1} liquid feed rate, 60 mL min^{-1} hydrogen feed rate, the temperature was changed in 50-90°C interval. The liquid product was collected after the feeding of substrate for 30 min. The performance of catalysts was evaluated by the averaging of the 2 samples taken at 30-35 min and 55-60 min after the start of experiment. The novel batch of catalysts was used in every experiment because of slight decrease in activity with time-on stream. Catalytic stability was studied by the time-on stream experiments by periodical sampling and analysis of products (every 20 min) and by repetition of standard experiments using the regenerated catalyst.

The activity of spent Au/Al_2O_3 catalyst can be recovered by the treatment in a methanol flow. After reaction the cartridge CatCart®30 was washed with methanol flow (1 mL min^{-1}) for 30 min.

The liquid samples were analyzed with a gas chromatography system (Agilent 6890N) equipped with HP 5-MS column (60.0 m × 320 μm × 0.25 μm) and the flame ionization detector. The reaction products were identified by gas chromatography/mass spectrometry technique using Agilent 7000B Triple Quad System equipped with the same column. The conversion of aldehydes was calculated using n-decane as the internal standard. The crude secondary anilines were purified by silica gel column chromatography and characterized by ^1H and ^{13}C NMR spectroscopy.

Yields of N-containing products were calculated by GC as the ratio of the product concentration to the sum of the concentrations of all products (quantitative conversion of the nitroarenes was observed in all experiments).

6. The time-dependent investigation of Au/Al_2O_3 catalyst in one-pot reductive amination of benzaldehyde with nitrobenzene

The time-dependent investigation of Au/Al_2O_3 catalyst in one-pot reductive amination of aldehydes with nitroarenes showed slight decrease of secondary amines yields with time-on stream. A reduction in the yield of N-benzylaniline at 80°C from 84% to 82% was occurred after 135 minutes on stream in the reaction of nitrobenzene with benzaldehyde in toluene (reaction conditions: 0.025 mol L^{-1} nitrobenzene, 0.0375 mol L^{-1} benzaldehyde, 50 bar H_2) (Figure S6).

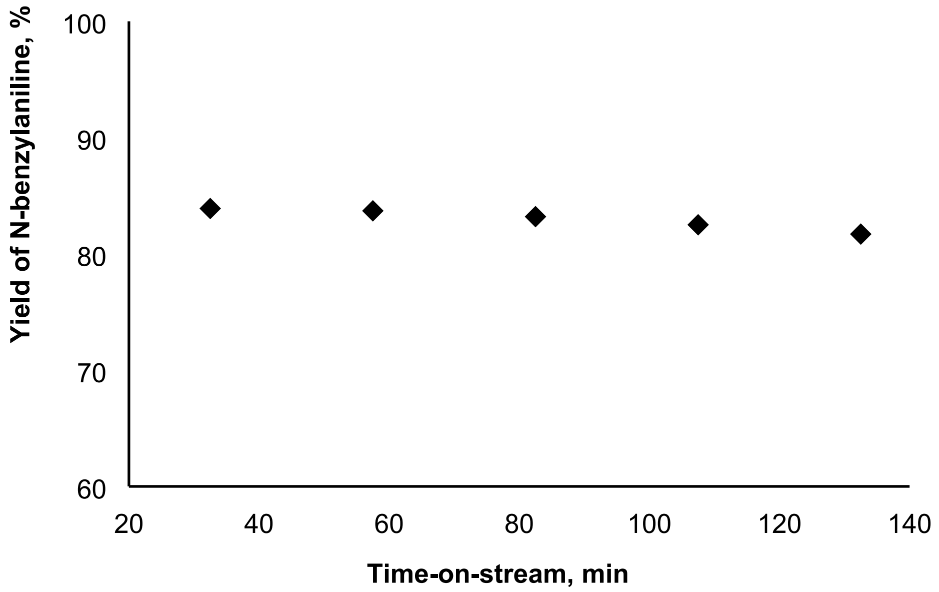
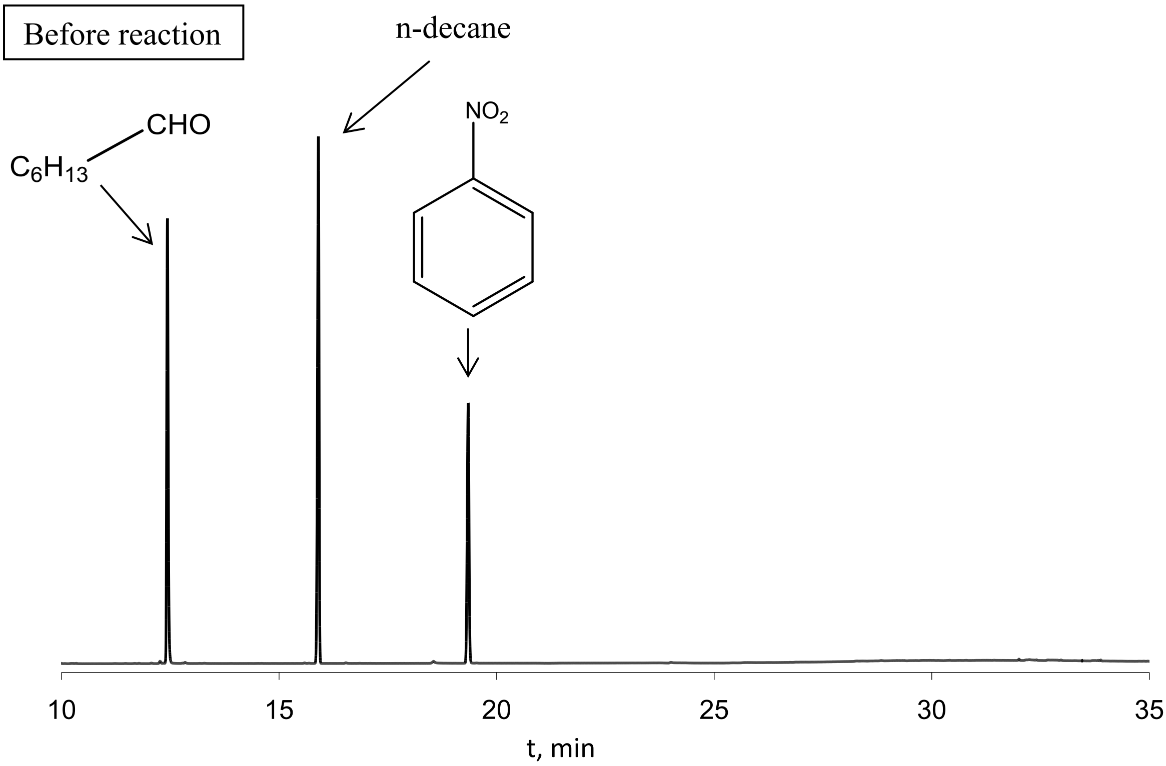
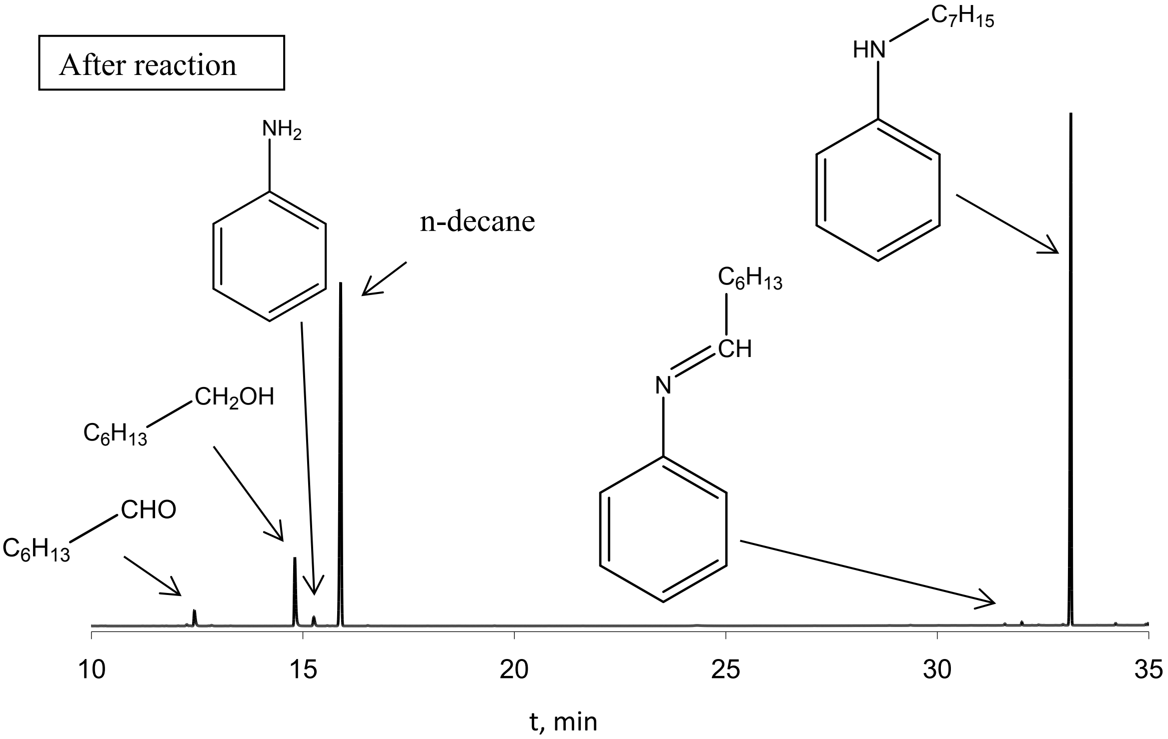


Figure S6. The time dependence of N-benzylaniline yield over Au/Al_2O_3 catalyst in the continuous flow conditions at 80°C and 50 bar H_2.

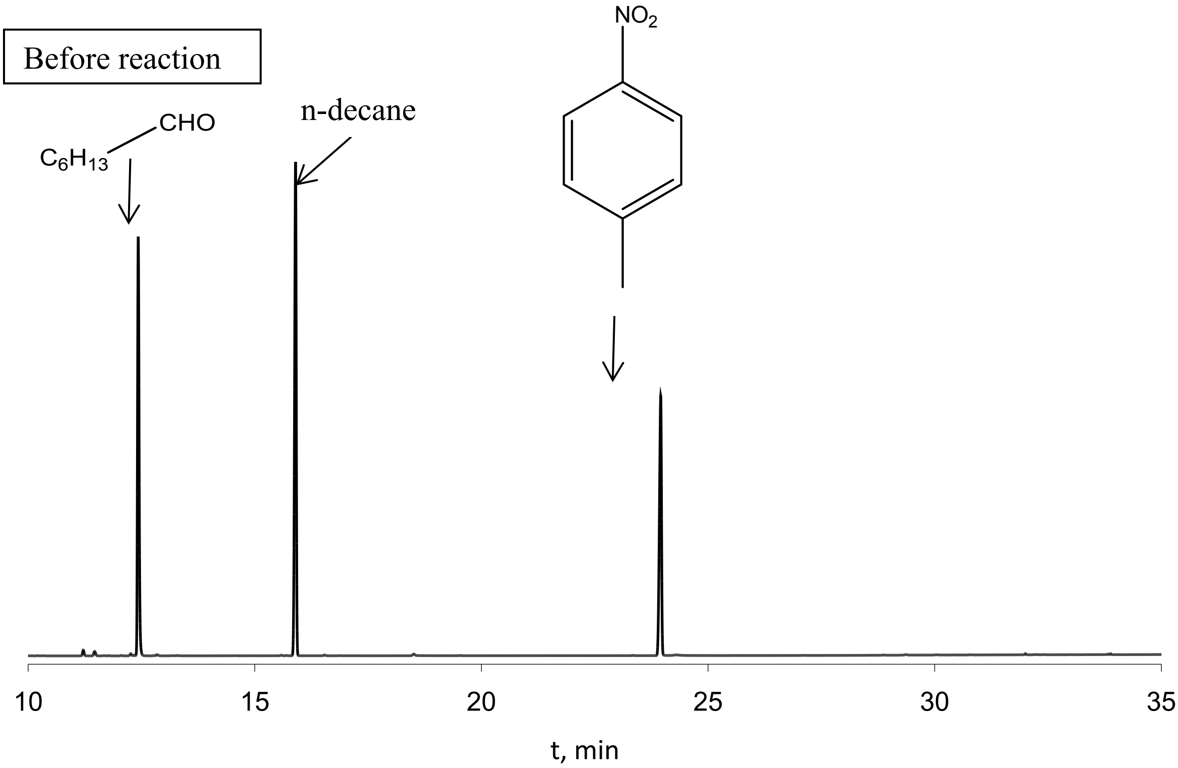
7. GC chromatograms

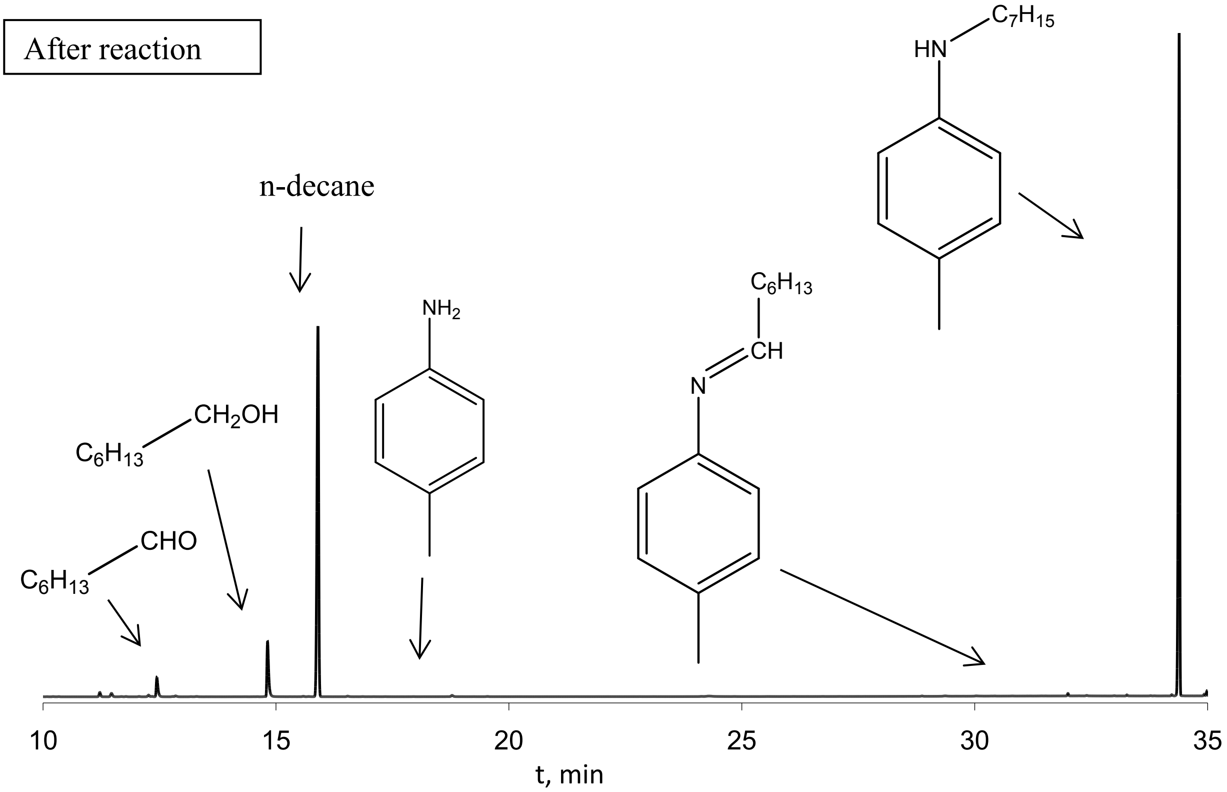
GC chromatograms for Table 1 Entry 8



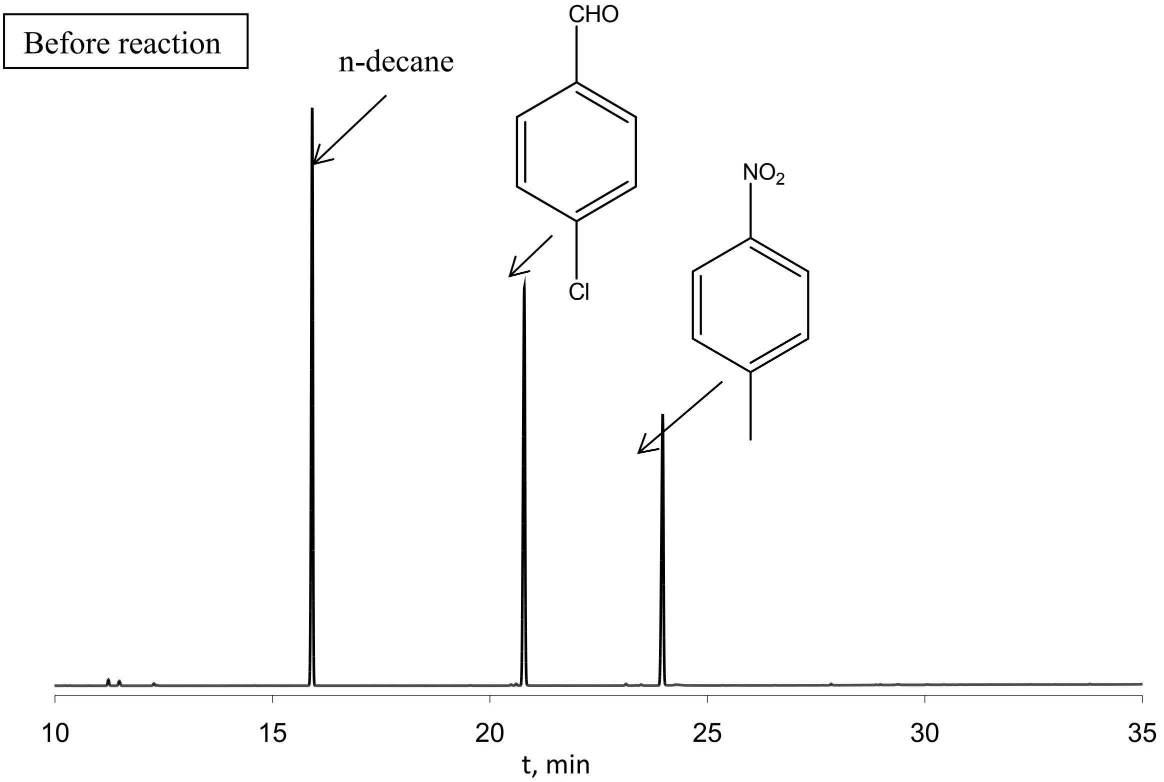


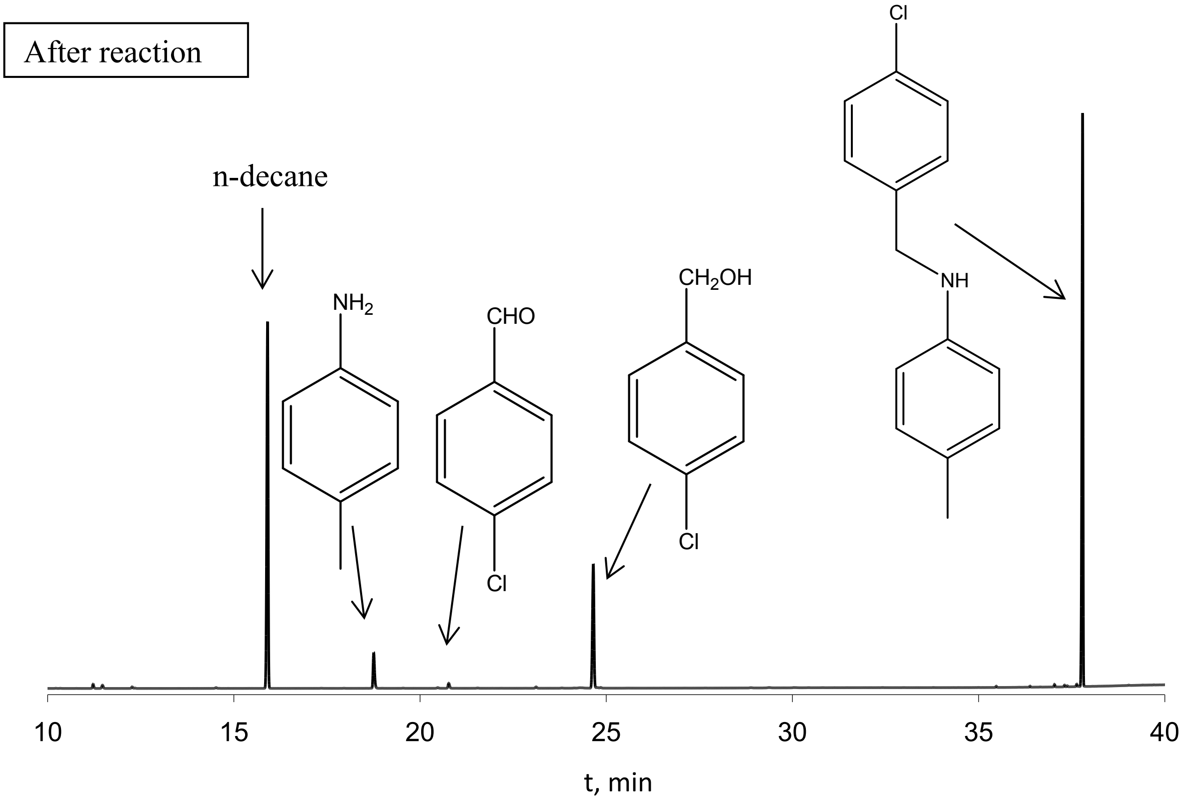
GC chromatograms for Table 1 Entry 11



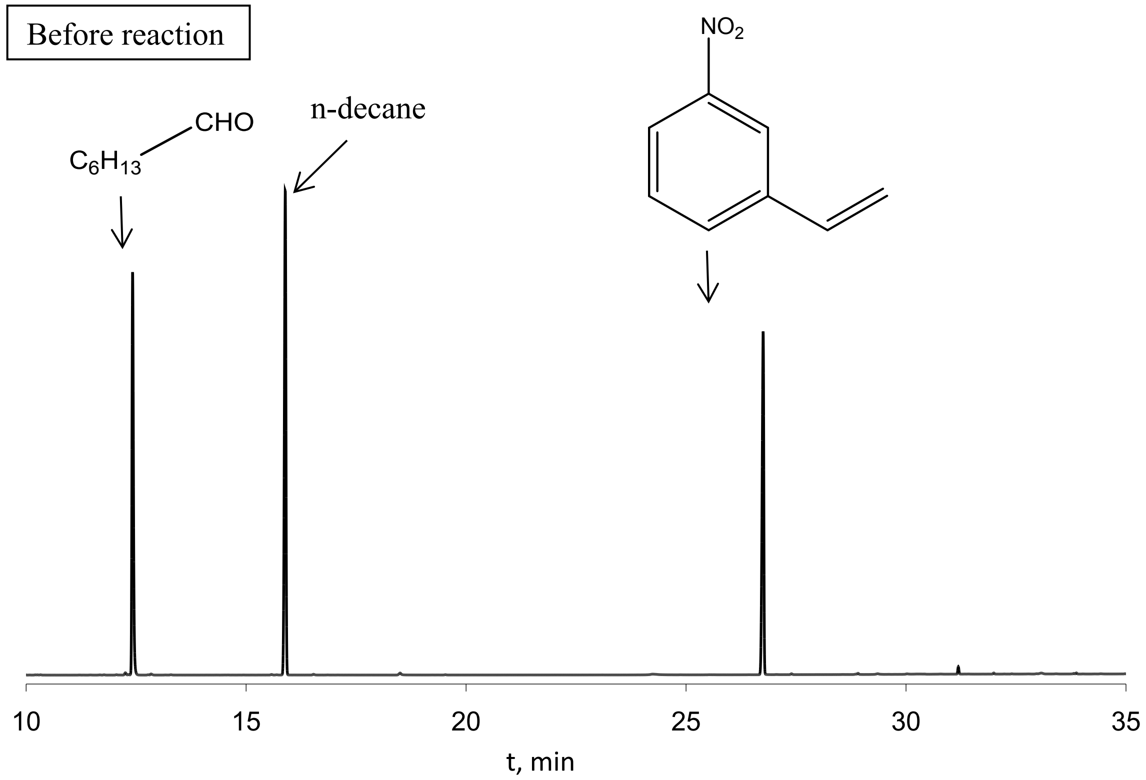


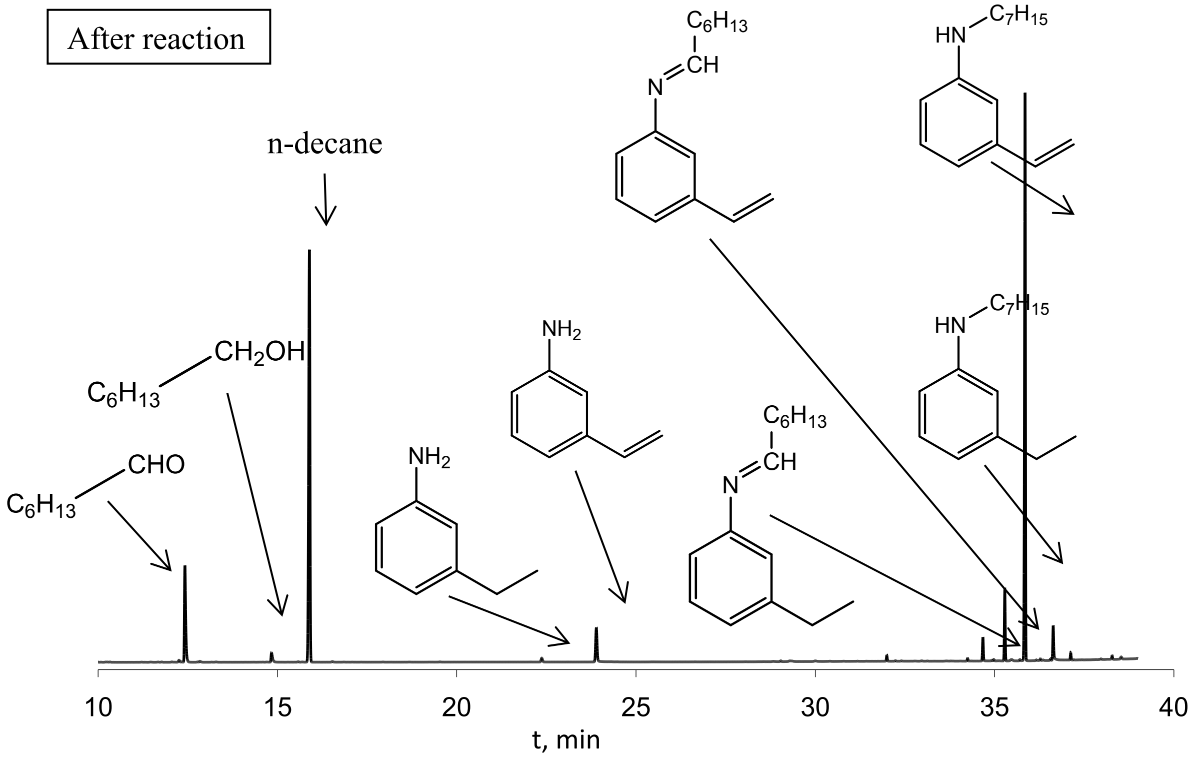
GC chromatograms for Table 1 Entry 15





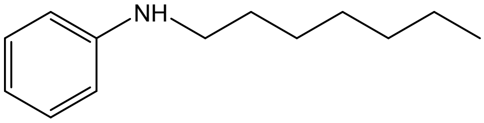
GC chromatograms for Table 2 Entry 2





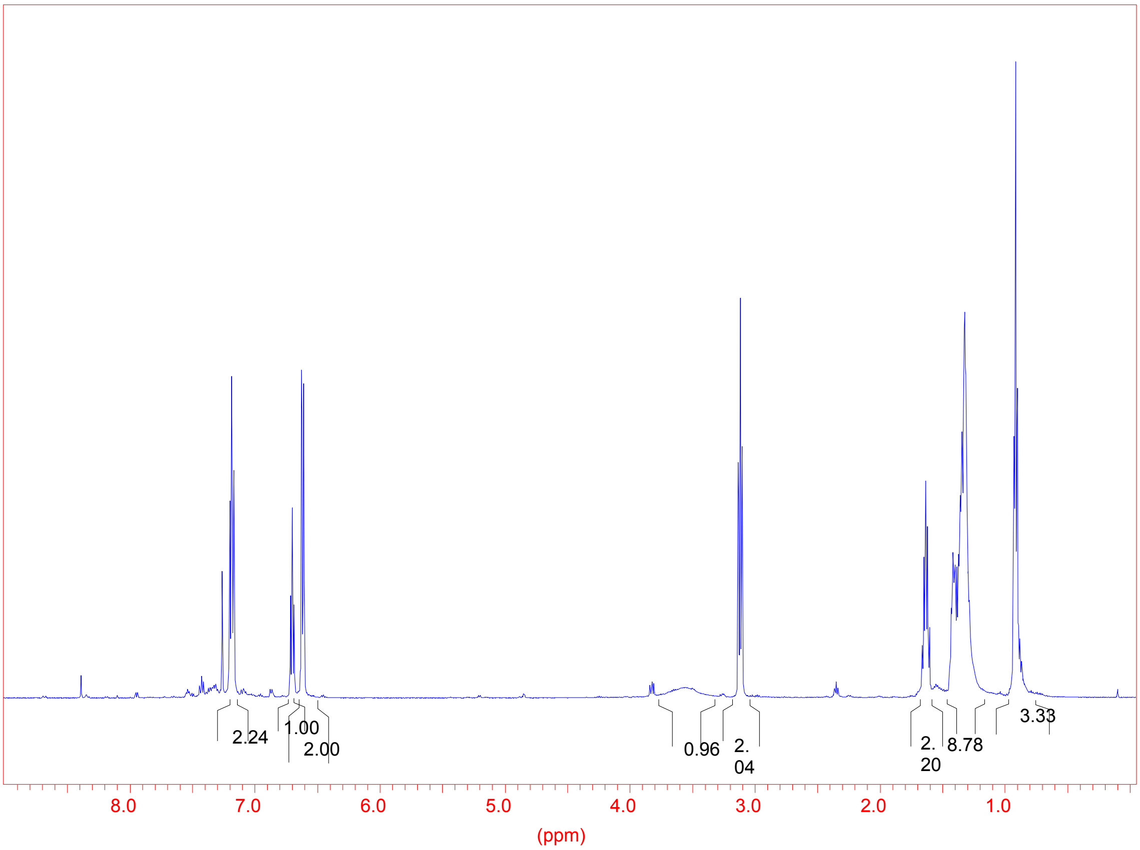
8. NMR data

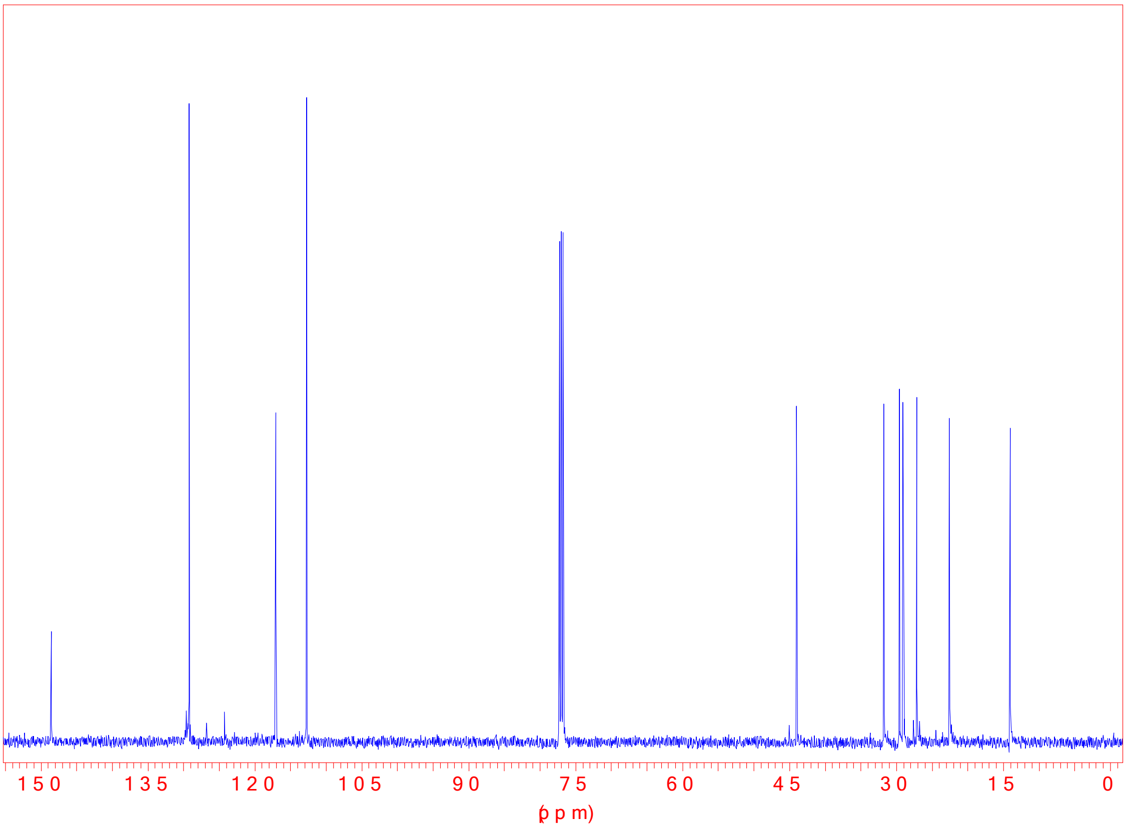
The ^{1}H NMR and ^{13}C NMR chemical shifts are reported relative to tetramethylsilane. The resonance of the residual protons of the solvent was used as internal standard for ^{1}H (δ 7.26 $CDCl_3$) and all deuterium solvent signals for ^{13}C (δ 77.0 $CDCl_3$). ^{1}H assignment abbreviations are the following: singlet (s), doublet (d), triplet (t), broad singlet (brs), doublet of doublets (dd) and multiplet (m). All the previously reported compounds were characterized by comparing their NMR spectra to the previously reported data [S6-S8].



^{1}H NMR (400 MHz, $CDCl_3$): δ 0.81-0.98 (m, 3H), 1.20-1.45 (m, 8H), 1.59-1.68 (m, 2H), 3.08-3.15 (t, 2H), 3.31-3.78 (brs, 1H), 6.59-6.64 (d, 2H), 6.67-6.73 (t, 1H), δ 7.15-7.24 (m, 2H).

^{13}C NMR (100 MHz, $CDCl_3$): δ 14.0, 22.6, 27.1, 29.1, 29.6, 31.8, 44.0, 112.7, 117.1, 129.2, 148.6.

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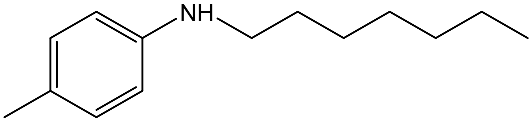
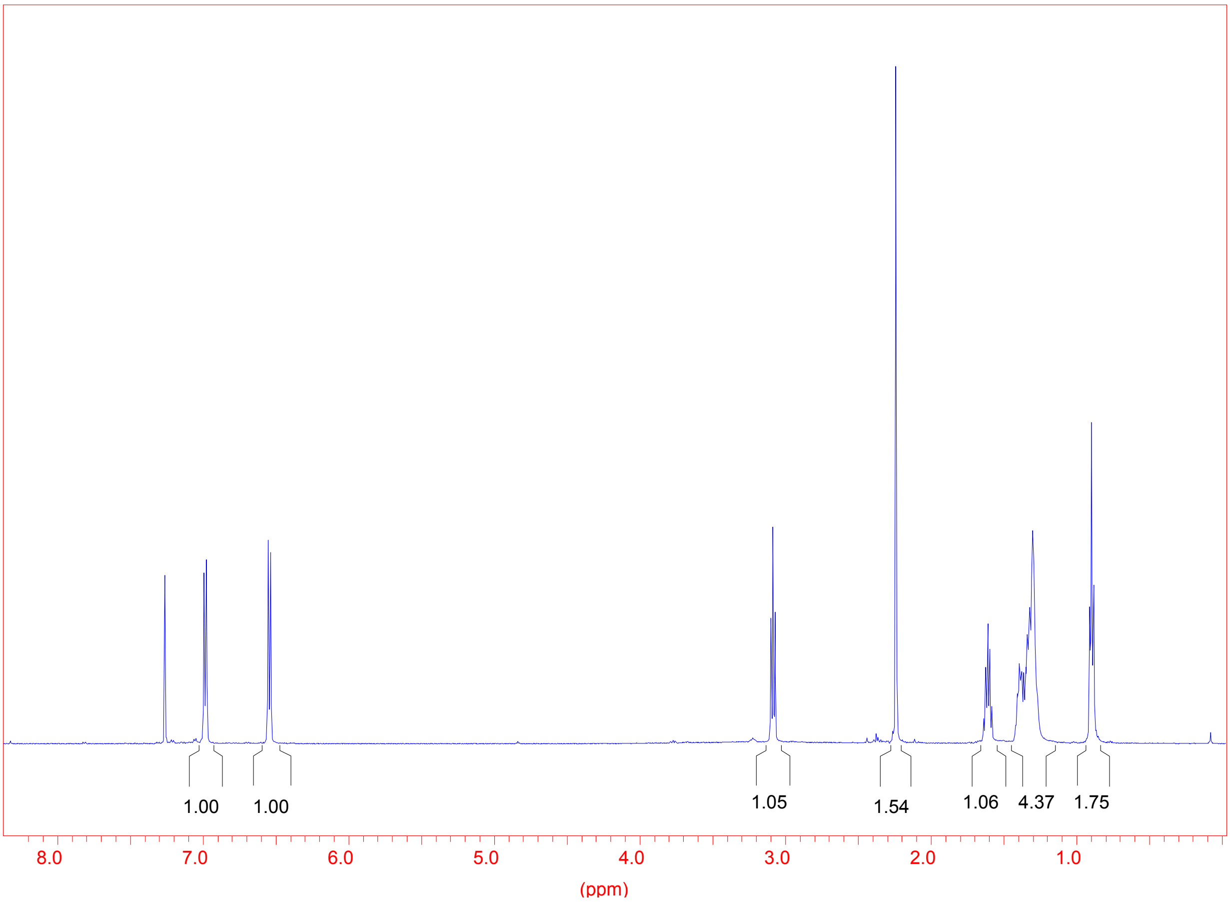
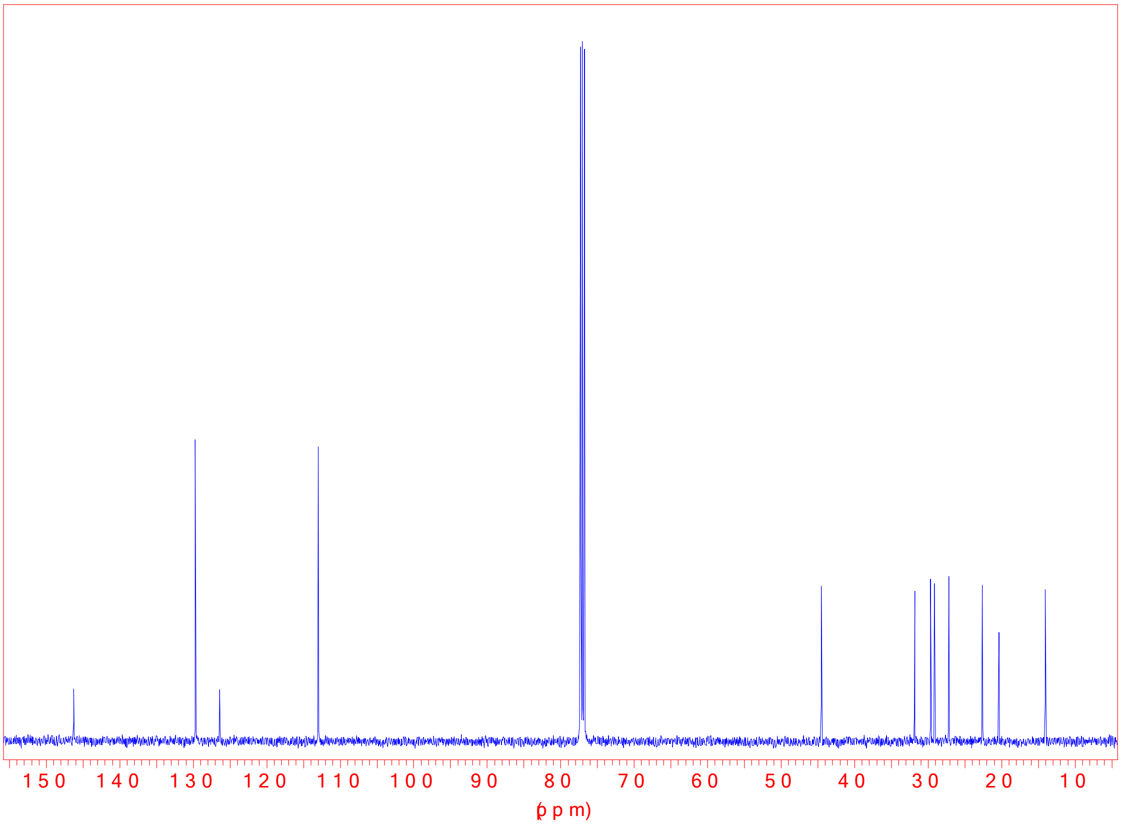


^{1}H NMR (400 MHz, $CDCl_3$): δ 0.82-0.95 (m, 3H), 1.20-1.44 (m, 8H), 1.56-1.66 (m, 2H), 2.21-2.26 (s, 3H), 3.05-3.12 (t, 2H), 6.51-6.57(d, 2H), 6.95-7.02 (d, 2H).

^{13}C NMR (100 MHz, $CDCl_3$): δ 14.0, 20.4, 22.6, 27.2, 29.1, 29.6, 31.8, 44.5, 113.0, 126.4, 129.7, 146.3.

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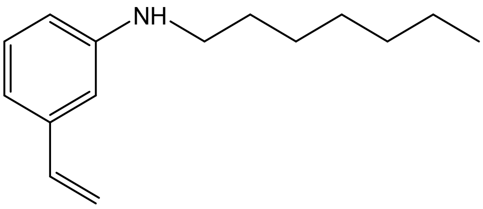
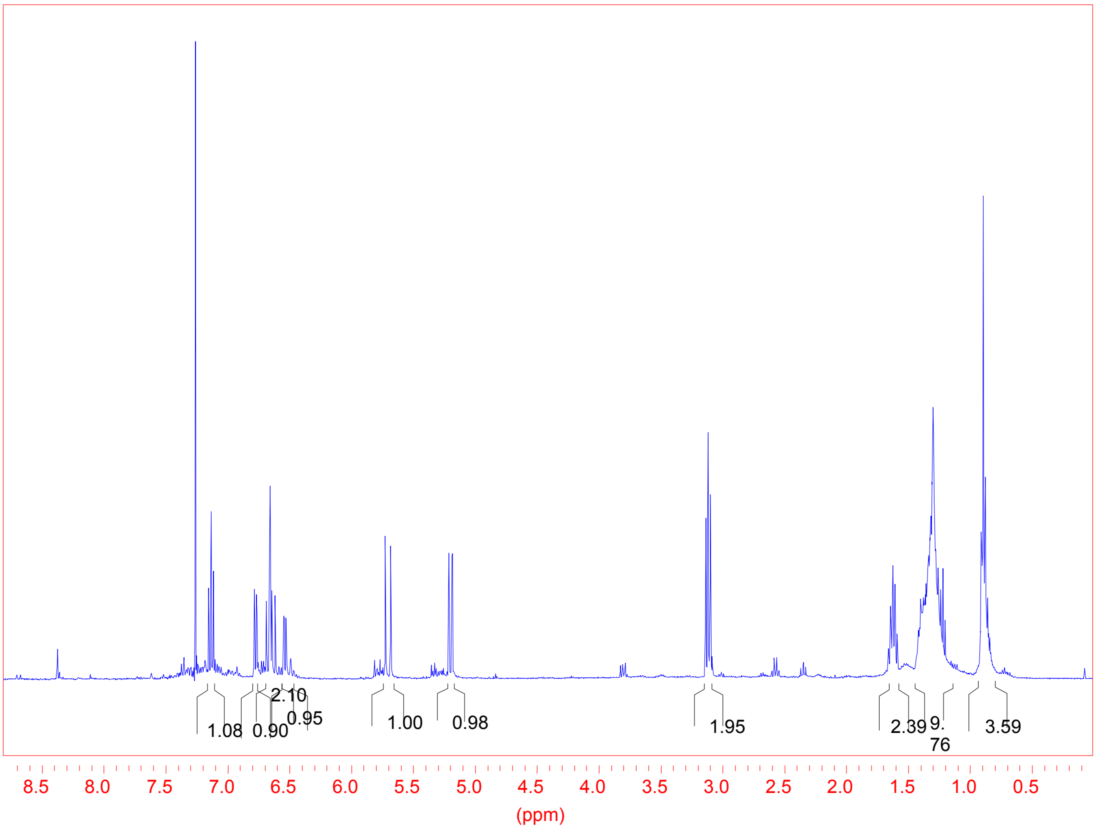
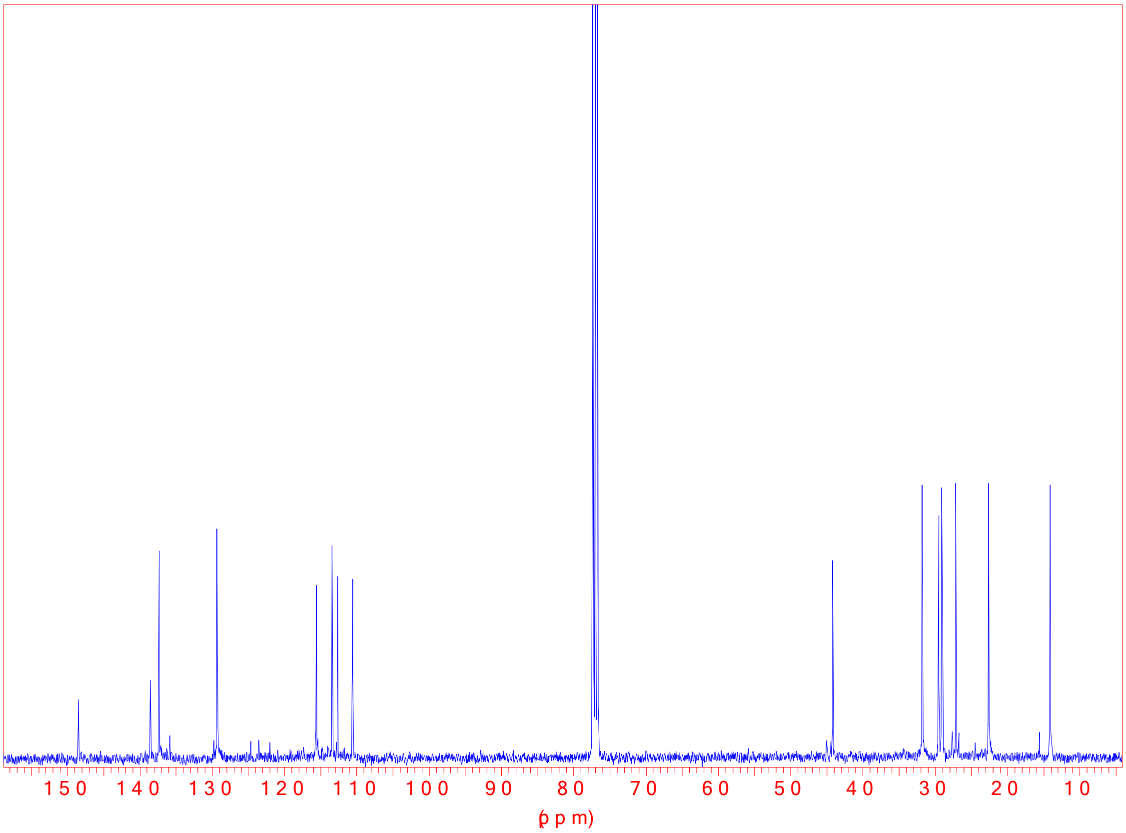


^{1}H NMR (400 MHz, CDCl$_3$): δ 0.80-0.95 (m, 3H), 1.17-1.44 (m, 8H), 1.58-1.67 (m, 2H), 3.07-3.15 (t, 2H), 5.17-5.22 (dd, 1H), 5.67-5.74 (dd, 1H), 6.51-6.56 (m, 1H), 6.61-6.69 (m, 2H), 6.76-6.80 (m, 1H), 7.11-7.16 (t, 1H).

^{13}C NMR (100 MHz, CDCl$_3$): δ 14.0, 22.6, 27.1, 29.1, 29.5, 31.8, 44.2, 110.5, 112.6, 113.4, 115.6, 129.3, 137.3, 138.5, 148.5.

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