Flow Synthesis of Cyclobutanones via [2+2] Cycloaddition of Keteneiminium Salts and Ethylene Gas

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Supporting Information Placeholder

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1. General Information
Unless stated otherwise, reagents were obtained from commercial sources and used without purification. New compounds have been fully characterized. NMR characterisation was performed on reported ones. $^1$H NMR spectra were recorded on Bruker Avance DPX-600 (600 MHz), with the residual solvent peak as the internal reference (CDCl$_3$ = 7.26 ppm). $^1$H resonances are reported to the nearest 0.01 ppm. $^{13}$C-NMR spectra were recorded on the same spectrometer with proton decoupling, with the solvent peak as the internal reference (CDCl$_3$ = 77.00 ppm). All $^{13}$C resonances are reported to the nearest 0.01 ppm. The multiplicity of $^1$H signals are indicated as: s = singlet, d = doublet, dd = doublet of doublets,ddd = doublet of doublets of doublets, t = triplet, q = quadruplet, sext = sextet, m = multiplet, br = broad, or combinations of thereof. Coupling constants ($J$) are quoted in Hz and reported to the nearest 0.1 Hz. Where appropriate, measures of the same coupling constant are averaged. The removal of solvent under reduced pressure was carried out on a standard rotary evaporator. Infrared spectra were recorded on a Perkin-Elmer Spectrum RX One FT-IR ATR (Attenuated Total Reflectance) spectrometer. The samples were prepared as thin films deposited on the ATR, unless otherwise specified. Only structurally important absorptions are quoted. Absorption maxima ($\nu_{\text{max}}$) are reported in wavenumbers (cm$^{-1}$). All gas-flow reactions were performed on a Vapourtec R2+/R4 module, a peristaltic Vapourtec SF-10 pump$^1$ and using a tube-in-tube reactor to introduce gases into a continuous flow stream. For the design of the tube-in-tube reactor see previous publications.$^2$
2. General procedure for the preparation of the amides (1a-r)

To a solution of carboxylic acid (1 mmol) in anhydrous CH$_2$Cl$_2$ (3 ml) were added bis-allylamine (1.1 mmol), N-(3-dimethylaminopropyl)-N-ethylcarbodiimide (EDC) (1.5 mmol) and 4- (dimethylamino)pyridine (DMAP) (0.2 mmol). The resulting solution was stirred overnight at room temperature, then diluted with CH$_2$Cl$_2$ (5 ml) and washed with 10 % HCl (3 x 10 ml). The combined organic layer was washed with brine, dried over anhydrous MgSO$_4$ and filtered. The solvent was removed in vacuo and the crude residue was purified by silica gel column chromatography using Hex/AcOEt (1:1) as eluent.

2.1. Characterisation data of the amides (1a-r)

$N,N$-diallyl-2-(p-tolyl)acetamide (1a)

Yellowish oil, 85 % yield. FT-IR (v$_{max}$, cm$^{-1}$) 1639. $^1$H-NMR (600 MHz, CDCl$_3$) $\delta$ 7.14 (dd, $J = 16.4, 8.1$ Hz, 4H), 5.85 – 5.63 (m, 2H), 5.15 (dddd, $J = 29.8, 18.6, 13.7, 1.2$ Hz, 4H), 4.00 (d, $J = 6.0$ Hz, 2H), 3.86 (d, $J = 5.0$ Hz, 2H), 3.67 (s, 2H), 2.33 (s, 3H).

$^{13}$C-NMR (151 MHz, CDCl$_3$) $\delta$ 171.2, 136.3, 133.2, 132.9, 132.0, 129.3, 128.6, 117.2, 116.8, 49.4, 47.8, 40.4, 21.0.

$N,N$-diallyl-2-(3-(trifluoromethyl)phenyl)acetamide (1b)

Yellowish oil, 85 % yield. FT-IR (v$_{max}$, cm$^{-1}$) 1639. $^1$H-NMR (600 MHz, CDCl$_3$) $\delta$ 7.51 – 7.37 (m, 4H), 5.74 – 5.70 (m, 2H), 5.15 – 5.09 (m, 4H), 3.99 (d, $J = 5.9$ Hz, 2H), 3.88 (d, $J = 4.4$ Hz, 2H), 3.72 (s, 2H). $^{13}$C-NMR (151 MHz, CDCl$_3$) $\delta$ 170.1, 136.1, 132.8, 132.6, 130.6, 128.8, 125.8, 124.9, 123.6, 123.1, 117.4, 116.7, 49.4, 48.1, 39.8.
\( \text{N,N-diallyl-2-(thiophen-3-yl)acetamide (1c)} \)

Yellowish oil, 72 % yield. **FT-IR** (\( \nu_{\max}, \text{cm}^{-1} \)) 1634. \( ^1\text{H-NMR} \) (600 MHz, CDCl\(_3\)) \( \delta \) 7.16 (dd, \( J = 4.9, 3.0 \text{ Hz}, 1\text{H} \)), 6.99 (m, 1H), 6.93 (d, \( J = 5.0 \text{ Hz}, 1\text{H} \)), 5.73 – 5.53 (m, 2H), 5.15 – 4.93 (m, 4H), 3.90 (d, \( J = 6.1 \text{ Hz}, 2\text{H} \)), 3.78 (d, \( J = 5.0 \text{ Hz}, 2\text{H} \)), 3.60 (s, 2H). \( ^{13}\text{C-NMR} \) (151 MHz, CDCl\(_3\)) \( \delta \) 170.5, 134.9, 133.0, 132.8, 128.2, 125.6, 121.9, 117.2, 116.6, 49.4, 47.8, 35.3.

\( \text{N,N-diallyl-2-(3,4-dimethoxyphenyl)acetamide (1d)} \)

Yellowish oil, 85 % yield. **FT-IR** (\( \nu_{\max}, \text{cm}^{-1} \)) 1634. \( ^1\text{H-NMR} \) (600 MHz, CDCl\(_3\)) \( \delta \) 6.81 (m, 2H), 6.76 (m, 1H), 5.81 – 5.63 (m, 2H), 5.23 – 5.04 (m, 4H), 3.99 (d, \( J = 5.8 \text{ Hz}, 2\text{H} \)), 3.86 (bs, 8H), 3.64 (s, 2H). \( ^{13}\text{C-NMR} \) (151 MHz, CDCl\(_3\)) \( \delta \) 171.1, 149.0, 147.8, 133.0, 132.9, 127.6, 120.8, 117.1, 116.7, 111.7, 111.2, 55.8, 55.8, 49.4, 47.8, 40.3.

\( \text{N,N-diallyl-2-(benzo[d][1,3]dioxol-5-yl)acetamide (1e)} \)

Yellowish oil, 80 % yield. **FT-IR** (\( \nu_{\max}, \text{cm}^{-1} \)) 1636. \( ^1\text{H-NMR} \) (600 MHz, CDCl\(_3\)) \( \delta \) 6.80 – 6.68 (m, 2H), 6.66 (d, \( J = 8.0 \text{ Hz}, 1\text{H} \)), 5.90 (s, 2H), 5.80 – 5.65 (m, 2H), 5.24 – 5.03 (m, 4H), 3.98 (d, \( J = 6.0 \text{ Hz}, 2\text{H} \)), 3.86 (d, \( J = 4.8 \text{ Hz}, 2\text{H} \)), 3.59 (s, 2H). \( ^{13}\text{C-NMR} \) (151 MHz, CDCl\(_3\)) \( \delta \) 171.1, 147.8, 146.4, 133.0, 132.8, 128.7, 121.8, 117.3, 116.8, 109.2, 108.2, 100.9, 49.3, 47.9, 40.1.
$N,N$-diallyl-2-(p-methoxyphenyl)acetamide (1f)

![Chemical Structure](image)

Yellowish oil, 70% yield. **FT-IR** ($\nu_{\text{max}}, \text{cm}^{-1}$) 1635. **$^1$H-NMR** (600 MHz, CDCl$_3$) $\delta$ 7.11 (d, $J = 8.7$ Hz, 2H), 6.78 (d, $J = 8.8$ Hz, 2H), 5.75 – 5.56 (m, 2H), 5.20 – 4.94 (m, 4H), 3.92 (d, $J = 6.0$ Hz, 2H), 3.79 (d, $J = 5.0$ Hz, 2H), 3.69 (s, 3H), 3.57 (s, 2H). **$^{13}$C-NMR** (151 MHz, CDCl$_3$) $\delta$ 171.1, 158.4, 133.1, 132.9, 129.7, 127.1, 117.1, 116.6, 113.9, 55.1, 49.3, 47.7, 39.6.

2,2’(1,4-phenylene)bis($N,N$-diallylacetamide) (1g)

![Chemical Structure](image)

Yellowish solid, 83%. **FT-IR** ($\nu_{\text{max}}, \text{cm}^{-1}$) 1652, 1634. **$^1$H-NMR** (600 MHz, CDCl$_3$) $\delta$ 7.22 (s, 4H), 5.81 – 5.65 (m, 4H), 5.26 – 5.06 (m, 8H), 4.00 (d, $J = 5.9$ Hz, 4H), 3.88 – 3.84 (m, 4H), 3.69 (s, 4H). **$^{13}$C-NMR** (151 MHz, CDCl$_3$) $\delta$ 170.9, 133.6, 133.1, 132.8, 129.0, 117.3, 116.8, 49.4, 47.9, 40.3.

$N,N$-diallyl-2-(5-methylbenzofuran-3-yl)acetamide (1h)

![Chemical Structure](image)

Yellowish oil, 70% yield. **FT-IR** ($\nu_{\text{max}}, \text{cm}^{-1}$) 1640. **$^1$H-NMR** (400 MHz, CDCl$_3$) $\delta$ 7.56 (s, 1H), 7.37 (d, $J = 8.7$ Hz, 2H), 7.13 (dd, $J = 8.3$, 1.7 Hz, 1H), 6.50 (d, $J = 6.4$ Hz, 2H), 5.34 – 4.97 (m, 4H), 4.06 (d, $J = 6.0$ Hz, 2H), 3.96 (d, $J = 4.8$ Hz, 2H), 2.46 (s, 3H). **$^{13}$C-NMR** (151 MHz, CDCl$_3$) $\delta$ 169.98, 153.67, 142.62, 133.04, 132.82, 127.57, 125.90, 119.30, 117.55, 116.85, 113.94, 112.72, 111.09, 49.60, 48.21, 37.08, 29.29.
\[ \text{N,N-diallyl-2-(2-chlorophenyl)acetamide (1i)} \]

Yellowish oil, 72% yield. FT-IR (\(v_{\text{max}}, \text{cm}^{-1}\)) 1639. \(^1\text{H-NMR}\) (600 MHz, CDCl\(_3\)) \(\delta\) 7.39 (d, \(J = 1.6\) Hz, 1H), 7.38 (d, \(J = 1.8\) Hz, 1H), 7.27 – 7.20 (m, 2H), 5.85 – 5.73 (m, 2H), 5.29 – 5.11 (m, 4H), 4.05 (d, \(J = 6.0\) Hz, 2H), 3.96 – 3.90 (m, 2H), 3.82 (s, 2H). \(^{13}\text{C-NMR}\) (151 MHz, CDCl\(_3\)) \(\delta\) 170.0, 134.0, 133.4, 133.0, 132.5, 130.9, 129.4, 128.3, 126.9, 117.5, 116.8, 49.4, 48.1, 37.9.

\[ \text{N,N-diallyl-2-(4-cyanophenyl)acetamide (1j)} \]

Yellowish oil, 78% yield. FT-IR (\(v_{\text{max}}, \text{cm}^{-1}\)) 2227, 1636. \(^1\text{H-NMR}\) (600 MHz, CDCl\(_3\)) \(\delta\) 7.59 (d, \(J = 7.9\) Hz, 2H), 7.36 (d, \(J = 7.8\) Hz, 2H), 5.82 – 5.69 (m, 2H), 5.28 – 5.05 (m, 4H), 3.99 (d, \(J = 5.4\) Hz, 2H), 3.89 (s, 2H), 3.73 (s, 2H). \(^{13}\text{C-NMR}\) (151 MHz, CDCl\(_3\)) \(\delta\) 169.6, 140.7, 132.7, 132.5, 132.2, 130.0, 118.8, 117.7, 116.9, 110.7, 49.4, 48.3, 40.1.

\[ \text{N,N-diallyl-2-(4-nitrophenyl)acetamide (1k)} \]

Yellowish oil, 73% yield. FT-IR (\(v_{\text{max}}, \text{cm}^{-1}\)) 1637. \(^1\text{H-NMR}\) (600 MHz, CDCl\(_3\)) \(\delta\) 8.20 – 8.11 (m, 2H), 7.42 (d, \(J = 8.6\) Hz, 2H), 5.85 – 5.68 (m, 2H), 5.30 – 5.05 (m, 4H), 4.01 (s, 2H), 3.94 – 3.89 (m, 2H), 3.79 (s, 2H). \(^{13}\text{C-NMR}\) (151 MHz, CDCl\(_3\)) \(\delta\) 169.4, 146.9, 142.8, 132.7, 132.5, 130.1, 123.6, 117.7, 116.9, 49.4, 48.3, 39.8.
**Ethyl 10-(diallylamino)-10-oxodecanoate (I)**

![Chemical Structure](image)

Yellowish oil, 71% yield. **FT-IR** ($v_{\text{max}}$, cm$^{-1}$) 1641. **$^1$H-NMR** (600 MHz, CDCl$_3$) $\delta$ 5.81 – 5.72 (m, 2H), 5.25 – 5.10 (m, 4H), 4.14 (q, $J = 7.1$ Hz, 2H), 4.00 (d, $J = 5.9$ Hz, 2H), 3.88 (dd, $J = 2.9$, 1.8 Hz, 2H), 2.30 (dt, $J = 10.9$, 7.6 Hz, 4H), 1.66 – 1.58 (m, 5H), 1.28 (dd, $J = 21.8$, 14.7 Hz, 11H). **$^{13}$C-NMR** (151 MHz, CDCl$_3$) $\delta$ 173.7, 173.0, 133.3, 132.9, 116.9, 116.3, 60.0, 49.0, 47.7, 34.2, 32.8, 29.2, 29.1, 29.0, 28.9, 25.2, 24.8, 14.2.

**N,N-diallyl-11-bromoundecanamide (I)**

![Chemical Structure](image)

Amorphous white solid, 83% yield. **FT-IR** ($v_{\text{max}}$, cm$^{-1}$) 1653. **$^1$H-NMR** (600 MHz, CDCl$_3$) $\delta$ 5.83 – 5.73 (m, 2H), 5.26 – 5.09 (m, 4H), 4.00 (d, $J = 5.9$ Hz, 2H), 3.89 (d, $J = 4.7$ Hz, 2H), 3.42 (t, $J = 6.9$ Hz, 2H), 2.35 – 2.30 (m, 2H), 1.91 – 1.82 (m, 2H), 1.65 (dd, $J = 14.6$, 7.2 Hz, 2H), 1.43 (dd, $J = 14.6$, 7.1 Hz, 2H), 1.29 (d, $J = 13.3$ Hz, 10H). **$^{13}$C-NMR** (151 MHz, CDCl$_3$) $\delta$ 173.1, 133.4, 132.9, 117.0, 116.4, 49.0, 47.7, 34.1, 33.0, 32.8, 29.4, 29.3, 29.2, 28.7, 28.1, 25.3.

**N,N-diallyloctanamide (I)**

![Chemical Structure](image)

Yellowish oil, 48% yield. **FT-IR** ($v_{\text{max}}$, cm$^{-1}$) 1641. **$^1$H-NMR** (600 MHz, CDCl$_3$) $\delta$ 5.75 – 5.63 (m, 2H), 5.16 – 5.01 (m, 4H), 3.91 (d, $J = 6.0$ Hz, 2H), 3.83 – 3.78 (m, 2H), 2.29 – 2.18 (m, 2H), 1.62 – 1.53 (m, 2H), 1.28 – 1.15 (m, 8H), 0.80 (t, $J = 6.9$ Hz, 3H). **$^{13}$C-NMR** (151 MHz, CDCl$_3$) $\delta$ 173.1, 133.3, 132.8, 116.9, 116.3, 49.0, 47.6, 32.9, 31.6, 29.3, 29.0, 25.2, 22.5, 14.0.
**N,N-diallylcyclohexanecarboxamide (1o)**

![Chemical structure of N,N-diallylcyclohexanecarboxamide](image)

Colorless oil, 40 % yield. **FT-IR** ($v_{\text{max}}, \text{cm}^{-1}$) 1630. **$^1H$-NMR** (600 MHz, CDCl$_3$) $\delta$ 5.78 (m, 2H), 5.30 – 5.01 (m, 4H), 3.97 (s, 2H), 3.90 (s, 2H), 2.50 – 2.35 (m, 1H), 1.87 – 1.45 (m, 7H), 1.26 (s, 3H). **$^{13}C$-NMR** (151 MHz, CDCl$_3$) $\delta$ 176.3, 133.5, 116.7, 116.3, 48.9, 47.7, 40.8, 29.6, 25.8, 25.7.

**N,N-diallylpent-4-ynamide (1p)**

![Chemical structure of N,N-diallylpent-4-ynamide](image)

Yellowish oil, 53 % yield. **FT-IR** ($v_{\text{max}}, \text{cm}^{-1}$) 1637. **$^1H$-NMR** (600 MHz, CDCl$_3$) $\delta$ 5.81 – 5.63 (m, 2H), 5.35 – 4.95 (m, 4H), 3.96 (d, $J = 6.4$ Hz, 2H), 3.91 – 3.79 (m, 2H), 2.59 – 2.43 (m, 4H), 1.98 – 1.92 (m, 1H). **$^{13}C$-NMR** (151 MHz, CDCl$_3$) $\delta$ 176.3, 133.5, 116.7, 116.3, 48.9, 47.7, 40.8, 29.6, 25.8, 25.7.

**N,N-diallyl-3-phenylpropanamide (1q)**

![Chemical structure of N,N-diallyl-3-phenylpropanamide](image)

Yellowish oil, 86 % yield. **FT-IR** ($v_{\text{max}}, \text{cm}^{-1}$) 1637. **$^1H$-NMR** (600 MHz, CDCl$_3$) $\delta$ 7.26 (t, $J = 7.5$ Hz, 2H), 7.23 – 7.15 (m, 3H), 5.79 – 5.64 (m, 2H), 5.20 – 5.03 (m, 4H), 3.98 (d, $J = 6.1$ Hz, 2H), 3.81 – 3.75 (m, 2H), 3.01 – 2.94 (m, 2H), 2.65 – 2.57 (m, 2H). **$^{13}C$-NMR** (151 MHz, CDCl$_3$) $\delta$ 172.1, 141.3, 133.2, 132.8, 128.4, 126.0, 117.1, 116.4, 49.0, 48.0, 34.8, 31.4.
Yellowish oil, 60% yield. FT-IR ($\nu_{\text{max}}, \text{cm}^{-1}$) 1635. \textbf{^1H-NMR} (600 MHz, CDCl$_3$) $\delta$ 8.37 (d, $J = 9.2$ Hz, 1H), 8.17 (t, $J = 6.7$ Hz, 2H), 8.12 (d, $J = 3.5$ Hz, 1H), 8.11 (d, $J = 2.0$ Hz, 1H), 8.06 – 7.97 (m, 3H), 7.88 (d, $J = 7.7$ Hz, 1H), 5.79 (ddt, $J = 16.2$, 10.2, 6.0 Hz, 1H), 5.67 (ddt, $J = 17.1$, 10.1, 4.9 Hz, 1H), 5.21 – 5.02 (m, 4H), 4.03 (d, $J = 6.0$ Hz, 2H), 3.83 – 3.73 (m, 2H), 3.50 – 3.40 (m, 2H), 2.45 (t, $J = 7.1$ Hz, 2H), 2.28 – 2.20 (m, 2H). \textbf{^13C-NMR} (151 MHz, CDCl$_3$) $\delta$ 172.5, 136.2, 133.4, 132.8, 131.4, 130.9, 129.8, 128.8, 127.4, 127.3, 127.3, 126.6, 125.7, 125.0, 124.9, 124.8, 124.7, 124.7, 123.5, 117.1, 116.5, 49.1, 47.9, 32.8, 32.3, 27.0.
3. Initial screening, optimised flow protocol for the synthesis of cyclobutanones (3a-r) and scale up procedure

Initial screening of flow parameters

Table S1. Screening of main parameters for the synthesis of cyclobutanone 3a.

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Optimised flow protocol

A solution of the amide 1 (2.2 mmol, 0.20 M) and 2-fluoro-pyridine 2b (2.64 mmol, 0.24 M) in anhydrous CH$_2$Cl$_2$ was pumped (flow rate 0.25 mL/min) through a tube-in-tube gas reactor pressurised with ethylene gas ($\Delta$P = 10 bar) and combined at a T-piece with a solution of triflic anhydride (2.64 mmol, 0.24 M) in anhydrous CH$_2$Cl$_2$ (pumped at 0.25 mL/min using a Vapourtec SF-10 peristaltic pump) to react in a 10 mL perfluorooalkoxy (PFA) polymeric coil, heated at 60 °C. The reactor output was directed through a 5 bar back pressure regulator, collected in a flask containing water and stirred overnight. The organic layer was recovered, the solvent was evaporated in vacuo and the mixture purified by flash chromatography to give the cyclobutanone product 3a-r.
A solution of the amide 1c (0.20 M) and 2-fluoro-pyridine 2b (0.24 M) in anhydrous CH₂Cl₂ (Pump A) was pumped (flow rate 0.25 mL/min) through a tube-in-tube gas reactor pressurised with ethylene gas (ΔP = 10 bar) and combined at a T-piece with a solution of triflic anhydride (0.24 M) in anhydrous CH₂Cl₂ (loaded in a PFA coil 60 mL, Pump B) (flow rate 0.25 mL/min) to react in a 10 mL perfluoroalkoxy (PFA) polymeric coil, heated at 60 °C. The reactor output was directed through a 5 bar back pressure regulator and collected in a reservoir. The solution was combined at a T-piece with a stream of distilled water (each channel pumped at 2.5 mL/min) and reacted at 80 °C in a static mixer coil (residence time of 7 min). The biphasic system was then directed to a membrane based liquid-liquid separator, whereby the organic layer was recovered and evaporated in vacuo. The crude mixture was purified by flash chromatography to give the cyclobutanone product 3c (3.92 g, 92% yield).
3.1. Characterisation data of cyclobutanones (3a-r)

2-(p-tolyl)cyclobutan-1-one (3a)

(SiO₂, CH₂Cl₂/ Hexane = 3:1). Yellowish oil, 89 % yield. FT-IR (νmax, cm⁻¹) 1779. ¹H NMR (600 MHz, CDCl₃) δ: 7.17 (s, 4H), 4.56 – 4.48 (m, 1H), 3.28 – 3.19 (m, 1H), 3.09 – 3.00 (m, 1H), 2.60 – 2.50 (m, 1H), 2.36 (s, 3H), 2.27 – 2.19 (m, 1H). ¹³C NMR (151 MHz, CDCl₃) δ: 208.2, 136.6, 133.5, 129.3, 126.8, 64.3, 44.8, 21.0, 17.8. HRMS for C₁₁H₁₀ON, calculated 161.0966, found 161.0962.

2-(3-(trifluoromethyl)phenyl)cyclobutan-1-one (3b)

(SiO₂, CH₂Cl₂/ Hexane = 3:1). Yellowish oil, 84 % yield. FT-IR (νmax, cm⁻¹) 1781. ¹H NMR (600 MHz, CDCl₃) δ: 7.54 – 7.44 (m, 4H), 4.63 – 4.56 (m, 1H), 3.36 – 3.24 (m, 1H), 3.10-3.00 (m, 1H), 2.59 (ddd, J = 21.8, 10.7, 4.8 Hz, 1H), 2.31 – 2.23 (m, 1H). ¹³C NMR (151 MHz, CDCl₃) δ: 206.4, 137.3, 130.9, 130.4, 130.4, 129.0, 123.8, 123.6, 63.8, 44.9, 17.4. HRMS for C₁₁H₉OF₃, calculated 214.0605, found 214.0600.

2-(thiophen-3-yl)cyclobutan-1-one (3c)

(SiO₂, CH₂Cl₂/ Hexane = 19:1). Yellow oil, 92 % yield. FT-IR (νmax, cm⁻¹) 1775. ¹H-NMR (600 MHz, CDCl₃) δ: 7.33 – 7.29 (m, 1H), 7.14 – 7.11 (m, 1H), 7.01 (dd, J = 5.0, 1.2 Hz, 1H), 4.55 (td, J = 8.2, 2.1 Hz, 1H), 3.26 – 3.17 (m, 1H), 3.01-3.09 (m, 1H), 2.54 (ddd, J = 21.5, 10.7, 5.0 Hz, 1H), 2.20 – 2.11 (m, 1H). ¹³C-NMR (151 MHz, CDCl₃) δ: 207.4, 136.8, 126.5, 126.0, 120.7, 60.3, 44.9, 18.2. HRMS for C₈H₉OS, calculated 153.0374, found 153.0371.
2-(3,4-Dimethoxyphenyl)cyclobutan-1-one (3d)

H₃CO

OCH₃ 

(SiO₂, CH₂Cl₂/ Hexane = 19:1). Orange amorphous solid, 91% yield. FT-IR (νmax, cm⁻¹) 1774. ¹H NMR (600 MHz, CDCl₃) δ 6.82 – 6.71 (m, 3H), 4.47 – 4.40 (m, 1H), 3.85 (s, 3H), 3.82 (s, 3H), 3.22 – 3.11 (m, 1H), 3.01 – 2.92 (m, 1H), 2.48 (qd, J = 10.7, 4.9 Hz, 1H), 2.20 – 2.10 (m, 1H). ¹³C NMR (151 MHz, CDCl₃) δ 208.2, 149.0, 148.0, 129.2, 118.9, 111.3, 110.3, 64.0, 55.9, 55.8, 44.6, 17.9. HRMS for C₁₂H₁₅O₃, calculated 207.1021, found 207.1015.

2-(Benzo[d][1,3]dioxol-5-yl)cyclobutan-1-one (3e)

(SiO₂, CH₂Cl₂/ Hexane = 19:1). Red oil, 81% yield. FT-IR (νmax, cm⁻¹) 1775. ¹H-NMR (600 MHz, CDCl₃) δ 6.80 – 6.72 (m, 2H), 6.72 – 6.66 (m, 1H), 5.93 (s, 2H), 4.48 – 4.41 (m, 1H), 3.26 – 3.15 (m, 1H), 3.04 – 2.96 (m, 1H), 2.51 (qd, J = 10.6, 4.9 Hz, 1H), 2.20 – 2.10 (m, 1H). ¹³C-NMR (151 MHz, CDCl₃) δ 207.9, 147.8, 146.5, 130.3, 120.0, 108.3, 107.5, 101.0, 64.2, 44.6, 18.1. HRMS for C₁₁H₁₁O₃, calculated 191.0708, found 191.0704.

2-(4-Methoxyphenyl)cyclobutan-1-one (3f)

H₃CO

(SiO₂, Hexane/AcOEt = 19:1). Orange amorphous solid, 85% yield. FT-IR (νmax, cm⁻¹) 1777. ¹H-NMR (600 MHz, CDCl₃) δ 7.18 (d, J= 8.5 Hz, 2 H), 6.88 (d, J= 8.8 Hz, 2 H), 4.51-445 (m, 1 H), 3.80 (s, 3 H), 3.26- 3.17 (m, 1 H), 3.05- 2.98 (m, 1 H), 2.56- 2.48 (m, 1 H), 2.22- 2.14 (m, 1 H). ¹³C-NMR (151 MHz, CDCl₃) δ 208.4, 158.6, 128.7, 128.1, 114.1, 63.9, 55.3, 44.7, 18.0. HRMS for C₁₁H₁₃O₂, calculated 177.0916, found 177.0917.
2,2’-(1,4-Phenylene)bis(cyclobutan-1-one) (3g)

(SiO₂, CH₂Cl₂/Hexane = 70:30). Yellowish solid, 78 % yield. **FT-IR** (νmax, cm⁻¹) 1765. **¹H NMR** (600 MHz, CDCl₃) δ 7.23 (s, 4H), 4.58 – 4.49 (m, 2H), 3.28 – 3.19 (m, 2H), 3.09 – 2.99 (m, 2H), 2.54 (qd, J = 10.7, 4.9 Hz, 2H), 2.28 – 2.16 (m, 2H). **¹³C NMR** (151 MHz, CDCl₃) δ 207.7, 135.23, 127.2, 64.2, 44.8, 17.7. **HRMS** for C₁₄H₁₅O₂, calculated 215.1072, found 215.1067.

2-(Benzofuran-3-yl)cyclobutan-1-one (3h)

(SiO₂, CH₂Cl₂/Hexane = 3:1). Yellowish oil, 65 % yield. **FT-IR** (νmax, cm⁻¹) 1779. **¹H-NMR** (600 MHz, CDCl₃) δ 7.55 (d, J = 1.0 Hz, 1H), 7.36 (d, J = 8.4 Hz, 1H), 7.32 (s, 1H), 7.13 (dd, J = 8.4, 1.1 Hz, 1H), 4.68 – 4.59 (m, 1H), 3.39 – 3.29 (m, 1H), 3.21 – 3.15 (m, 1H), 2.63 (qd, J = 10.7, 5.0 Hz, 1H), 2.45 (s, 3H), 2.22 – 2.18 (m, 1H). **¹³C-NMR** (151 MHz, CDCl₃) δ 206.8, 153.8, 141.2, 132.1, 126.7, 125.9, 119.6, 115.9, 111.1, 55.2, 45.5, 21.3, 17.3.

2-(2-Chlorophenyl)cyclobutan-1-one (3i)

(SiO₂, CH₂Cl₂/Hexane = 19:1). Orange oil, 51 % yield. **FT-IR** (νmax, cm⁻¹) 1779. **¹H-NMR** (600 MHz, CDCl₃) δ 7.57 – 7.44 (m, 4H), 4.65 – 4.58 (m, 1H), 3.35 – 3.27 (m, 1H), 3.13 – 3.05 (m, 1H), 2.62 (qd, J = 10.7, 4.8 Hz, 1H), 2.33 – 2.25 (m, 1H). **¹³C-NMR** (151 MHz, CDCl₃) δ 206.4, 137.2, 130.4, 129.0, 123.8, 123.8, 123.6, 123.6, 63.8, 45.0, 17.5. **HRMS** for C₁₀H₁₀OCl, calculated 181.0420, found 181.0416.
2-(4-Cyanophenyl)cyclobutan-1-one (3j)

(SiO₂, CH₂Cl₂/Hexane = 19:1). Yellow oil, 60 % yield. FT-IR (νmax, cm⁻¹) 1778. ¹H-NMR (600 MHz, CDCl₃) δ: 7.62 (d, J= 8.2 Hz, 2 H), 7.38 (d, J=8.0 Hz, 2 H), 4.61 (m, 1 H), 3.34 – 3.25 (m, 1 H), 3.11 – 3.02 (m, 1 H), 2.60 (qd, J=10.7, 4.8 Hz, 1 H), 2.31 – 2.22 (m, 1 H). ¹³C-NMR (151 MHz, CDCl₃) δ: 205.7, 141.5, 132.3, 127.7, 118.7, 110.7, 64.0, 45.0, 17.2. HRMS for C₁₁H₁₀ON, calculated 172.0762, found 172.0757.

2-(4-Nitrophenyl)cyclobutan-1-one (3k)

(SiO₂, CH₂Cl₂/Hexane = 3:1). Red amorphous solid, 58 % yield. FT-IR (νmax, cm⁻¹) 1780. ¹H-NMR (600 MHz, CDCl₃) δ: 8.15 (d, J= 8.2 Hz, 2 H), 7.42 (d, J= 8.2 Hz, 2 H), 4.66 (m, 1 H), 3.35-3.27 (m, 1 H), 3.12- 3.03 (m, 1 H), 2.67-2.59 (m, 1 H), 2.34-2.25 (m, 1 H). ¹³C-NMR (151 MHz, CDCl₃) δ: 205.4, 146.8, 143.6, 127.7, 123.7, 63.8, 45.1, 17.3. HRMS for C₁₀H₈O₃N, calculated 191.0582, found 191.0579.

Ethyl 8-(2-oxocyclobutyl)octanoate (l)

(SiO₂, CH₂Cl₂/Hexane = 3:1). Yellowish oil, 52 % yield. FT-IR (νmax, cm⁻¹) 1777, 1740. ¹H-NMR (600 MHz, CDCl₃) δ: 4.14 (q, J = 7.1 Hz, 2H), 3.29 (m, 1H), 3.03 (m, 1H), 2.93 (m, 1H), 2.30 (t, J = 7.5 Hz, 2H), 2.19 (ddd, J = 21.0, 10.4, 5.2 Hz, 1H), 1.74 – 1.59 (m, 4H), 1.53 – 1.45 (m, 1H), 1.40 – 1.26 (m, 11H). ¹³C-NMR (151 MHz, CDCl₃) δ: 212.4, 173.6, 60.6, 60.2, 44.4, 34.3, 29.2, 29.1, 29.0, 27.0, 24.9, 16.9, 14.2.
2-(9-Bromononyl)cyclobutan-1-one (3m)

(SiO₂, CH₂Cl₂/Hexane = 3:1). White amorphous solid, 68 % yield. **FT-IR (νmax, cm⁻¹) 1779.** ¹H NMR (600 MHz, CDCl₃) δ 3.42 (t, J = 6.9 Hz, 2H), 3.25 (m, 1H), 3.03 (m, 1H), 2.93 (m, 1H), 2.19 (ddd, J = 21.1, 10.4, 5.2 Hz, 1H), 1.90 – 1.84 (m, 2H), 1.73 – 1.62 (m, 2H), 1.53 – 1.26 (m, 13H). ¹³C NMR (151 MHz, CDCl₃) δ 212.4, 60.6, 44.4, 29.5, 29.4, 29.3, 29.3, 28.7, 28.1, 27.0, 16.9.

2-Hexylcyclobutan-1-one (3n)

( SiO₂, CH₂Cl₂: Hexane = 19: 1). Yellowish oil, > 95 % yield (with internal standard). **FT-IR (νmax, cm⁻¹) 1776.** ¹H NMR (600 MHz, CDCl₃) δ 3.29 – 3.22 (m, 1H), 3.04 – 2.95 (m, 1H), 2.93 – 2.85 (m, 1H), 2.15 (ddd, J = 21.1, 10.4, 5.2 Hz, 1H), 1.71 – 1.58 (m, 2H), 1.51 – 1.42 (m, 1H), 1.39 – 1.16 (m, 7H), 0.85 (t, J = 7.0 Hz, 3H). ¹³C NMR (151 MHz, CDCl₃) δ 212.6, 60.5, 44.3, 31.6, 29.5, 29.1, 26.9, 22.5, 16.8, 14.0. **HRMS** for C₁₀H₁₉O, calculated 155.1436, found 155.1435.

**Spiro[3.5]nonan-1-one (3o)**

(SiO₂, CH₂Cl₂: Hexane = 9: 1). Colorless oil, 85 % yield (with internal standard). **FT-IR (νmax, cm⁻¹) 1764.** ¹H NMR (600 MHz, CDCl₃) δ: 2.95 (t, J = 8.2 Hz, 2H), 1.81 (t, J = 8.4 Hz, 2H), 1.71 – 1.32 (m, 10H). ¹³C NMR (151 MHz, CDCl₃) δ 216.0, 65.7, 41.2, 32.0, 25.4, 24.0, 22.4.
2-(Prop-2-yn-1-yl)cyclobutan-1-one (3p)

(SiO₂, CH₂Cl₂: Hexane = 19:1). Colorless oil, 47% yield (with internal standard). FT-IR (vmax, cm⁻¹) 3300, 1778. ¹H-NMR (600 MHz, CDCl₃) δ 3.53 – 3.45 (m, 1H), 3.18 – 3.06 (m, 1H), 3.04 – 2.94 (m, 1H), 2.54 – 2.47 (m, 2H), 2.31 – 2.23 (m, 1H), 2.04 – 1.91 (m, 2H). ¹³C-NMR (151 MHz, CDCl₃) δ 209.1, 80.4, 69.7, 57.7, 45.1, 18.1, 15.8.

2-Benzylcyclobutan-1-one (3q)

(SiO₂, CH₂Cl₂/ Hexane = 95:5). Yellowish oil, 92% yield. IR (vmax, cm⁻¹) 1772. ¹H NMR (600 MHz, CDCl₃) δ 7.38 – 7.29 (m, 2H), 7.26 – 7.19 (m, 3H), 3.70 – 3.55 (m, 1H), 3.13 – 2.97 (m, 2H), 2.96 – 2.74 (m, 2H), 2.17 (dd, J = 21.2, 10.5, 5.1 Hz, 1H), 1.85 – 1.69 (m, 1H). ¹³C NMR (151 MHz, CDCl₃) δ 210.8, 138.9, 128.7, 128.5, 126.3, 61.2, 44.5, 35.2, 16.6. HRMS for C₁₁H₁₃O, calculated 161.0966, found 161.0967.

2-(2-(Pyren-2-yl)ethyl)cyclobutan-1-one (3r)

(SiO₂, CH₂Cl₂/ Hexane = 70:30). Yellow oil, 61% yield. IR (vmax, cm⁻¹) 1770. ¹H NMR (600 MHz, CDCl₃) δ 8.28 (d, J = 9.2 Hz, 1H), 8.21 – 8.17 (m, 2H), 8.12 (dd, J = 8.5, 5.9 Hz, 2H), 8.02 (t, J = 7.6 Hz, 3H), 7.86 (d, J = 7.8 Hz, 1H), 3.56 – 3.44 (m, 1H), 3.42 – 3.32 (m, 2H), 3.09-3.0 (m, 1 H), 3.0-2.92 (m, 1 H), 2.31 – 2.23 (m, 1H), 2.14 (dd, J = 21.2, 10.5, 5.2 Hz, 1H), 2.09 – 2.01 (m, 1H), 1.69 – 1.62 (m, 1H). ¹³C NMR (151 MHz, CDCl₃) δ 212.0, 135.7, 131.4, 130.9, 130.0, 128.7, 127.5, 127.4, 127.3, 126.7, 125.9, 125.1, 125.0, 124.9, 124.8, 124.8, 123.2, 59.9, 44.6, 31.7, 30.8, 17.0. HRMS for C₂₂H₁₉O, calculated 299.1436, found 299.1428.
4. $^1\text{H}$- and $^{13}\text{C}$-NMR spectra

$N,N$-diallyl-2-(p-tolyl)acetamide (Ia)
N,N-diallyl-2-(3-(trifluoromethyl)phenyl)acetamide (1b)
$N,N$-diallyl-2-(thiophen-3-yl)acetamide (1c)
$N,N$-diallyl-2-(3,4-dimethoxyphenyl)acetamide (1d)
N,N-diallyl-2-(benzo [d] dioxol-5-yl)acetamide (1e)
N,N-diallyl-2-(p-methoxyphenyl)acetamide (1f)
$2,2'-(1,4$-phenylene)bis(N,N-diallylacetamide) (1g)$
N,N-diallyl-2-(2-chlorophenyl)acetamide (1i)
$N,\text{N-diallyl-2-(4-cyanophenyl)acetamide (1j)}$
N,N-diallyl-2-(4-nitrophenyl)acetamide (1k)
Ethyl 10-(diallylamino)-10-oxodecanoate (II)
N,N-diallyl-11-bromoundecanamide (1m)
$N,N$-diallyloctanamide (1n)
$N,N$-diallylcyclohexanecarboxamide (1o)
N,N-diallylp-4-ynamide (1p)
N,N-diallyl-3-phenylpropanamide (1q)
N,N-diallyl-4-(pyren-1-yl)butanamide (Ir)
2-(p-Tolyl)cyclobutan-1-one (3a)
2-(3-(Trifluoromethyl)phenyl)cyclobutan-1-one (3b)
2-(Thiophen-3-yl)cyclobutan-1-one (3c)
2-(3,4-Dimethoxyphenyl)cyclobutan-1-one (3d)
2-(Benzo[d][1,3]dioxol-5-yl)cyclobutan-1-one (3e)
2-(4-Methoxyphenyl)cyclobutan-1-one (3f)
2,2’-(1,4-Phenylene)bis(cyclobutan-1-one) (3g)
2-(5-Methyl-benzofuran-3-yl)cyclobutan-1-one (3h)
2-(2-Chlorophenyl)cyclobutan-1-one (3i)
(4-Cyanophenyl)cyclobut-1-one (3j)
2-(4-Nitrophenyl)cyclobutan-1-one (3k)
Ethyl 8-(2-oxocyclobutyl)octanoate (3l)
2-(9-Bromononyl)cyclobutan-1-one (3m)
2-Hexylcyclobutan-1-one (3n)
Spiro[3.5]nonan-1-one (3o)
2-(Prop-2-yn-1-yl)cyclobutan-1-one (3p)

2-Benzylcyclobutan-1-one (3q)
2-(2-(Pyren-2-yl)ethyl)cyclobutan-1-one (3r)
References

1 www.vapourtec.co.uk/
4 Zaiput technology membrane based liquid-liquid separator, see: http://www.zaiput.com/