

Direct CuO nanoparticles catalyzed synthesis of poly-substituted furans via oxidative C-H/C-H functionalization in aqueous medium

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ESI 1. General Information:

All chemicals were purchased from Aldrich, Sd-Fine, Merck and HIMEDIA (India) and used as received, except all solvents which were used after distillation. All reactions were carried out with oven-dried glassware under air. Distilled petroleum ether and ethyl acetate were used for column chromatography. Analytical TLC was performed on Merck 60F254 silica gel plates (0.25 mm thickness). Column chromatography was performed on silica gel (60-120 mesh size, HIMEDIA, India). ^1H NMR spectra were recorded on Bruker AV 300, AV 400 and AV 500. The ^1H NMR chemical shifts are reported relative to the center of solvent resonance (CDCl_3 : 7.26 (1H)). Chemical shifts are expressed in parts per million (δ) and the signals were reported as s (singlet), d (doublet), t (triplet), q (quartet), m (multiplet) and coupling constants J were given in Hz. ^{13}C NMR spectra were recorded at 75 MHz in CDCl_3 solution. Chemical shifts are expressed in parts per million (δ) and are referenced to CDCl_3 ($\delta = 77.16$) as internal standard.

ESI 2. Methods for the preparation of CuO Nano-particles:

The preparation of CuO nanoparticles were carried out following reported procedure. Solution of $\text{Cu}(\text{NO}_3)_2 \cdot 3\text{H}_2\text{O}$ (3 g) was dissolved in distilled water and vigorously mixed under sonication for 2 h at 70 $^\circ\text{C}$. Subsequently, 0.3 M NaOH was added drop by drop into the solutions till the pH is reached up to 11 and black precipitate is formed. Then centrifuged and rinsed with distilled water and left in an atmosphere environment to dry. The resulting powder is then calcinated at 400 $^\circ\text{C}$ in an oven for 3 hours.

ESI 3. General method for the synthesis of 3,4-dicabonyl substituted furan derivative from α,β -unsaturated ketones and 1,3-diketone (Table 2):

A mixture of α,β -unsaturated ketones (0.5 mmol), 1,3-diketone (2.5 mmol), TBHP (1 equiv.) and CuO nanoparticles (10 mg) was refluxed in ethanol: water (1:1, 2 ml) for 3 hours. After completion of the reaction (TLC monitored), the resulting mixture was cooled to room temperature and centrifuged to separate the catalyst followed by extraction with ethyl acetate. After completion of the reaction (TLC monitored), the resulting mixture was cooled to room temperature and centrifuged to separate the catalyst. The organic layer was extracted with ethyl acetate (25 mL), washed with brine solution (3×5 mL) and dried over anhydrous sodium sulphate. Evaporation of solvent left the crude solid product which was purified by column

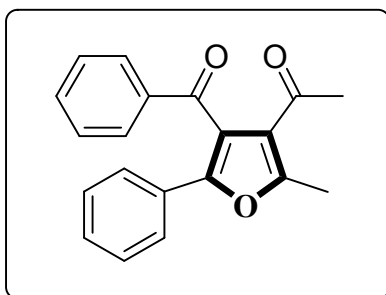
chromatography on silica gel (ethyl acetate/petroleum ether = 1/9) to provide pure 3,4-dicarbonyl functionalized product.. The product was confirmed by ^1H NMR and ^{13}C NMR spectroscopy and elemental analysis. The spectroscopic data and elemental analysis of the compounds has been given in ESI 5.

ESI 4. General method for the synthesis of 3,4-dicarbonyl substituted furan derivative from α,β -unsaturated ketones and β -keto ester (Table 3):

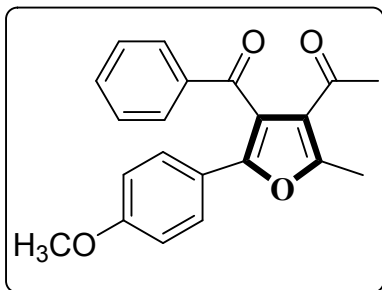
A mixture of α,β -unsaturated ketones (0.5 mmol), β -keto ester (2.5 mmol), TBHP (1 equiv.) and CuO nanoparticles (10 mg) was refluxed in ethanol: water (1:1, 2 ml) for 3 hours under open atmosphere. After completion of the reaction (TLC monitored), the resulting mixture was cooled to room temperature and centrifuged to separate the catalyst. The organic layer was extracted with ethyl acetate (25 mL), washed with brine solution (3×5 mL) and dried over anhydrous sodium sulphate. Evaporation of solvent left the crude solid product which was purified by column chromatography on silica gel (ethyl acetate/petroleum ether = 1/9) to provide pure 3,4-dicarbonyl functionalized product. The product was confirmed by ^1H NMR and ^{13}C NMR spectroscopy and elemental analysis. The spectroscopic data and elemental analysis of the compounds has been given in ESI 5.

ESI 5. Detailed spectral data of the 3,4-dicarbonyl functionalized furan derivatives listed in Table 2 and Table 3

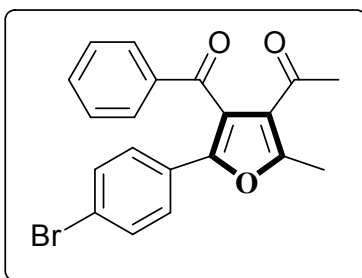
The ^1H and ^{13}C NMR spectra were recorded 300 MHz, 400 MHz or 500 MHz Bruker NMR spectrometer and CDCl_3 was used as solvent.



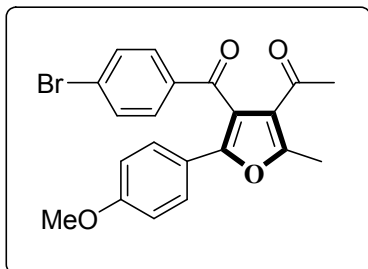
1-(4-Benzoyl-2-methyl-5-phenylfuran-3-yl)ethanone: White solid (3a; Table 2, Isolated yield 85%); ^1H NMR (500 MHz, CDCl_3): δ 7.98 (d, $J = 7.5$ Hz, 2H), 7.82-7.79 (m, 3H), 7.49-7.46 (m, 3H), 7.25 (d, $J = 8.5$, 2H), 2.74 (s, 3H), 2.29 (s, 3H); FT-IR (KBr) $\nu = 3400, 3082, 2923, 1689, 1596, 1494, 1450, 1365, 1211, 1151, 950, 748, 584$ cm^{-1} ; Anal calc for $\text{C}_{20}\text{H}_{16}\text{O}_3$: C, 78.93; H, 5.30 %; Found: C, 78.88; H, 5.34 %; HRMS, calculated for $\text{C}_{20}\text{H}_{16}\text{NaO}_3$ ($\text{M}+\text{Na}^+$): 327.0992, found: 327.0994.



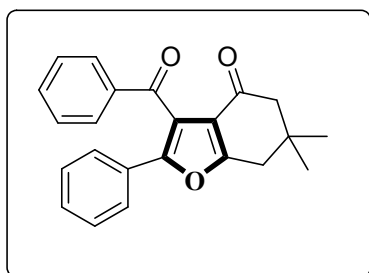
1-(4-Benzoyl-5-(4-methoxyphenyl)-2-methylfuran-3-yl)ethanone: Pale yellow solid (3c; Table 2, Isolated yield 81%); ^1H NMR (500 MHz, CDCl_3): δ 8.01 (d, $J = 7.5$ Hz, 2H), 7.61-7.55 (m, 3H), 7.51 (t, $J = 7.5$ Hz, 2H), 6.95 (d, $J = 8.5$, 2H), 3.86 (s, 3H), 2.55 (s, 3H), 2.16 (s, 3H); FT-IR (KBr) $\nu = 3433, 2925, 1598, 1506, 1442, 1419, 1338, 1299, 1261, 1172, 1016, 823, 779, 688, 532$ cm^{-1} ; Anal calc for $\text{C}_{21}\text{H}_{18}\text{O}_4$: C, 75.43; H, 5.43 %; Found: C, 75.40; H, 5.45 %; HRMS, calculated for $\text{C}_{21}\text{H}_{18}\text{NaO}_4$ ($\text{M}+\text{Na}^+$): 357.1097, found: 357.1094.



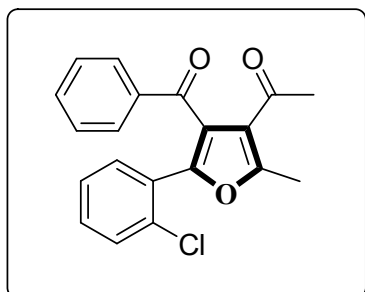
1-(4-Benzoyl-5-(4-bromophenyl)-2-methylfuran-3-yl)ethanone: White solid (3e; Table 2, Isolated yield 91%); ^1H NMR (300 MHz, CDCl_3): δ 7.95 (d, $J = 5.7$ Hz, 2H), 7.62-7.57 (m, 1H), 7.51-7.37 (m, 4H), 7.27-7.26 (t, $J = 1.8$ Hz, 2H), 2.77 (s, 3H), 2.30 (s, 3H); ^{13}C NMR (75 MHz, CDCl_3): δ 193.53, 190.40, 157.94, 143.52, 138.18, 133.98, 133.09, 132.38, 129.94, 128.83, 128.83, 128.65, 124.96, 122.75, 29.41, 15.56; FT-IR (KBr) $\nu = 3452, 3057, 1911, 1657, 1604, 1582, 1482, 1442, 1329, 1218, 1070, 1010, 977, 819, 686, 531$ cm^{-1} ; Anal calc for $\text{C}_{20}\text{H}_{15}\text{BrO}_3$: C, 62.68; H, 3.95 %; Found: C, 62.67; H, 3.94 %.



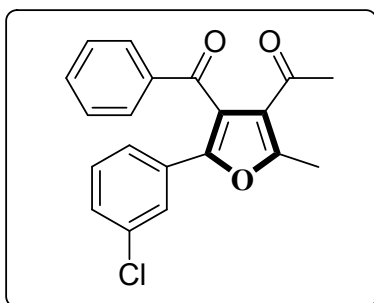
1-(4-(4-Bromobenzoyl)-5-(4-methoxyphenyl)-2-methylfuran-3-yl)ethanone: Pale yellow solid (3g; Table 2, Isolated yield 83%); ^1H NMR (300 MHz, CDCl_3): δ 7.89 (d, $J = 6.3$ Hz, 2H), 7.65-7.60 (m, 4H), 6.94 (d, $J = 6.6$ Hz, 2H), 3.86 (s, 3H), 2.58 (s, 3H), 2.17 (s, 3H); ^{13}C NMR (75 MHz, CDCl_3): δ 192.87, 189.56, 162.03, 156.23, 145.44, 137.40, 132.01, 130.49, 130.10, 127.75, 127.69, 119.33, 114.64, 55.59, 28.79, 14.54; FT-IR (KBr) $\nu = 3453, 3001, 2971, 2934, 2840, 2361, 1654, 1590, 1507, 1329, 1253, 1170, 1068, 816, 535$ cm^{-1} ; Anal calc for $\text{C}_{21}\text{H}_{17}\text{BrO}_4$: C, 61.03; H, 4.15 %; Found: C, 61.00; H, 4.16 %.



3-Benzoyl-6,6-dimethyl-2-phenyl-6,7-dihydrobenzofuran-4(5H)-one: Colourless oil (3k; Table 2, Isolated yield 81%); ^1H NMR (500 MHz, CDCl_3): δ 7.88 (d, $J = 8.0$ Hz, 2H), 7.54 (t, $J = 7.5$ Hz, 1H), 7.43-7.37 (m, 2H), 7.33 (d, $J = 6.20$ Hz, 2H), 7.28-7.21 (m, 3H), 2.83 (s, 2H), 2.41 (s, 2H), 1.30 (s, 6H); FT-IR (KBr) $\nu = 3426, 3058, 3027, 2957, 2873, 1685, 1600, 1452, 1383, 1271, 1149, 1055, 750, 640$ cm^{-1} ; Anal calc for $\text{C}_{23}\text{H}_{20}\text{O}_3$: C, 80.21; H, 5.85 %; Found: C, 80.23; H, 5.89 %.

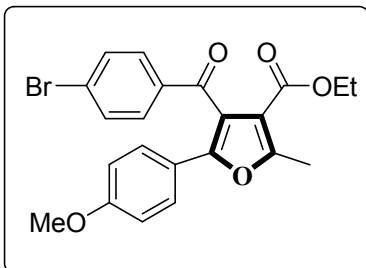


1-(4-Benzoyl-5-(2-chlorophenyl)-2-methylfuran-3yl)ethanone: Pale yellow solid (3m; Table 2, Isolated yield 88%); ^1H NMR (300 MHz, CDCl_3): δ 7.84 (d, $J = 6.0$ Hz, 2H), 7.52 (d, $J = 4.5$ Hz, 1H), 7.46 (d, $J = 4.8$ Hz, 1H), 7.42-7.33 (m, 3H), 7.29-7.25 (m, 2H), 2.72 (s, 3H), 2.24 (s, 3H); ^{13}C NMR (75 MHz, CDCl_3): δ 203.53, 198.23, 160.22, 158.73, 144.36, 133.36, 133.02, 132.26, 130.43, 128.77, 128.70, 128.62, 128.29, 127.34, 124.56, 97.78, 29.84, 16.62; FT-IR (KBr) $\nu = 3423, 2915, 2842, 1621, 1393, 1062$ cm^{-1} ; Anal calc for $\text{C}_{20}\text{H}_{15}\text{ClO}_3$: C, 70.90; H, 4.46 %; Found: C, 70.86; H, 4.49 %; HRMS, calculated for $\text{C}_{20}\text{H}_{15}\text{ClNaO}_3$ ($\text{M}+\text{Na}^+$): 361.0607, found: 361.0604.

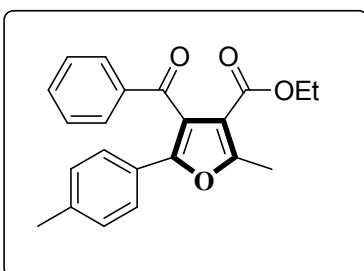


1-(4-Benzoyl-5-(3-chlorophenyl)-2-methylfuran-3yl)ethanone: Pale yellow solid (3n; Table 2, Isolated yield 82%); ^1H NMR (400 MHz, CDCl_3): δ 7.94 (d, $J = 7.2$ Hz, 2H), 7.52 (d, $J = 4.5$ Hz, 1H), 7.54 (s, 1H), 7.46-7.36 (m, 3H), 7.34-7.13 (m, 3H), 2.70 (s, 3H), 2.21 (s, 3H); ^{13}C NMR (100 MHz, CDCl_3): δ 198.24, 192.68, 145.98, 143.82, 134.65, 133.35, 130.82,

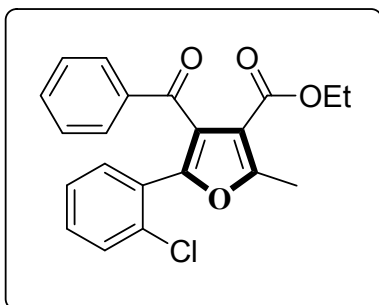
130.43, 130.31, 130.09, 129.85, 128.87, 128.78, 127.83, 127.64, 127.53, 127.27, 29.84, 16.62; FT-IR (KBr) ν = 3670, 2938, 1671, 1262, 736 cm^{-1} ; Anal calc for $\text{C}_{20}\text{H}_{15}\text{ClO}_3$: C, 70.90; H, 4.46 %; Found: C, 70.91; H, 4.50 %



1-(4-(4-Bromobenzoyl)-5-(4-methoxyphenyl)-2-methylfuran-3-carboxylate: Pale yellow oil (5c; Table 3, Isolated yield 74%); ^1H NMR (300 MHz, CDCl_3): δ 7.88 (d, J = 6.3 Hz, 2H), 7.65-7.60 (m, 2H), 7.35 (d, J = 11.7 Hz, 2H), 6.94 (d, J = 6.3 Hz, 2H), 4.42 (q, J = 7.2 Hz, 2H), 3.86 (s, 3H), 2.72 (s, 3H), 0.98 (t, J = 2.7 Hz, 3H); ^{13}C NMR (75 MHz, CDCl_3): δ 192.01, 189.57, 162.04, 160.52, 145.45, 136.42, 132.02, 130.50, 130.11, 127.76, 127.61, 124.51, 119.34, 114.65, 55.59, 31.14, 13.45; FT-IR (KBr) ν = 3433, 2981, 2931, 2842, 1714, 1669, 1604, 1506, 1323, 1222, 1098, 1026, 835, 755, 604 cm^{-1} ; Anal calc for $\text{C}_{22}\text{H}_{19}\text{BrO}_5$: C, 59.61; H, 4.32 %; Found: C, 59.57; H, 4.34 %.

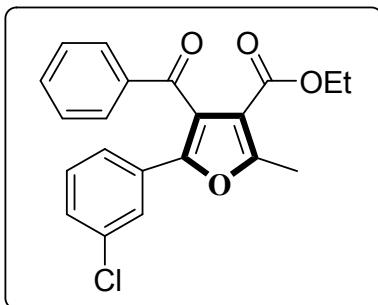


Methyl 4-benzoyl-2-methyl-5-(*p*-tolyl)furan-3-carboxylate: Pale yellow oil (5d; Table 3, Isolated yield 76%); ^1H NMR (300 MHz, CDCl_3): δ 7.84 (d, J = 11.5 Hz, 2H), 7.63-7.50 (m, 5H), 7.26 (t, J = 5.4 Hz, 2H), 4.05 (q, J = 7.2 Hz, 2H), 2.71 (s, 3H), 2.42 (s, 3H), .94 (t, J = 7.8 Hz, 3H); ^{13}C NMR (75 MHz, CDCl_3): δ 190.83, 162.13, 158.08, 145.10, 141.24, 138.53, 138.48, 132.80, 132.51, 132.32, 129.86, 128.73, 128.62, 121.28, 116.23, 59.86, 21.68; Anal calc for $\text{C}_{22}\text{H}_{20}\text{O}_4$: C, 75.84; H, 5.79 %; Found: C, 75.81; H, 5.81 %.



Methyl 4-benzoyl-2-methyl-5-(*o*-chloro)furan-3-carboxylate: Pale yellow oil (5j; Table 3, Isolated yield 89%); ^1H NMR (400 MHz, CDCl_3): δ 7.96 (d, J = 6.8 Hz, 2H), 7.72 (d, 1H), 7.59 (dd, J = 7.6 Hz, 1H), 7.49-7.45 (m, 3H), 7.37-7.32 (m, 2H), 4.14 (q, J = 7.2 Hz, 2H), 2.72 (s, 3H), 0.91 (t, J = 6.8 Hz, 3H); ^{13}C NMR (75 MHz, CDCl_3): δ 200.47, 174.63, 171.12, 145.81, 140.50, 136.62, 133.88, 133.62, 131.34, 129.50, 128.88, 128.74, 128.30, 127.43, 126.38, 95.95, 61.02, 14.27, 14.05; FT-IR (KBr) ν = 3433, 2915, 2853, 1714, 1621, 1083, 730 cm^{-1} ; Anal calc for $\text{C}_{21}\text{H}_{17}\text{ClO}_4$: C, 68.39; H, 4.65 %; Found: C, 68.38; H, 4.69 %; HRMS, calculated for $\text{C}_{21}\text{H}_{17}\text{ClNaO}_4$ ($\text{M}+\text{Na}^+$): 391.0713, found: 391.0710.

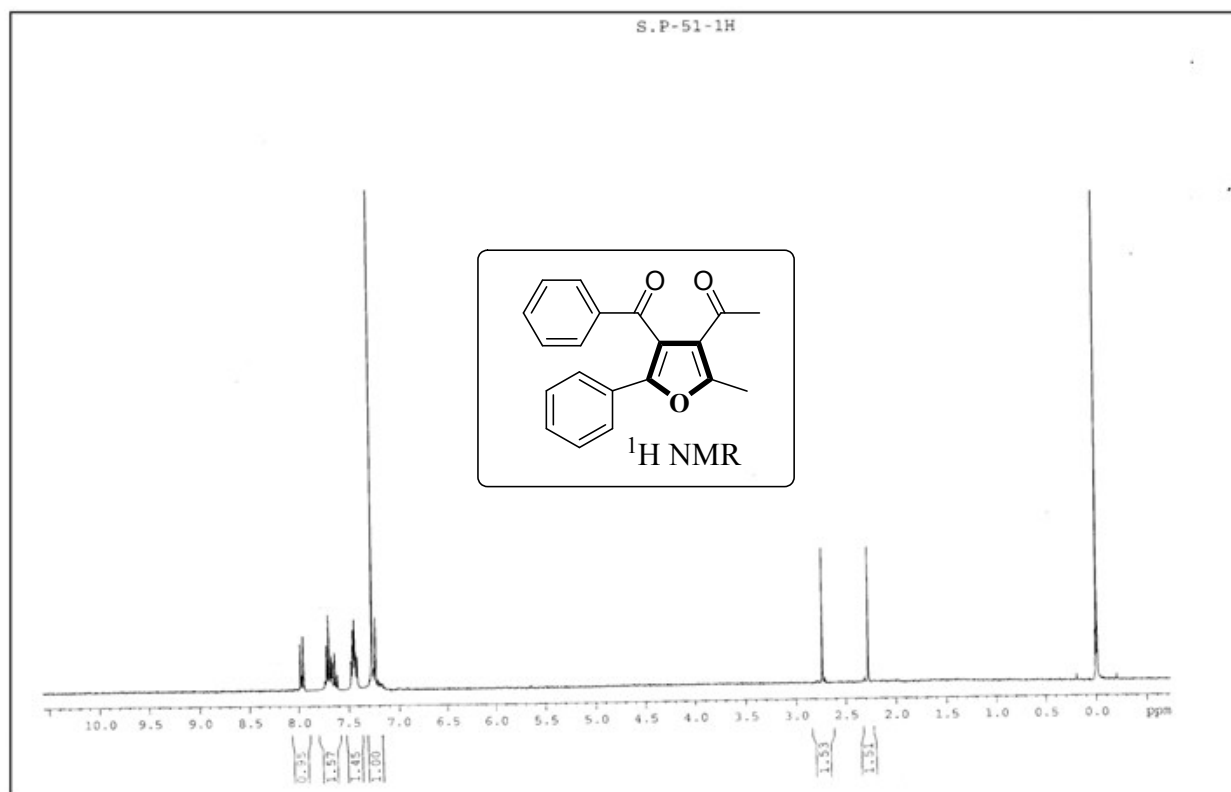
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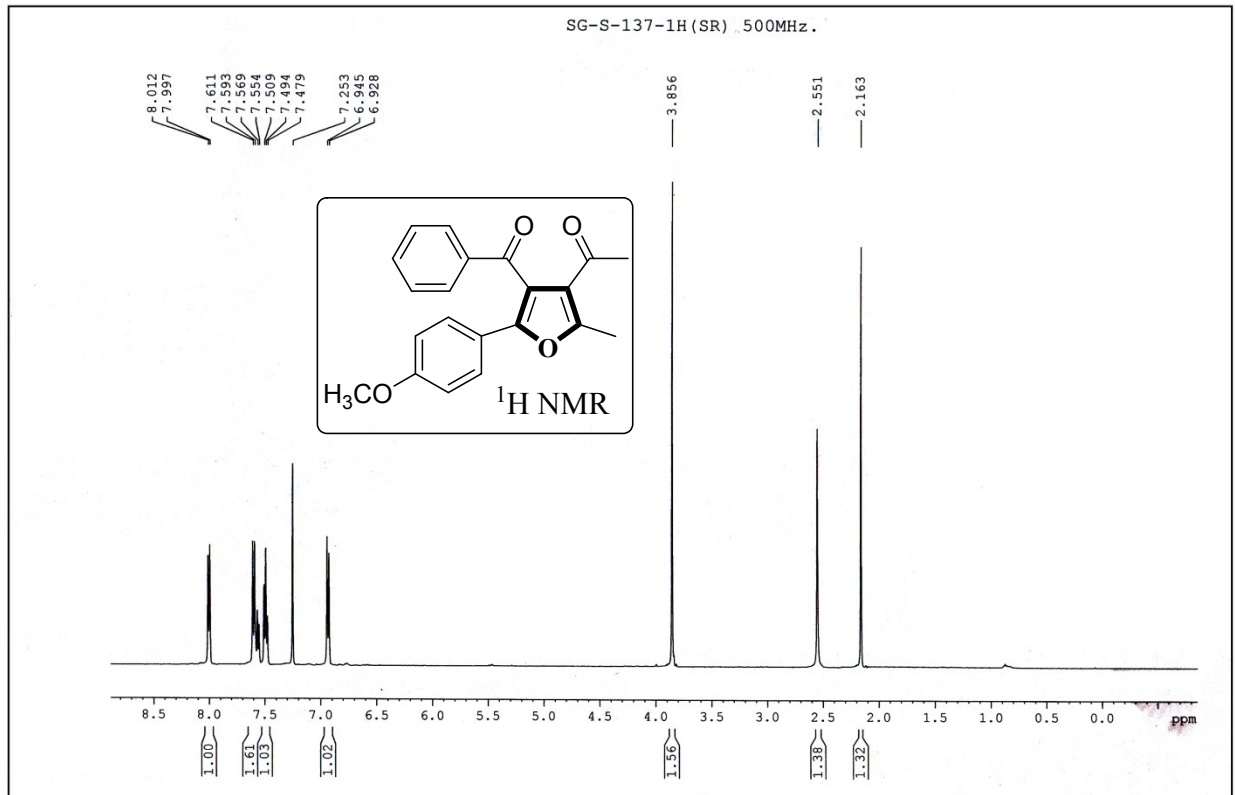
Methyl 4-benzoyl-2-methyl-5-(m-chloro)furan-3-carboxylate:
Pale yellow oil (5k; Table 3, Isolated yield 81%); ¹H NMR (300 MHz, CDCl₃): δ 7.94 (d, *J* = 4.5 Hz, 2H), 7.60 (s, 1H), 7.54 (dd, *J* = 4.2 Hz, 1H), 4.09 (q, *J* = 4.2 Hz, 2H), 2.70 (s, 3H), 1.09 (t, *J* = 4.2 Hz, 3H); ¹³C NMR (75 MHz, CDCl₃): δ 200.03, 193.73, 163.73, 145.17, 143.19, 137.67, 136.56, 134.78, 134.65, 133.94, 129.99, 129.09, 128.90, 128.78, 128.30, 127.77, 61.30, 14.13, 14.10; FT-IR (KBr) ν = 3453, 2335, 1662, 1270, 740, 680 cm⁻¹; Anal calc for C₂₁H₁₇ClO₄: C, 68.39; H, 4.65 %; Found: C, 68.41; H, 4.66 %.

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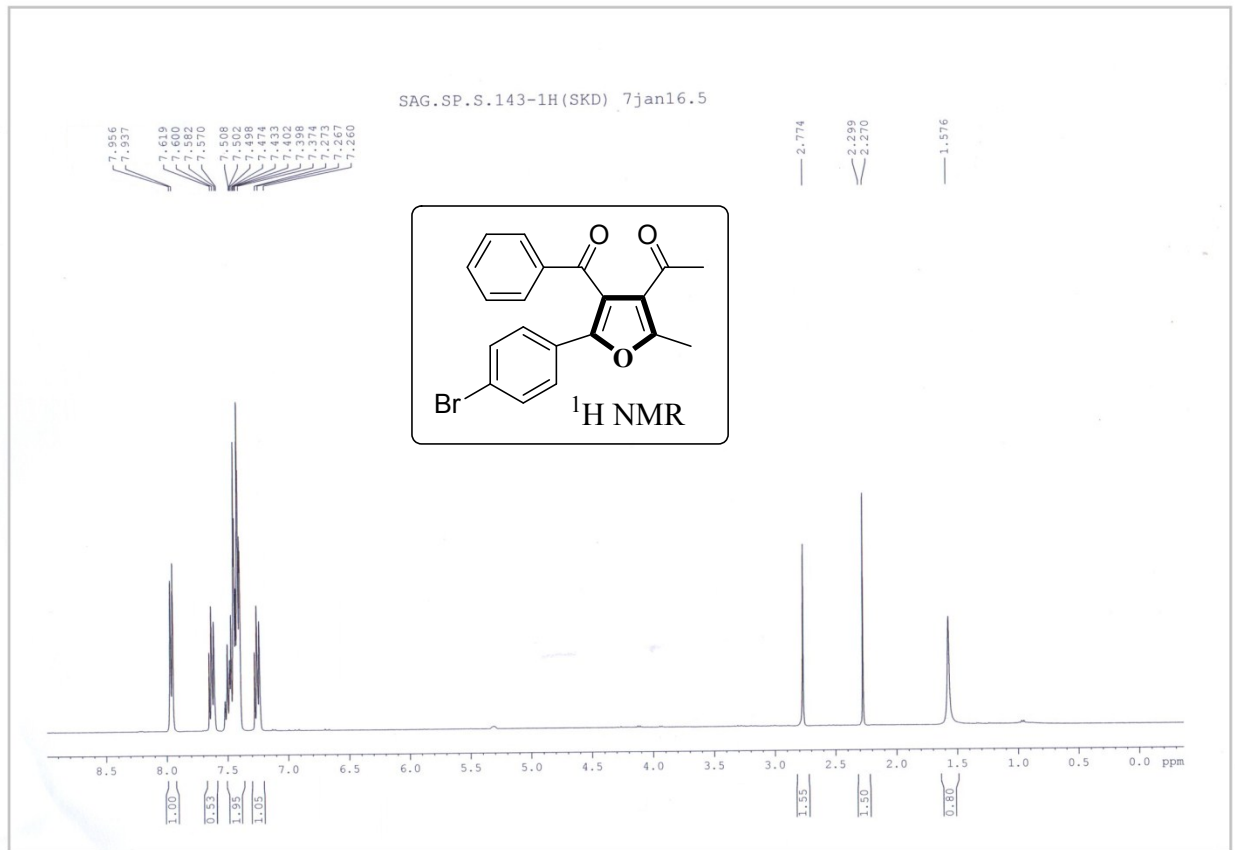
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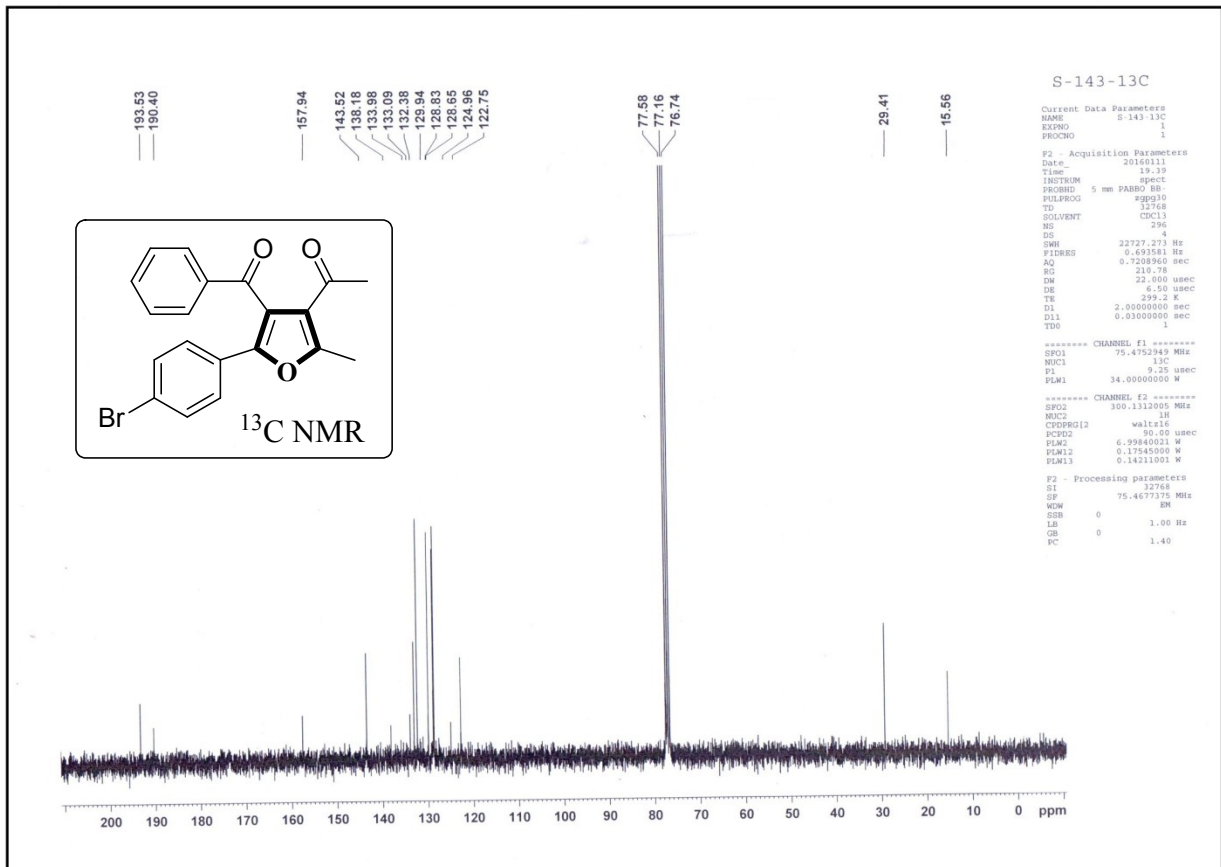
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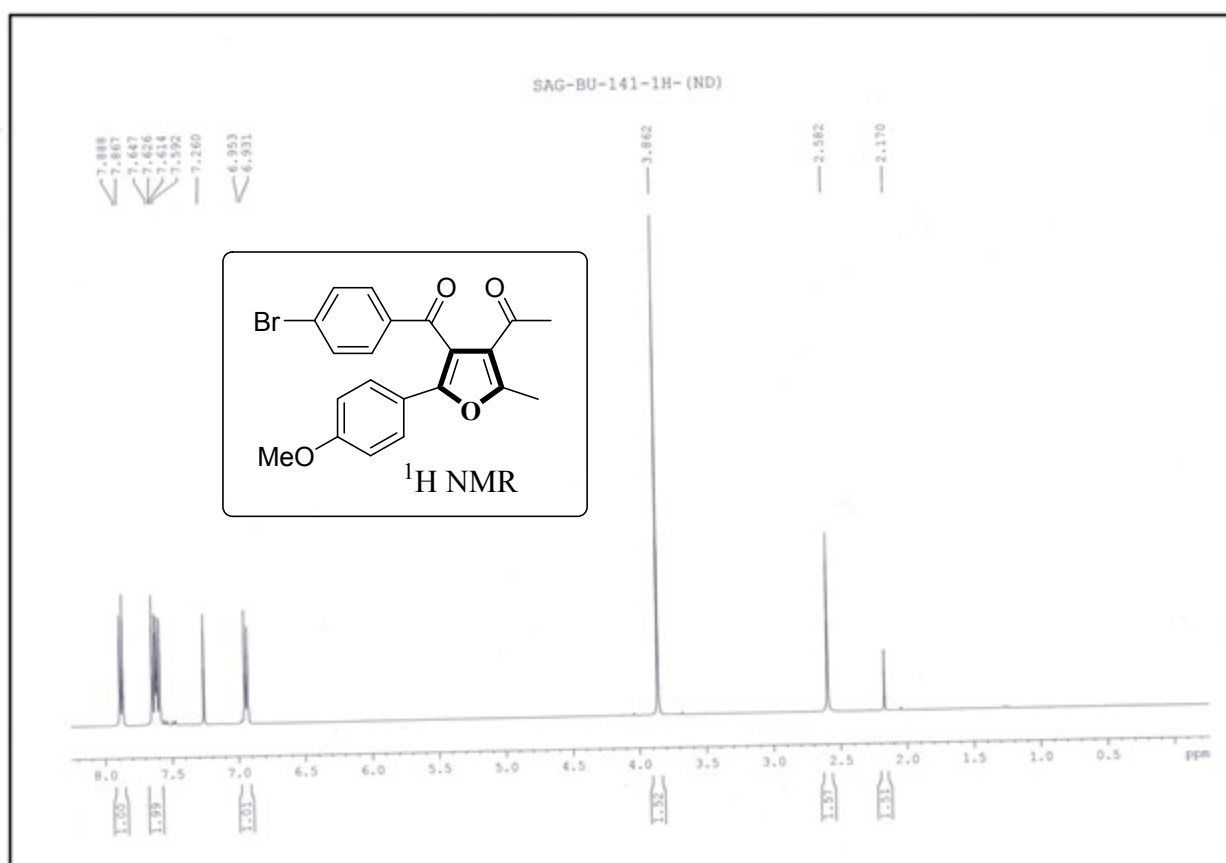
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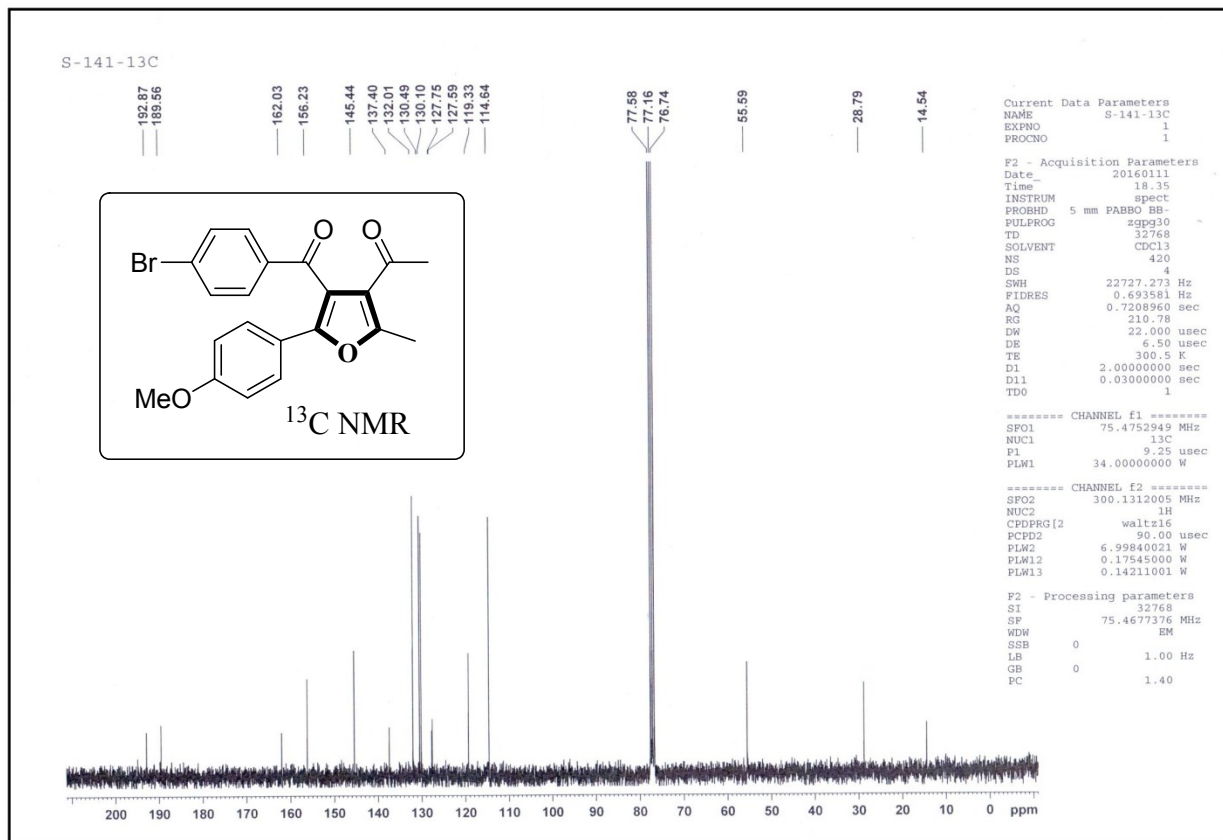


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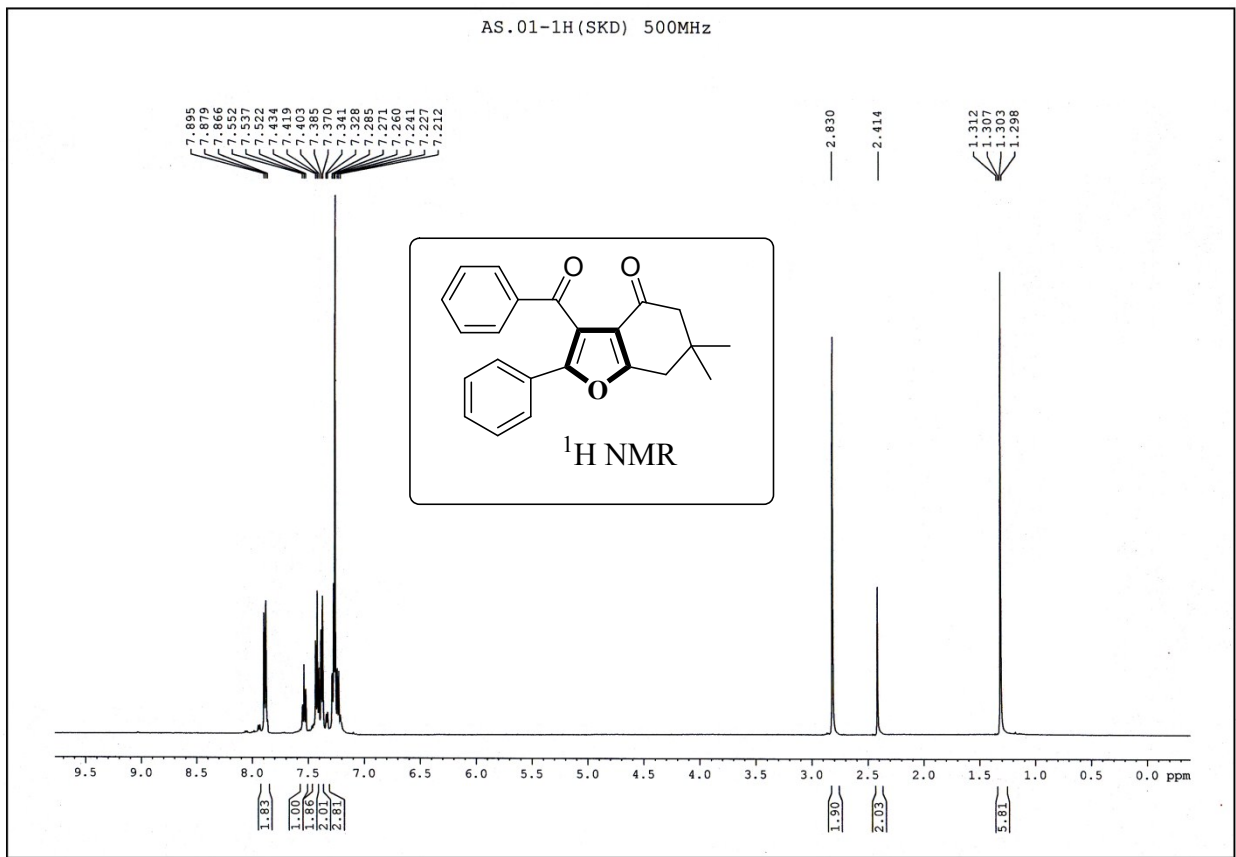


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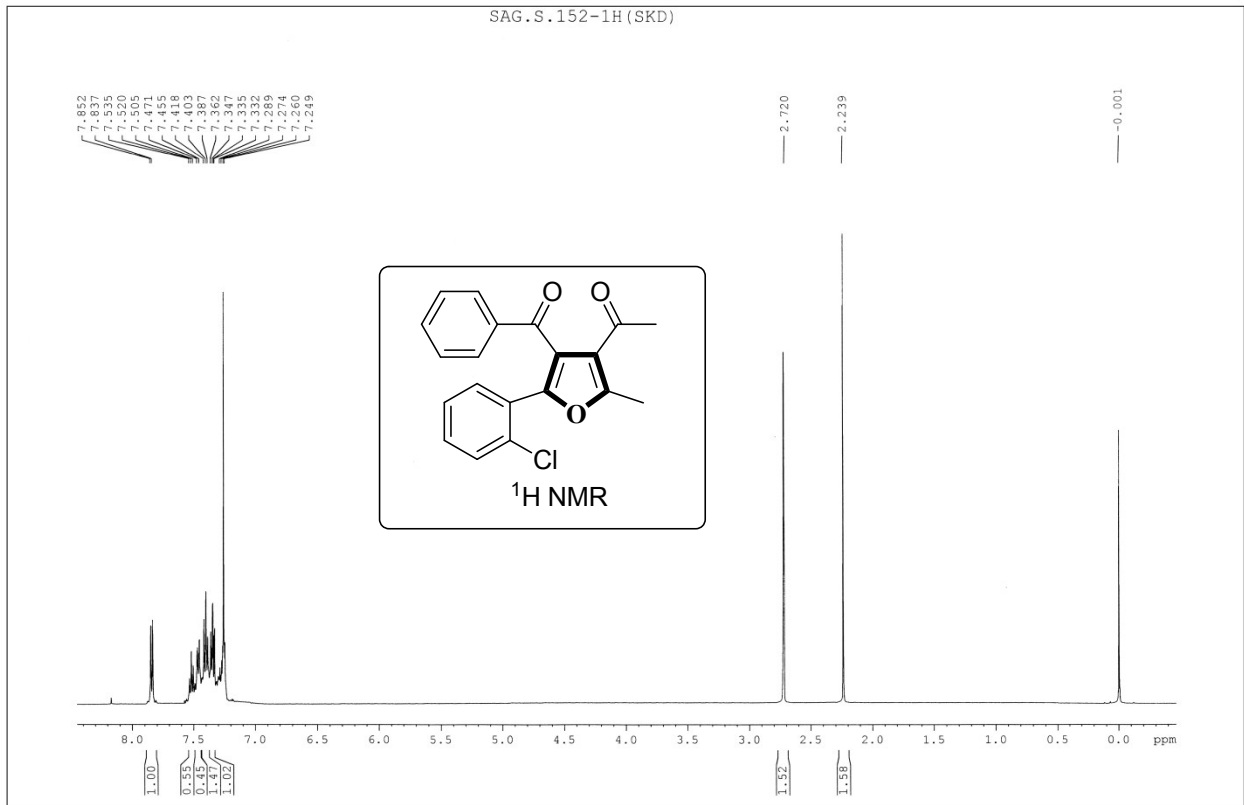




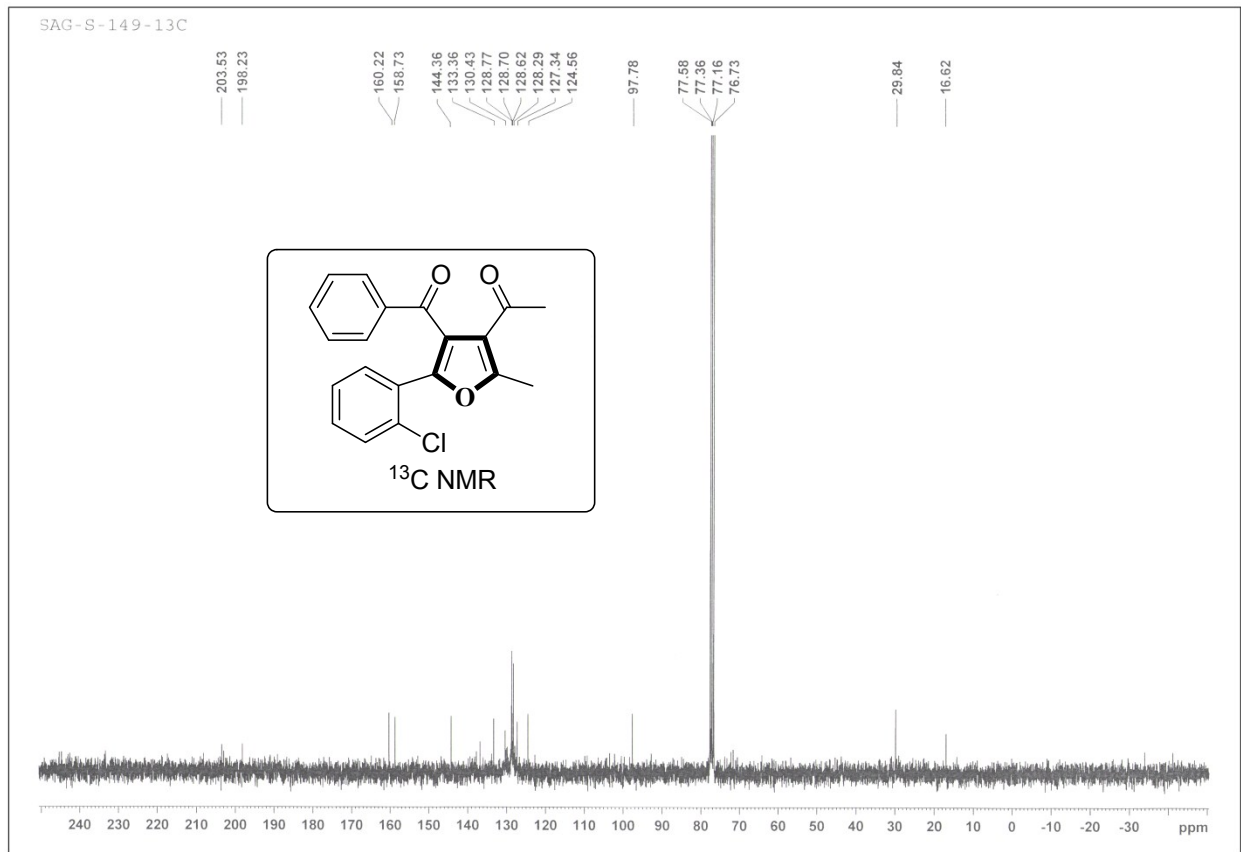
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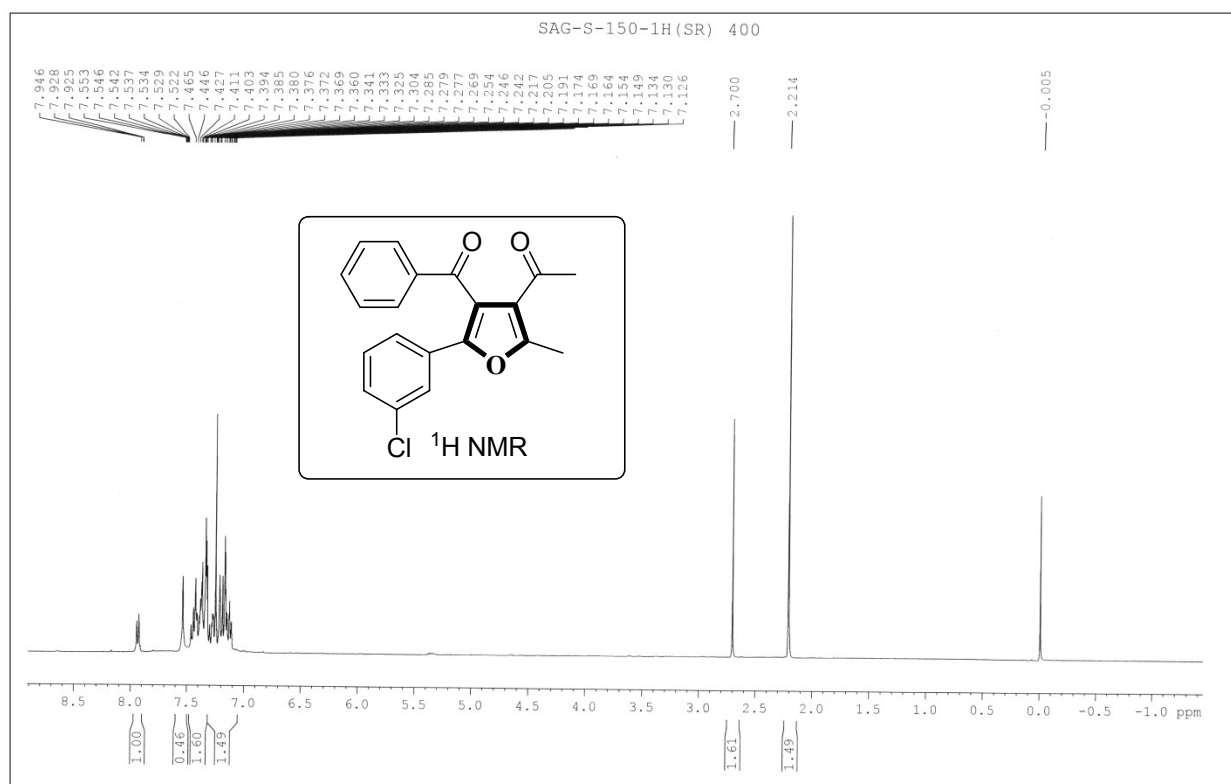
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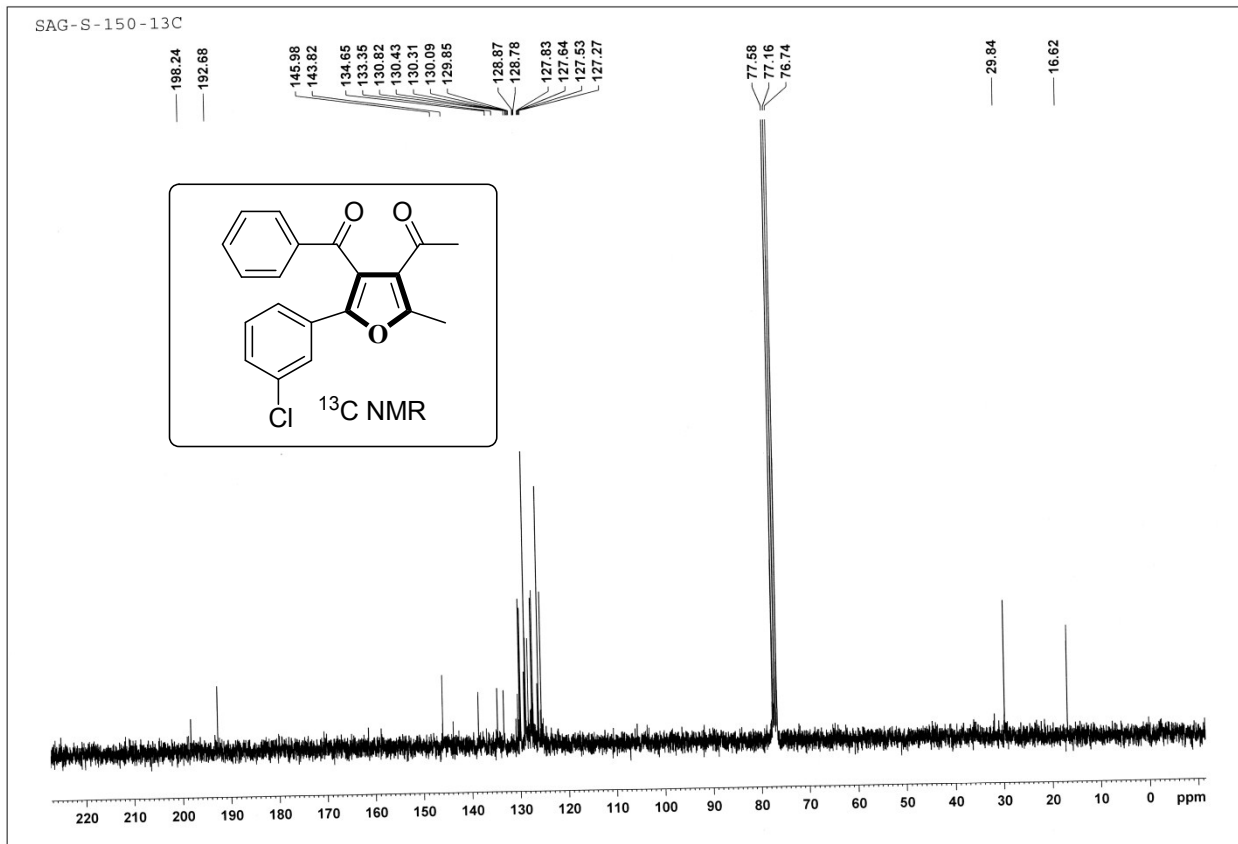
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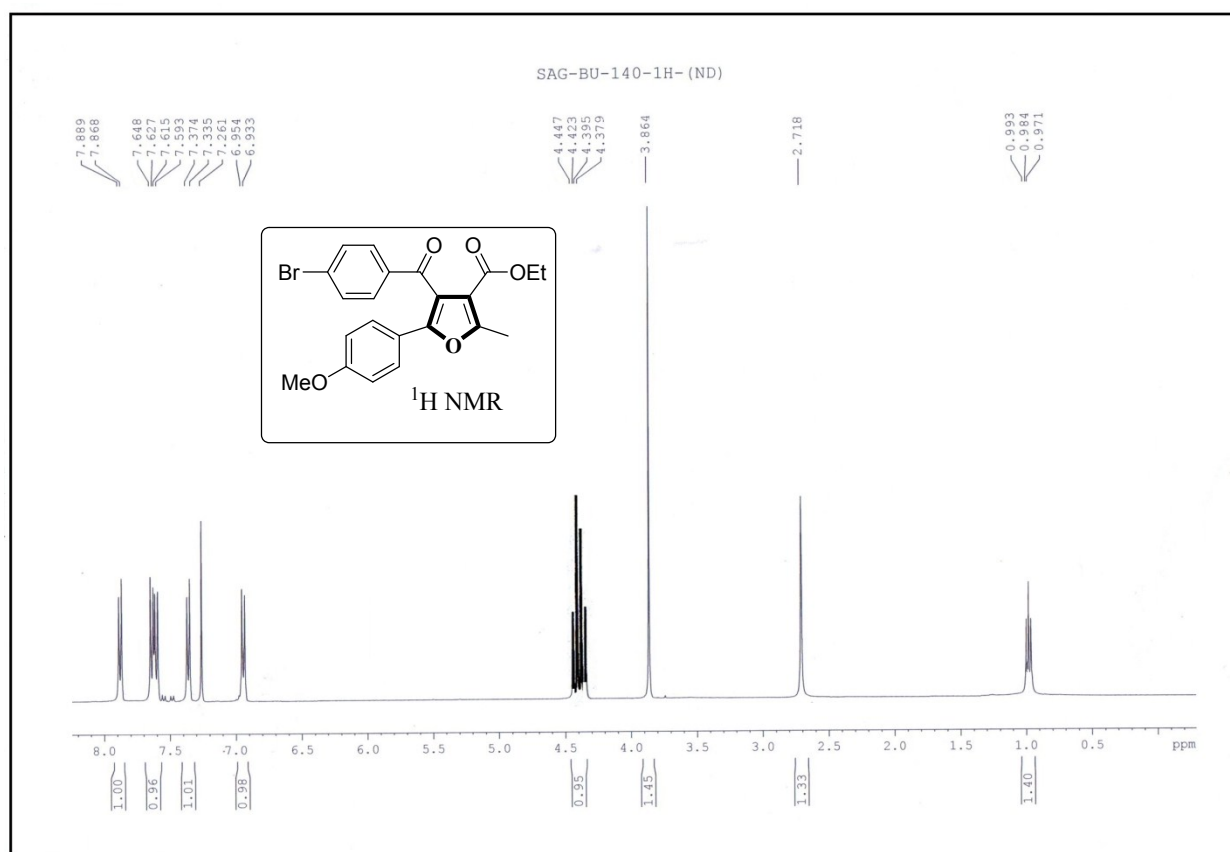
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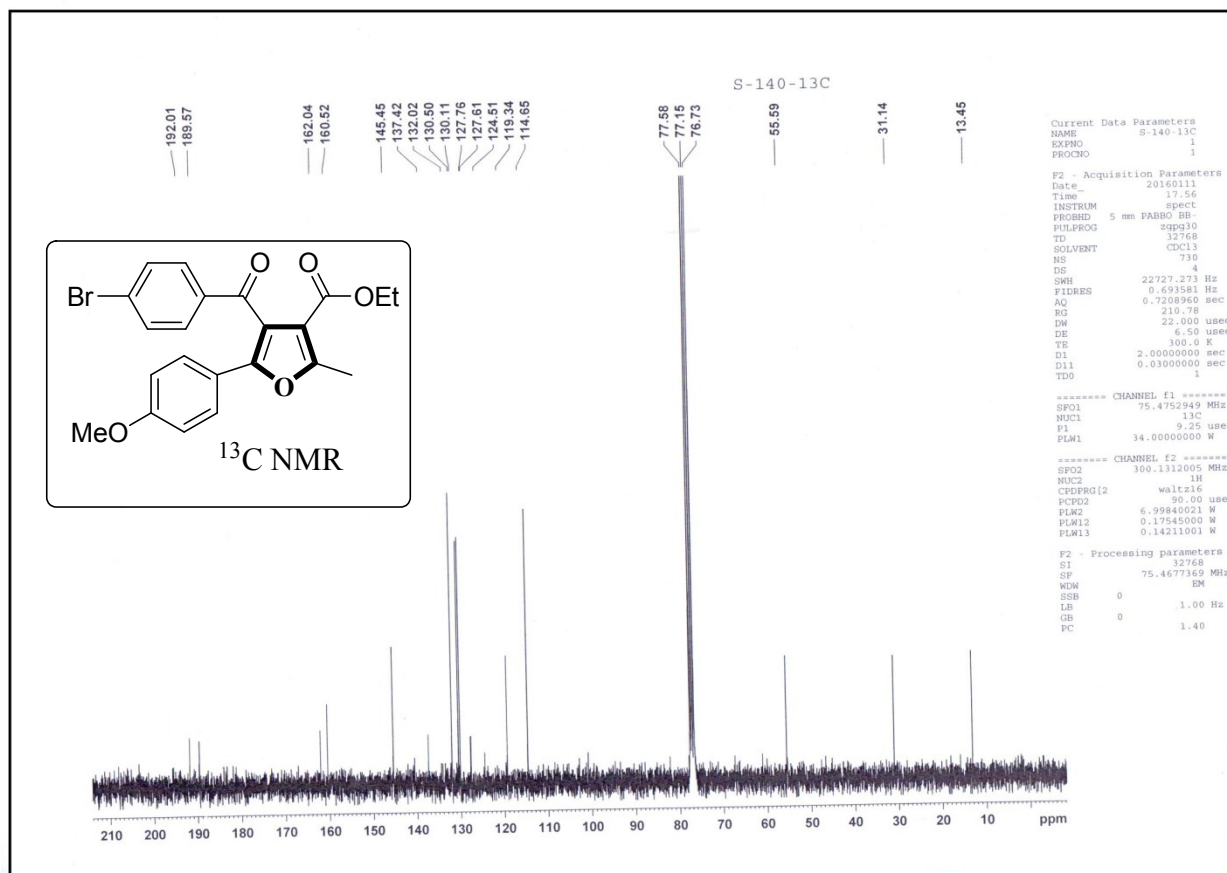


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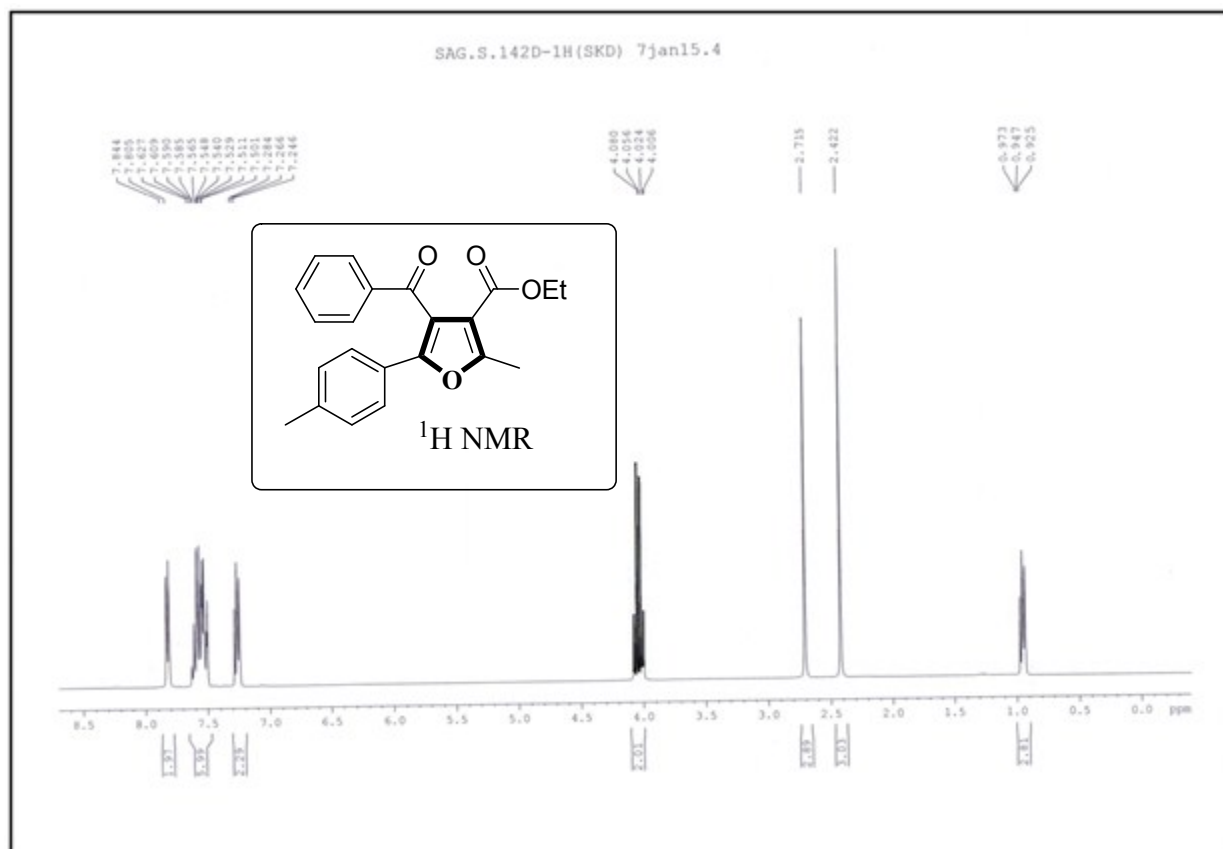


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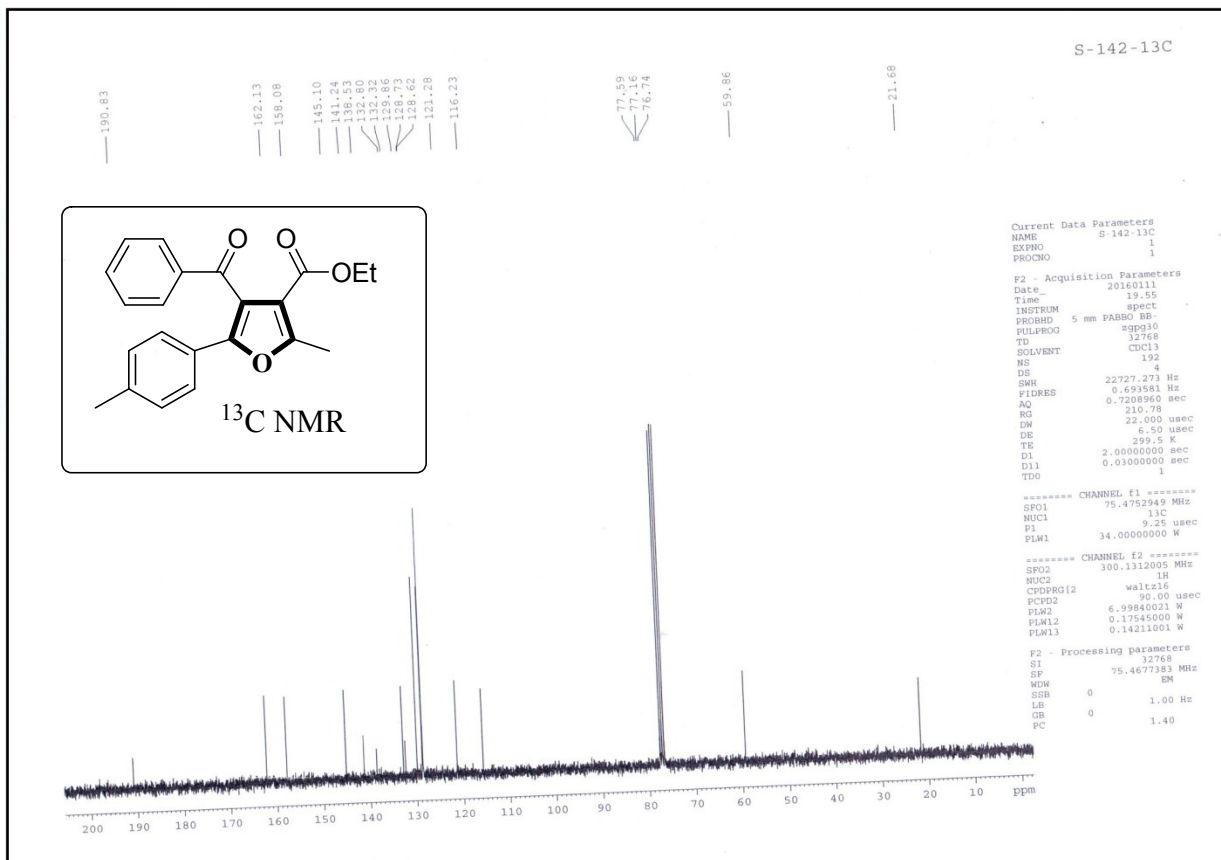




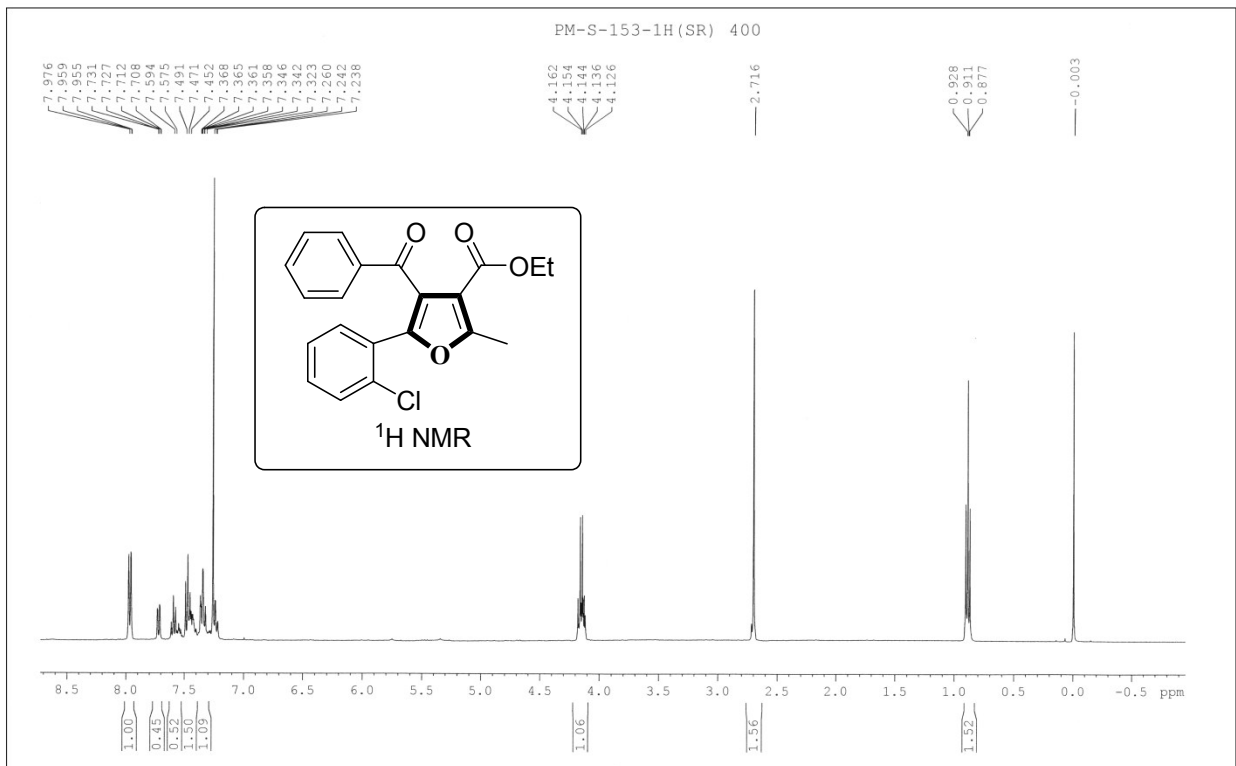
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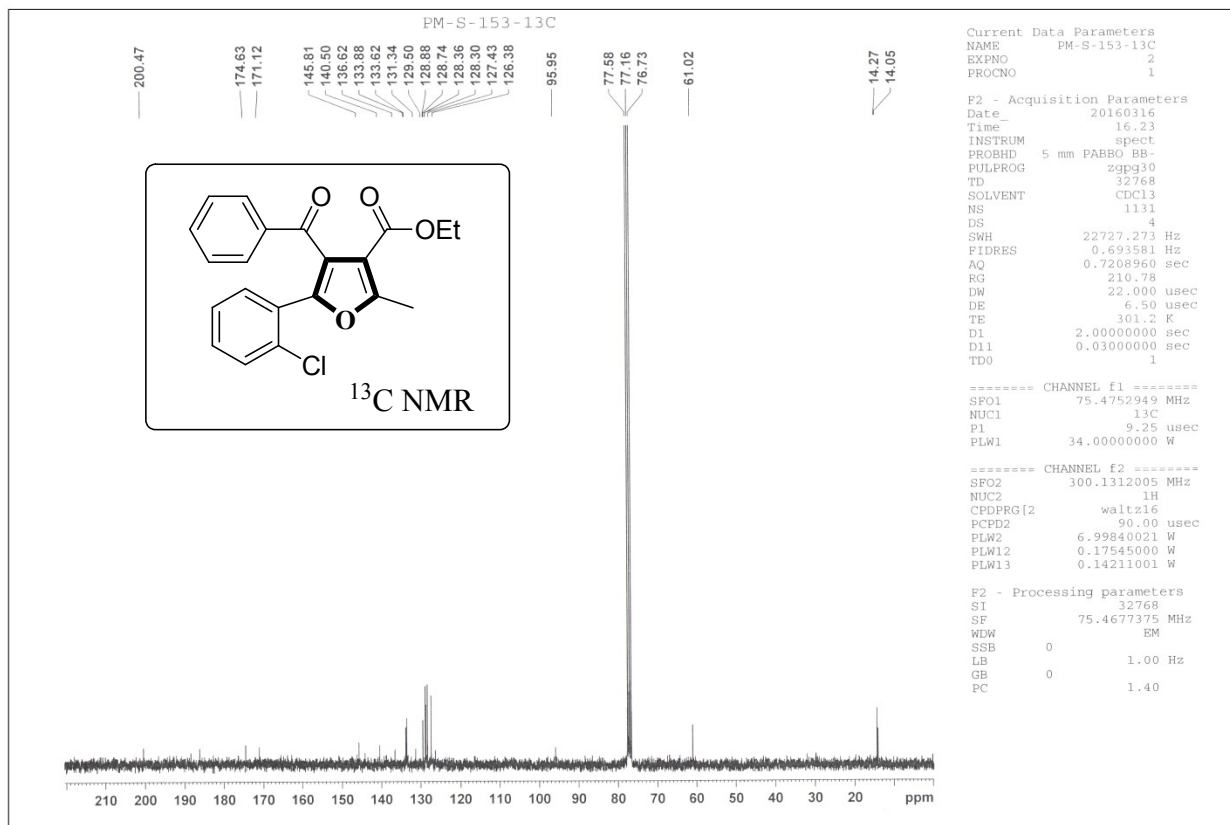


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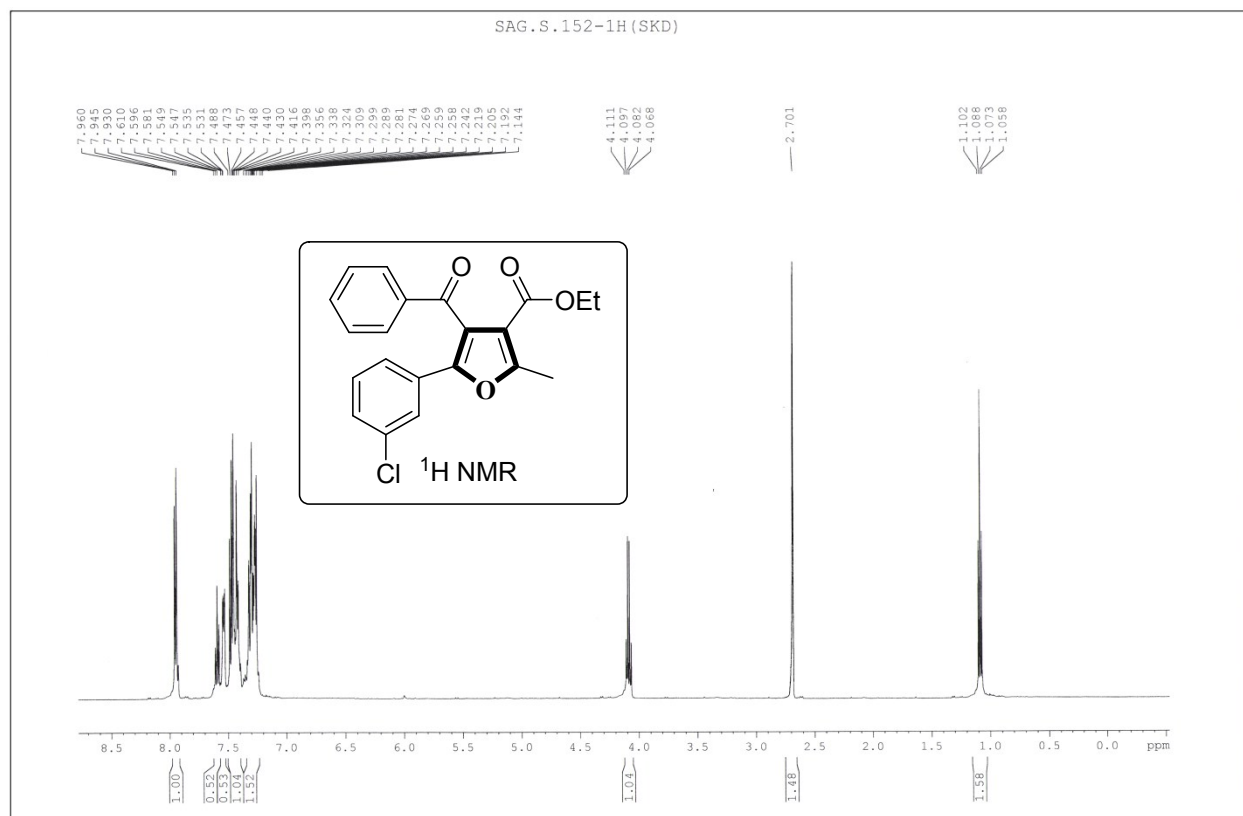


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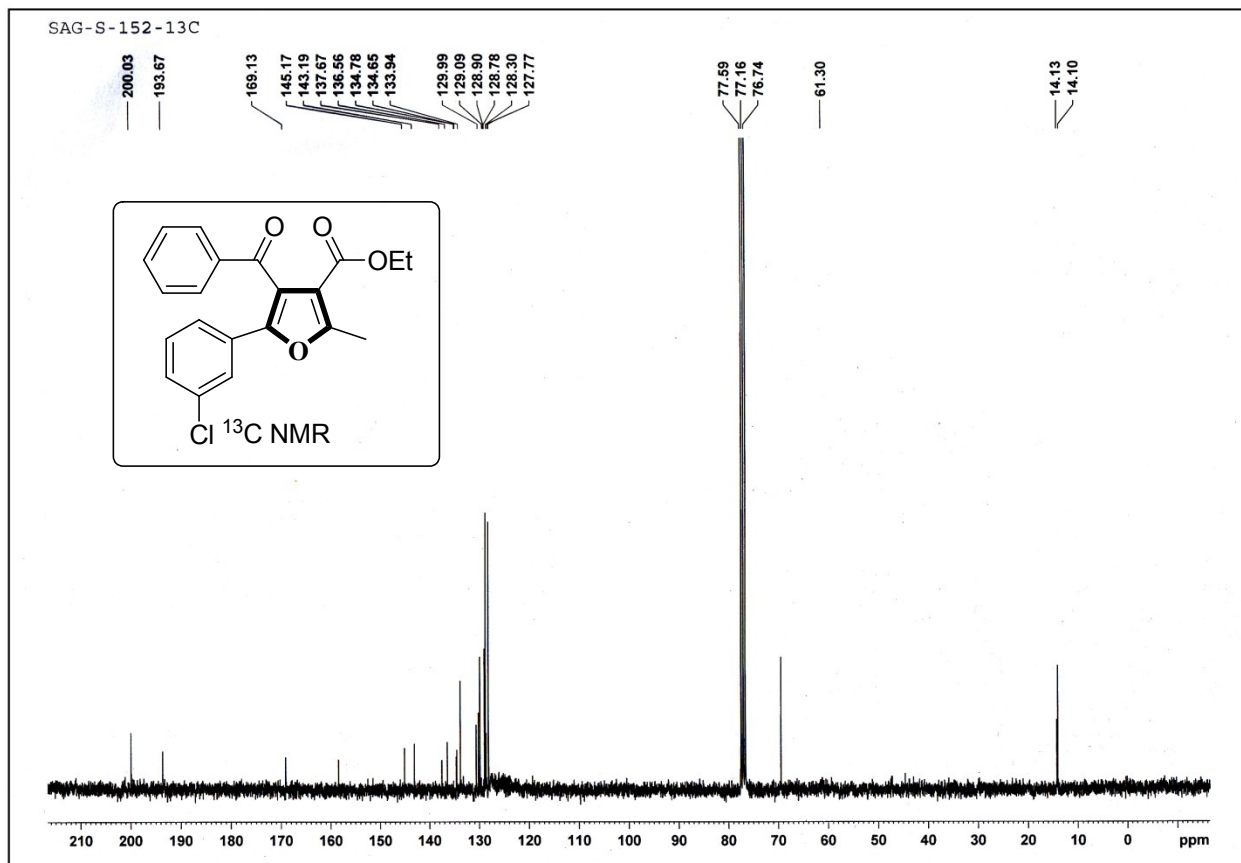




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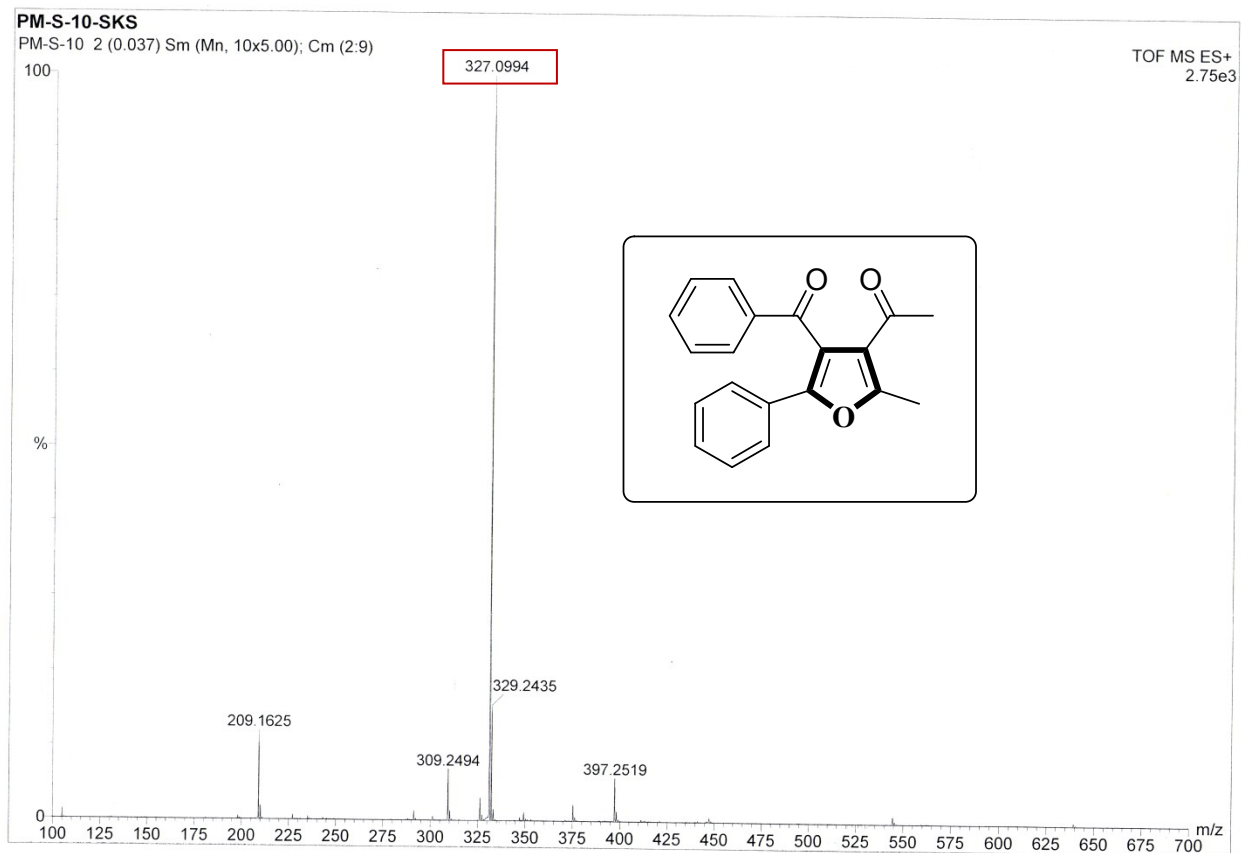


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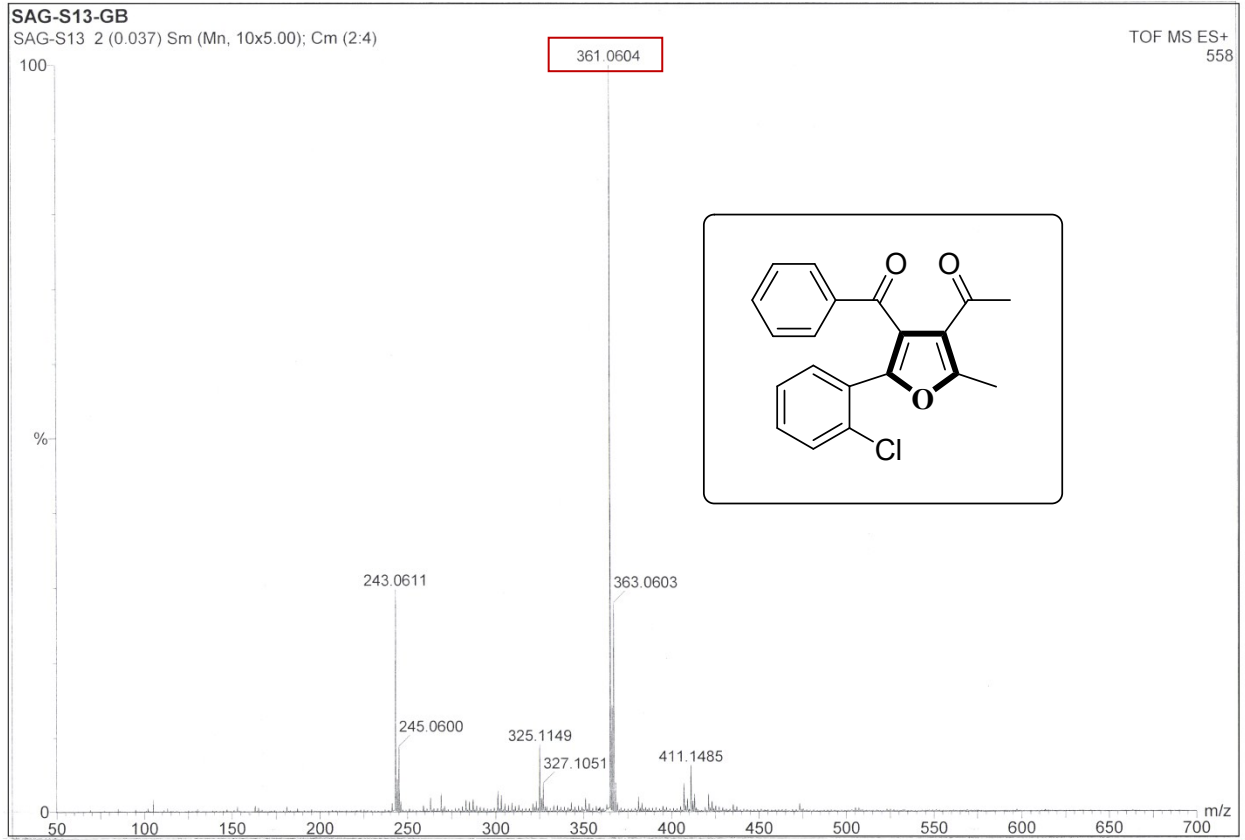


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ESI 7. Copy of HR-MS of the compounds in Table 2 and Table 3:



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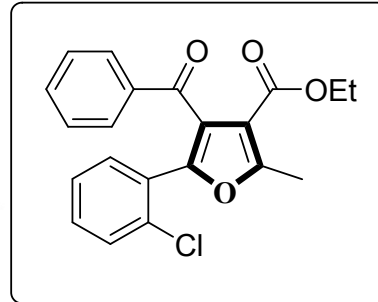
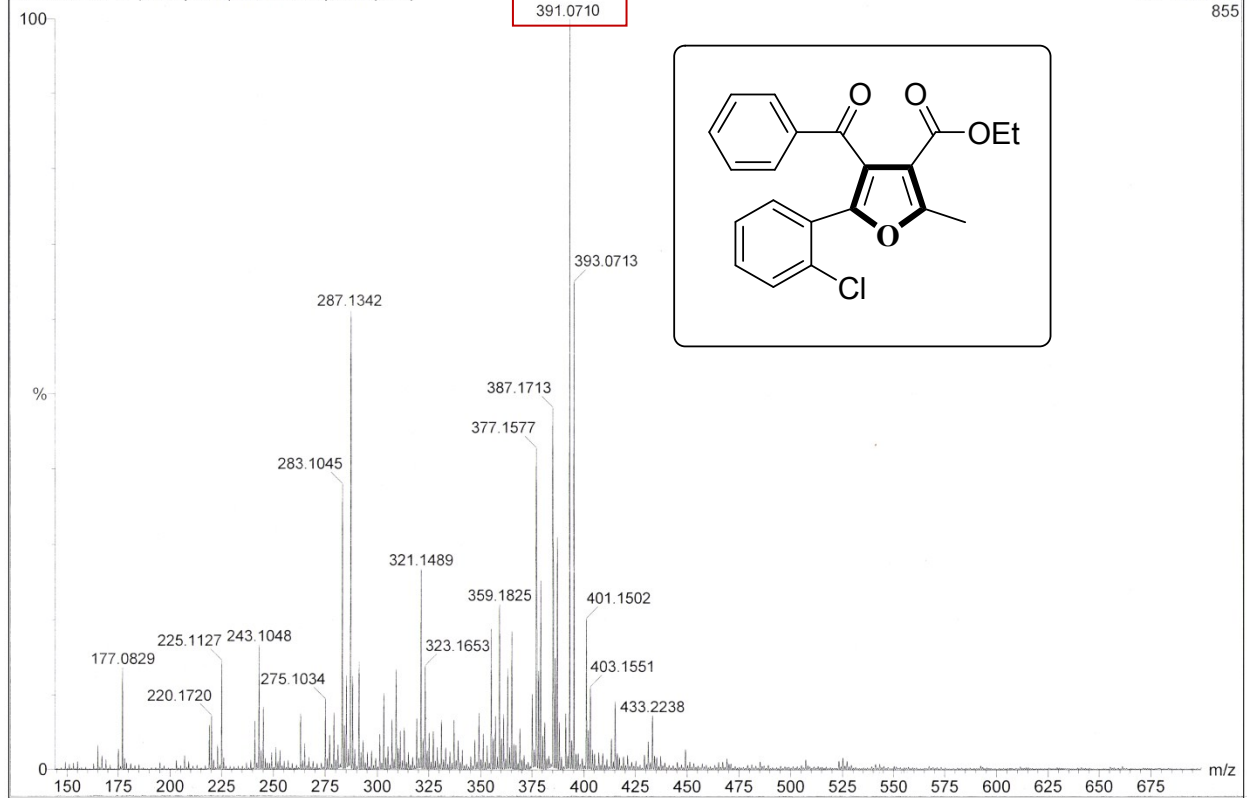


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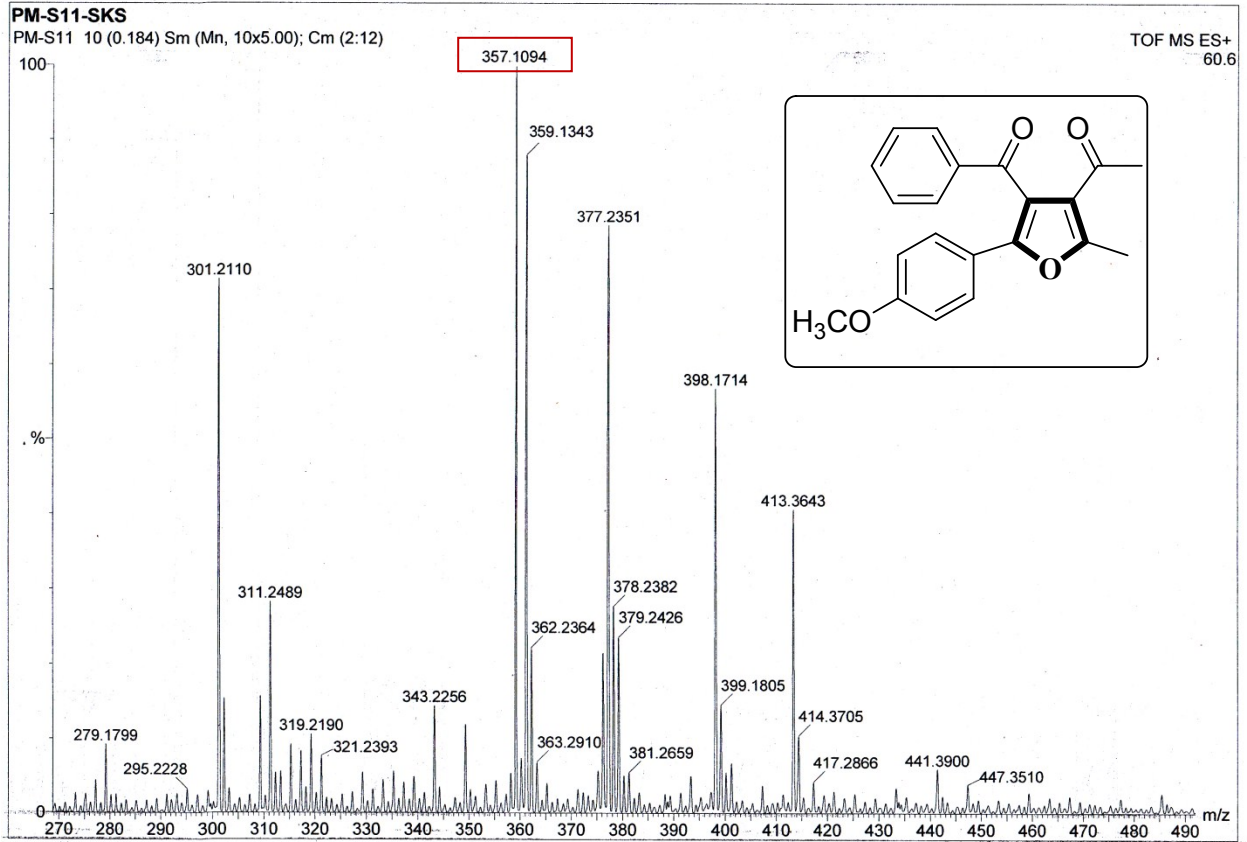
SAG-BU-16-SKS

SAG-BU-16 11 (0.205) Sm (Mn, 10x5.00); Cm (2:11)

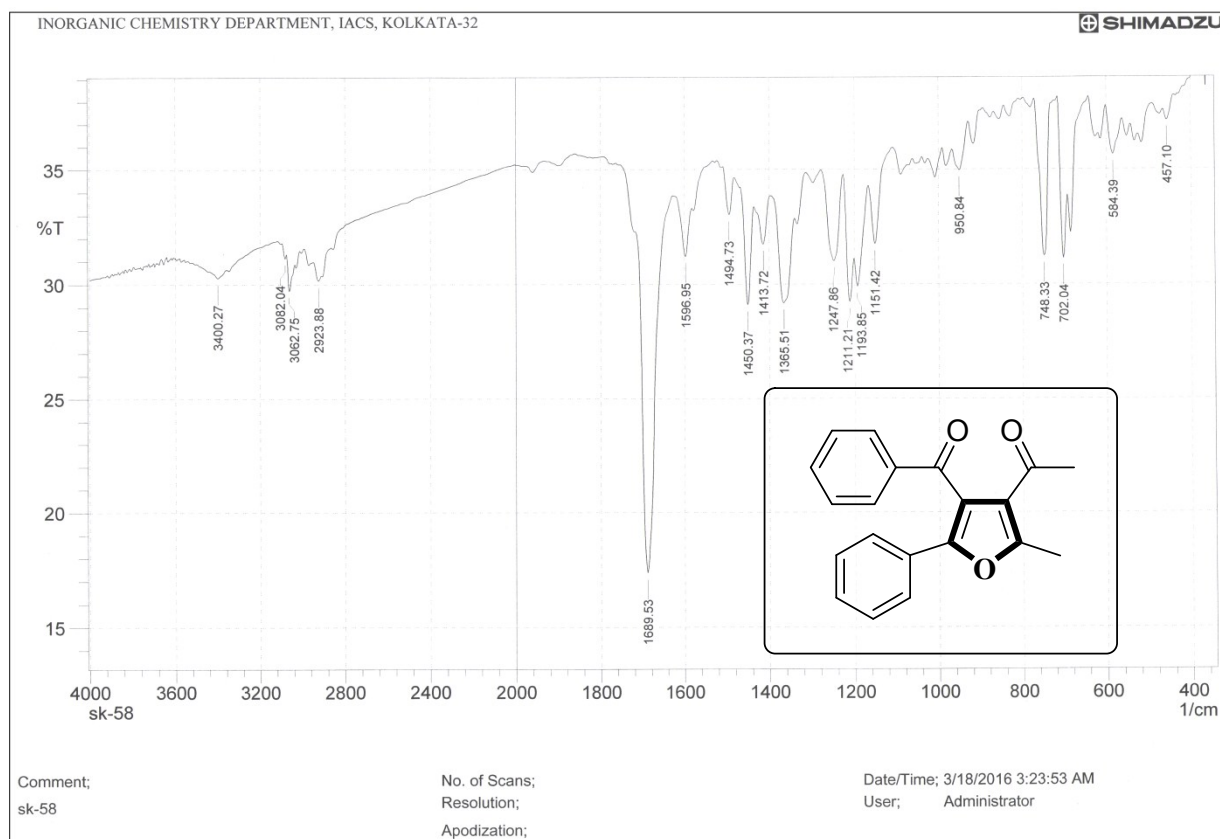
TOF MS ES+
855



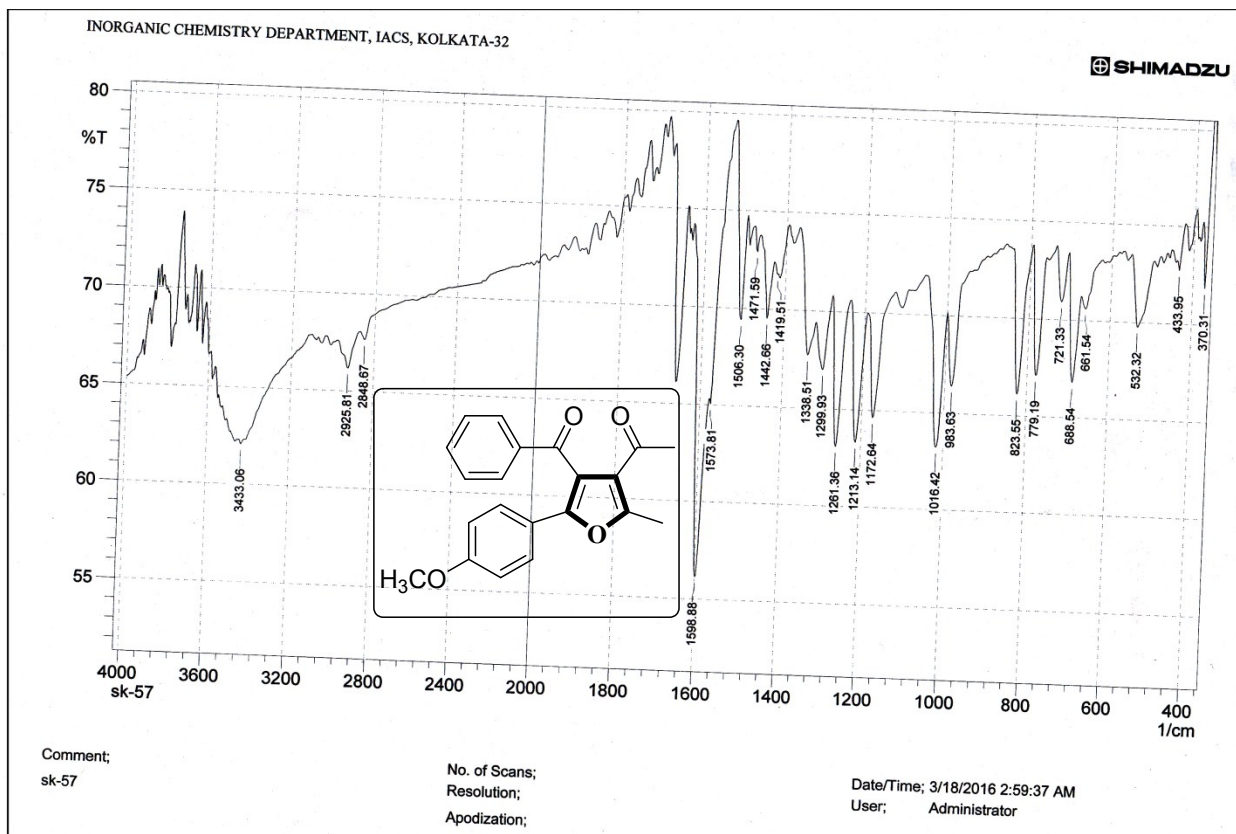
ESI



ESI 8. Copy of IR-spectra of the compounds in Table 2 and Table 3:

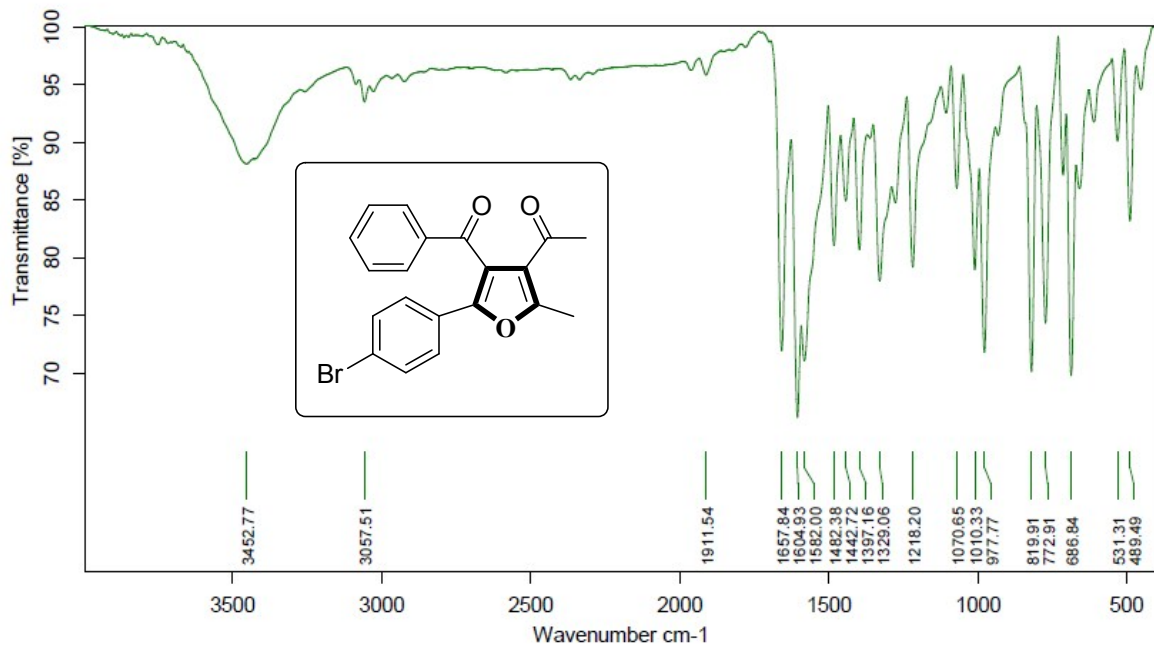


ESI



MKM-B-4.0

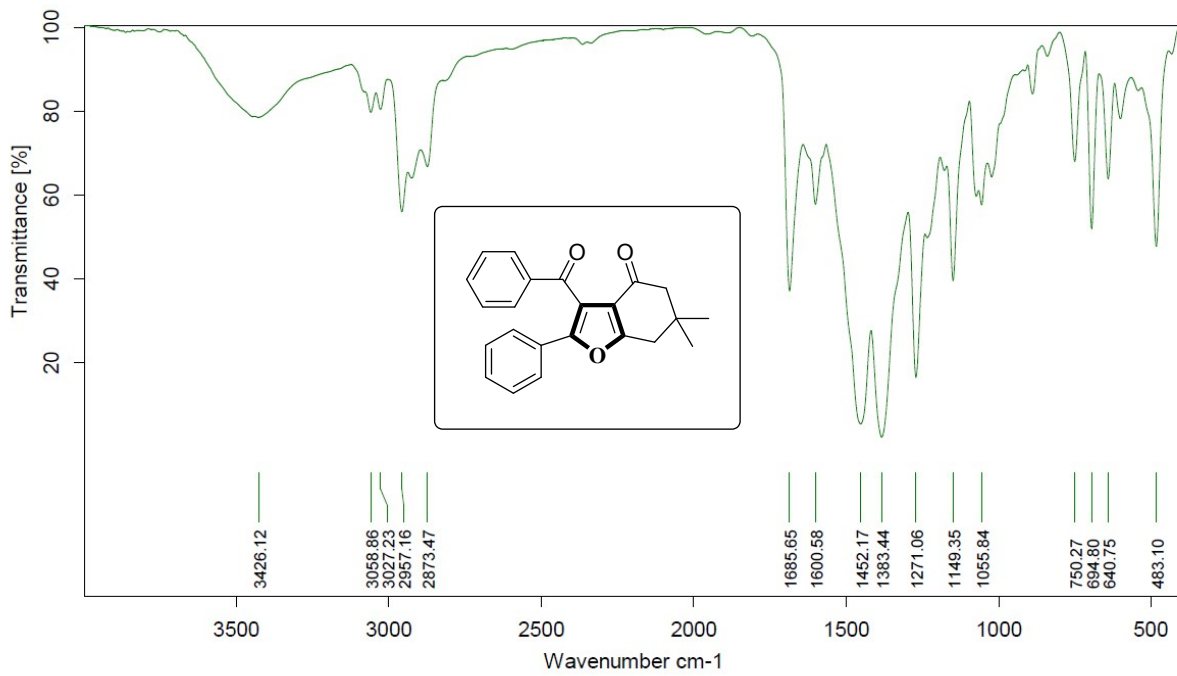
21-03-2016 15:12:15



ESI

MKM-B-3.0

21-03-2016 15:03:4

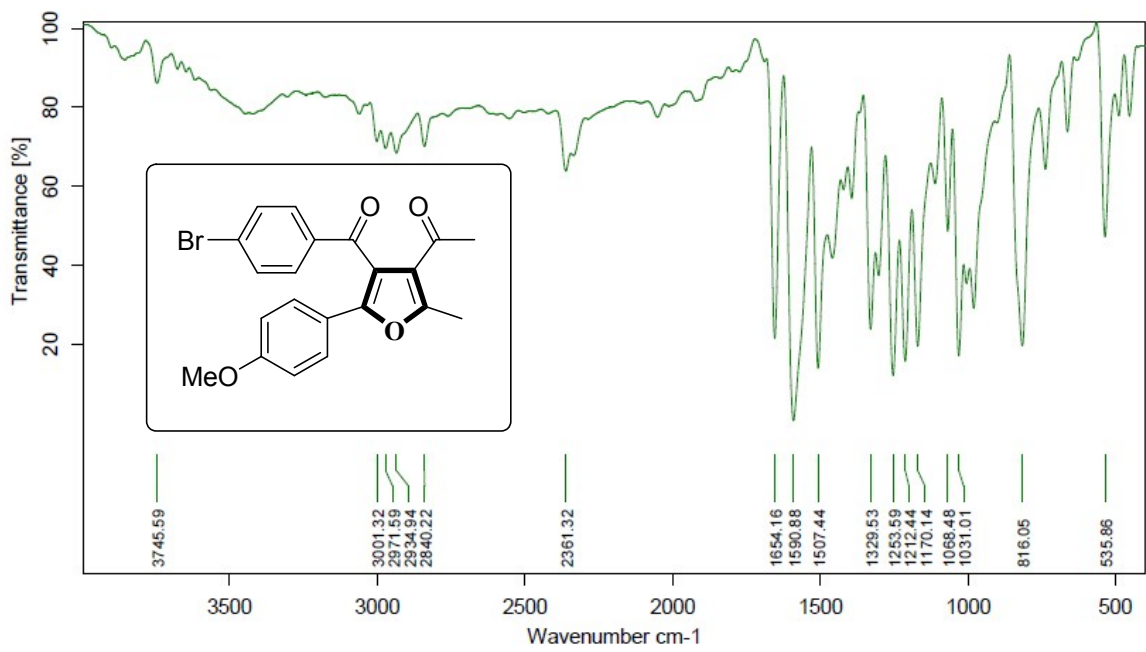


Comment: Sample in BUFFER

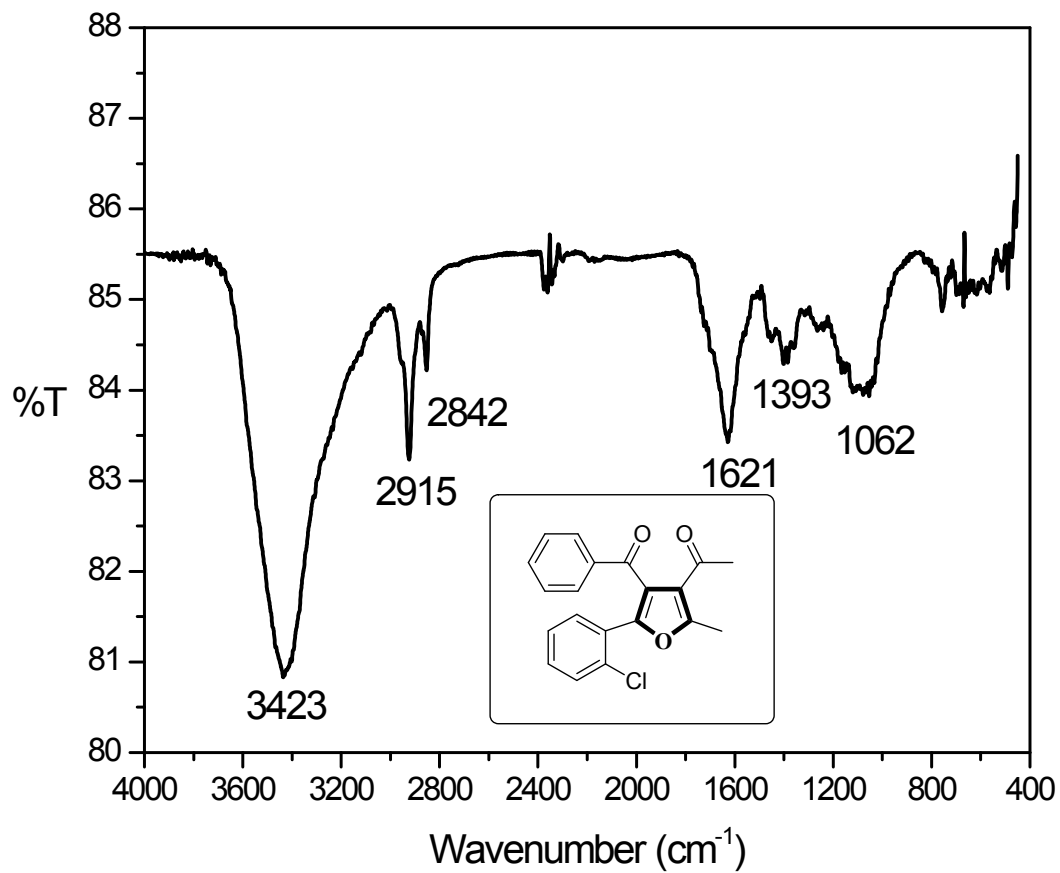
Bruker FTIR, TENSOR 27

MKM-B-2.0

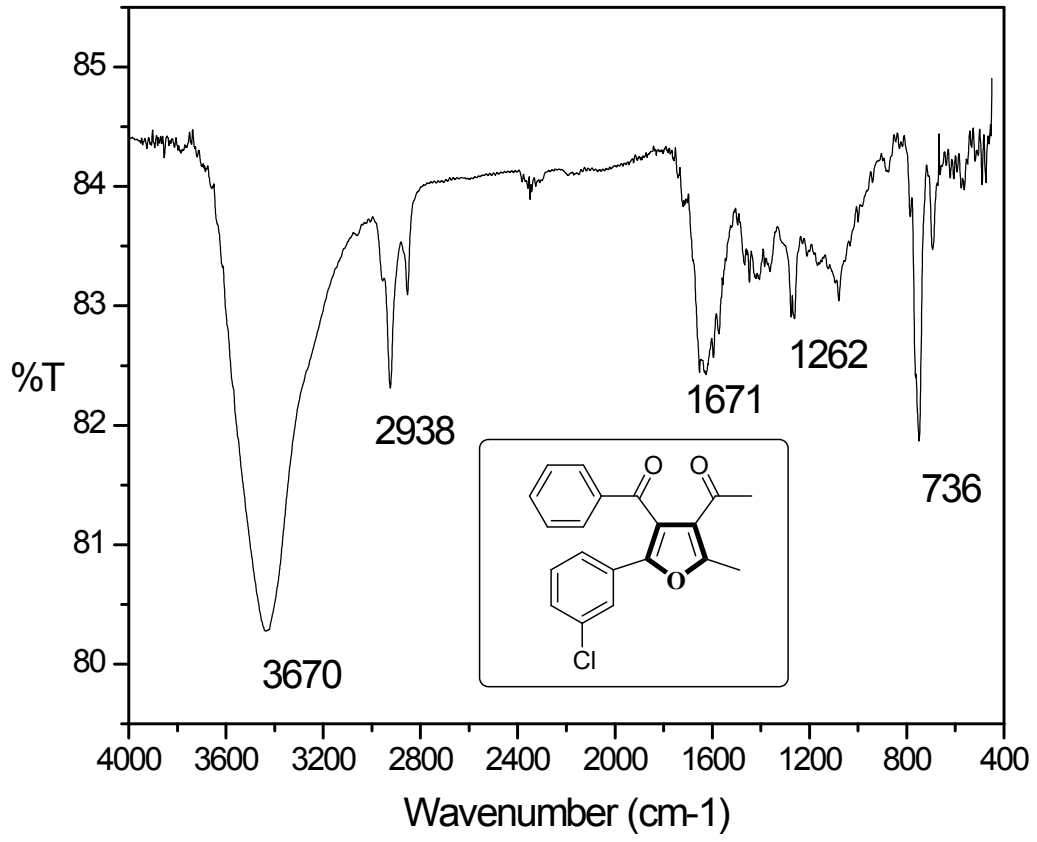
21-03-2016 14:55:29



ESI

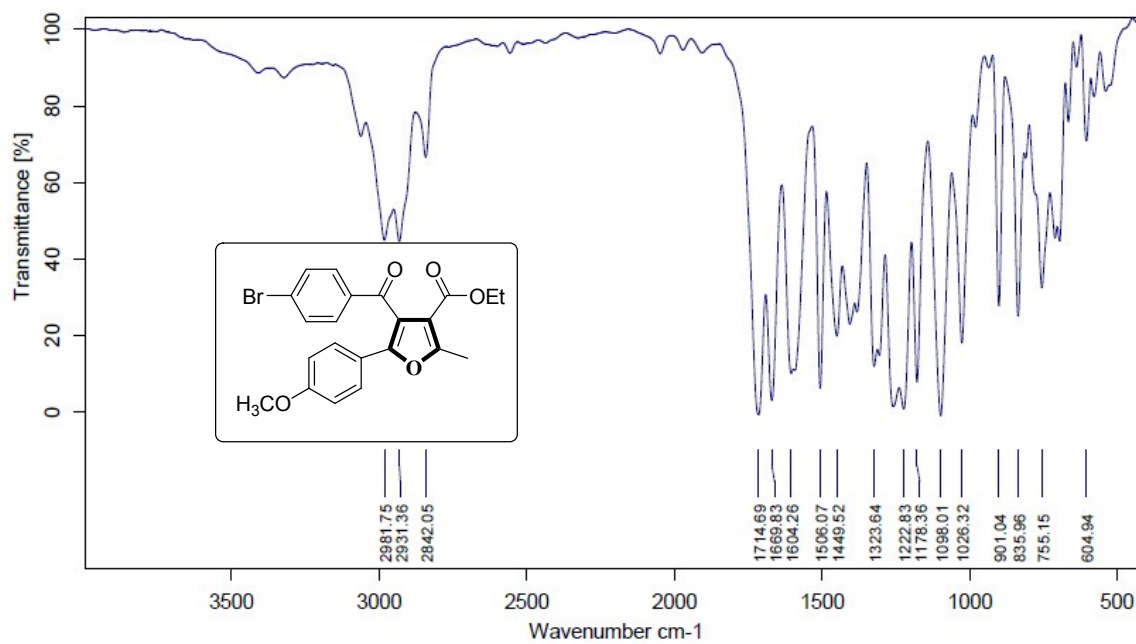


ESI



MKM-B-1.0

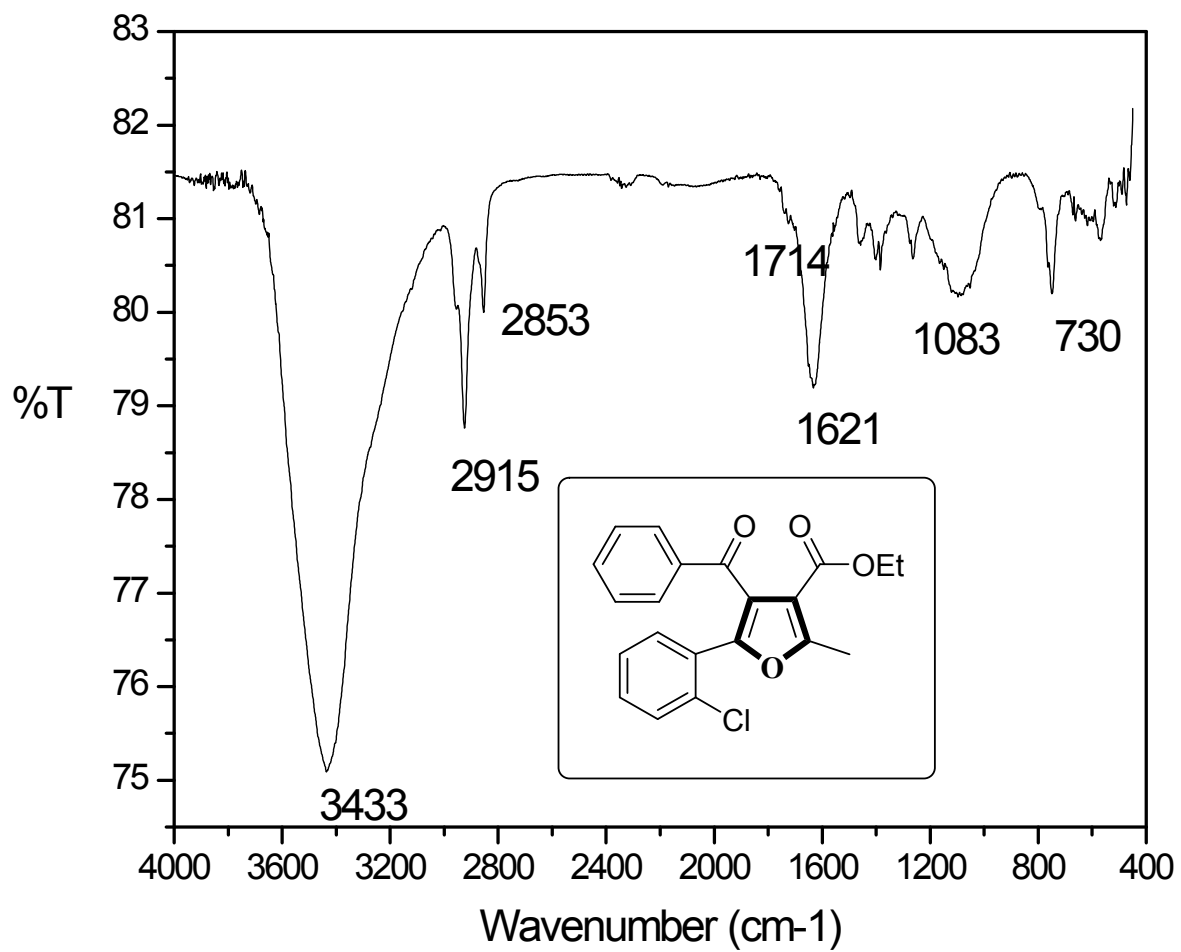
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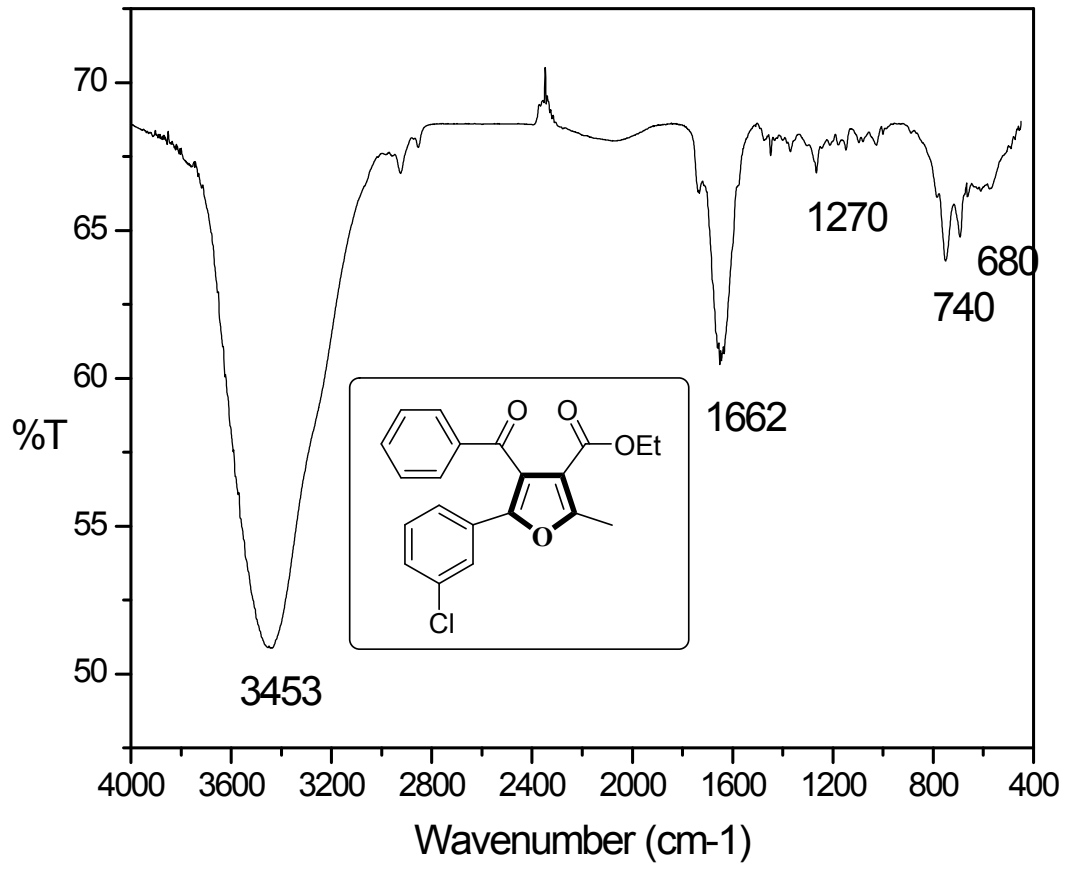
Comment: Sample in KBr

Bruker FTIR, TENSOR 27

ESI



ESI



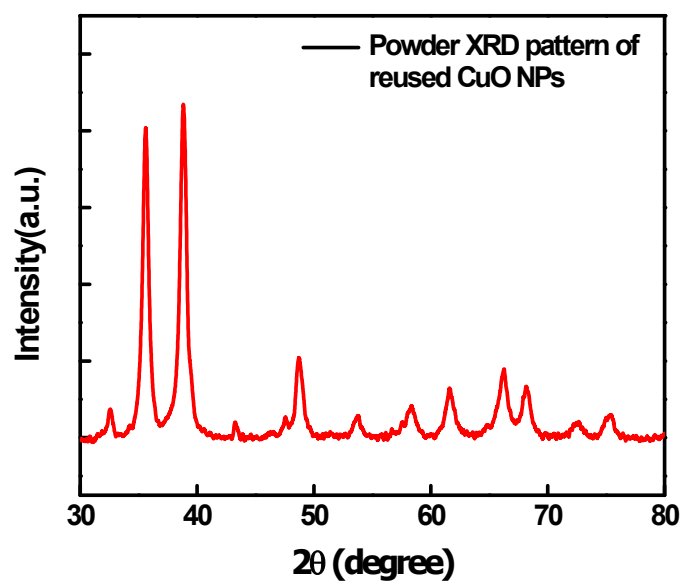
ESI-9. Powder XRD of recycled CuO NPs:

Fig. S1: Powder XRD of recycled CuO NPs