Electronic Supplementary Material (ESI) for RSC Advances.

3, 6-di(pyridin-2-yl)-1,2,4,5-tetrazine capped Pd(0) nanoparticles: catalyst for copper-free Sonogashira coupling of aryl halide in aqueous medium

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Experimental

Materials

Reagent grade chemicals obtained from commercial sources were used as received. Solvents were purified and dried according to standard methods. PVP stabilized Pd(0) nanoparticles was prepared according to the method reported previously in literature.

Physical measurements

FT-IR spectra were recorded using KBr disks on a JASCO FTIR-460 Plus spectrophotometer. ^{1}H NMR spectra were recorded on a BrukerAvance DPX spectrometer at 300 and 400 MHz with chemical shifts (δ, ppm) relative to tetramethylsilane (TMS). Powder X-ray diffraction (XRD) patterns were obtained on a Philips PW 1140 parallel beam X-ray diffractometer with Bragg-Bretano focusing geometry and monochromatic CuKα radiation (λ = 1.540598 Å). Gas chromatography analysis was performed with an Agilent Technologies 6890 N network GC system equipped with a fused silica capillary HP–5 column (30 m × 0.32 mm) and a FID detector. Transmission electron microscopy (TEM) images and selected area diffraction (SAED) patterns were collected by using JEOL JEM-2100 microscope working at 200 kV.

Synthesis of 3,6-di(pyridin-2-yl)-1,4-dihydro-1,2,4,5-tetrazine (H_2pytz). To a solution of 2-cyano pyridine (0.32 g, 3 mmol) in ethanol (10 mL) was added hydrazine monohydrate (0.23 g, 4.5 mmol) followed by sulfur powder (0.05 g, 1.5 mmol). The resulting solution was stirred at room temperature for 10 min and then refluxed for 1 h. The mixture was then cooled to room temperature and the solution was concentrated by rotary evaporator to give a yellow crystalline compound. Yellow solid, (214 mg, 60%) Mp 193-194°C, FT-IR (KBr, ν/cm^{-1}) 3336 w, 3323 s, 3298 w, 3059 w, 1590 m, 1566 m, 1472 m, 1445 s, 1385 s, 1287 m, 1252 w, 1155 w, 1113 m, 993 m, 882 m, 785 s, 744 s, 679 m. ^{1}H NMR (300 MHz, $CDCl_3$): δ 8.573 (t, 4H,*J* = 8.0 Hz), 8.052 (d, 2H, *J* = 8.0 Hz), 7.762−7.728 (m, 2H), 7.338 (dd, 2H,*J* = 8.0 Hz). ^{13}CNMR (125 MHz, $CDCl_3$): δ 148.60, 147.69, 146.85, 139.92, 125.06, 121.52. HRMS (ESI-TOF) $[M + Na]^+$ calculated for $C_{12}H_{10}N_6Na$ 261.2440, found 261.1530.

3,6-Di(pyridin-2-yl)-1,2,4,5-*s*-tetrazine (pytz) capped-palladium nanoparticles (TzPdNPs). The synthesis of 3,6-di(pyridin-2-yl)-1,2,4,5-*s*-tetrazine (pytz) capped-palladium nanoparticles (TzPdNPs) was achieved by the reduction of Na_2PdCl_4 with 3,6-di(pyridin-2-yl)-1,4-dihydro-1,2,4,5-tetrazine (H_2pytz). A 100 mL round bottom flask containing solution of 3,6-di(pyridin-2-yl)-1,4-dihydro-1,2,4,5-tetrazine (0.24 g, 1 mmol) in ethanol (50 mL) was placed in an ultrasonicator bath and disodium tetrachloro palladinate (0.294 g, 1 mmol) in 10 mL water was added to it drop wise. After five minutes, a brownish black precipitate was formed slowly indicating the formation of palladium nanoparticles. The resulting particles were isolated by centrifugation (10 min, 12 000 rpm) and washed subsequently with water, ethanol, and dichloromethane. The product was then dried in vacuum oven and kept for further characterization. Brownish black colored solid, FT-IR (KBr, ν/cm^{-1}) 3430br, 1627m, 1601m, 1453 s, 1418 s, 1380s, 1330w, 1266 s, 1164 w, 1082 w, 1052 w, 1029 m, 782 s, 742 m, 658w, 626 s.

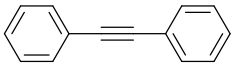
General procedure for the Sonogashira reaction of aryl chloride. In a 50 mL round bottom flask aryl chloride (2.0 mmol), phenyl acetylene (2.0 mmol, 0.21 g), TzPdNPs (2 mg), tetra butyl ammonium bromide (TBAB, 20 mg) and K_2CO_3 (2 mmol, 0.277 g) in 10 mL water was refluxed at 100ºC under aerobic condition. The progress of the reaction was monitored by TLC and GC. After completion of the reaction vessel was cooled to room temperature and was extracted with chloroform (3×10 mL). The combined chloroform layers were dried over anhydrous Na_2SO_4 and the solvent was removed in vacuo. The crude product was then purified by flash chromatography using hexane as elute.

Sonogashira reaction of 1,4-dicholorobenzene chloride. Same reaction procedure was followed with 1,4-dicholorobenzene (2.0 mmol) and phenyl acetylene (4.0 mmol, 0.42 g).

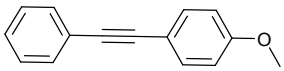
General procedure for the Sonogashira reaction of heterocyclic aryl iodide with trimethylsilyl acetylene. In a 50 mL round bottom flask heterocyclic aryl iodide (2.0 mmol), trimethylsilyl acetylene (2.0 mmol, 0.2 g), TzPdNPs (2 mg), tetra butyl ammonium bromide (TBAB, 20 mg) and K_2CO_3 (2 mmol, 0.277 g) in 10 mL water was stirred at room temperature under aerobic condition. The progress of the reaction was monitored by TLC and GC.After completionof the reaction the mixture was extracted with chloroform (3×10 mL).The combined chloroform layers were dried over anhydrous Na_2SO_4 and the solvent was removed in vacuo. The crude product was then purified by flash chromatography using hexane as elute.

One pot synthesis of heterocyclic terminal alkynes from heterocyclic aryl iodides. In a 50 mL round bottom flask heterocyclic aryl iodide (2.0 mmol), trimethylsilyl acetylene (2.0 mmol, 0.2 g), TzPdNPs (2 mg), tetra butyl ammonium bromide (TBAB, 20 mg) and K_2CO_3 (2 mmol, 0.277 g) in 10 mL water was stirred at room temperature under aerobic condition. The progress of the reaction was monitored by TLC and GC. After completion of the coupling reaction, KOH (0.056 gm, 1.0 mmol) was added to the reaction mixture. Stirring was continued for another 1 h at room temperature. Reaction was again monitored by TLC and GC. After completion of the reaction, the mixture was extracted with chloroform (3×10 mL). The combined chloroform layers were dried over anhydrous Na_2SO_4 and the solvent was removed in vacuo. The crude product was then purified by flash chromatography using hexane as elute.

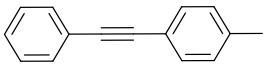
1,2-diphenylethyne (Scheme 1, entry 1). White solid, yield 86%, ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.521 (dd, 4H, *J* =7.5, 4.2 Hz), 7.357-7.308 (m, 6H).



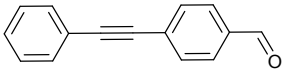
1-methoxy-4-(phenylethynyl)benzene(Scheme 1, entry 2) White solid, yield 62%, ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.565-7.475 (m, 4H), 7.376-7.324 (m, 3H), 6.891(d, 2H, *J* = 6.6 Hz), 3.824 (s, 3H).



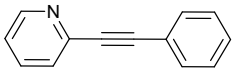
1-methyl-4-(phenylethynyl)benzene (Scheme 1, entry 3). White solid, yield 67%, ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.546-7.503 (m, 2H), 7.425(d, 1H, *J* = 23.1 Hz), 7.362-7.322 (m, 4H), 7.157 (d, 2H, *J* = 7.8 Hz), 2.369 (s, 3H).



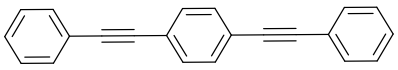
4-(phenylethynyl)benzaldehyde(Scheme 1, entry 4). White solid, yield 85%, ^{1}H NMR (300 MHz, $CDCl_3$): δ 9.957 (s, 1H), 7.805(d, 2H, *J* = 8.4 Hz), 7.612 (d, 2H, *J*= 8.4 Hz), 7.477 (s, 1H), 7.315 (t, 4H, *J* = 2.7 Hz).



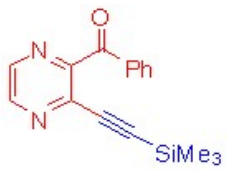
2-(phenylethynyl)pyridine(Scheme 1, entry 5). White solid, yield 71%, ^{1}H NMR (300 MHz, $CDCl_3$): δ 8.632 (s, 1H), 7.678-7.607 (m, 1H), 7.593-7.495 (m, 4H), 7.368-7.347 (m, 2H), 7.341-7.201 (m, 1H).



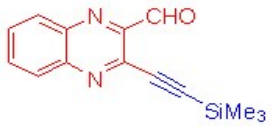
1,4-bis(phenylethynyl)benzene(Scheme 1, entry 6). White solid, yield 81%, ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.553-7.524 (m, 10H), 7.503-7.266(m, 4H).



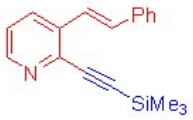
Phenyl(3-((trimethylsilyl)ethynyl)pyrazin-2-yl)methanone(Scheme 2, entry 1). White solid, yield 80%, ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.672 (d, 1H,*J* = 1.8 Hz), 8.5941-8.5318 (m, 1H), 7.83 (t, 2H, *J* = 7.32, 5.28 Hz), 7.639 (dd, 1H,*J* =17.48, 7.88 Hz), 7.493 (dd, 2H, *J* =14.24, 6.92 Hz).



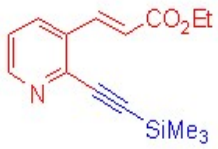
3-((trimethylsilyl)ethynyl)quinoxaline-2-carbaldehyde(Scheme 2, entry 2). White solid, yield 81%, ^{1}H NMR (400 MHz, $CDCl_3$): δ 10.552 (s, 1H), 8.253 (dd, 1H, *J* = 8.0, 1.0 Hz), 8.159 (dd, 1H, *J* =8.0, 1.0 Hz), 7.922 (dd, 1H, *J* = 8.0, 1.5 Hz), 7.880 (dd, 1H, *J* = 8.0, 1.5 Hz), 0.364 (s, 9H).



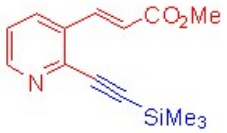
(E)-3-styryl-2-((trimethylsilyl)ethynyl)pyridine(Scheme 2, entry 3). Brown thick liquid, yield 85%, ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.437 (dd, 1H, *J* = 5.0, 1.5 Hz), 7.479 (dd, 1H, *J* = 8.0, 1.5 Hz), 7.2408-7.2038 (m, 3H), 7.18-7.15 (m, 2H), 7.024 (dd, 1H, *J* = 8.0, 5.0 Hz), 6.816 (dd, 2H, *J* = 16.0, 12.0 Hz), 3.388 (s, 1H).



(E)-ethyl 3-(2-((trimethylsilyl)ethynyl)pyridin-3-yl)acrylate(Scheme 2, entry 4). White solid, yield 79%, ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.556 (dd, 1H, *J* = 5.0, 1.5 Hz), 8.122 (d, 1H, *J* = 16 Hz), 7.88 (dd, 1H, *J* = 8.0, 1.5 Hz), 7.27 (dd, 1H,*J* = 8.0, 5.0 Hz), 6.55 (d, 1H, *J* = 16.0 Hz), 4.28 (q, 2H, *J* = 7.2 Hz), 1.34 (t, 3H, *J* = 7.2 Hz), 0.31 (s, 9H).



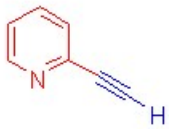
(E)-methyl 3-(2-((trimethylsilyl)ethynyl)pyridin-3-yl)acrylate(Scheme 2, entry 5). White solid, yield 83%, ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.565 (dd, 1H, *J* = 4.7, 1.5 Hz), 8.151 (d, 1H, *J* = 16.0 Hz), 7.890 (dd, 1H, *J* = 8.0, 1.5 Hz), 7.281 (dd, 1H, *J* = 8.0, 4.7 Hz), 6.567 (d, 1H, *J* = 16 Hz), 3.836 (s, 3H), 0.316 (s, 9H).



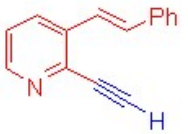
(**E)-methyl 3-(3-((trimethylsilyl)ethynyl)pyridin-4-yl)acrylate(Scheme 2, entry 6).**White solid, yield 87%, ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.729 (s, 1H), 8.525 (d, 1H, *J* = 5.3 Hz), 8.00 (d, 1H, *J* = 16 Hz), 7.397 (d, 1H, *J* = 5.3 Hz), 6.738 (d, 1H, *J* = 16 Hz), 3.840 (s, 3H), 0.309 (s, 9H)

(E)-4-styryl-3-((trimethylsilyl)ethynyl)pyridine(Scheme 2, entry 7). White solid, yield 84%, ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.676 (s, 1H), 8.469 (d, 1H, *J* = 5.0 Hz), 7.561 (d, 2H, *J* = 7.0 Hz), 7.504 (d, 2H, *J* = 5.0 Hz), 7.427-7.342 (m, 4H), 0.323 (s, 9H).

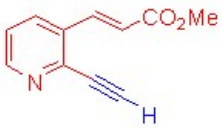
2-ethynylpyridine(Scheme 3, entry 1). White solid, yield 83%, ^{1}H NMR (300 MHz, $CDCl_3$): δ 10.585 (d, 1H, *J* = 12.0 Hz), 8.81 (dd, 1H, *J* = 4.8, 1.8 Hz), 8.21 (dd, 1H, *J* = 8.1, 1.8 Hz), 7.464 (dd, 1H, *J* = 7.8, 4.8 Hz), 3.64 (s, 1H).



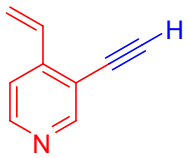
(E)-2-ethynyl-3-styrylpyridine(Scheme 3, entry 2). White solid, yield 76%, ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.48 (dd, 1H, *J* = 4.5, 1.5 Hz), 7.99 (dd, 1H, *J* = 8.0, 1.5 Hz), 7.58 (d, 1H, *J* = 16.0 Hz), 7.56 (d, 2H, *J* = 7.5 Hz), 7.39 (t, 2H, *J* = 7.5 Hz), 7.32 (t, 1H, *J* = 7.5 Hz), 7.30 (dd, 1H, *J* = 8.0, 4.5 Hz), 7.18 (d, 1H, *J* = 16.0 Hz), 3.46 (s, 1H).



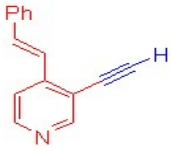
(E)-methyl 3-(2-ethynylpyridin-3-yl)acrylate(Scheme 3, entry 3). White solid, yield 73%, ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.59 (dd, 1H, *J* = 4.7, 1.5 Hz), 8.12 (d, 1H, *J* = 16.0 Hz), 7.91 (dd, 1H, *J* = 8.0, 1.5 Hz), 7.32 (dd, 1H, *J* = 8.0, 4.5 Hz), 6.54 (d, 1H, *J* = 16.0 Hz), 3.83 (s, 3H), 3.49 (s, 9H).



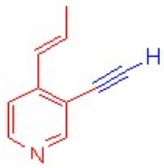
3-ethynyl-4-vinylpyridine(Scheme 3, entry 4). Colorless liquid, yield 81%, ^{1}H NMR (300 MHz, $CDCl_3$): δ 8.695 (s, 1H), 8.498 (d, 1H, *J* = 5.1 Hz), 7.424 (d, 1H, *J* = 5.1 Hz), 7.123 (dd, 1H, *J* = 17.7, 11.1 Hz), 6.054 (d, 1H, *J* = 17.7 Hz), 5.599 (d, 1H, *J* = 11.1 Hz), 3.432 (s, 1H).



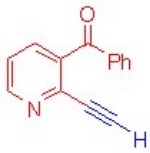
(E)-3-ethynyl-4-styrylpyridine(Scheme 3, entry 5). White solid, yield 78%, ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.714 (s, 1H), 8.51 (d, 1H, *J* = 5.4 Hz), 7.58 (d, 2H *J* = 7.3 Hz), 7.535(t, 1H, *J* = 16.0 Hz), 7.495 (s, 1H), 7.40 (dd, 3H, *J* = 7.15, 1.65 Hz), 7.3689-7.3327 (m, 1H), 3.499 (s,1H).



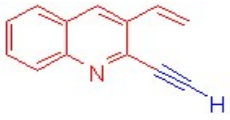
(E)-3-ethynyl-4-(prop-1-enyl)pyridine(Scheme 3, entry 6). Brown liquid, yield 74%, ^{1}H NMR (300 MHz, $CDCl_3$): δ 8.647 (s, 1H), 8.425 (d, 1H, *J* = 5.2 Hz), 7.344 (d, 1H, *J* = 5.2 Hz), 6.80 (d, 1H, *J* = 15.6 Hz), 6.653-6.535 (m, 1H), 3.406 (s, 1H), 1.972 (d, 3H, *J* = 6.6 Hz).



(2-ethynylpyridin-3-yl)(phenyl)methanone(Scheme 3, entry 7). White solid, yield 82%, ^{1}H NMR (300 MHz, $CDCl_3$): δ 8.79 (dd, 1H, *J* = 4.5, 1.2 Hz), 7.874-7.812 (m, 3H), 7.67 (t, 1H, *J* = 7.5, 7.2 Hz), 7.558-7.430 (m, 3H), 3.173 (s, 1H)



2-ethynyl-3-vinylquinoline(Scheme 3, entry 8). White solid, yield 86%, ^{1}H NMR (300 MHz, $CDCl_3$): δ 8.284 (s, 1H), 8.06 (d, 1H, *J* = 6.3 Hz), 7.796 (d, 1H, *J* = 6.0 Hz), 7.706-7.669 (m, 1H), 7.54 (dd, 1H, *J* = 5.4, 0.6 Hz), 7.351-7.280(m, 1H), 5.95(d, 1H, *J* = 13.2 Hz), 5.53 (d, 1H, *J* = 8.4 Hz), 3.452 (s, 1H).



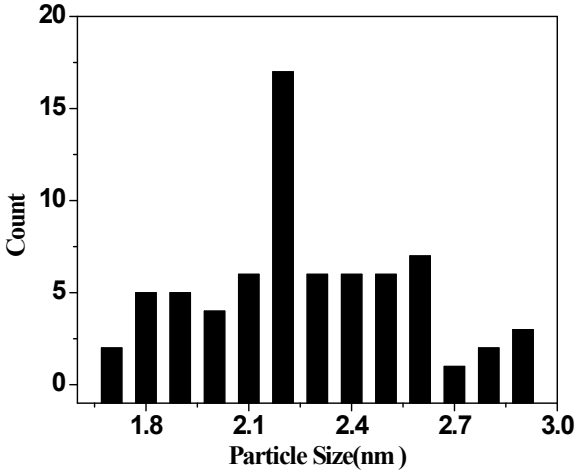


Fig. S1. Size distribution of 3, 6-di(pyridin-2-yl)-1,2,4,5-tetrazine (pytz) capped Pd(0) nanoparticles (TzPdNPs).

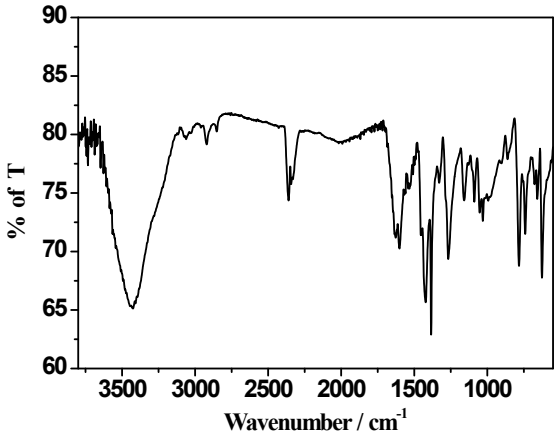


Fig. S2. FT–IR spectrum of 3, 6-di(pyridin-2-yl)-1,2,4,5-tetrazine (pytz) capped Pd(0) nanoparticles (TzPdNPs).

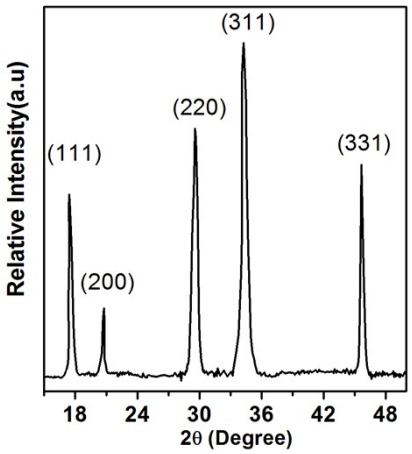
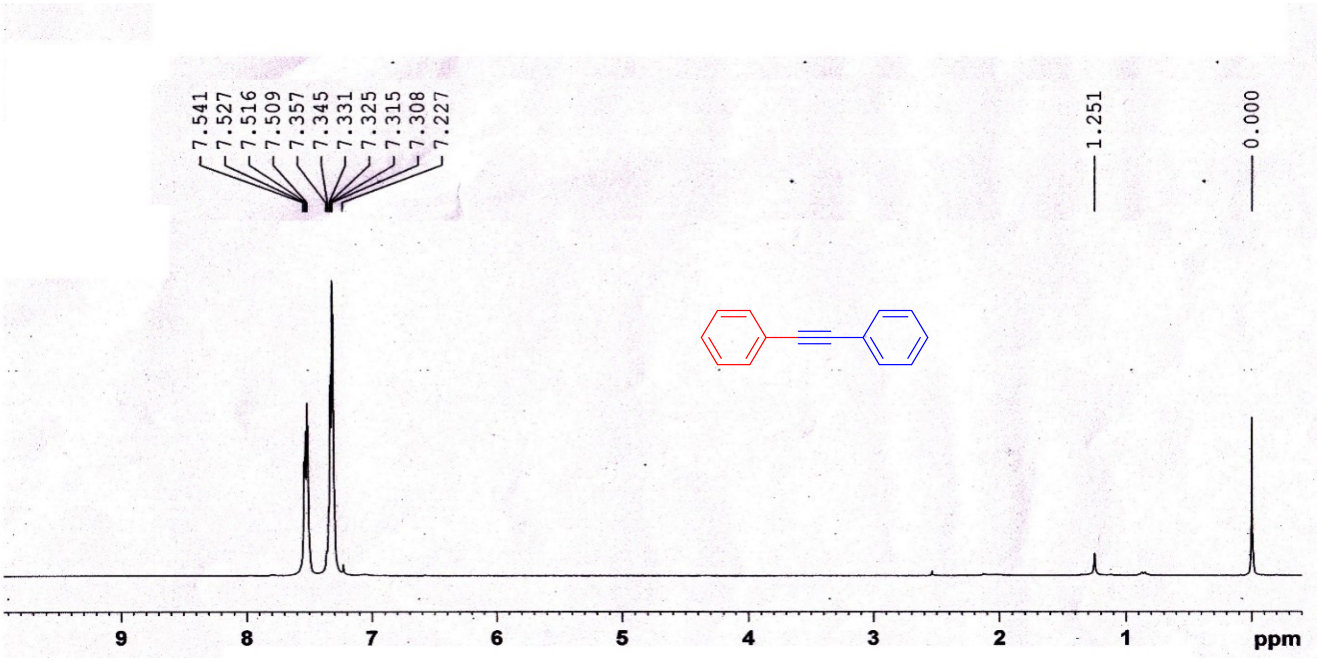
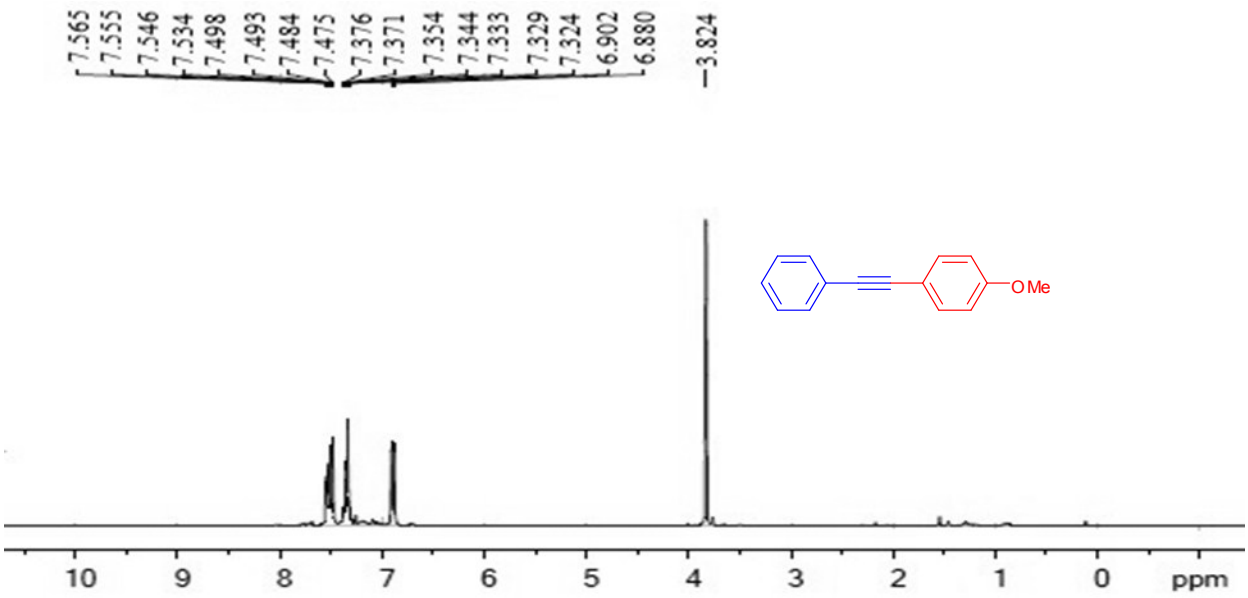


Fig. S3. Powder XRD pattern of the PVP stabilized Pd(0) nanoparticles.

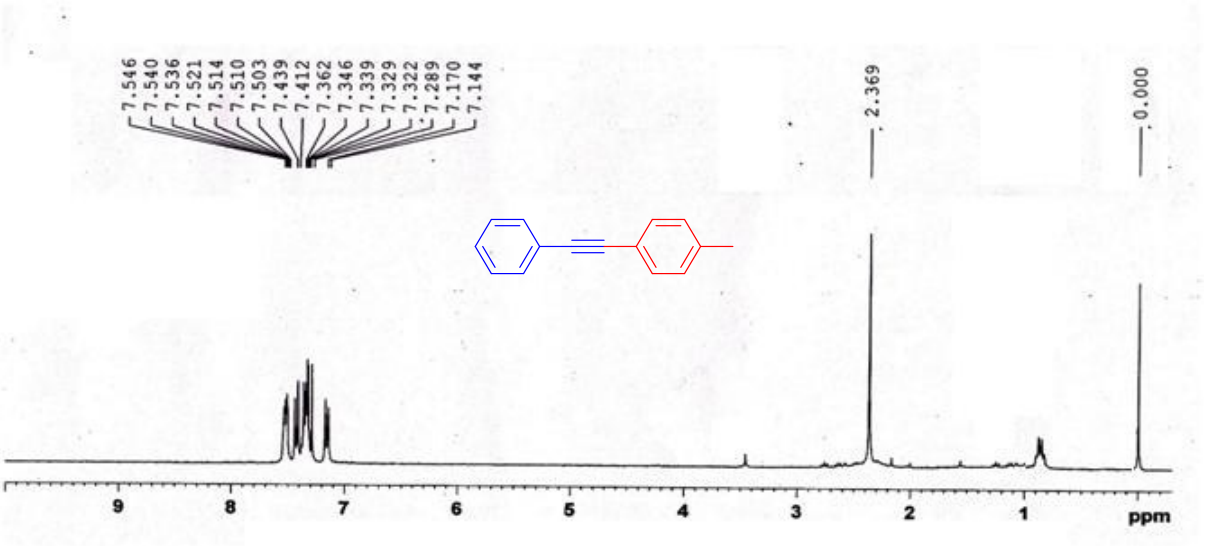
Proton NMR Spectra



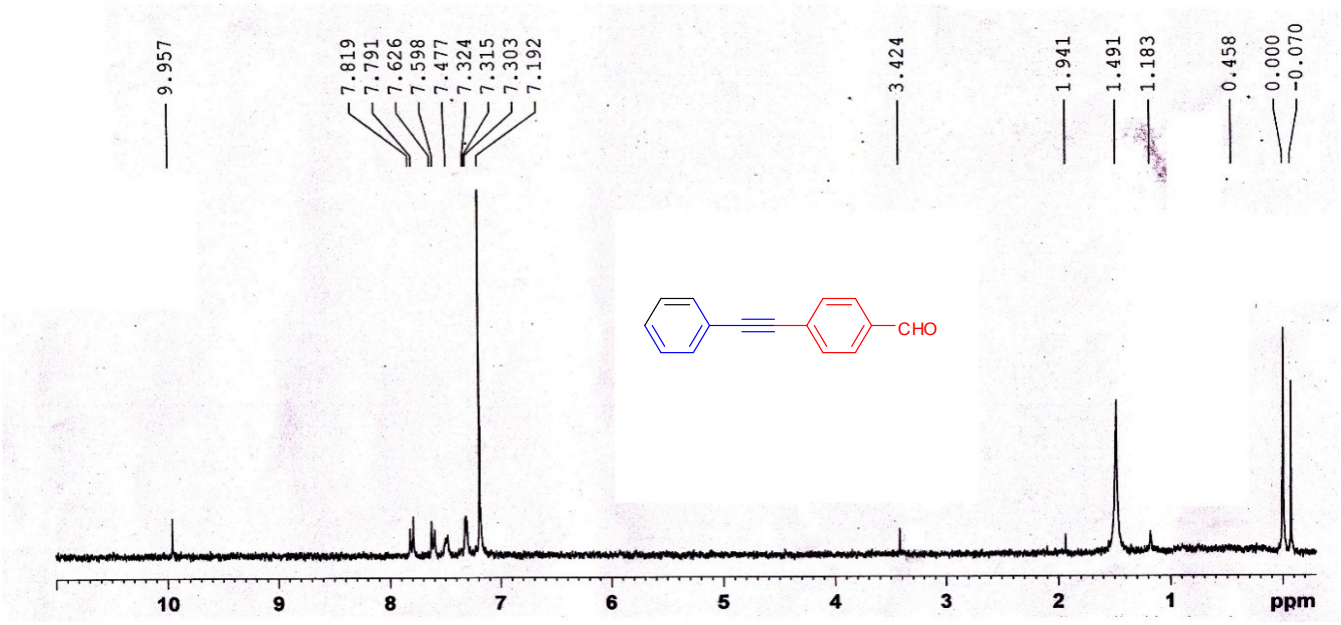
^{1}H NMR spectrum of scheme 1, entry 1 in $CDCl_3$



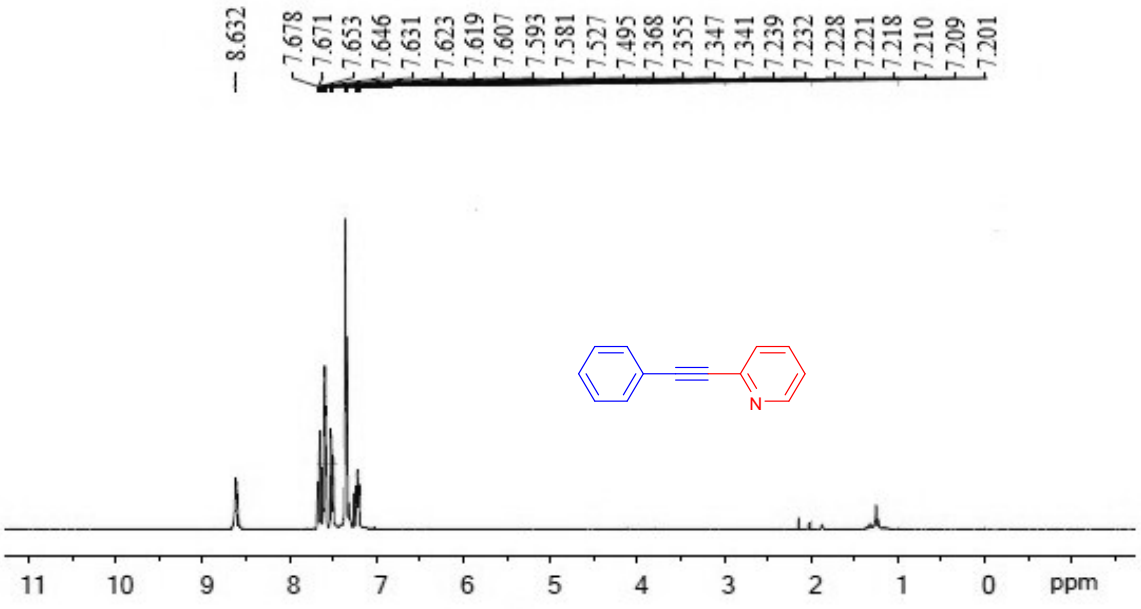
^{1}H NMR spectrum of scheme 1, entry 2 in $CDCl_3$



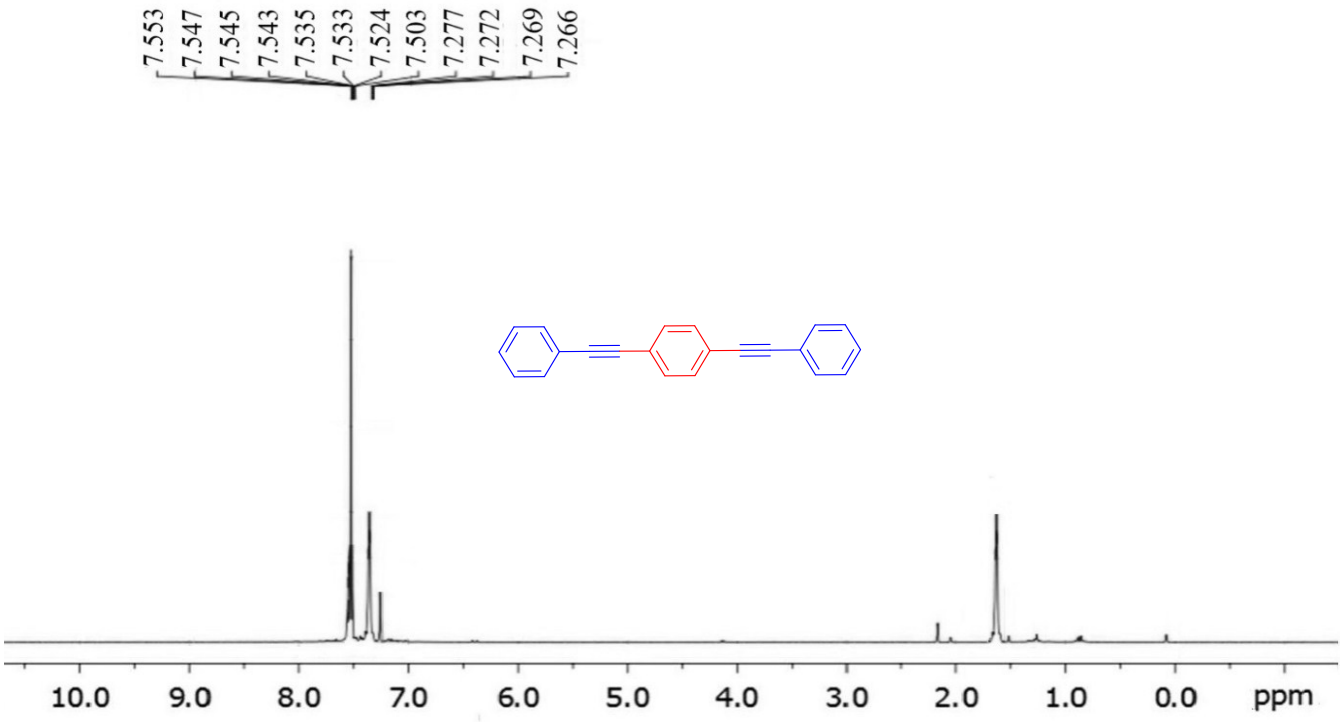
^{1}H NMR spectrum of scheme 1, entry 3 in $CDCl_3$



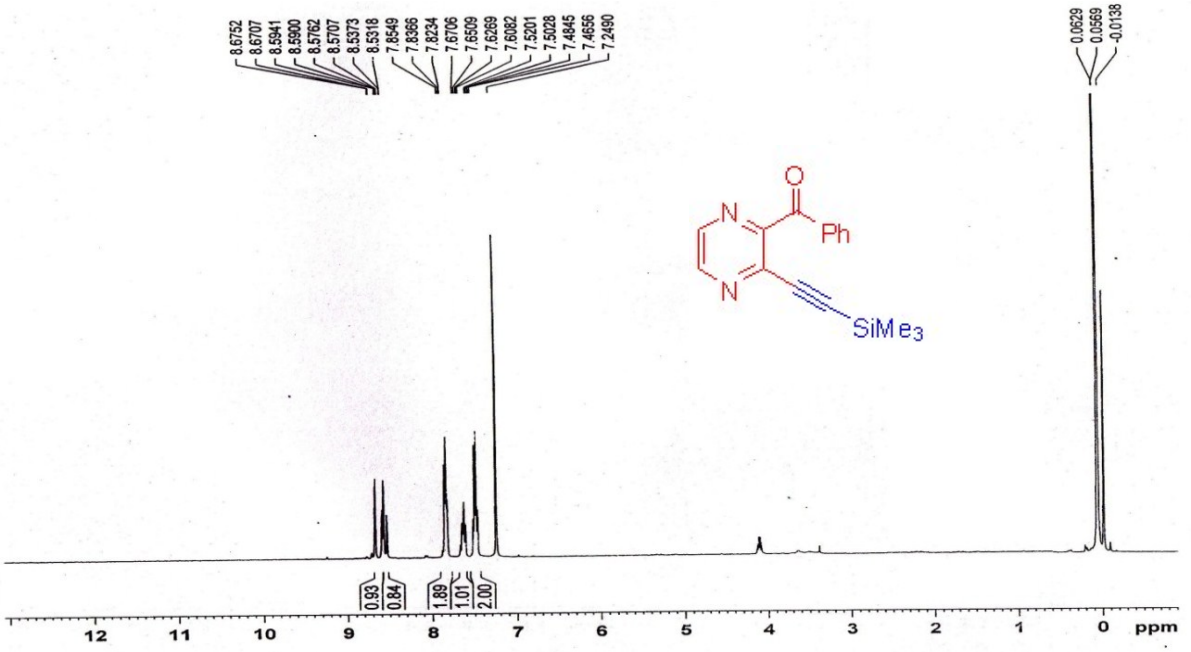
^{1}H NMR spectrum of scheme 1, entry 4 in $CDCl_3$



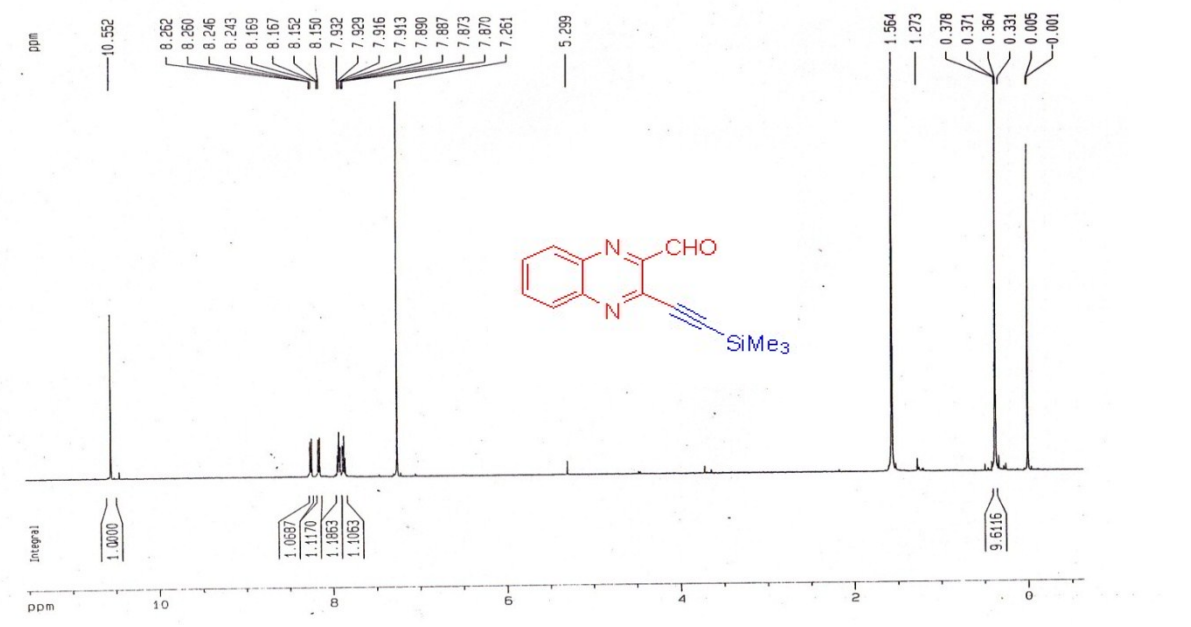
^{1}H NMR spectrum of scheme 1, entry 5 in $CDCl_3$



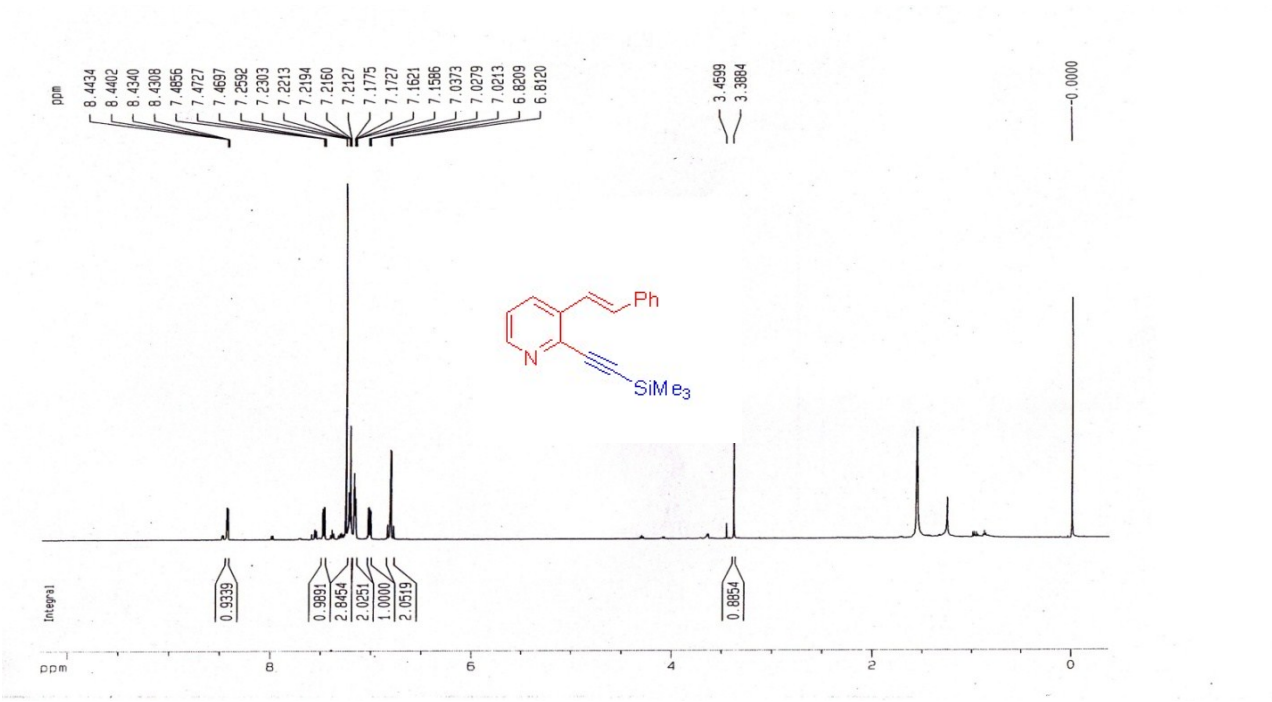
^{1}H NMR spectrum of scheme 1, entry 6 in $CDCl_3$



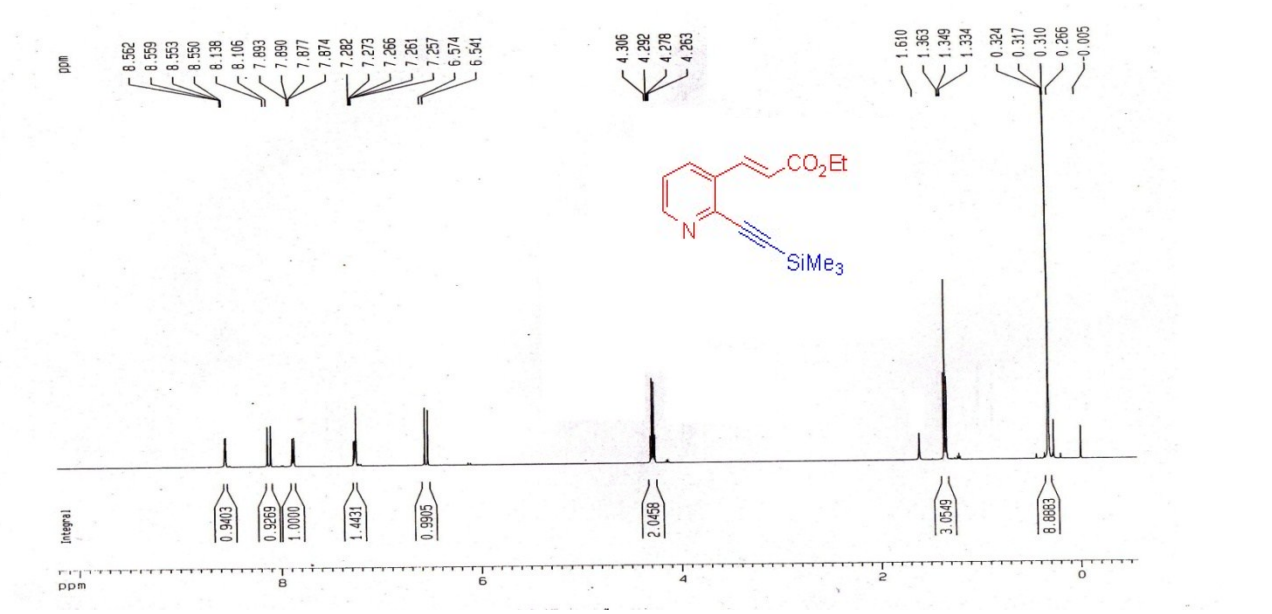
^{1}H NMR spectrum of scheme 2, entry 1 in $CDCl_3$



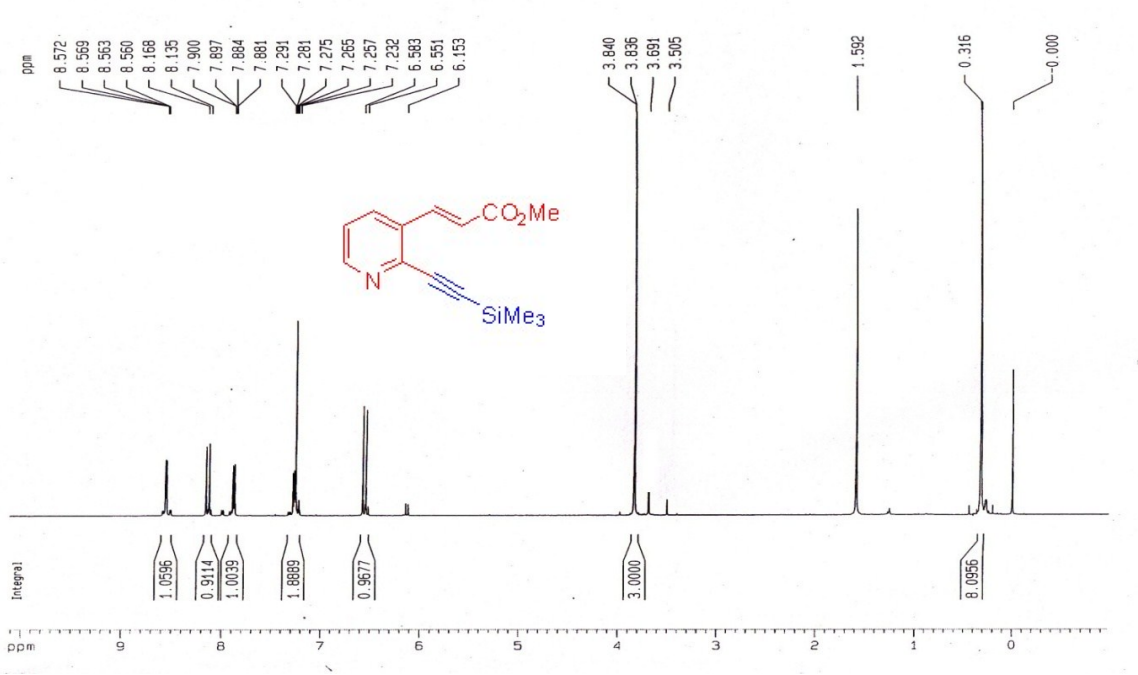
^{1}H NMR spectrum of scheme 2, entry 2 in $CDCl_3$



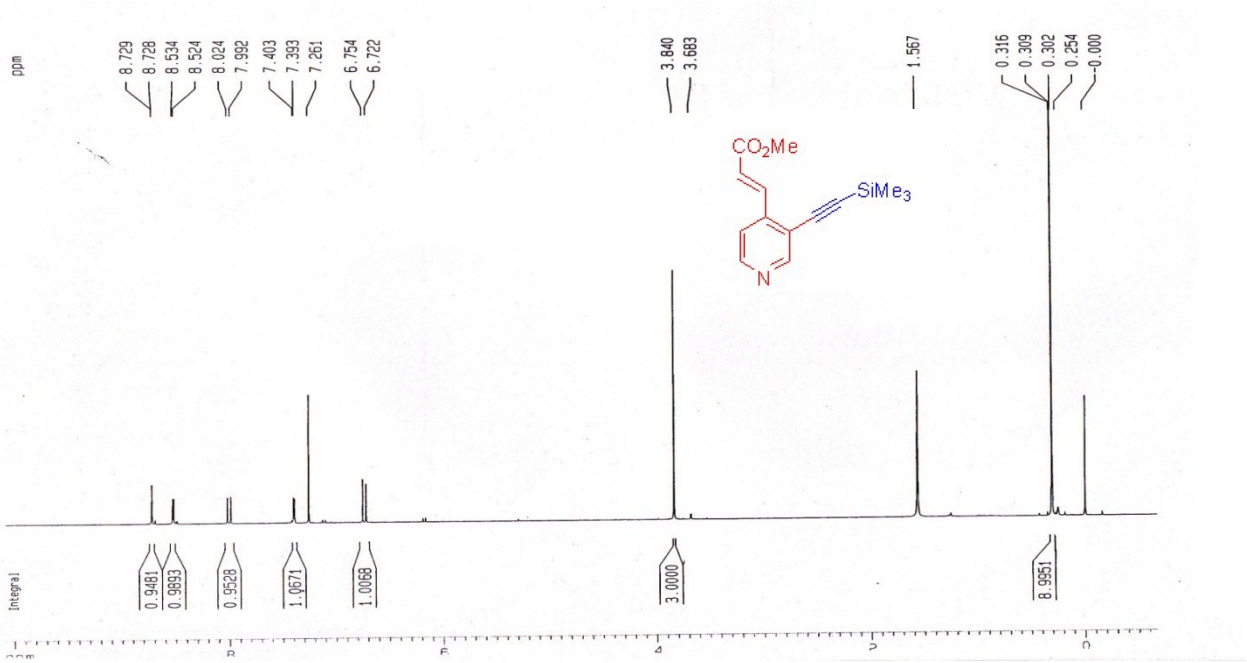
^{1}H NMR spectrum of scheme 2, entry 3 in $CDCl_3$



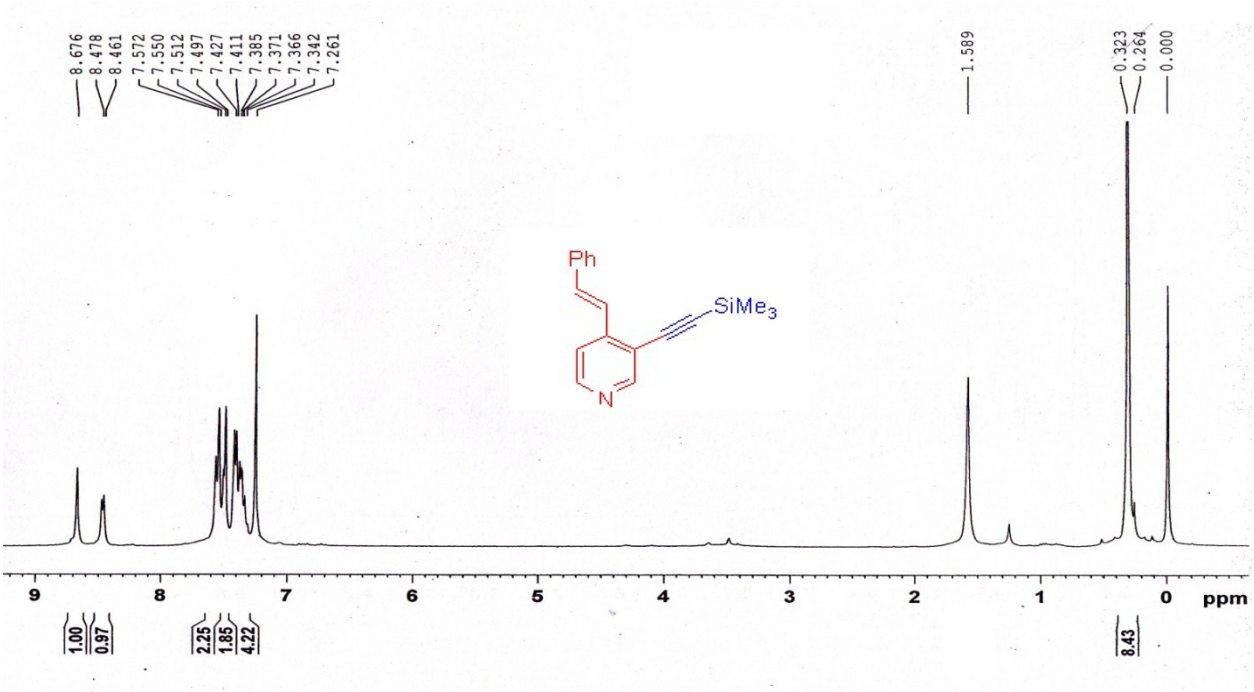
^{1}H NMR spectrum of scheme 2, entry 4 in $CDCl_3$



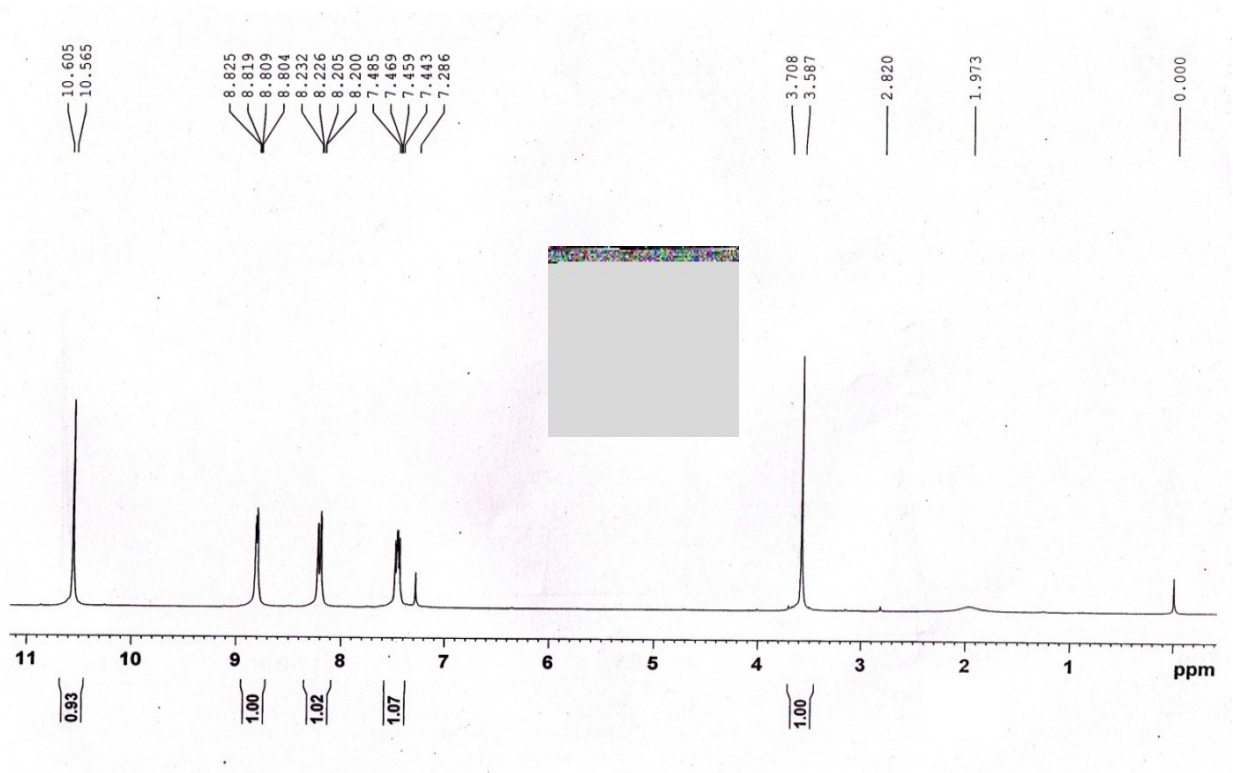
^{1}H NMR spectrum of scheme 2, entry 5 in $CDCl_3$



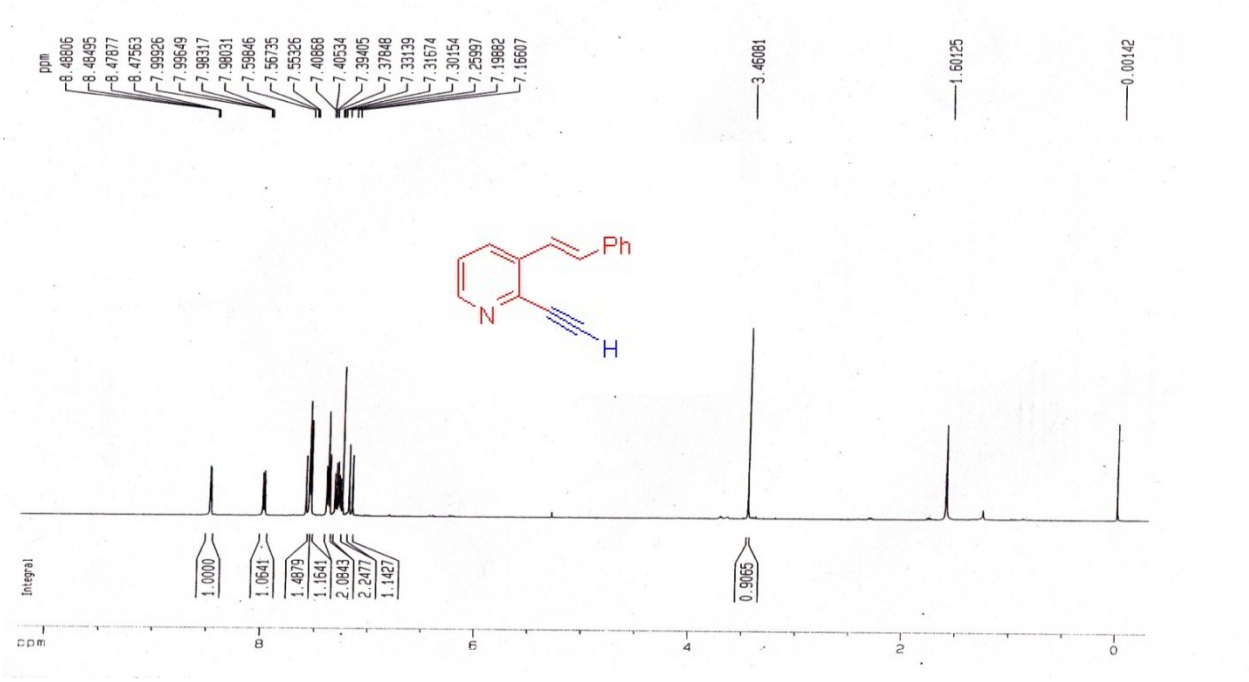
^{1}H NMR spectrum of scheme 2, entry 6 in $CDCl_3$



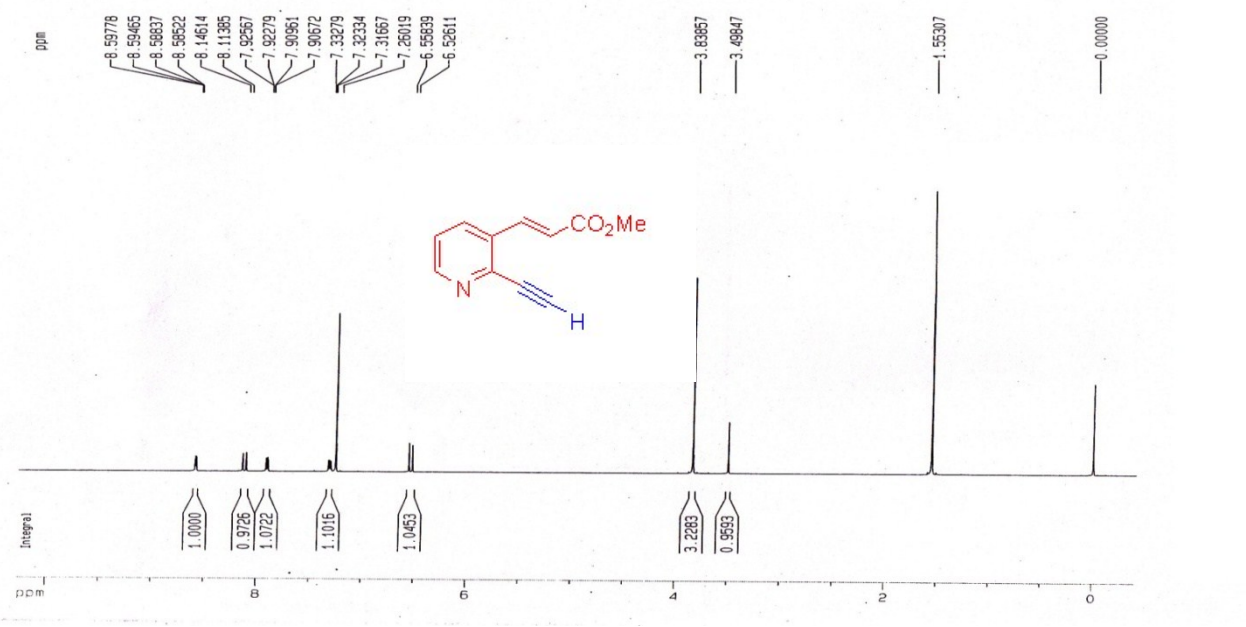
^{1}H NMR spectrum of scheme 2, entry 7 in $CDCl_3$



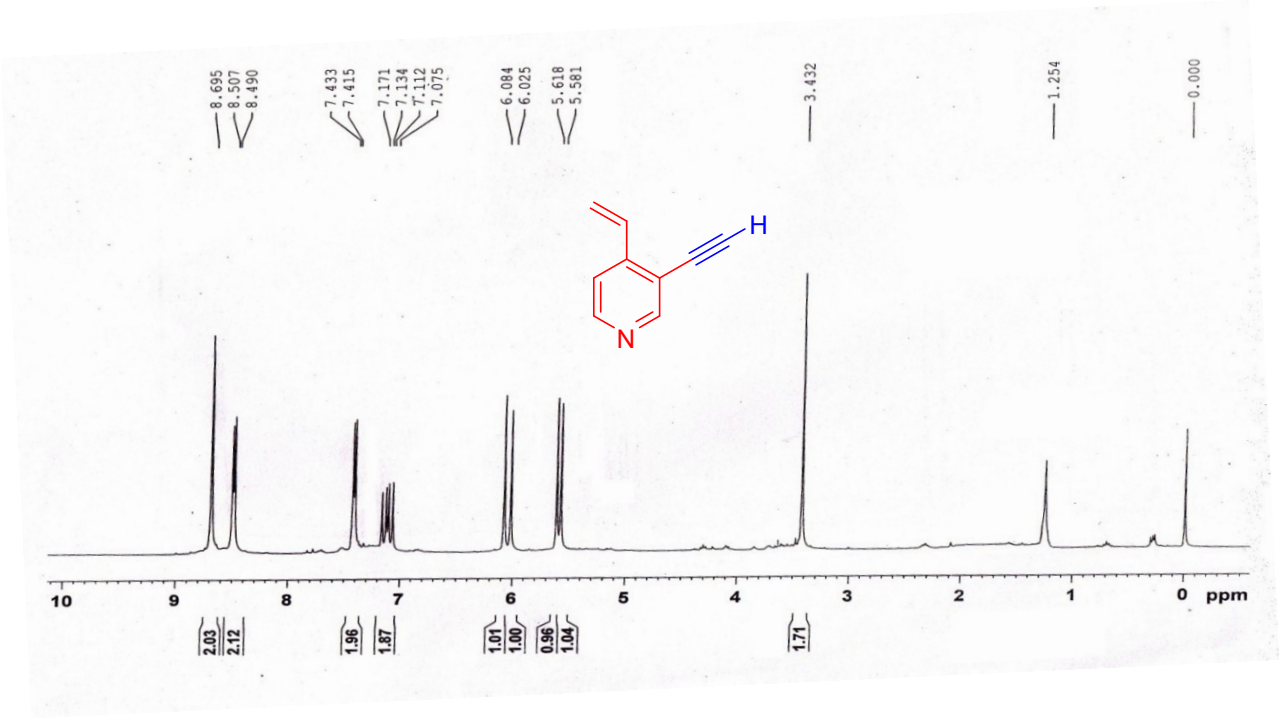
^{1}H NMR spectrum of scheme 3, entry 1 in $CDCl_3$



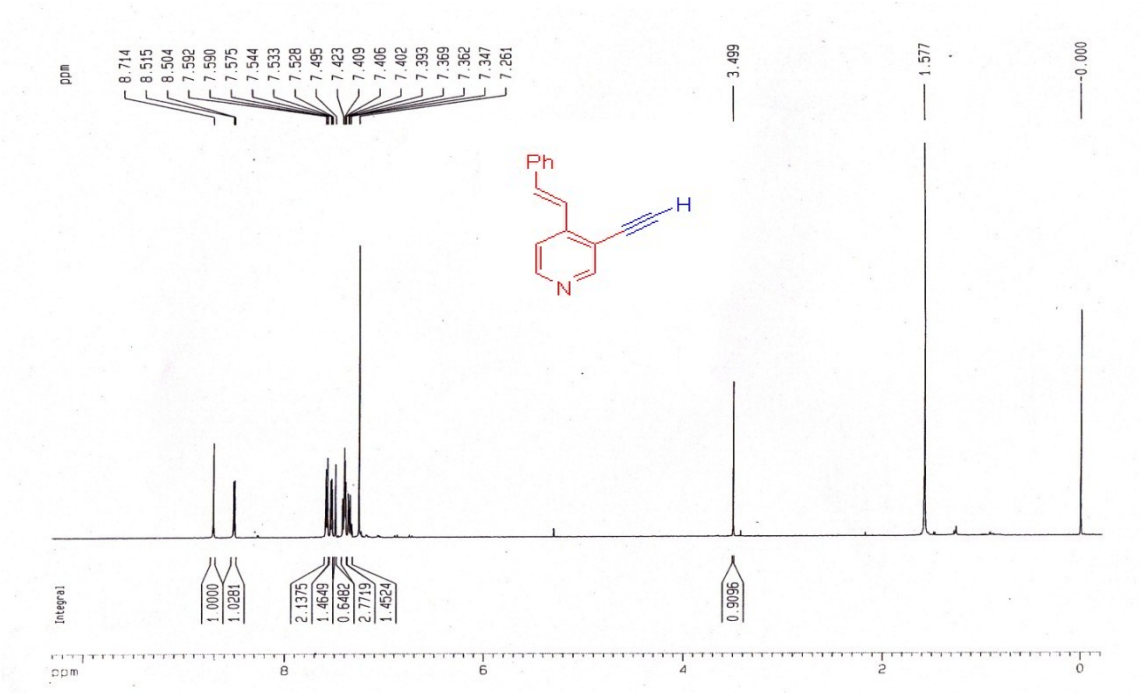
^{1}H NMR spectrum of scheme 3, entry 2 in $CDCl_3$



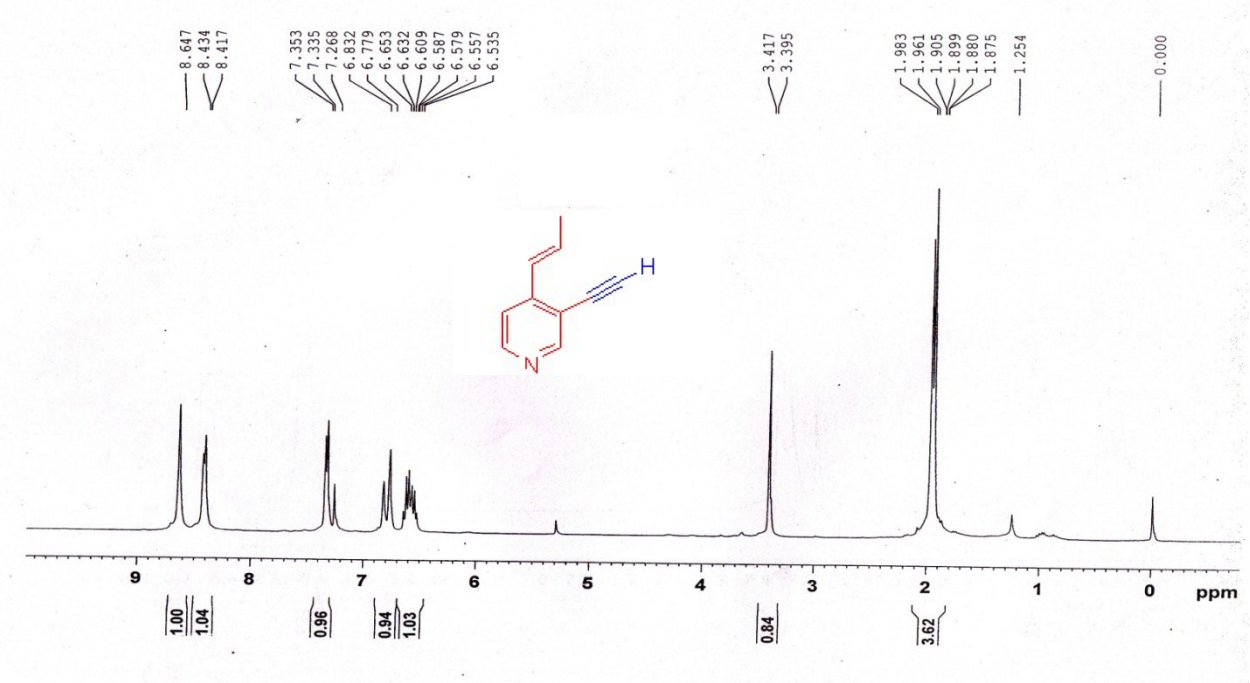
^{1}H NMR spectrum of scheme 3, entry 3 in $CDCl_3$



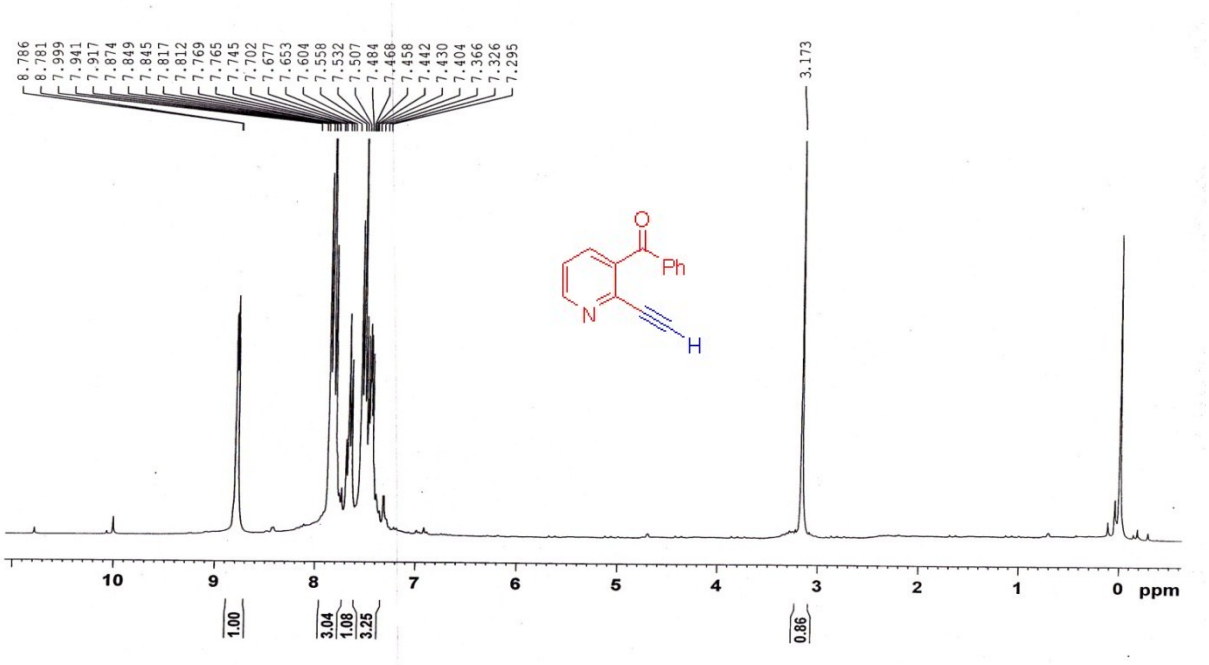
[1]H NMR spectrum of scheme 3, entry 4 in $CDCl_3$



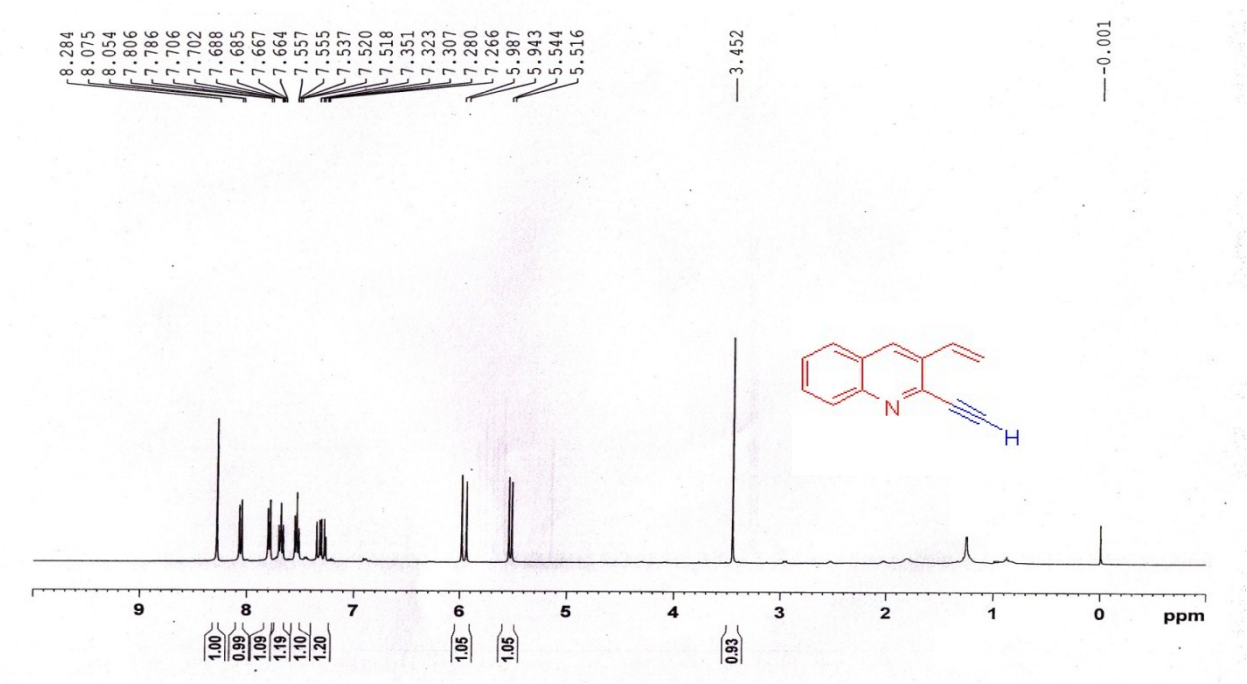
[1]H NMR spectrum of scheme 3, entry 5 in $CDCl_3$



^{1}H NMR spectrum of scheme 3, entry 6 in $CDCl_3$



^{1}H NMR spectrum of scheme 3, entry 7 in $CDCl_3$



^{1}H NMR spectrum of scheme 3, entry 8 in $CDCl_3$