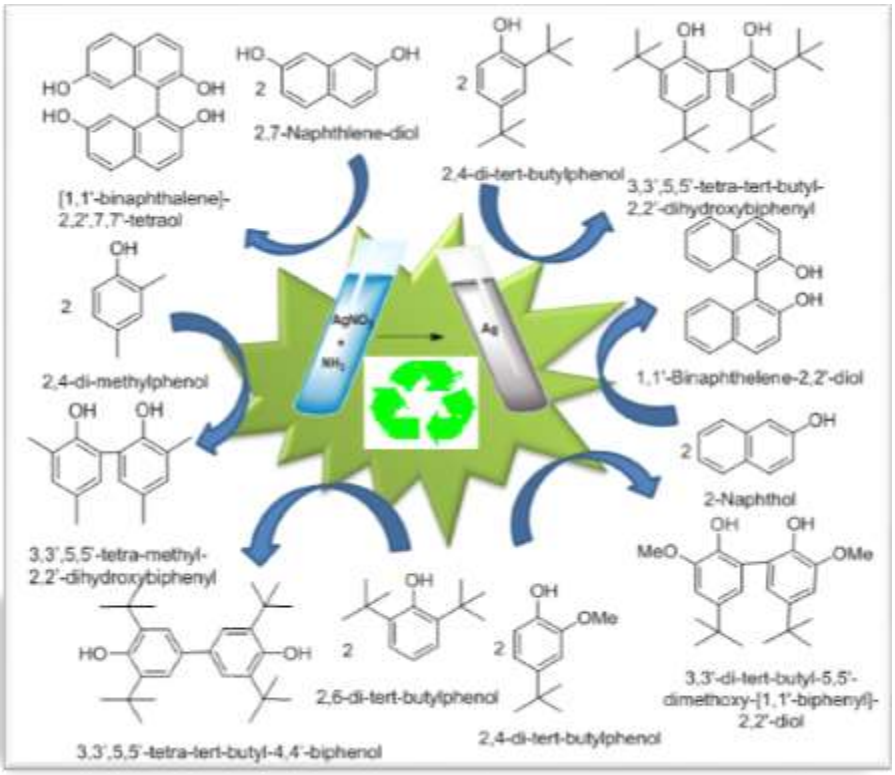
Chapter 2. C-C Oxidative Homo-Coupling of Phenols and Naphthol derivatives



Abstract

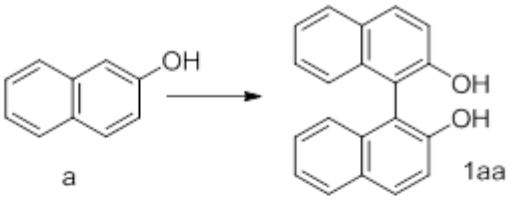
In this chapter, the Tollens' reagent or silver ammine complex has been explored for effective C-C oxidative coupling of phenol and naphthol derivatives. Systematic optimization of the reaction was carried out and especially for 2-naphthol. Total eight examples of phenol and naphthol derivatives reveal the scope and efficiency of this reagent. In this process, ten C-C coupled bi-phenol and bi-naphthol were obtained with good yields (up to 92%). This methodology when employed on a gram-scale yielded 63% BINOL. More importantly, the progress of the reaction happens with the distinct change from homogeneous to heterogeneous medium with clean isolation of biphenols and recyclability of silver in quantitative yields. A detailed study of recycling (above 95% even up to 5^{th} cycle) and reuse of 'silver' along with its quantification has been carried out, can be correlated to catalyst.

2.1 Introduction to the C-C oxidative coupling of phenol

To explore Tollens' reagent, the reactions of phenol derivatives were carried out which resulted in C-C oxidative coupled product formation. In this chapter homo-coupling of phenols and naphthol derivatives were studied.

The **C-C oxidative coupling** reactions are of important in organic chemistry for several years. The C-C oxidative coupling of phenol and Naphthol derivatives results in the biphenol or binaphthol, respectively. Biphenol and its derivatives contain C_1 or C_2 symmetry and are recognized as a structural building block of various natural products.[1,2] Derivatives of Biphenol and binaphthol have been widely studied to develop various ligands and transition metal complexes.[3] These compounds have been evolved as a versatile chiral auxiliary in asymmetric transformations and material preparation.[1,2,4–8] Biphenol derivatives have been developed as a fluorescent sensors.[9,10] Recently, BINOL finds application as a basic unit of nano-motor.[11]

Due to great scientific interest, numerous reports and extensive studies are going on for the development of C-C oxidative coupling reactions of phenol. In the routine laboratory practices, $FeCl_3$ is used, which was reported in 1870.[12,13] Various authors attempted C-C oxidative coupling of phenols using transition metal salts and their complexes such as copper[14–19], manganese[20–22], vanadium[23–25], aluminum[13,26], and titanium.[27,28] Apart from these $K_3[Fe(CN)_6]$[29], $K_2S_2O_8$ [30], peroxide[31], sodium hypochlorite[32] mediated reactions were also reported. Some reported reagents for C-C oxidative coupling of phenol and 2-naphthols in literature are shown in Figure F2.1.1. Most of these organic reaction methods are difficult to conduct, require harsh conditions, and form stoichiometric metal waste.



Reagent	mole eq.	conditions	yield
$FeCl_3$	2	NaCl, H_2O, reflux, 2-24 hr	87%
Cu(II) complex	1	H_2O, RT, N_2, 20 r	70%
Mn acetate	1	CH_3OH, N_2, reflux, 5 hr	60-69%
VCl_4	1	H_2O, RT, 42 hr	30%
$AlCl_3$	3.5	H_2O, RT, 100 hr	60%
$K_2S_2O_8$	2	CF_3COOH, RT, 16 hr	80%
$TiCl_4$	1	CH_3NO_2, Ar atm, 5**°C**, 4.5 hr	60%
$FeCl_3$	0.2	microwave,700 W, 20 minutes	90%
MnO_2	1	MDC irradition light 60W, 12hr	67%
$[Ag(NH_3)_2]^+$	**1**	**ethanol, RT, 44 hr**	**90%**

Figure F2.1.1: C-C oxidative coupling of 2-naphthol using reported reagents and Tollens' reagent

The C-C oxidative coupling reaction catalyzed by salts and complexes of iron[33–35], copper[36–41], functionalized graphite[42–44], ruthenium[45–48], palladium[49], and vanadium[50] were reported. This strategy has helped to a large extent to restrict the metal content in the reaction/industrial waste (effluent treatment) and hence improving the overall economy indeed.[8] The critical challenges encountered in catalytic reactions are regeneration or reactivation of catalyst after the completion of the reaction and recyclability of the catalyst.

The oxidation potential of silver ammine complex matching with an oxidation potential of phenols, as mentioned in chapter 1, therefore, Tollens' test on 2-naphthol has been carried out. To our surprise, 2-naphthol shown positive Tollens' test means, $[Ag(NH_3)_2]^+$ gets reduced to Ag^0 and forms silver-mirror on the walls of a test tube. We later observed that it is reported in the literature[51], but without validation of the product, BINOL formation. This test influenced us to study the silver ammine complex for the C-C oxidative coupling reaction of different derivatives of phenols and explore its catalytic reuse.

2.2 Present Strategy

(I) To analyze and understand the reaction between Tollens' reagent and 2-Naphthol.

(2) To increase the scope of this reaction, by investigating different phenol and naphthol derivatives (a total of eight were studied). The C-C Coupled products were isolated and purified by column chromatography. The products were then identified initially using melting point and then by FT-NMR (^{1}H and ^{13}C), and FT-IR spectroscopy, GC-mass-spectrometry (GC-MS and ESI-MS), and single-crystal X-ray diffraction analysis.

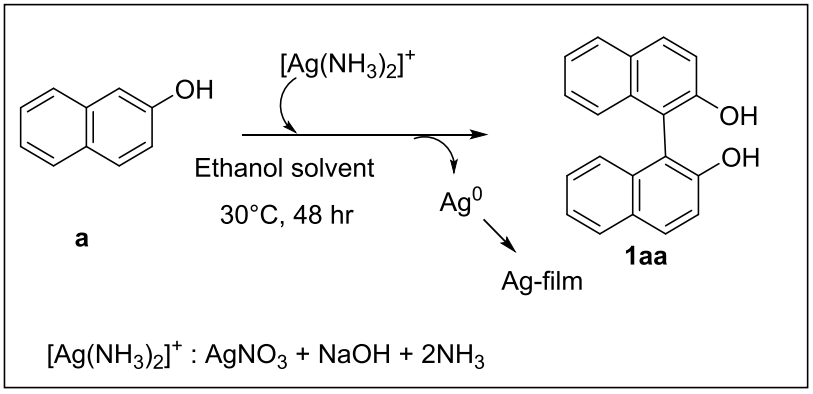
(II) Optimization of coupling reaction condition and propose reaction mechanism.

(III) To explore catalytic reuse of Silver. Developing strategy for quantification and recovery.

2.3 Result and Discussion

The Tollens' test of 2-naphthol was carried out using scheme S2.3.1, which resulted in the silver mirror formation on the walls of the test tube (Refer to section 2.5.3.1 for detailed experimental procedure). The progress of the reaction was monitored using TLC separation. The conversion of silver(*I*) was also monitored by precipitating it as for silver chloride by the addition of a small amount of hydrochloric acid. The reaction mixture was treated with ethyl acetate to separate organics and then subjected to column chromatography for further purification. After analyzing the product with FT-NMR (^{1}H and ^{13}C) (F2.6.1), FT-IR spectroscopy (F2.6.23), and mass spectrometry analysis (F2.6.12), C-C coupled product BINOL (1aa) formation was confirmed.[52] The spectral data are shown in section 2.5.6.

Scheme S2.3.1: General scheme for the reaction of 2-Naphthol (a) with Tollens' Reagent

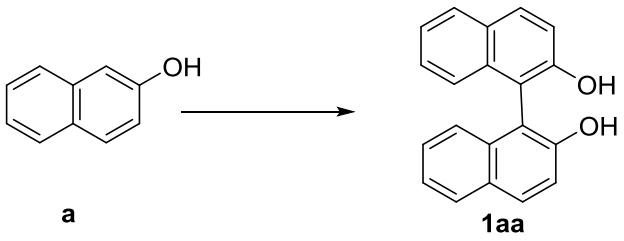


Optimization of reaction condition: Reactions were carried out by systematically modifying reaction conditions as shown in scheme S2.3.2. (Refer to section 2.5.3 for detailed experimental procedure).

- The Tollens' reaction of 2-naphthol (S2.3.2 1 and 2) was carried out at 30°C, these are required 44-48 hr for maximum conversion and resulted in 84% column purified 1aa. Whereas reaction carried out at 70°C temperature completed in 1 hr with around 73% 1aa formation.
- The reactions (S2.3.2 3 to 8) were carried out with only silver nitrate, sodium hydroxide-ammonia mixture, and silver nitrate-sodium hydroxide mixture. These reaction conditions do not oxidize 2-naphthol to 1aa; therefore, no conversion was observed.
- The coupling reactions of 2-naphthol carried out using silver ammine complex prepared by dissolving silver nitrate in ammonia (by ignoring NaOH) resulted in a comparatively higher yield of 75-93% of 1aa (S2.3.2 9 and 10).

- The yield of 1aa was not affected by the addition of excess silver ammine complex (S2.3.2 11 and 12), but a less than 50% yield was observed using reagent in 0.5 mole-equivalent (S2.3.2 13 and 14). Thus, depicting the need for one equivalent of silver ammine complex for complete conversion.

Scheme S2.3.2: Optimization of the reaction conditions for C-C oxidative coupling of 2-naphthol



a 1aa

	Reagent	temp.	time	isolated yield
1	$AgNO_3$ + NaOH + NH_3	30°C	48 hour	84%
2	$AgNO_3$ + NaOH + NH_3	70°C	60 min	73%
3	$AgNO_3$	30°C	24 hour	00%
4	$AgNO_3$	70°C	24 hour	00%
5	NaOH + NH_3	30°C	24 hour	00%
6	NaOH + NH_3	70°C	24 hour	00%
7	$AgNO_3$ + NaOH	30°C	24 hour	00%
8	$AgNO_3$ + NaOH	70°C	24 hour	5%
9	1 $AgNO_3$ + NH_3	30°C	48 hour	93%
10	1 $AgNO_3$ + NH_3	70°C	60 min	75%
11	2 $AgNO_3$ + NH_3	30°C	48 hour	90%
12	2 $AgNO_3$ + NH_3	70°C	60 min	70%
13	0.5 $AgNO_3$ + NH_3	30°C	48 hour	44%
14	0.5 $AgNO_3$ + NH_3	70°C	60 min	39%

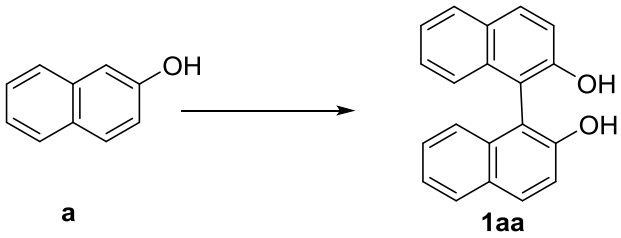
- The reaction of 2-naphthol carried out with silver ammine complex prepared by dissolving silver nitrate in ammonia (avoiding the addition of NaOH) at 30°C resulted in 93% of 1aa formation, which was the best condition (S2.3.2 9).

These experiments state silver ammine complex prepared directly by mixing silver nitrate in ammonia has advantages over standard Tollens' reagents. There are 1. Ease of reagent preparation, 2. reduced amount of byproduct formation, 3. facilitates easy workup (acidification), 4. The formation of silver oxide and hydroxides can be ignored, 5. Better yield, 6. Clean reaction and atom economy, and thus used for further study.

Effect of Temperature: Tollens' reactions of 2-naphthol were performed by heating reaction mixtures, as shown in scheme S2.3.3.

- The yields of 1aa were decreased from 93% to 58% on heating (S2.3.3 5 to 8, and 1 to 4). In addition, a decrease in the time required to complete the reaction from 48 hr to 60 minutes on heating from 30°C to 70°C, and above 70°C, the time required was similar.
- Byproduct formation was observed for the reactions carried out with heating above 70°C. However, The byproducts were not analyzed.

Scheme S2.3.3: Effect of temperature on the C-C oxidative coupling reaction of 2-naphthol



a 1aa

	Reagent	temperature	time	isolated yield
1	$AgNO_3$ + NaOH + NH_3	30°C	48 hr	84%
2	$AgNO_3$ + NaOH + NH_3	50°C	60 min	75%
3	$AgNO_3$ + NaOH + NH_3	70°C	60 min	73%
4	$AgNO_3$ + NaOH + NH_3	80°C	60 min	53%
5	$AgNO_3$ + NH_3	30°C	48 hr	93%
6	$AgNO_3$ + NH_3	50°C	60 min	77%
7	$AgNO_3$ + NH_3	70°C	60 min	75%
8	$AgNO_3$ + NH_3	80°C	60 min	58%

Effect of Solvent: The 2-naphthol and Silver amine complex reactions were also carried out by replacing ethanol with another solvent, as listed in table T2.1. 0.2 mmol silver nitrate dissolved to 0.2 ml of liq. Ammonia, and mixed to 0.2 mmol 2-naphthol dissolved in 2.0 ml of solvent, at 25°C; The time for reaction and isolated % yields of 1aa were noted in T2.1. The results show the feasibility of the C-C oxidative coupling of phenols using Tollens' reagent in a wide range of solvents. Water miscible solvents resulted in better yields due to the solubility of both reactant and reagent, but only water could not give a better result. The corresponding graph is shown in image F2.2.1. We emphasize that reagents were used on a mmol scale here; thus, solvent miscibility may give different results for large-scale reactions. The yields were not affected, by keeping the reaction mixture for a longer time (in T2.1 entry 2,3, and 4).

Table T2.1: Effect of solvent on C-C oxidative coupling reactions of 2-naphthol*

No.	Solvent	Temperature	Time	Isolated Yield of 1aa
Unit	2.0 ml	°C		%
1	Tetrachloromethane	25°C	4 day	10
2	Dichloromethane	25°C	3 hr	62
3	Tetra hydro furan	25°C	3hr	51
4	Chloroform	25°C	3 hr	50
5	Ethanol	25°C	2 day	92
6	Methanol	25°C	4 day	71
7	Acetone	25°C	4 day	22
8	Acetonitrile	25°C	4 day	20
9	Dimethylformamide	25°C	2 day	82
10	Water	25°C	4 day	43

* Reaction conditions: phenol-a (0.2 mmol) in 0.2 ml solvent + silver ammine complex (0.2 mmol silver nitrate + 0.2 ml liq. ammonia) at 25°C

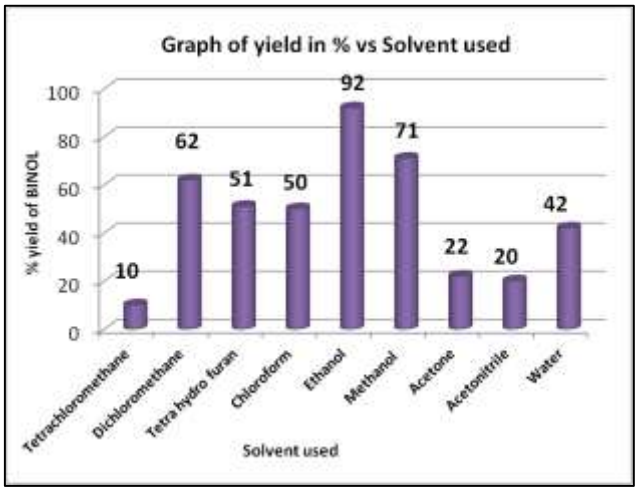
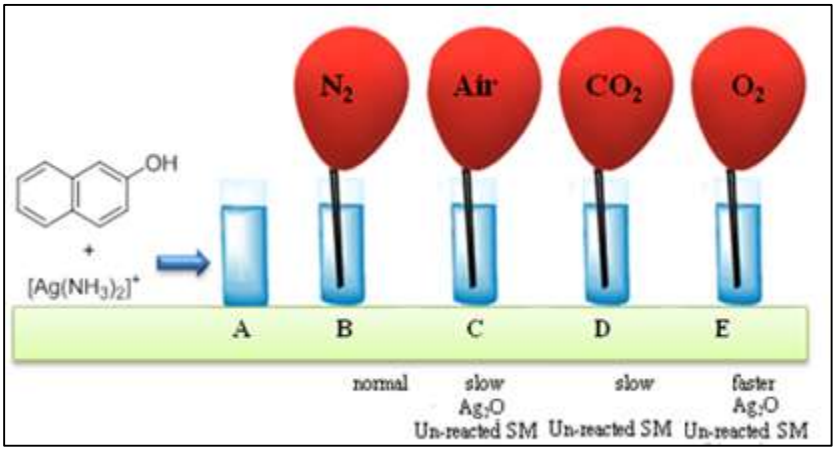


Figure F2.3.2: % Yield of 2aa obtained by varying solvents during Tollens' reaction

- On increasing the amount of solvent or diluted reaction system, the time required for complete conversion was increased. Apart from this, a decrease in the yield was also noted, probably due to the formation of byproducts from self-oxidation.

Effect of Gas Purging: The reaction of 2-naphthol was performed by continuous purging gases, as shown in Figure F2.2.3 (Refer to section 2.5.3.3 for detailed experimental procedure).

Figure F2.3.3 Effect of gas purging in Tollens' reaction (cartoon image)*;



* cartoon image of setup: rate of silver formation compare to reaction A: Ag_2O silver oxide and un-reacted starting material (SM) remained

- The reaction and silver mirror formation was not affected by purging nitrogen gas. However, on passing oxygen from the reaction mixture, silver mirror formation was observed faster.
- These reactions were carried out using heating, which resulted in by-product formation. Here the nitrogen gas purged reaction gave fewer bi-products compared to the reactions performed under air, carbon dioxide, and oxygen atmosphere.
- The reactions carried out under an oxygen atmosphere lead to the desired sole product. But, reactions under nitrogen, argon, carbon dioxide showed multiple spots on the TLC plate along with the expected product. Thus, the need for atmospheric oxygen was confirmed for this coupling reaction.

Gram-scale reaction: Gram-scale reaction of 2-naphthol performed using silver ammine complex (Refer section 2.5.3.4 for detailed experimental procedure). This reaction yielded 0.6341 g, 63.4% isolated column chromatographic 1aa.

Crystallization:

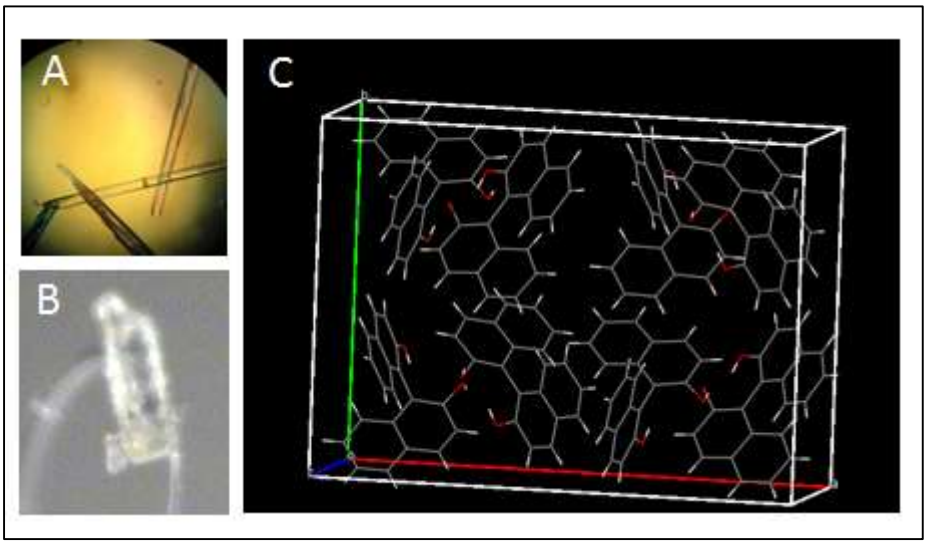


Figure F2.3.4: Photographs of 1aa: (A) and (B) Crystals in a optical microscope; (C) single-crystal unit cell

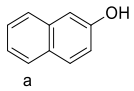
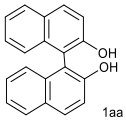
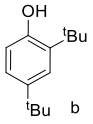
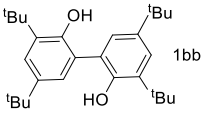
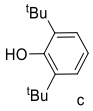
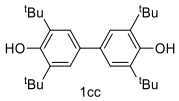
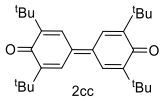
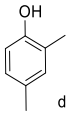
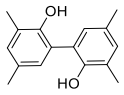
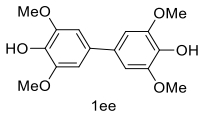
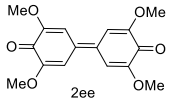
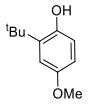
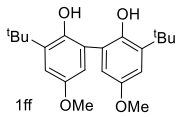
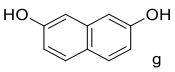
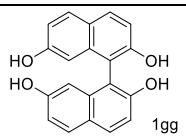
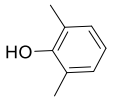
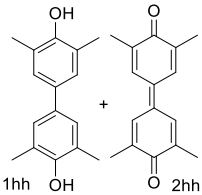
In-situ crystallization of BINOL was observed during many reactions, as shown in the experimental section 2.5.3.5. The needle shape crystals of BINOL were obtained, as shown in Figure F2.3.4. The single crystal-XRD analysis shows an orthorhombic crystal system with the Iba2 space group, as shown in section 2.5.6, similar to reported crystal data.[53] Crystals of 2-Naphthol, unreacted, were also obtained with BINOL, and these conditions were noted in the experimental section.

Scope of Reaction:

- After the standardization, the Tollens' reaction was performed on total eight derivatives of naphthol and phenol such as 2-naphthol (**a**), 2,7-dihydroxynaphthalene (**g)**, 2,4-di-*tert*-butylphenol (**b)**, 2,6-di-*tert*-butylphenol (**c**), 2,4-di-methylphenol (**d**), 2,6-di-methoxyphenol (**e**), 2-*tert*-butyl-4-methoxyphenol (**f**), Naphthalene-2,7-diol (**g**) and 2,6-dimethylphenol (**h**). All chemicals were taken in exact *stoichiometric* quantities as per the redox equation as listed in table T2.3 (Refer section 2.5.4 for detailed experimental procedure). All the products were isolated using column chromatography and completely characterized. Reaction of silver ammine complex and phenol derivatives a-h resulted into (1,1'-binaphthalene)-2,2'-diol (1aa), 3,3',5,5'-tetra-*tert*-butyl-(1,1'-biphenyl)-2,2'-diol (1bb), 3,3',5,5'-tetra-*tert*-butyl-(1,1'-biphenyl)-4,4'-diol (1cc), 3,3',5,5'-tetramethyl-(1,1'-biphenyl)-2,2'-diol (1dd), 3,3',5,5'-tetramethoxy-(1,1'-biphenyl)-4,4'-diol (1ee), 3,3'-di-*tert*-butyl-5,5'-dimethoxy-(1,1'-biphenyl)-2,2'-diol (1ff), (1,1'-binaphthalene)-2,2',7,7'-tetraol (1gg) and 3,3',5,5'-tetramethyl-(1,1'-biphenyl)-4,4'-diol (1hh) formation respectively. All the products were well characterized by FT-NMR (^{1}H and ^{13}C), FT-IR spectroscopy, and mass spectrometric analysis, as shown in section 2.5.6, and the spectral data are shown in section 2.6 from Figures F2.6.1 to F2.6.33.
- The *ortho-ortho* homo-coupling products were observed mainly in the case of biphenyl formation. When *tert*-butyl/methoxy/methyl groups substituted the *ortho* positions, then *para-para* homo-coupling was observed.
- The addition of a quantitative amount of NaOH in the *para-para* coupling reaction led to substantial quinone formation.
- 1cc rapidly converts to 2cc in quinine form if kept in basic conditions in the presence of open-air, and thus the reaction of phenol-c carried out at 50°C resulted in the 3,3',5,5'-Tetra-*tert*-butyl-4,4'-diphenoquinone (2cc) formation.
- 1ee rapidly converts to 2ee in quinine form if kept in basic conditions in the presence of open-air, and thus the reaction of e carried out at 70°C resulted in 3,3',5,5'-Tetra-*tert*-butyl-4,4'-diphenoquinone (2ee) formation.
- Reaction of phenol h results into the 3,3',5,5'-tetramethyl-(1,1'-biphenyl)-4,4'-diol (1hh) formation along with 3,3',5,5'-tetramethyl-(1,1'-biphenyl)-diphenoquinone (2hh) and polymeric products if kept it for longer time in reaction mixture. As shown in mass spectra in Figures F2.6.21 and F2.6.22.

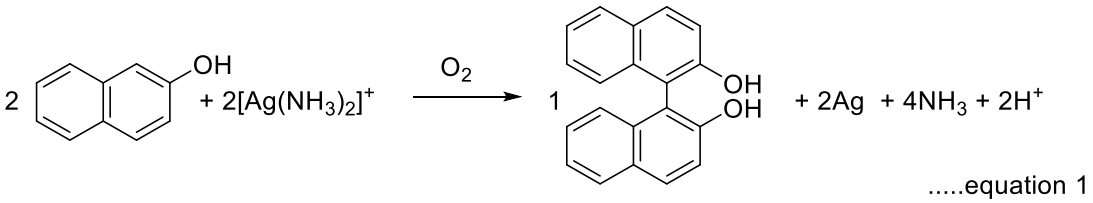
- 93% 1bb product was obtained by gram-scale C-C oxidative coupling reaction of phenol-b with silver ammine complex (at room temperature).

Table T2.2 C-C oxidative coupling of phenol and naphthol derivatives*.

Substrate	Product	Reagent[(I)]	Solvent[(II)]	T[(III)]	Time [(IV)]	yield[(V)]
 a	 1aa	$AgNO_3$+NH_3	Ethanol	30°C	44 hr	92%
		$AgNO_3$+NH_3	Ethanol	70°C	60 min	75%
		$AgNO_3$+NaOH+NH_3	Ethanol	30°C	44 hr	84%
		0.5$AgNO_3$ +NH_3	Ethanol	70°C	60 min	39%
		2 $AgNO_3$+NH_3	Ethanol	70°C	60 min	39%
 b	 1bb	$AgNO_3$+NH_3	Ethanol	30°C	60 min	95%
		$AgNO_3$+NH_3	Ethanol	70°C	5 min	82%
		$AgNO_3$+NH_3	Ethanol	50°C	5 min	79%
 c	 1cc	$AgNO_3$+NH_3	Ethanol	30°C	5 min	70%
	 2cc	$AgNO_3$+NaOH+NH_3	Ethanol	50°C	5 min	78%
 d	 1dd	$AgNO_3$+NH_3	Ethanol	30°C	30 min	85 %
		$AgNO_3$+NaOH+NH_3	Ethanol	30°C	5 min	83%
		$AgNO_3$+NH_3	Ethanol	50°C	5 min	79%
 e	 1ee	$AgNO_3$+NH_3	Ethanol	30°C	5 min	70%
	 2ee	$AgNO_3$+NaOH+NH_3	Ethanol	70°C	5 min	25%
 f	 1ff	$AgNO_3$+NH_3	H_2O	30°C	5 min	74%
 g	 1gg	$AgNO_3$ +NH_3	Ethanol	30°C	72 hr	62[a] %
		$AgNO_3$+NH_3	Ethanol	70°C	3 hr	51%
 h	 1hh 2hh	$AgNO_3$+NH_3	Ethanol	30°C	5 min	--

*Reaction conditions: Phenol (0.2 mmol) [(I)] Tollens' reagent : $AgNO_3$ (1 equivalent) + NaOH solution (0.2 mmol, 0.1 N, 0.2 ml) + liquor ammonia (0.2 ml); [(II)]Absolute ethanol or water solvent (0.5 ml); [(III)]temperature and [(IV)]time ; [(V)] isolated column purified yield in %.

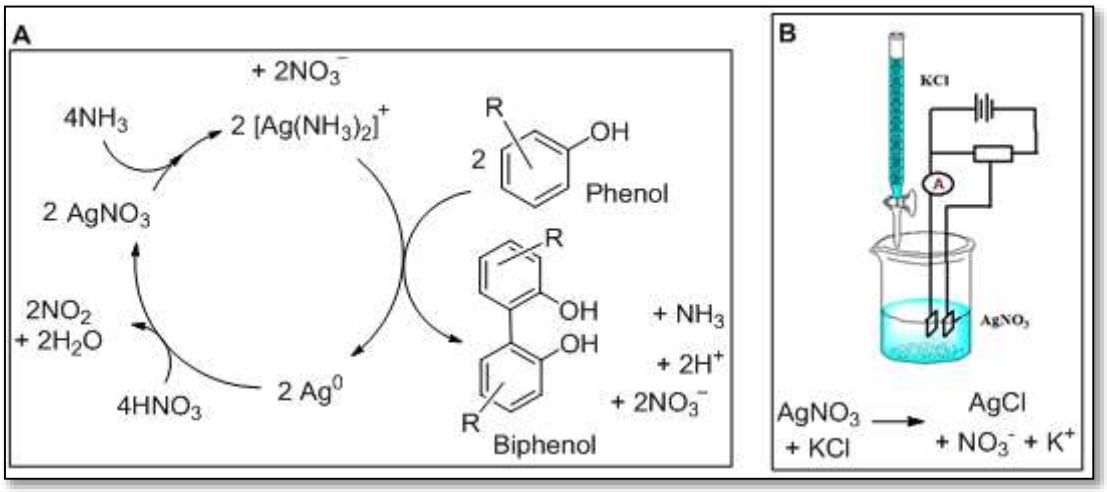
Recyclability of Tollens' reagent:



.....equation 1

One can propose a stoichiometric equation for C-C oxidative coupling of 2-Naphthol (a) as shown in equ. 1. This indicates the reaction generates quantitative waste. During the reaction, the homogenous behavior of the silver ammine complex changes to heterogeneous metallic silver form with the product formation. Since the silver was completely isolable, it was recovered and reused as shown in scheme 2.3.4.

Scheme S2.3.4: Recycling of silver in C-C oxidative coupling of phenol derivatives*



* (A) General scheme for recycling of silver in C-C oxidative coupling reaction; (B) Cartoon image showing the setup of *conductometric* analysis

Recycling of silver:

The silver (Ag^0) formed after the C-C oxidative coupling of phenol-b was washed with water and organic solvents to remove impurities. Silver was treated with concentrated nitric acid to form silver nitrate. This recovered silver nitrate was treated with ammonia and used as a reagent for the next coupling reaction. Thus recovered silver nitrate was quantified using *conductometric* titration by titrating against standard 0.02 N KCl solution. Thus, Ag^+ can be reused as shown in table T2.3 (Refer to section 2.5.6 for detailed experimental procedure). Here the 0^{th} reuse or recycle represents fresh silver ammine complex used, and 1^{st} recycle/reuse presents recovered silver obtained from the previous cycle is used for 1^{st} recycling experiment, and so on.

Table T2.3 Recycling experiment and reuse of silver for C-C oxidative coupling of Phenol-b*

No. of recycle	**$AgNO_3$ (I)**	**Conc. HNO_3 (II)**	**Water (III)**	**liq. NH_3 (IV)**	**Phenol-b (V)**	**ethanol (VI)**	**Temperature (VII)**	**Time (IIX)**	**Yield (IX)**	**Recovered Ag (X)**
	mmol	ml	Ml	ml	mmol	ml	°C	Min	%	%
0	0.2	-	-	0.3	0.2	0.2	35°C	60	95	98.9
1	-	0.2	0.1	0.5	0.2	0.2	35°C	60	94	98.9
2	-	0.2	0.1	0.5	0.2	0.2	35°C	60	94	98.9
3	-	0.2	0.1	0.5	0.2	0.2	35°C	60	90	97.9
4	-	0.2	0.1	0.5	0.2	0.2	35°C	70	88	96.2
5	-	0.2	0.1	0.5	0.2	0.2	35°C	75	76	95.9
0	0.2	-	-	0.3	0.2	0.2	70°C	7	95	98.9
1	-	0.2	0.1	0.5	0.2	0.2	70°C	7	95	98.9
2	-	0.2	0.1	0.5	0.2	0.2	70°C	10	93	97.9
3	-	0.2	0.1	0.5	0.2	0.2	70°C	10	90	97.9
4	-	0.2	0.1	0.5	0.2	0.2	70°C	10	88	96.7
5	-	0.2	0.1	0.5	0.2	0.2	70°C	10	70	95.9

*reaction conditions (I-IIX): silver ammine complex: (I) fresh silver nitrate,(or recovered Ag + (II) conc. HNO_3) + (III) water + (IV) liquor ammonia; (V)phenol-b in (VI)ethanol; mix silver ammine complex and phenol solution for (VII)Time and (IIX) temperature.; (IX-X) After the reaction (X) recovered silver after each cycles measured using *conductometric* titration, and (IX) isolated yield of 1bb.

Recycling, recovery, and reuse of silver salt: The recycling reactions were performed for phenol-a, b, c, d, and e, as per the general procedure; corresponding results are noted in Tables 2.4 and 2.5. Up to 95% reagent was recovered after the 5^{th} cycle of use, as shown in Figure F2.3.5. The Total conversion of the silver complex to silver was observed, but yields of isolated bisphenols were less, as shown in table T2.5, which may be due to the over oxidized by-product formation of 1aa, and 1dd (2cc, and 2ee quinone).

Table T2.4: Recovered silver from recycling experiments from C-C oxidative coupling reaction of phenol (a-e) derivatives after reuse

	Recovered silver from the reaction of phenol derivatives				
Phenol / No. of cycle	A	c	e	b	d
0th reuse	98.9%	98.9%	98.9%	98.9%	98.9%
1st reuse	98.9%	98.9%	98.9%	98.9%	98.9%
2nd reuse	98.9%	98.9%	97.9%	98.9%	98.2%
3rd reuse	97.9%	97.9%	97.9%	97.9%	97.9%
4th reuse	96.9%	96.9%	96.9%	96.2%	97.9%
5th reuse	95.9%	95.9%	95.9%	95.9%	96.9%

Table T2.5: Yield of the isolated coupled product (1aa–1ee) obtained from the reaction of phenol (a-e) using recycling experiments

	% yield of products isolated from recycling experiments				
Phenol product / No. of cycle	1aa	1cc	1ee	1bb	1dd
0th reuse	73%	89%	72%	95%	79%
1st reuse	70%	85%	70%	94%	76%
2nd reuse	68%	82%	68%	94%	68%
3rd reuse	66%	75%	60%	90%	60%
4th reuse	60%	72%	58%	88%	58%
5th reuse	52%	69%	50%	76%	55%

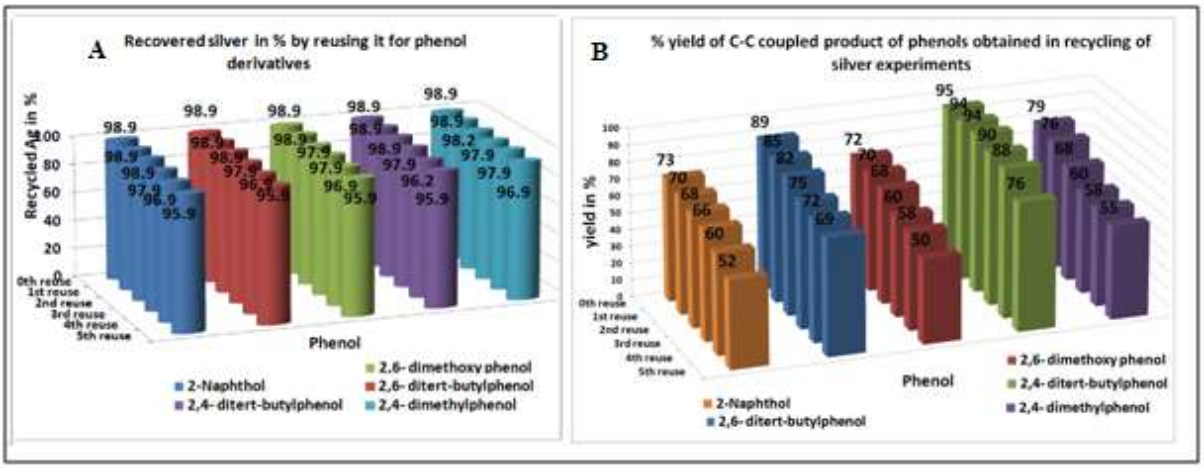
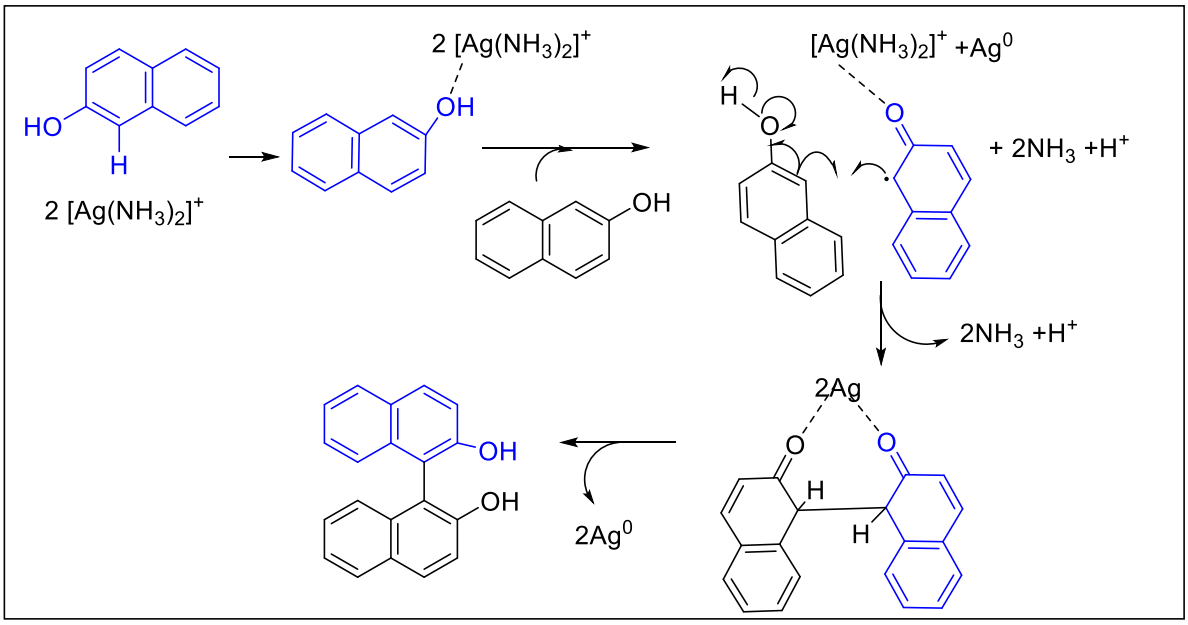


Figure F2.3: Results of recycling of silver*

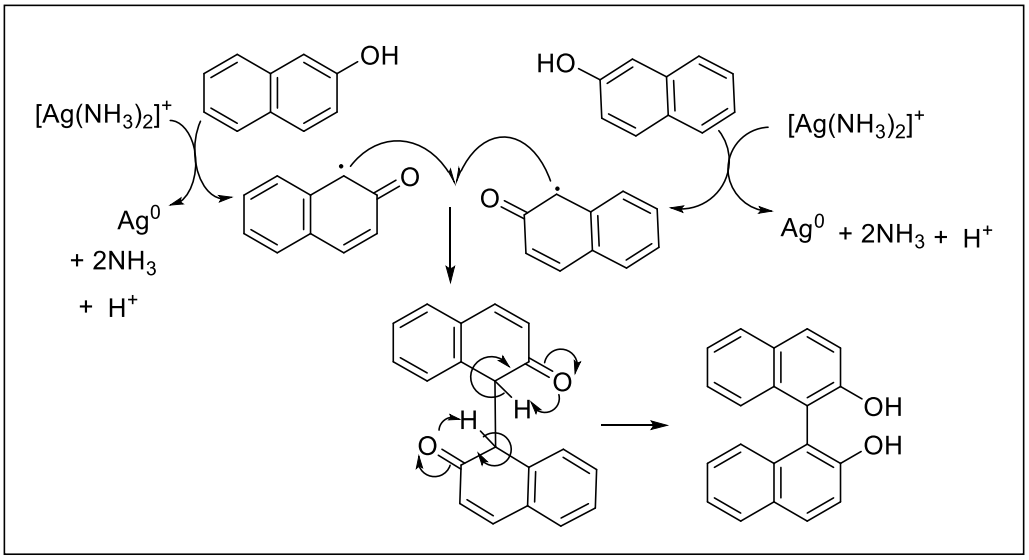
*(A: Plot of recovered Silver from each recycle from coupling reactions of phenol derivatives in 0th to 5th cycle of silver reuse, and B: % yield of coupled product obtained from coupling reactions of phenol derivatives verses 0th to 5th cycle of silver reuse.)

Proposed Mechanisms:

Scheme S2.3.5: Probable Radical-anion oxidative coupling mechanism

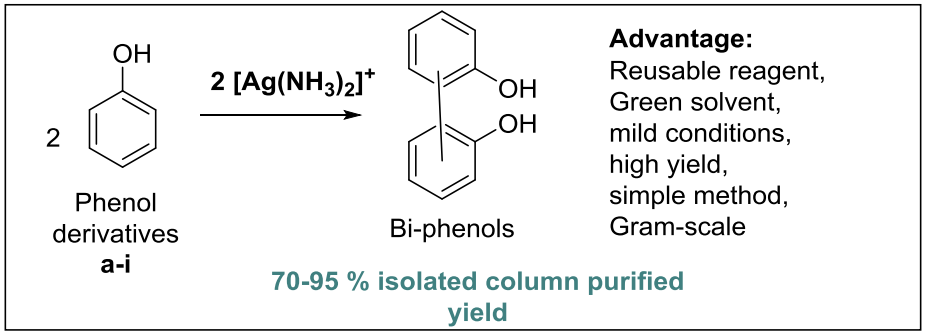


Scheme S2.3.6: Probable radical-radical oxidative coupling mechanism



The oxidation of 2-naphthols and reduction of silver(*I*) ammine complex results in BINOL and silver formation. Two mechanisms were proposed for this conversion similar to the reported in the literature.[7,54,55] Scheme S2.3.5 shows C-C oxidative coupling of 2-naphthol molecules via a radical-anionic coupling mechanism, while scheme S2.3.6 depicts radical-radical coupling mechanism.

2.4 Conclusion



Scheme S2.4: Summary of C-C oxidative coupling of phenol derivatives using Tollens' reaction

In conclusion, the novel use of Tollens' reagent for C-C oxidative coupling of phenol and naphthol derivatives was discovered, and disclosed in this chapter, as shown in scheme S2.4.

- The C-C oxidative coupling of the total of eight derivatives of phenol and 2-naphthol were carried out successfully. The products were isolated quantitatively with good yield (70-95%) and characterized using mass spectrometry, FT-NMR (^{1}H and ^{13}C), and FT-IR spectroscopy analysis.
- The reaction was optimized to obtain desired product using a simple method and mild conditions. The reaction was studied by varying reagent preparation methods, quantity, solvent, dilution, temperature, and gas purging. The room temperature conditions and stoichiometric requirement of reagent prepared by dissolving silver nitrate in ammonia were investigated as satisfactory conditions, and 93% of BINOL was obtained using it.
- The 93% 1bb and 63% 1aa yield obtained from the gram-scale reaction of phenol b and a respectively, show the reagent's feasibility.
- The recycling method was developed to reuse the Ag^{+} similar to catalyst. The recycling was successfully carried out up to 5 cycles. The recovered silver nitrate was quantified using *conductometric* titration with standard KCl solution, which shows more than 95% recovery after 5th recycle.
- Two mechanisms were proposed based on optimization studies, which needs further study to confirm. The next two chapters will also help in detailed understanding.

2.5 Experimental

2.5.1 Materials

Silver nitrate used of 99.9999% purity from Sigma-Aldrich. Potassium Chloride used of 99.999% purity purchased from Sigma-Aldrich. All other chemicals used were of analytical grade quality, purchased commercially from Sigma-Aldrich, Alfa Aesar, TCI, or Avra chemicals, and used without further purification. Absolute alcohol (99.6 % v/v) was acquired from the Maharaja Sayajirao University of Baroda and used without further purification. Water was double-distilled de-ionized. (Specific conductivity of less than 10 μS cm^{-1} at 30°C). All other solvents were purchased commercially from local sources.

2.5.2 Methods and Characterization

- The reactions were carried out in the presence of air. (mentioned if not)
- All the reactions were performed at least four times. Yields of reactions are presented in percentage, which is an average of results of repeated experiments. Maximum ±1.5% difference was observed in isolated yield of organic compounds, a determined error.
- Thin-layer chromatography was performed using a TLC 60 F254 plate of silica gel of 60 mesh coated on an aluminum plate purchased from Merck.
- The vessels used in the reaction were pre-cleaned and rinsed with dilute HNO_3 and de-ionized water. Most of the reactions were performed in an oven-dried, custom-made glass test tube of 10 ml. It is mentioned if another vessel is used.
- The products were purified by column chromatography using Fluka chromatographic silica gel (40-60 μm).
- Proton nuclear magnetic resonance (^{1}H NMR) spectra and carbon nuclear magnetic resonance (^{13}C NMR) spectra were recorded on Advanced Bruker-400 NMR spectrophotometers with $CDCl_3$ or DMSO-d_6. Chemical shifts for protons are reported in parts per million downfield from tetramethylsilane, and coupling constants are shown in Hertz (Hz). Chemical shift multiplicity as s = singlet, d = doublet, t = triplet, q = quartet, and m = *multiplet.*
- The MS data were collected from electron spray ionization mass spectral measurement (ESI-MS) or Gas chromatography-mass spectrometry (GC-MS), which were performed using ESI-mass Applied Biosystem API 2000 mass spectrometer or Thermo scientific DSQ-II, respectively.

- The Infrared spectra (400–4000 cm^{-1}) were recorded on α-Bruker FTIR with samples prepared as KBr pellets.
- The conductivity of solutions was measured using Digital Conductivity meter D-511.
- The Crystals were analyzed using a single crystal-XRD machine, Oxford X-CALIBUR-S diffractometer equipped with a CCD detector, with CuKα radiation(λ= 1.541841Å) at 293K and processed with CrysAlisPro, Agilent Technologies, and structure was solved using SHELXL program.

2.5.3 Method development and Optimization of C-C oxidative coupling of 2-Naphthol

2.5.3.1 General procedure for Tollens' Test of 2-Naphthol

Tollens' reagent was prepared by adding sodium hydroxide solution (0.1 N, 0.2 ml) into the 0.5 ml of silver nitrate (0.0340 g, 0.2 mmol) solution followed by the addition of liquor ammonia (0.2 ml). 2-Naphthol (0.029 g, 0.2 mmol) solution prepared in 1.0 ml absolute ethanol was added into the Tollens' reagent and stirred at 30°C for 48 hr. After complete conversion, the reaction mixture was subjected to centrifugation for separating metallic silver from the solution. The remaining crude silver was washed with an organic solvent such as ethyl acetate and dichloromethane. All these solvents were dried over Na_2SO_4, and evaporated. The residue was purified using column chromatography on silica gel to yield the desired product.

2.5.3.2 Effect of reagent on C-C oxidative coupling reaction of 2-Naphthol

The reagents were prepared using 0.2 mmol $AgNO_3$ and one-mole equivalents of NaOH and 0.2 ml of liquor ammonia. The solution of 0.2 mmol 2-naphthol in 1.0 ml ethanol was added to the reagent and kept at 30°C. After complete conversion, the product was extracted, and purified column chromatographed yields were noted. The product was analyzed with ^{1}H FT-NMR (F2.6.1), ^{13}C FT-NMR (F2.6.1), FT-IR spectroscopy (F2.6.23), and mass spectrometry analysis (F2.6.12), C-C coupled product BINOL (1aa) formation was confirmed. The spectral data are shown in section 2.5.6.

2.5.3.3 Purging of Gases (air/oxygen/Nitrogen) and C-C oxidative reaction

2-Naphthol (0.0140 g, 0.1 mmol) solution prepared in absolute ethanol (2.0 ml) was added to the silver-ammonia complex solution prepared by dissolving Silver nitrate (0.0170 g, 0.1 mmol) in liquor ammonia (0.2 ml). The mixture was stirred on a water bath at 68-70°C temperature using a magnetic stirrer. Different gases were purged continuously from the solution using a gas balloon of air, carbon dioxide, oxygen, or nitrogen. The reaction progress

and product formation was monitored using thin-layer chromatography and compared with reaction kept without purging gases.

2.5.3.4 Gram scale reaction of 2-Naphthol with Tollens' reagent

The silver-ammonia complex solution prepared by dissolving silver nitrate (1.1800 gm, 6.95 mmol) in 3.0 ml liquor ammonia was added to the 50 ml round bottom flask containing 3.0 ml 2-Naphthol (1.000 gm, 6.95 mmol) solution in absolute ethanol. The mixture was stirred for 30 minutes at 68-70°C temperature on an oil bath using a magnetic stirrer. The product was extracted, and purified column chromatographed yields were noted.

2.5.3.5 *In-situ* crystallization

Tollens' reagent was prepared by dissolving silver nitrate (0.0340 g, 0.2 mmol) in 1.0 ml liquor ammonia. 2-Naphthol (0.029 g, 0.2 mmol) solution prepared in 1.0 ml absolute ethanol was added to the Tollens' reagent and kept aside, at 30°C for 2-3 days. The crystals of 2aa were observed in the reaction mixture. Crystal of 1aa was also obtained by changing reagent stoichiometry using the same procedure, as shown in table T2.6.

Once crystals of a and 1aa were obtained together in the reaction mixture, on using reaction conditions T2.6-6.

Table T2.6 The reaction conditions and reagents used to obtain In-situ crystallization of BINOL-1aa

No.	$AgNO_3$	liq. NH_3	2-naphthol (phenol-a)	Alcohol	Temperature	Time	Crystallized material
	mmol	ml	mmol	ml	°C	day	
1	0.2	1	0.2	1	30 °C	2 day	1aa
2	0.4	1	0.2	1	30 °C	3 day	1aa
3	0.4	1	0.4	1	30 °C	3 day	1aa
4	0.2	1	0.2	2	30 °C	5 day	1aa
5	0.4	1	0.2	1	30 °C	3 day	1aa
6	0.06	3	0.12	6	30 °C	10 day	a + 1aa

2.5.4 General procedure for C-C oxidative coupling of phenols

Phenol (a-h) (0.2 mmol) solution prepared in absolute ethanol (0.5 to 1.0 ml) was added to the silver-ammonia complex solution prepared by dissolving Silver nitrate (0.0170 g, 0.1 mmol) in liquor ammonia (0.2 ml) in an oven-dried glass test tube equipped with a magnetic stirrer bar. The mixture was stirred at room temperature or heated on an oil bath using a magnetic stirrer for a stipulated time till maximum conversion. The reaction was monitored using TLC. The reaction mixture was subjected to centrifugation for the separation of metallic silver from the reaction mixture. The remaining crude silver was washed with an organic solvent such as ethyl acetate and dichloromethane. All these solvents were dried over Na_2SO_4 and evaporated. Finally, the residue was purified using column chromatography on silica gel to yield the product. All the products were well characterized with FT-NMR (^1H and ^{13}C), FT-IR spectroscopy, and mass spectrometry analysis, as shown in section 2.5.6, and the spectral data are shown in section 2.6 from Figures F2.6.1 to F2.6.33

2.5.5 Catalytic reuse of reagent: General procedure of recycling and reuse of Silver (Ag) for C-C oxidative coupling reaction of phenols

- 0.2 mmol of phenolic solution (in alcohol) were added to the silver ammine complex (1st time prepared by 0.2 mmol of silver nitrate in 1.0 ml of ammonia) prepared freshly or recycled. The reactions were carried out until the total consumption of phenol.
- The extraction of organics separated the reaction mixture containing organic and silver metallic silver. All the organics were dried and purified by column chromatography.
- The remaining silver was washed with water and organic solvents such as acetone or Chloroform and dried. The centrifugation method is used for the complete and easy recovery of silver. Recovered Silver (0.2 mmol) was treated with a minimum amount of concentrated nitric acid (≥ 0.2 ml, 98% solution) to obtain silver nitrate. Then, the liquor ammonia was added into the silver nitrate (probable 0.2 mmol) until it became basic and used directly as a recovered silver ammine complex to reuse the reagent.
- For quantification, the recovered silver nitrate was titrated against standard 0.02 N KCl solution using a *conductometric* method. [12]

Note: After quantification, the silver forms silver chloride, which can not be used further; thus, Six sets of the same reaction were kept together with the same conditions and used one by one for the next step.

2.5.6 Characterization of Products

C-C homo-coupling products 1aa, 1bb, 1cc, 1dd, 1ee, 1ff, 1gg, and 1hh were obtained from oxidative coupling reaction of phenol and naphthol derivatives, as shown in section 2.5.4. The 2cc and 2ee were obtained from over-oxidation of 1cc and 1ee. All the products were known and identified by matching their melting point, FT-NMR (^{1}H and ^{13}C) spectroscopic data, and mass spectrometry data with literature, as shown in section 2.6.

(1,1'-binaphthalene)-2,2'-diol (1aa) (BINOL)[56] was obtained by column chromatography on silica gel using petroleum ether and ethyl acetate: Yellowish white solid; 26 mg in 0.2 mmol scale reaction, 90% isolated column purified yield. 71% yield (average yield of six cycles recycling experiment), Melting point 210-212°C (rep. 210-212°C), ^{1}H NMR (400 MHz, $CDCl_3$, 291 K) : δ 5.09 (2H, Broad, -OH), 7.17 (2H, d, *J* = 8.0 Hz), 7.28-7.43 (6H, m), 7.92 (2H, d, *J* = 8.0 Hz), 8.02 (2H, d, *J* = 8.8 Hz); ^{13}C NMR (100 MHz, $CDCl_3$, 291 K) δ 110.8, 117.8, 124.1, 124.2, 127.5, 128.4, 129.4, 131.5, 133.4, 152.8; GCMS m/z: $[M-1]^{+1}$: 285.8 (molecular weight : 286.10 gm/mol); FTIR ν_{max}/cm^{-1} : 3486, 3403, 3044, 1618, 1506, 1509, 1470, 1434, 1381, 1216, 1175, 1146, 1124, 825, 751. The single crystal X-ray diffraction of crystal is given in table T2.7.

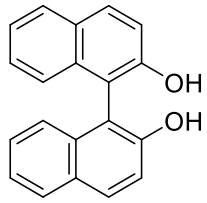


Table T2.7 The single-crystal data and structural refinement for 1aa

Single Crystal data of BINOL			
Identification code	Rac-BINOL	**Z**	8
Empirical formula	C20H14O2	**ρ calculated mg/mm^3**	1.293
Formula weight	286.31	**absorption coefficient**	0.083 μ/mm-1
Temperature	293 K	**F(000)**	1200.0
Crystal system	Orthorhombic	**2Θ range for data collection**	6.4 to 57.74°
Space group	Iba2	**Index ranges**	-29 ≤ h ≤ 20, -20 ≤ k ≤ 21, -11 ≤ l ≤ 10
a	21.644 Å (3)		
b	15.770 Å (2)		
c	8.6191 Å (12)	**Reflections collected**	5691
A	90.00°	**Independent reflections**	3163 [$R_{(int)}$ = 0.0535]
B	90.00°	**Goodness-of-fit on F2**	1.039
C	90.00°	**Final R indexes [I>=2σ (I)]**	R1 = 0.0762, wR2 = 0.0984
Volume	2941.9 Å^3 (7)	**Final R indexes [all data]**	R1 = 0.1462, wR2 = 0.1197

3,3',5,5'-tetra-*tert*-butyl-(1,1'-biphenyl)-2,2'-diol (1bb)[56] was obtained by column chromatography on silica gel using petroleum ether and ethyl acetate: 39 mg in 0.2 mmol scale reaction, 95% isolated column purified yield: Melting point 188-190°C, ^{1}H NMR (400 MHz, $CDCl_3$, 291 K) δ1.34 (18H, s), 1.47 (18H, s), 5.24 (2H, broad, -OH), 7.13 (2H, d, *J* = 2.4 Hz), 7.41 (2H, d, *J* = 2.4 Hz); ^{13}C NMR (100 MHz, $CDCl_3$, 291 K) δ 29.6, 31.6, 34.5, 35.2, 122.3, 124.8, 125.3, 136.2, 142.9, 149.8; GCMS m/z: $[M]^{+1}$: 410.27(molecular weight: 410.16 g/mol); FTIR ν_{max}/cm^{-1} : 3524, 2959, 2868, 1737, 1476, 1434, 1361, 1266, 1199, 1134, 851, 770, 650.

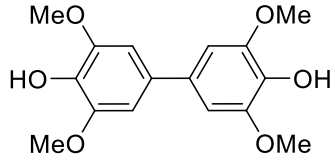
3,3',5,5'-tetra-*tert*-butyl-(1,1'-biphenyl)-4,4'-diol (1cc)[57] was obtained by column chromatography on silica gel using petroleum ether and ethyl acetate, yellow solid, 29 mg in 0.2 mmol scale reaction, 70% isolated column purified yield: Melting point 182°C (rep. 185°C), ^{1}H NMR (400 MHz, $CDCl_3$, 291 K) δ 1.38 (36H, s), 7.72(4H, s); ^{13}C NMR (100 MHz, $CDCl_3$, 291 K) δ 30.3, 34.4, 124.1, 133.9, 135.9, 152.8; ESI-MS m/z: $[M]^{+1}$: 410.3 (molecular weight: 410.16 g/mol); FTIR ν_{max}/cm^{-1} : 3525, 3464, 2962, 1689, 1481, 1095, 1026, 648, 586.

3,3',5,5'-Tetra-*tert*-butyl-4,4'-diphenoquinone (2cc)[56] was obtained by column chromatography on silica gel using petroleum ether and ethyl acetate: solid, 27 mg in 0.2 mmol scale reaction, 66% isolated column purified yield.; Melting point 235°C (rep. 242-244°), ^{1}H NMR (400 MHz, $CDCl_3$, 291 K) δ 1.29 (36 H, s), 7.63 (4H, s); ^{13}C NMR (100 MHz, $CDCl_3$, 291 K) δ 30.34, 36.0, 126.0, 136.2, 150.5, 186.5; ESI-MS m/z: $[M]^{+1}$: 408.1 (molecular weight: 408.6 g/mol); FTIR ν_{max}/cm^{-1}: 3002, 2958, 2910, 1638, 1603, 1557, 1481, 1457, 1361, 1261, 1090, 1041, 995, 898, 843, 514.

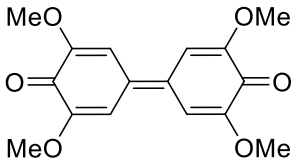
3,3',5,5'-tetramethyl-(1,1'-biphenyl)-2,2'-diol (1dd)[50] was obtained by column chromatography on silica gel using petroleum ether and ethyl acetate: white solid; 21 mg in 0.2 mmol scale reaction, 85% isolated column purified yield.; Melting point 134°C, ^{1}H NMR (400 MHz, $CDCl_3$, 291 K) δ 2.29(12H, d, *J* = 0.8 Hz), 5.09 (2H, broad, OH), 6.88 (2H , d, *J* = 0.8 Hz), 7.02 (2H , d, *J* = 2.0 Hz); ^{13}C NMR (100 MHz, $CDCl_3$, 291 K) δ 16.2, 20.5, 122.1, 125.2,

128.5, 130.0, 132.0, 149.1; ESI-MS m/z: $[M+1]^{+1}$: 243.6 (molecular weight: 242.32 g/mol); FTIR ν_{max}/cm^{-1} : 3484, 3382, 3007, 2916, 1735, 1609, 1479, 1437, 1322, 1230, 1183, 1119, 1034, 1018, 848, 793, 776, 561.

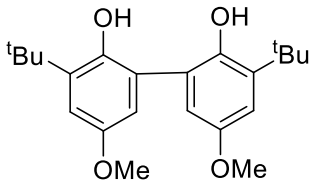
3,3',5,5'-tetramethoxy-(1,1'-biphenyl)-4,4'-diol (1ee)[58] was obtained by column chromatography on silica gel using petroleum ether and ethyl acetate; semisolid, 22 mg in 0.2 mmol scale reaction, 72% isolated column purified yield. ^{1}H NMR (400 MHz, DMSO-d_6, 291 K) δ 3.84 (12H, s), 6.82 (4H, s), 8.33 (2H, broad, -OH); ^{13}C NMR (100 MHz, DMSO-d_6, 291 K) 56.7, 104.8, 131.8, 135.4, 148.7; ESI-MS m/z: $[M]^{+1}$: 306.9 (molecular weight: 306.31 g/mol); FTIR ν_{max}/cm^{-1} : 3200, 2710, 2545, 1598, 1551 1360, 1305, 1275, 1198, 1175, 1148, 954, 880, 828, 692, 554.



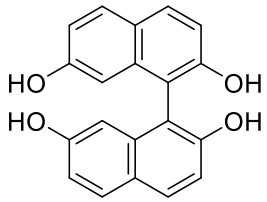
3,3',5,5'-tetramethoxy-4,4'-diphenoquinone (2ee)[54] was obtained by column chromatography on silica gel using petroleum ether and ethyl acetate: solid, 8 mg in 0.2 mmol scale reaction 25% isolated column purified yield. ^{1}H NMR (400 MHz, $CDCl_3$, 291 K) δ 3.84 (12H, s), 5.87 (4H, s); ^{13}C NMR (100 MHz, $CDCl_3$, 291 K) δ 56.5, 107.4, 157.3, 186.9; ESI-MS m/z: $[M+1]^{+1}$: 305.2 (molecular weight: 304.31 g/mol); FTIR ν_{max}/cm^{-1} : 2965, 1402, 1313, 1263, 1198, 1150, 953, 880, 843, 793, 549.



3,3'-di-*tert*-butyl-5,5'-dimethoxy-(1,1'-biphenyl)-2,2'-diol (1ff)[59] was obtained by column chromatography on silica gel using petroleum ether and ethyl acetate, 27 mg in 0.2 mmol scale reaction, 74% isolated column purified yield.; solid, Melting point 220-222°C, ^{1}H NMR (400 MHz, $CDCl_3$, 291 K) δ 1.42 (18H, s), 3.77 (6H, s), 5.05 (2H, broad, -OH), 6.63 (2H, d, J = 2.8 Hz), 6.96 (2H, d, J = 2.8 Hz); ^{13}C NMR (100 MHz, $CDCl_3$, 291 K) δ 29.5, 29.7, 35.2, 55.7, 111.7, 115.3, 123.3, 138.9, 145.9, 153.2; ESI-MS m/z: $[M]^{+1}$: 358.0 (molecular weight: 358.21 g/mol); FTIR ν_{max}/cm^{-1} : 3418, 3125, 2962, 1597, 1458, 1427, 1381, 1219, 1141, 1057, 887, 840, 779.

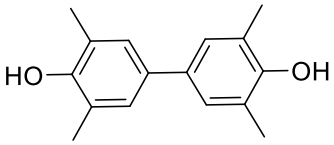


(1,1'-binaphthalene)-2,2',7,7'-tetraol (1gg)[56] was obtained by column chromatography on silica gel using petroleum ether and ethyl acetate, 20 mg in 0.2 mmol scale reaction, 62% isolated column purified yield: grey solid, Melting point 118°C., ^{1}H NMR (400 MHz, DMSO-d_6, 291 K) δ 6.26 (2H, d, J = 2.0 Hz), 6.75 (2H, dd, J = 2.4, 8.8 Hz), 7.04 (2H, d, J =

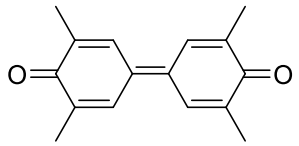


8.8 Hz), 7.66 (4H, m), 8.20 (2H, broad, -OH), 9.20 (2H, broad, -OH); ^{13}C NMR (100 MHz, $CDCl_3$, 291 K) δ 106.9, 113.1, 115.9, 116.2, 125.0, 130.7, 130.8, 136.8, 154.5, 156.6; GCMS m/z: $[M-1]^{+1}$: 317.45 (molecular weight: 318.3 g/mol); FTIR ν_{max}/cm^{-1} : 3387, 3332, 3055, 1627, 1512, 1388, 1303, 1197, 1165, 825.

3,3',5,5'-tetramethyl-(1,1'-biphenyl)-4,4'-diol (1hh)[60] was obtained by column chromatography on silica gel using petroleum ether and ethyl acetate: yellow solid; 5 mg in 0.2 mmol scale reaction, 10% isolated column purified yield.; Melting point 215°C, ^{1}H NMR (400 MHz, $CDCl_3$, 291 K) δ 2.31 (12H, s), 4.69 (2H, broad, OH), 7.75 (4H, s); ^{13}C NMR (100 MHz, $CDCl_3$, 291 K) δ 16.1, 121.1, 127.6, 134.0, 153.2; ESI-MS m/z: $[M]^{+1}$: 242.9 (molecular weight : 242.32 gm/mol); FTIR ν_{max}/cm^{-1} :3382, 3068, 2890, 1576, 1471, 1361, 1100, 790.



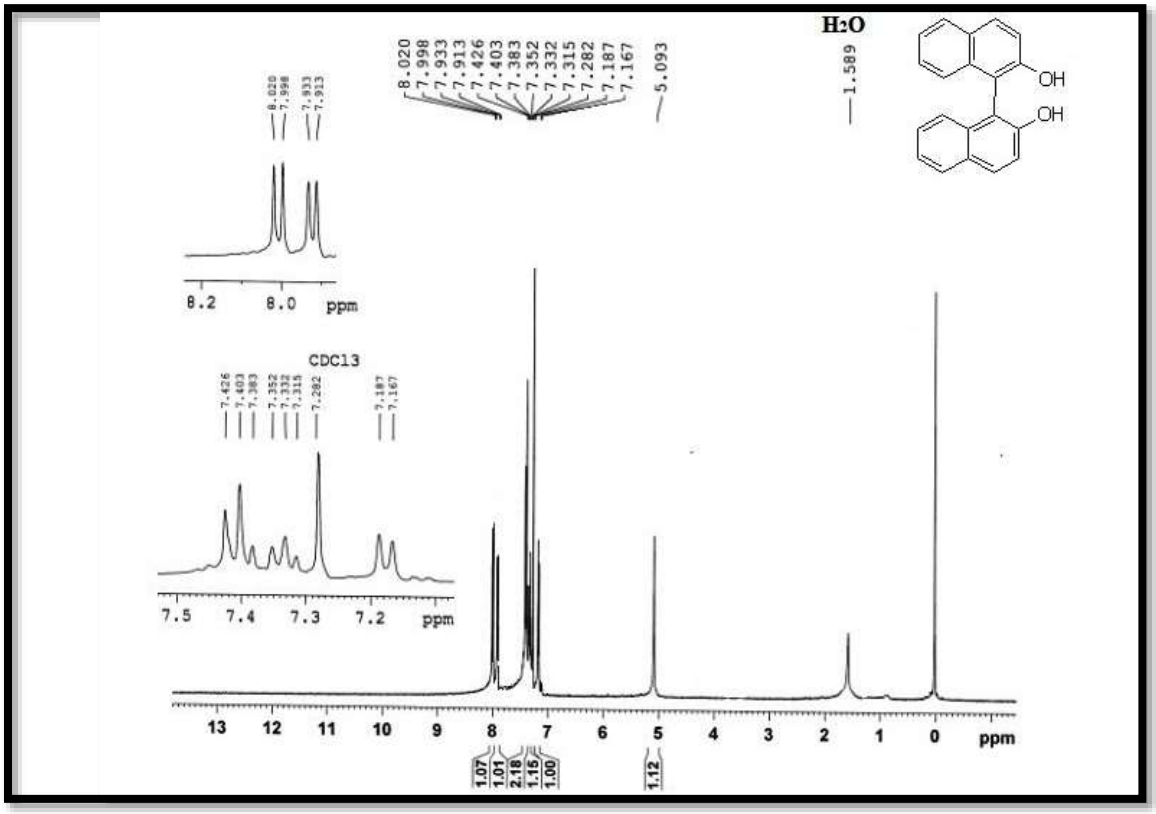
3,3',5,5'-tetramethyl-4,4'-diphenoquinone (2hh)[61] was obtained by column chromatography on silica gel using petroleum ether and ethyl acetate: yellow solid; 7 mg in 0.2 mmol scale reaction, 15% isolated column purified yield.; Melting point 190-193 °C, ^{1}H NMR (400 MHz, $CDCl_3$, 291 K) δ 2.26 (12H, s), 6.96 (4H, s); ^{13}C NMR (100 MHz, $CDCl_3$, 291 K) δ 17.2, 135.1, 135.7, 141.1, 182.1.; ESI-MS m/z: $[M+1]^{+1}$: 241.4 (molecular weight : 240.18 gm/mol); FTIR ν_{max}/cm^{-1} : 2950, 2908, 2870, 1634, 1604, 1566, 1458, 1358, 1087, 894.



2.6 Spectral Data

2.6.1 FT-NMR (^{1}H and ^{13}C) Spectral Data

Figure F2.6.1 FT-NMR (^{1}H and ^{13}C) spectra of 1aa



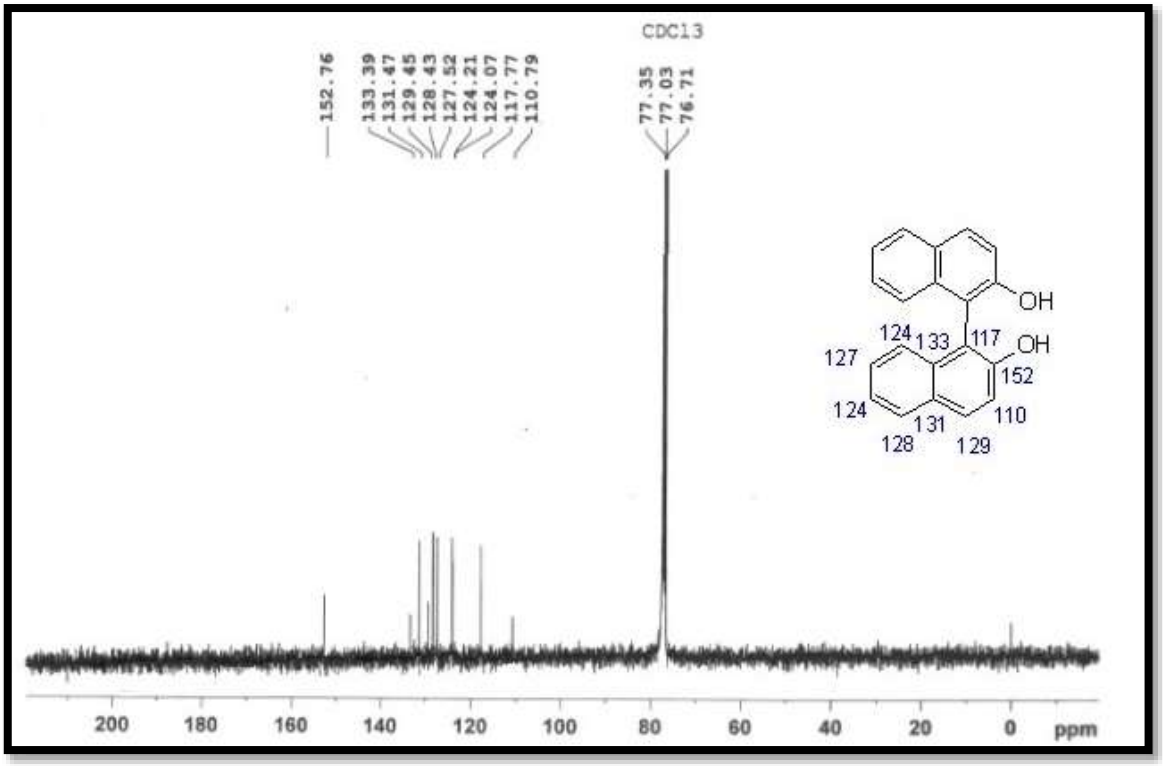
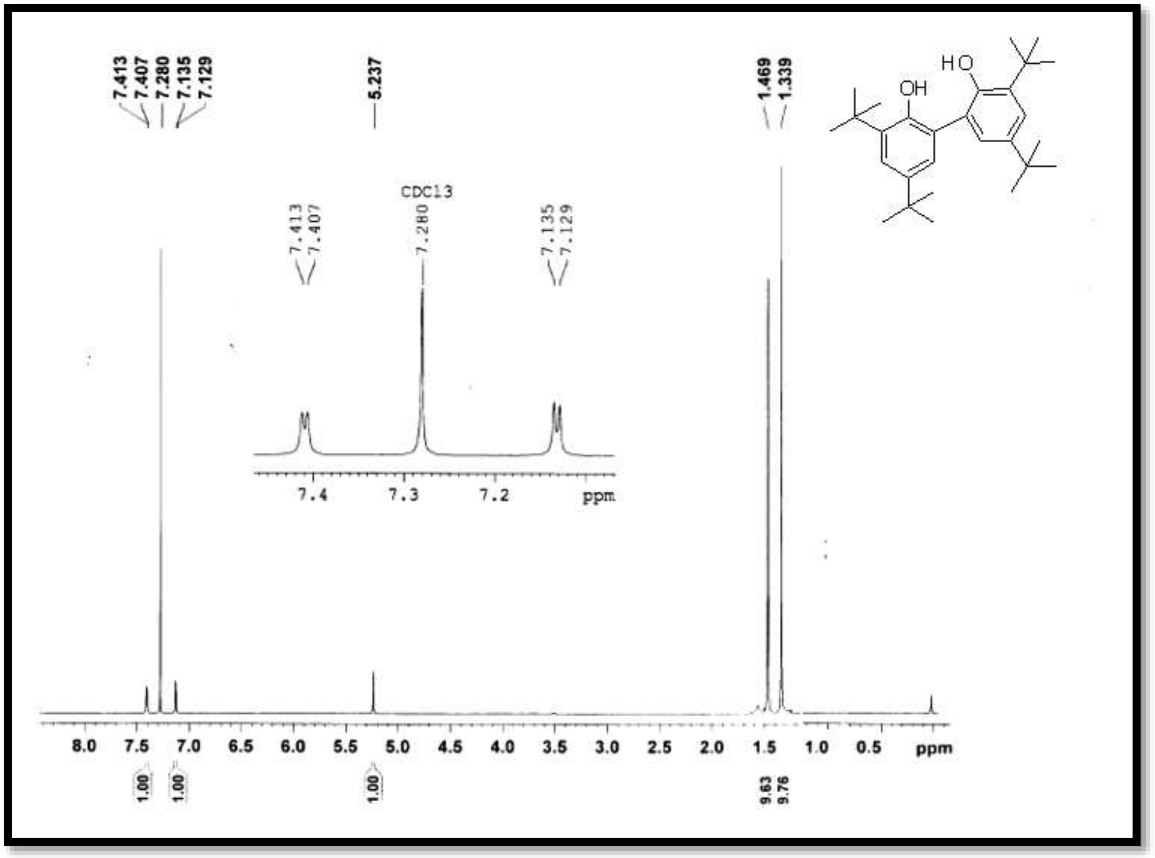


Figure F2.6.2 FT-NMR (^{1}H and ^{13}C) spectra of 1bb



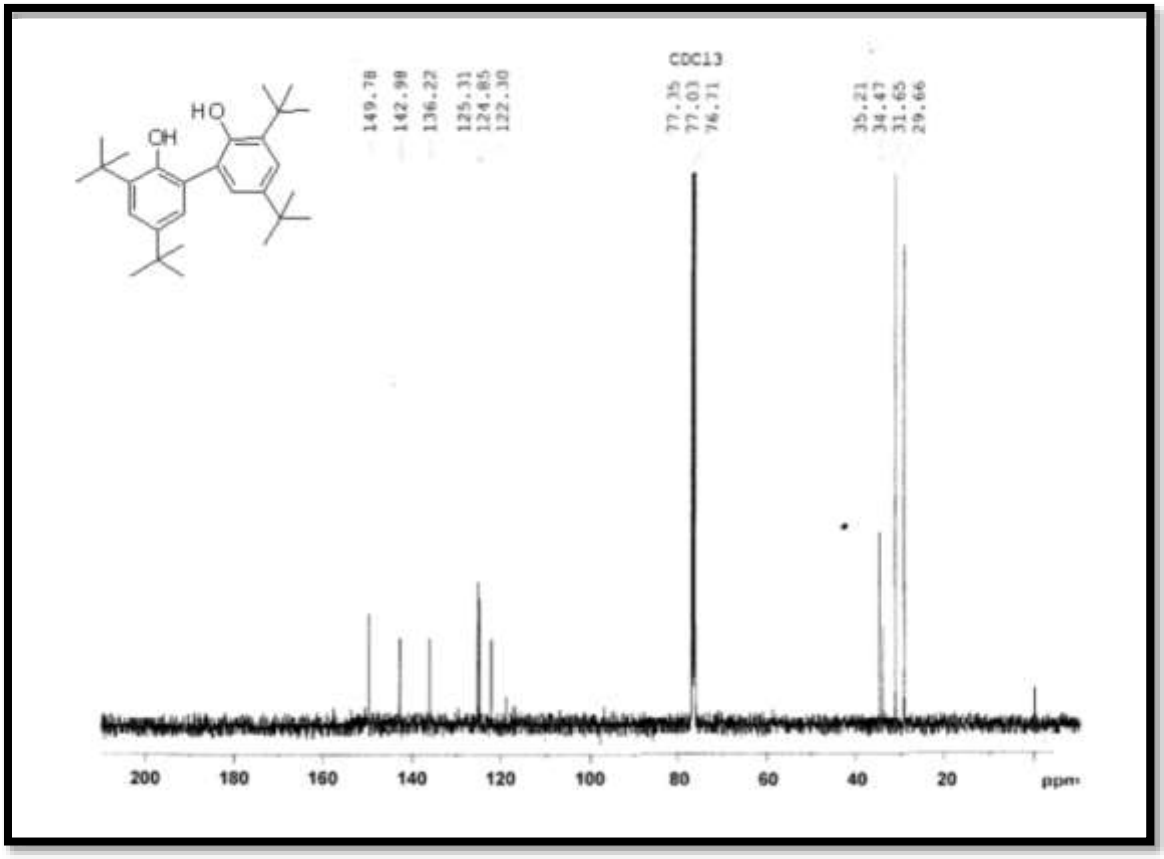
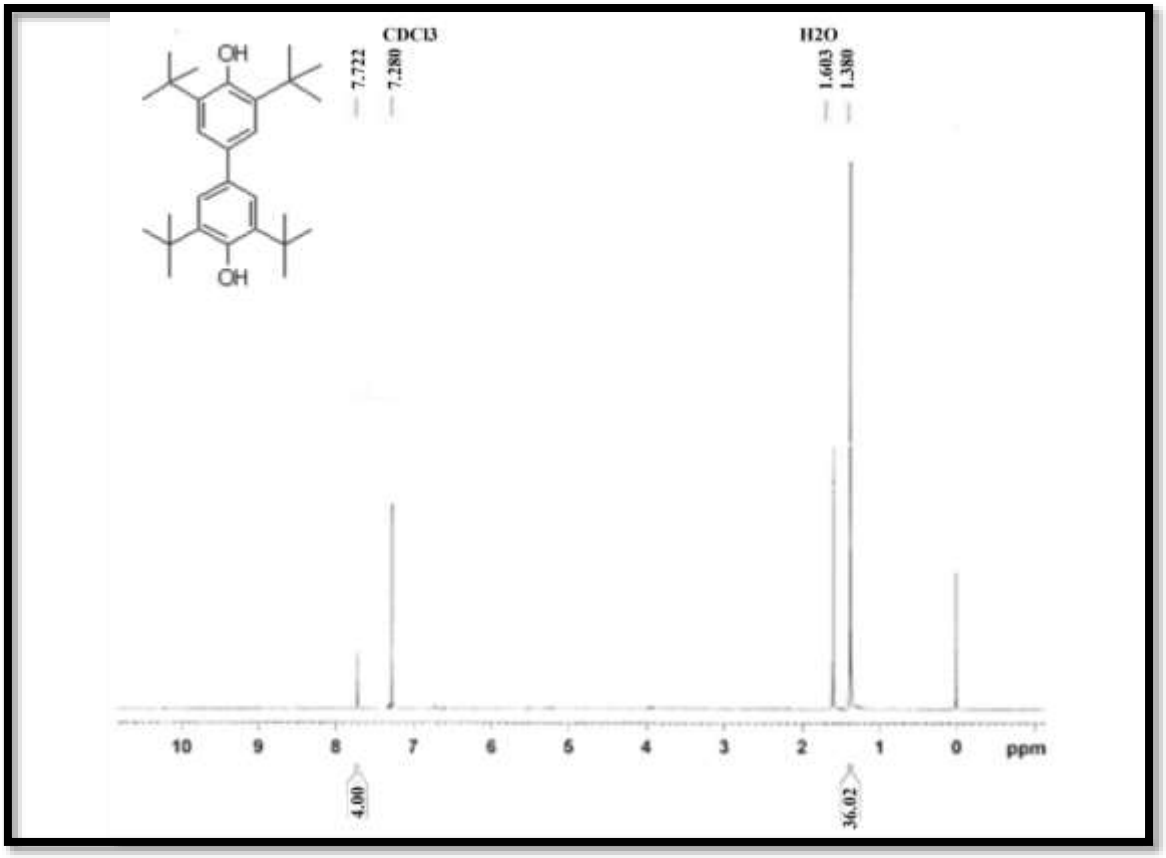


Figure F2.6. FT-NMR (^{1}H and ^{13}C) spectra of 1cc



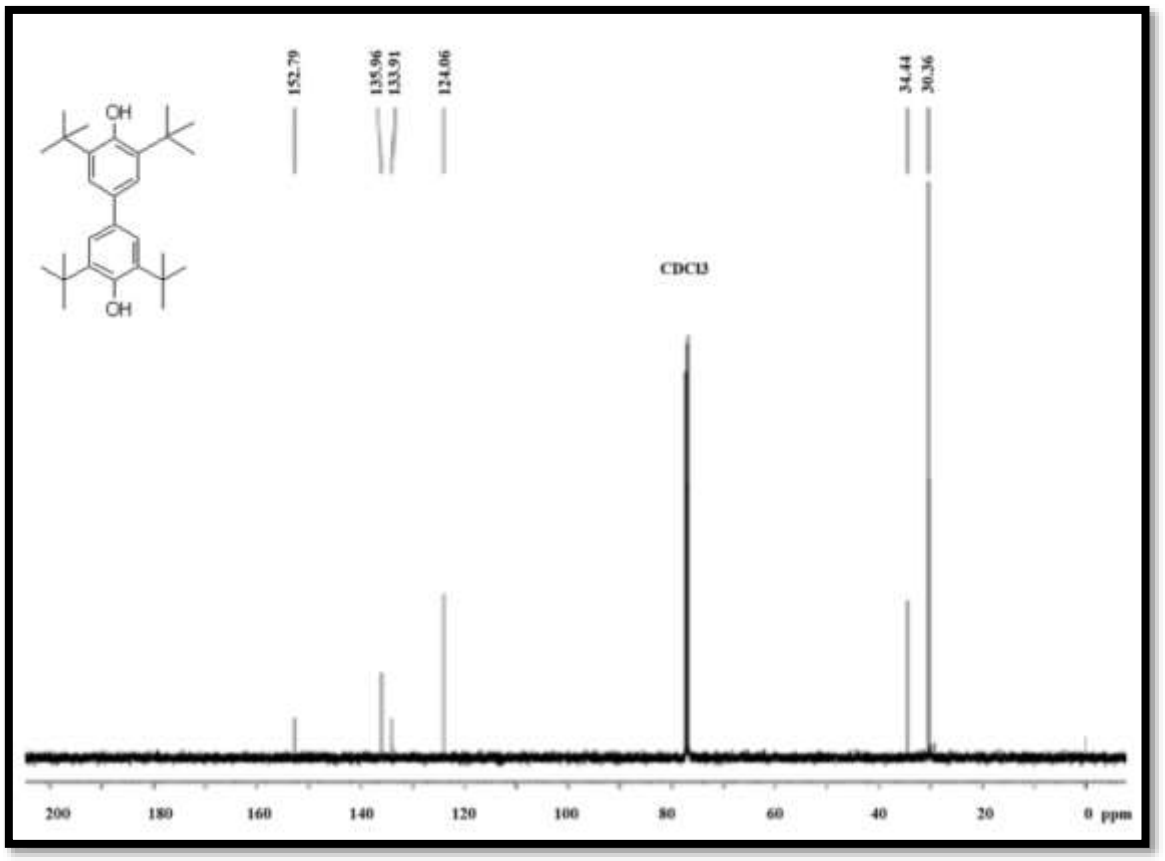
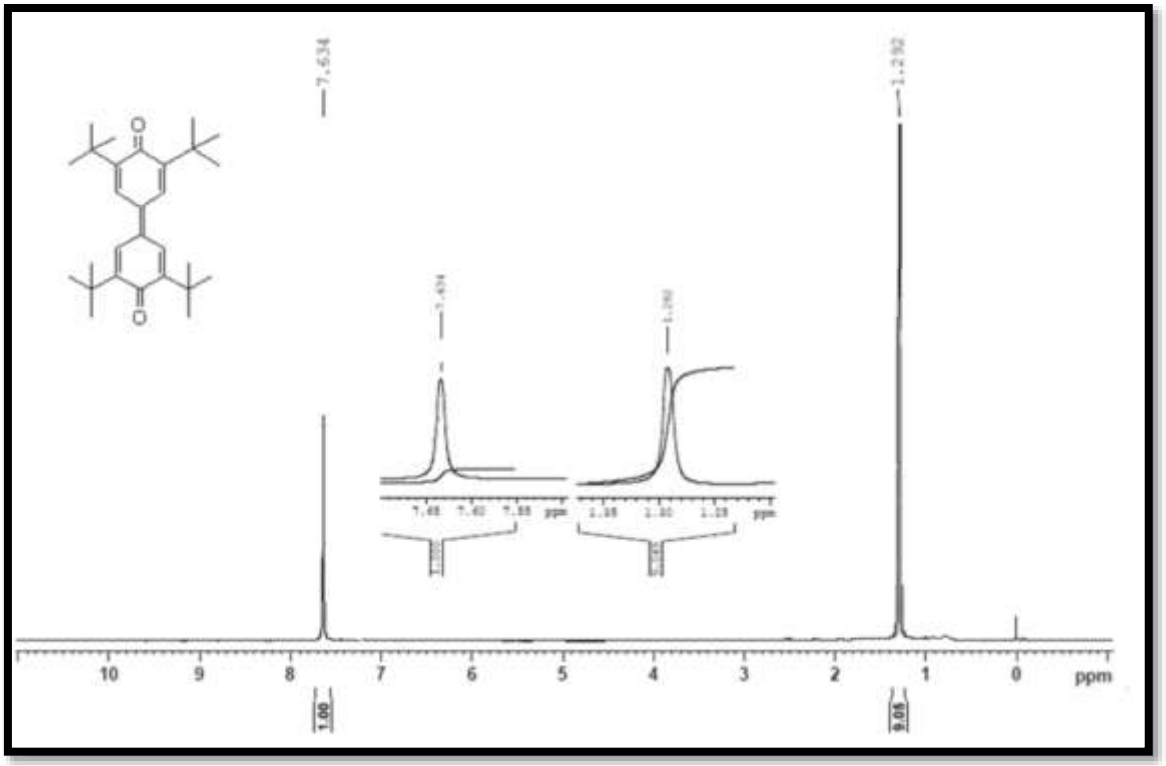


Figure F2.6.4 FT-NMR (^{1}H and ^{13}C) spectra of 2cc



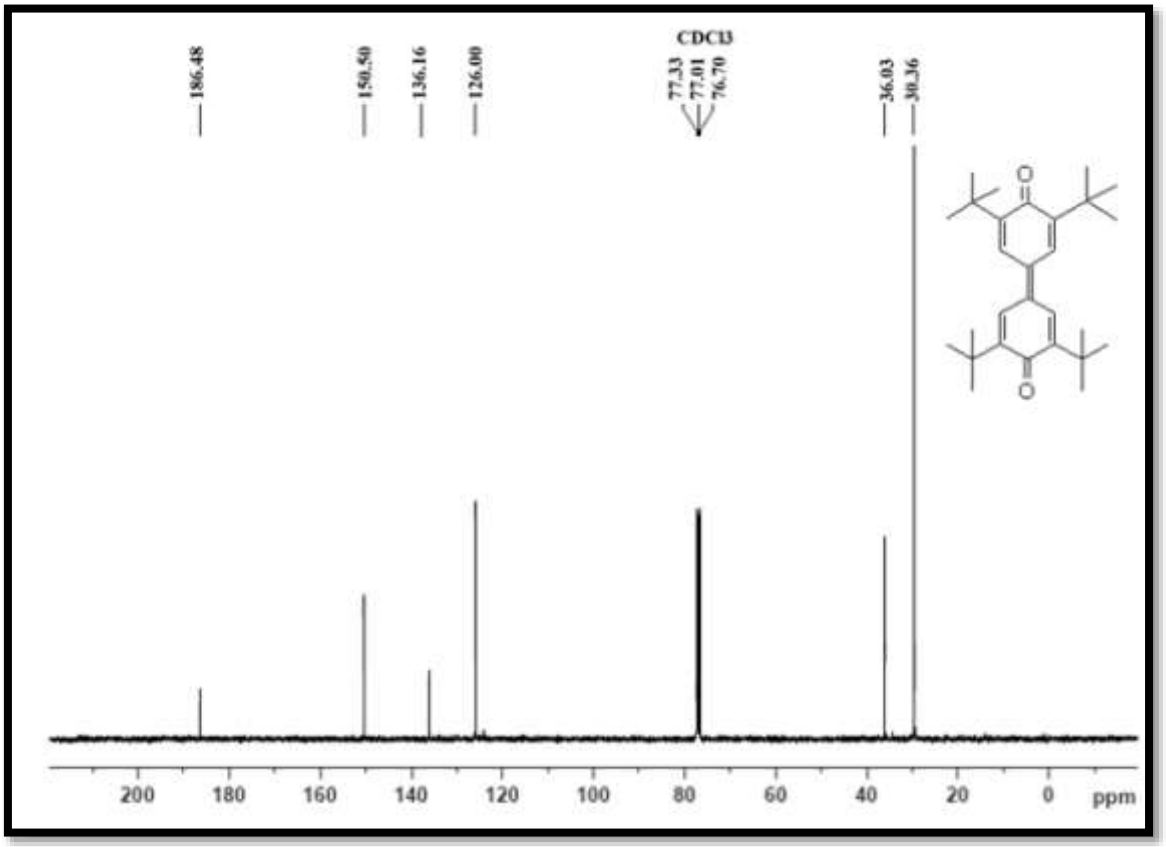


Figure F2.6.5 FT-NMR (^{1}H and ^{13}C) spectra **of 1dd**

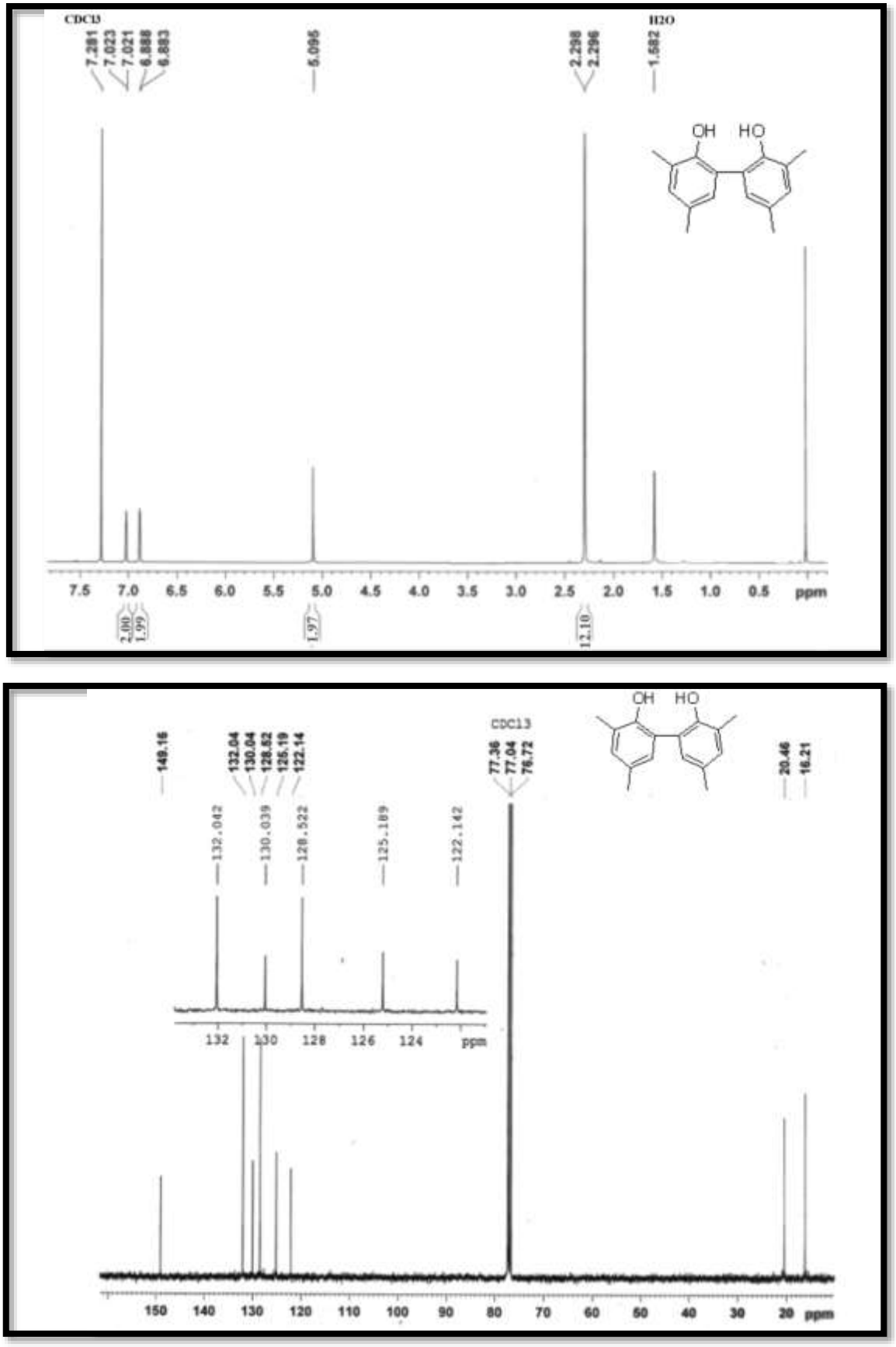
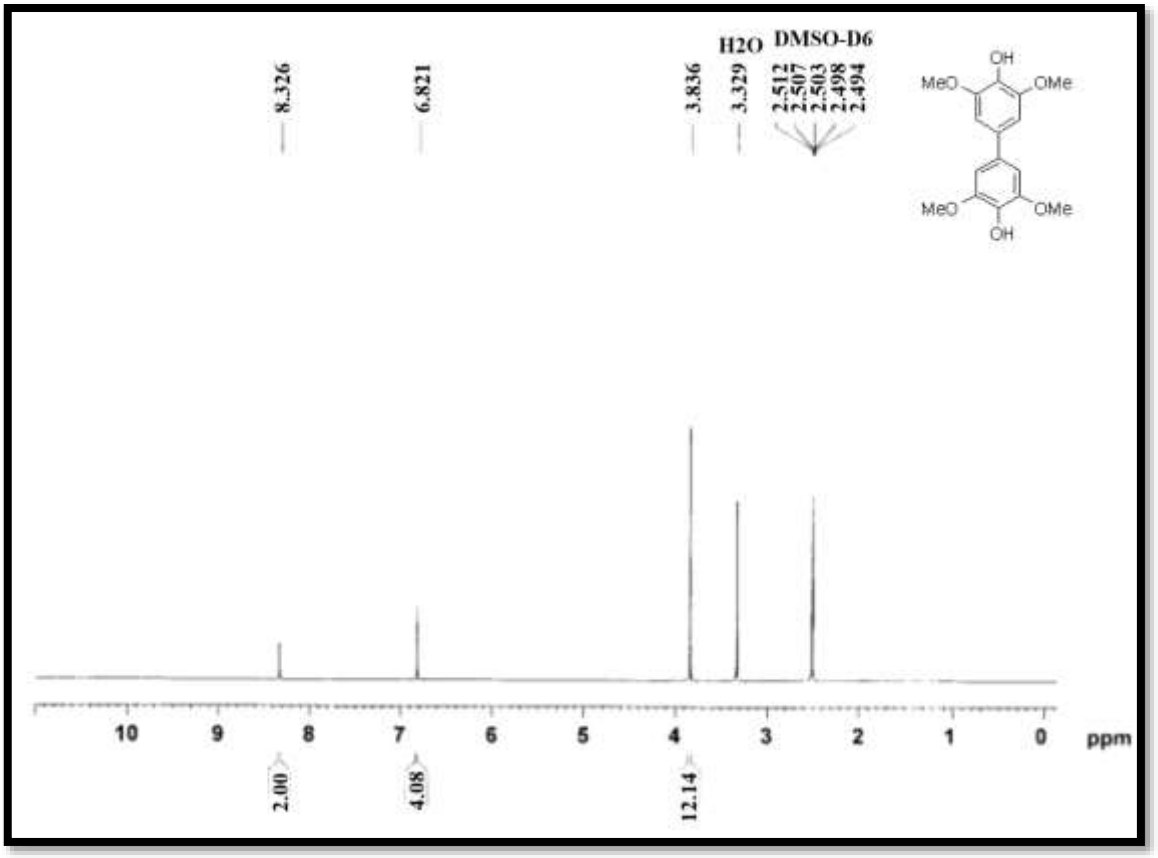


Figure F2.6.6 FT-NMR (^{1}H and ^{13}C) spectra of 1ee



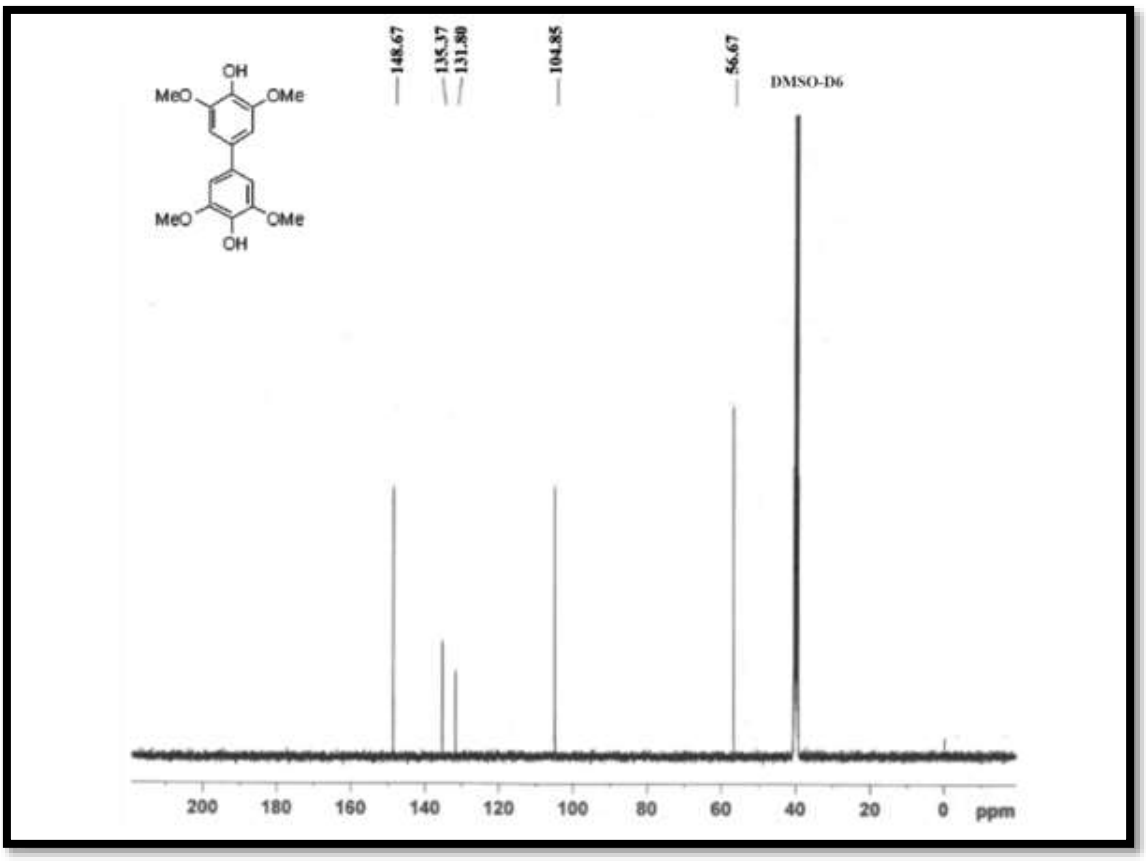
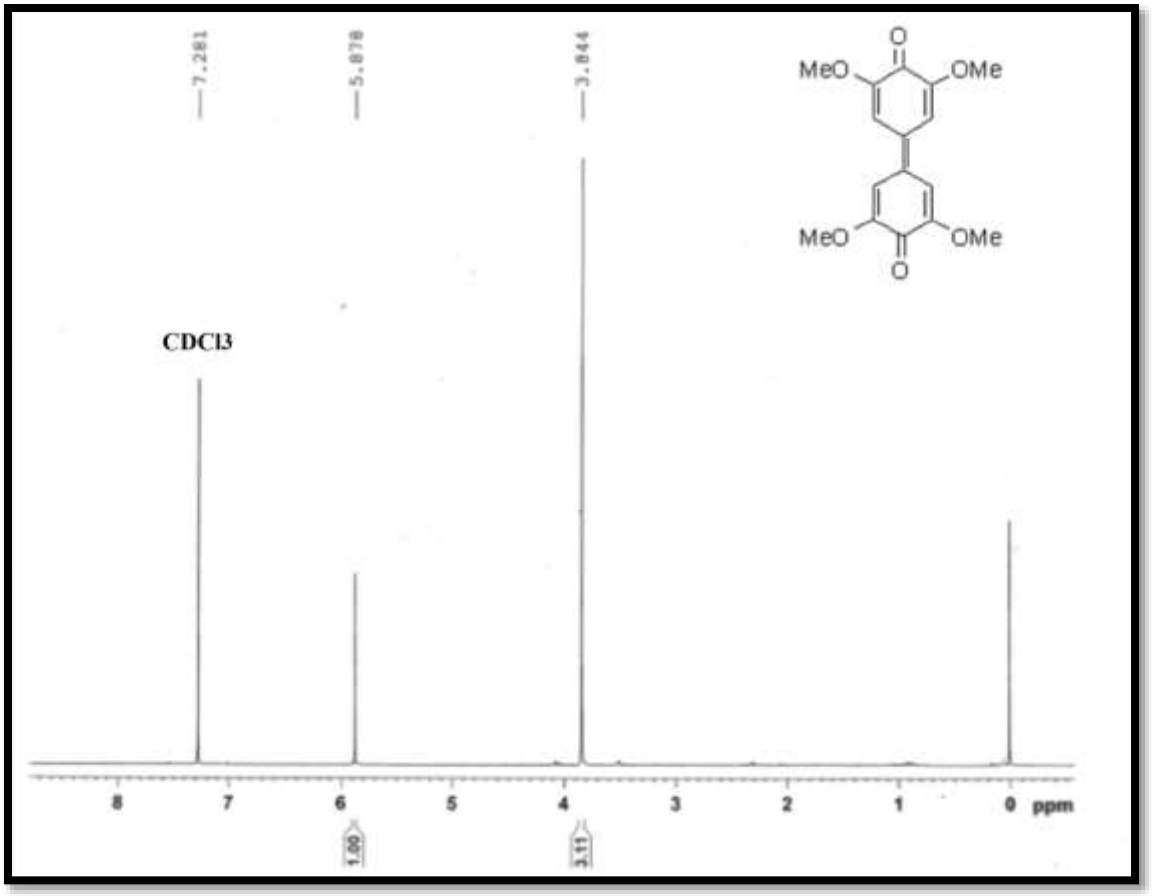


Figure F2.6.7 FT-NMR (^{1}H and ^{13}C) spectra **of 2ee**



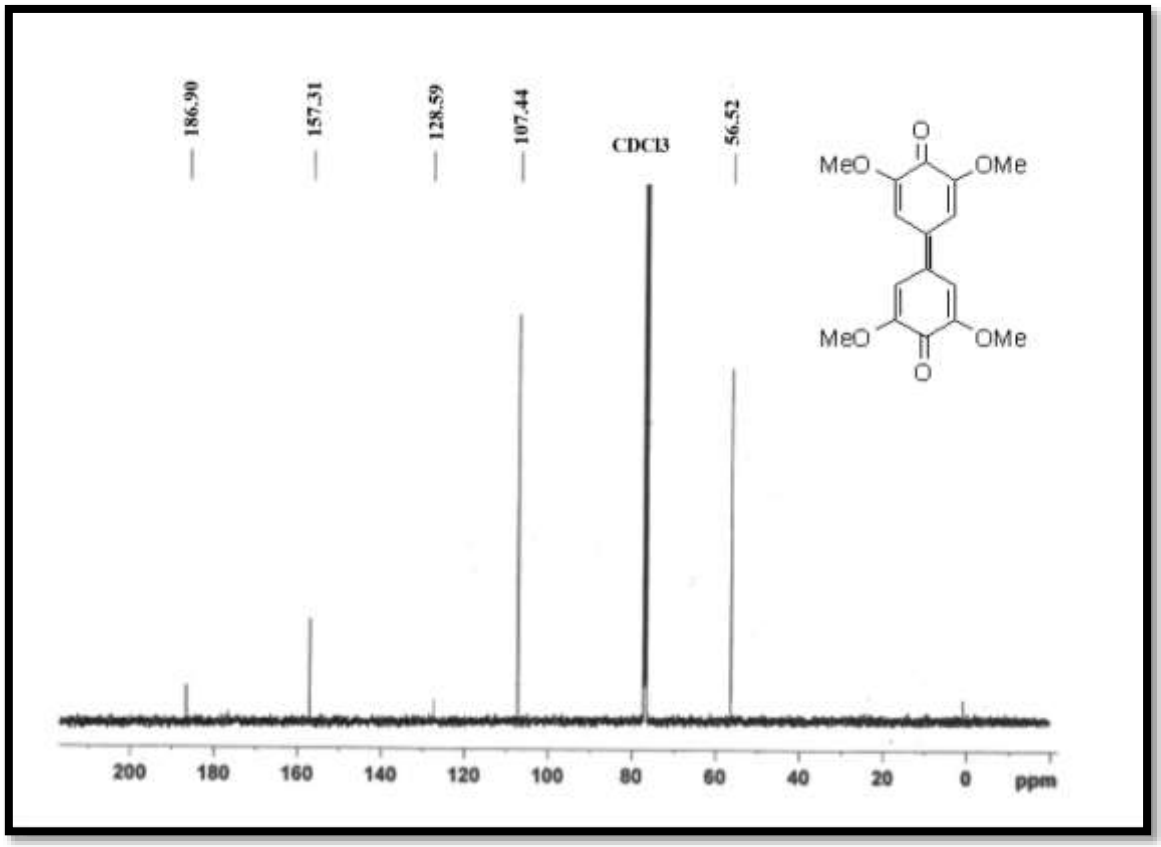
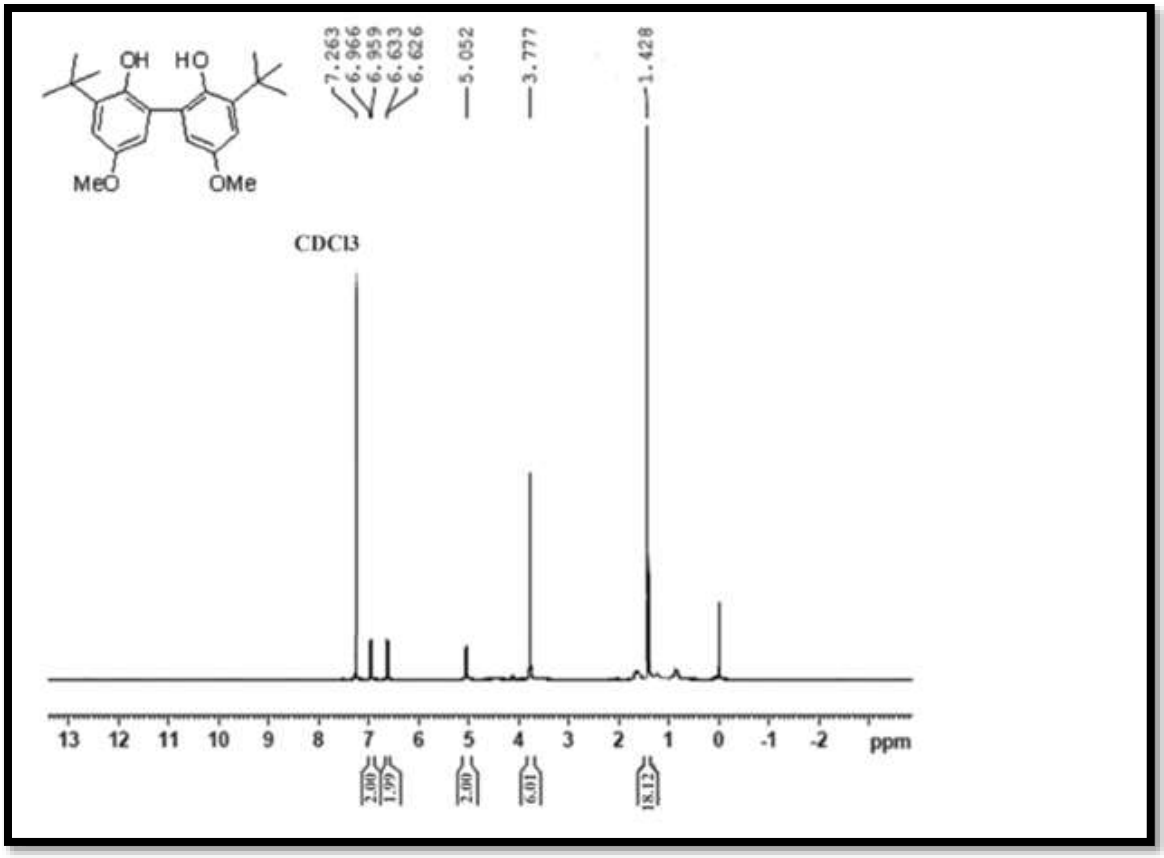


Figure F2.6.8 FT-NMR (^{1}H and ^{13}C) spectra **of 1ff**



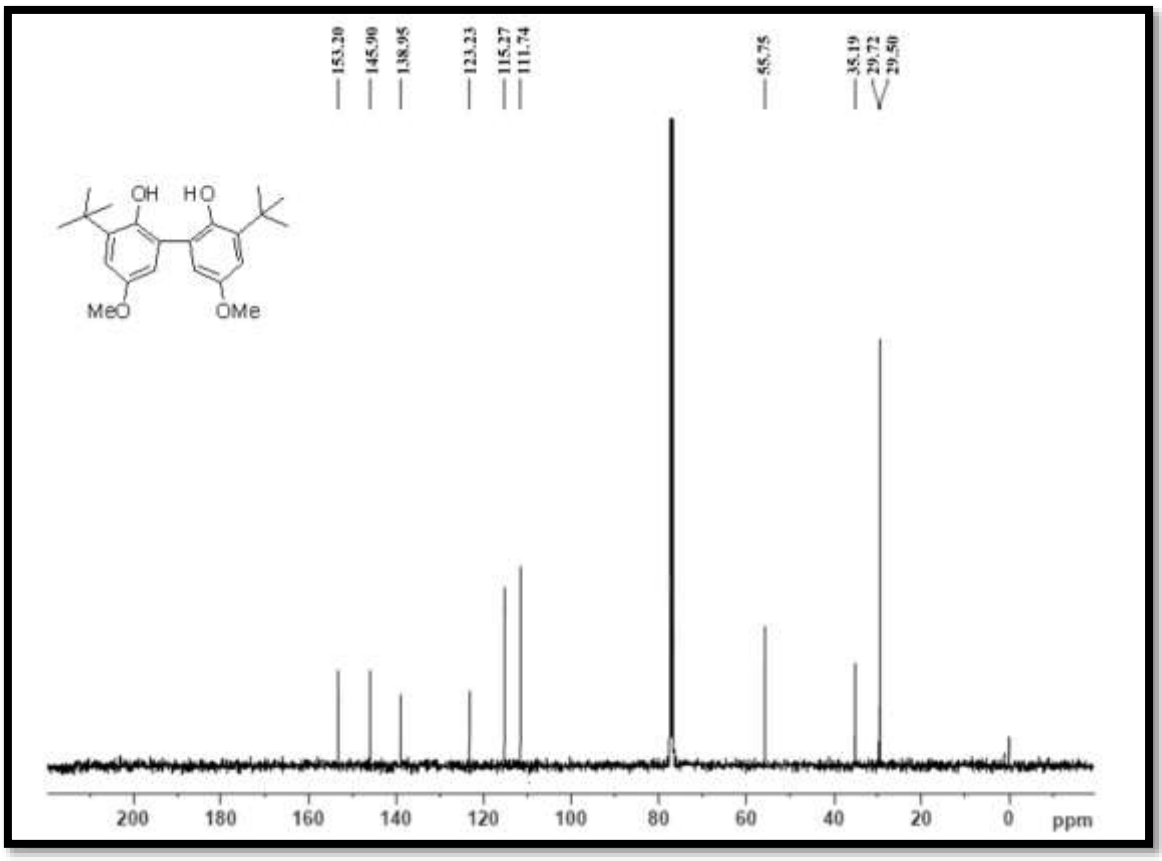
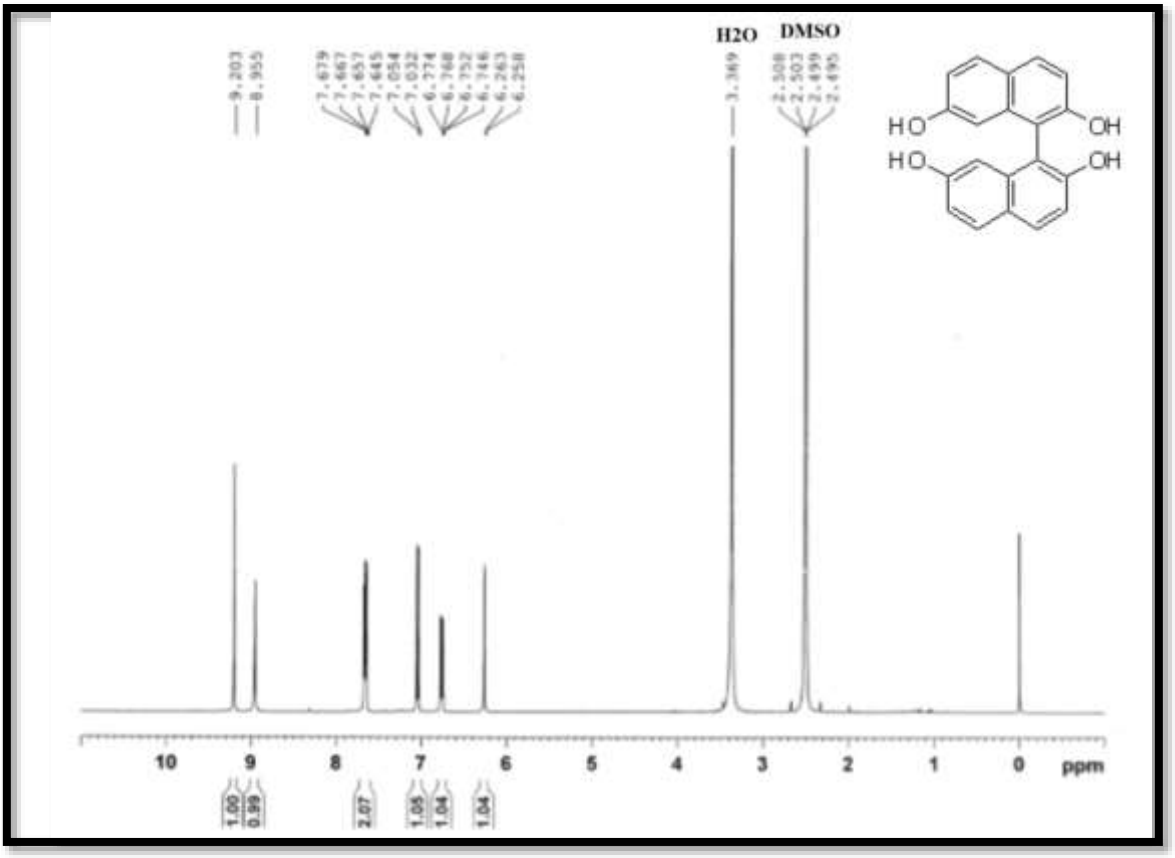


Figure F2.6.9 FT-NMR (^{1}H and ^{13}C) spectra **of 1gg**



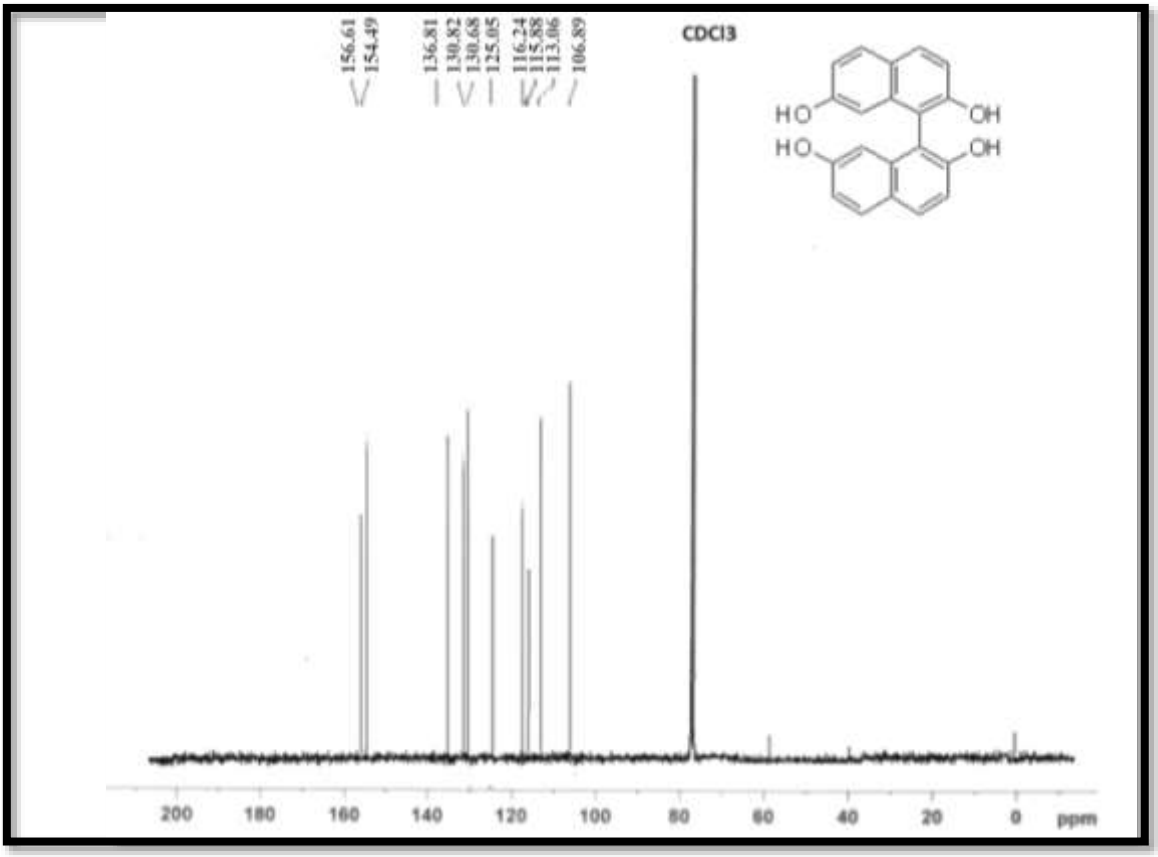


Figure F2.6.10 FT-NMR (^{1}H and ^{13}C) spectra **of 1hh**

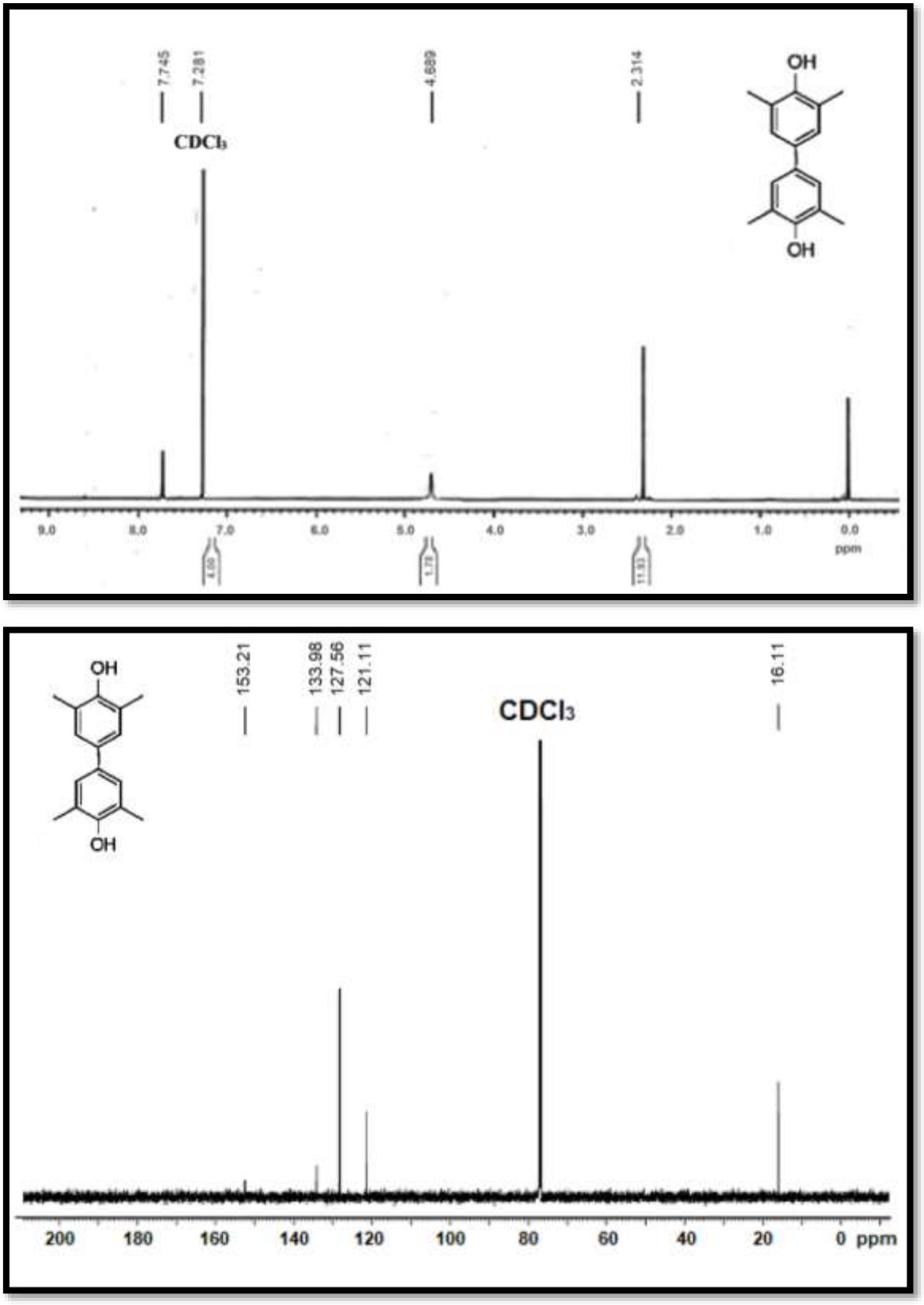
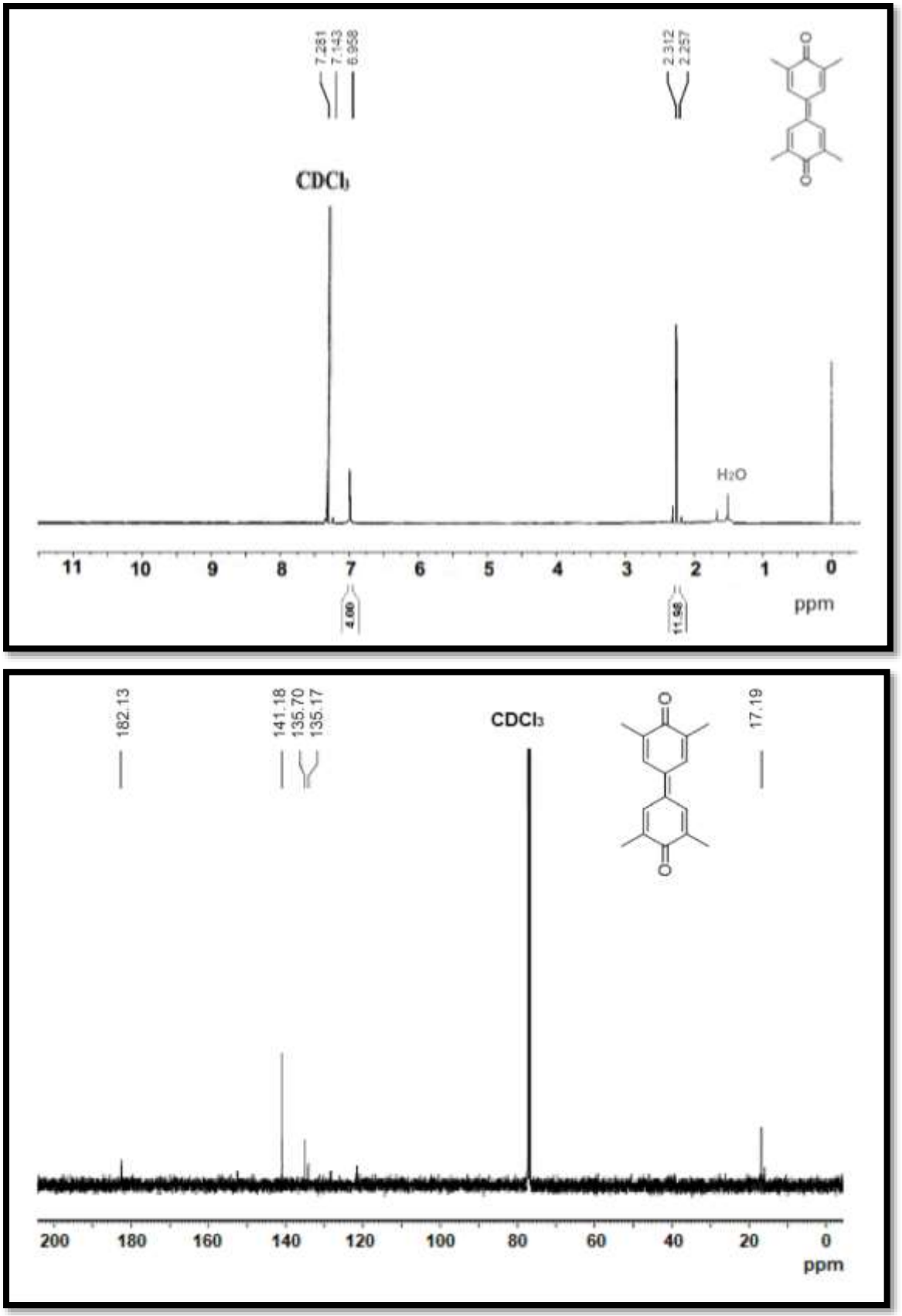


Figure F2.6.11 FT-NMR (^{1}H and ^{13}C) spectra of 2hh



2.6.2 Mass spectrometry data

Figure F2.6.12 GCMS spectra of 1aa

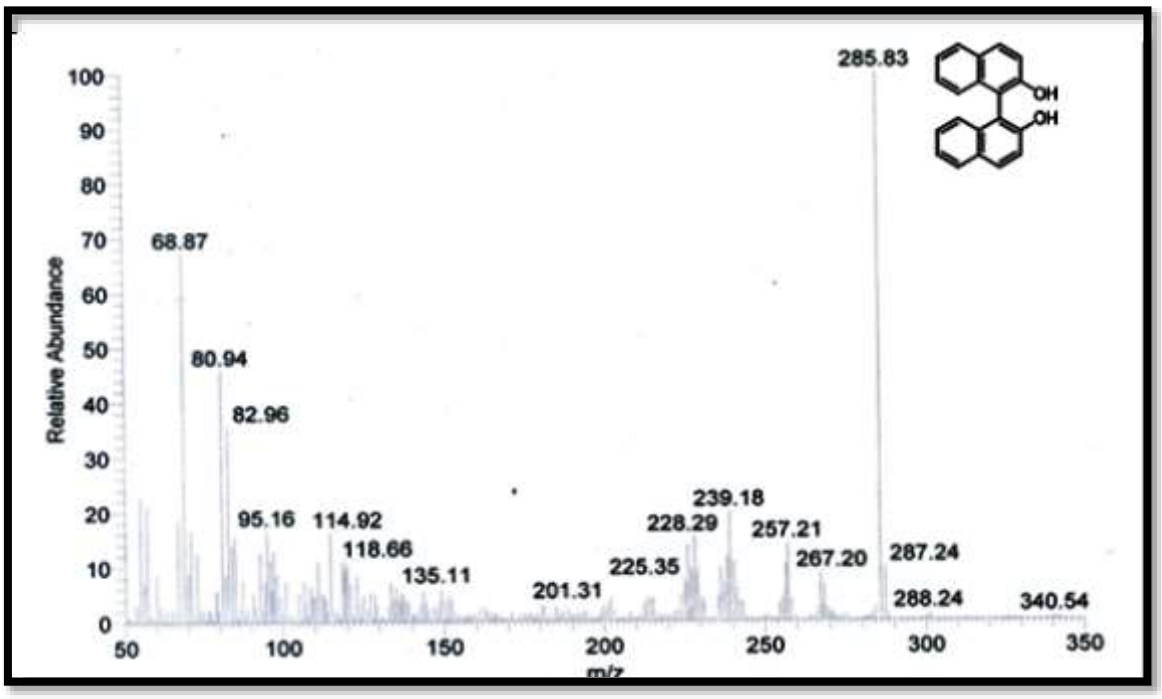


Figure F2.6.13 GC-MS spectra of 1bb

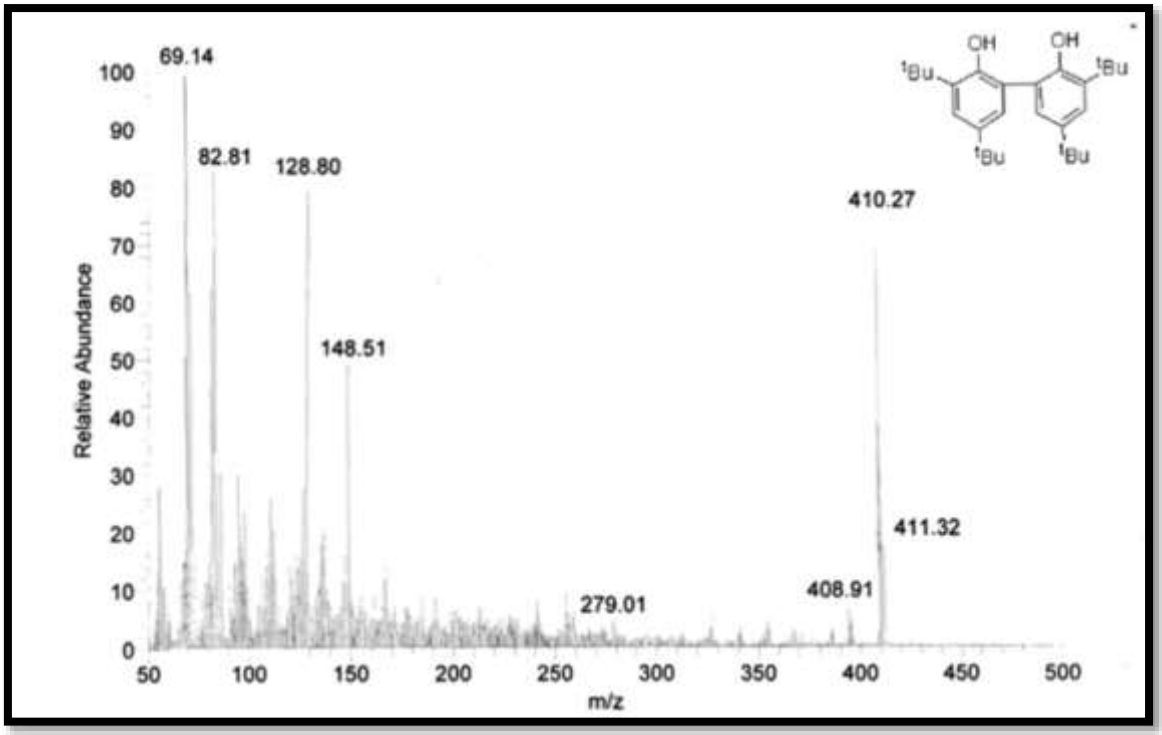


Figure F2.6.14 ESI-MS spectra of 1cc

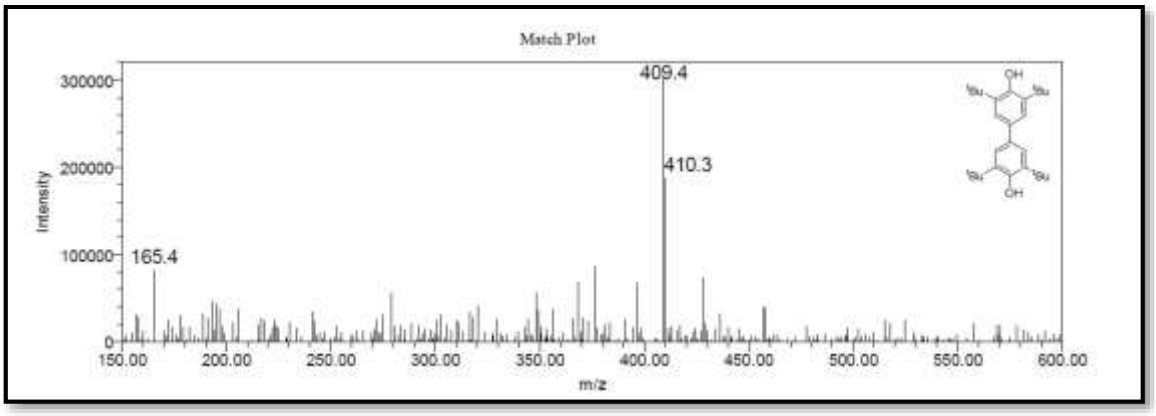


Figure F2.6.15 ESI-MS spectra of 2cc

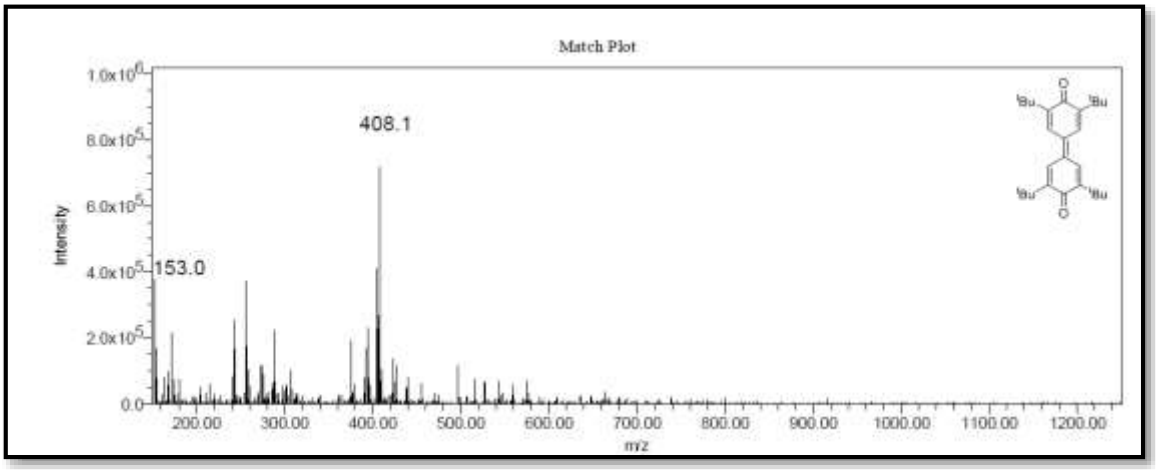


Figure F2.6.16 ESI-MS spectra of 1dd

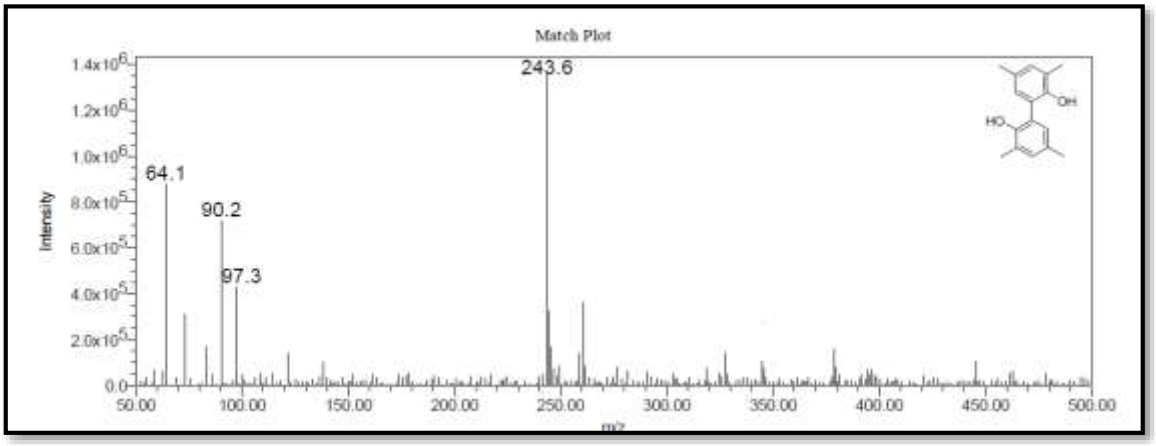


Figure F2.6.17 ESI-MS spectra of 1ee

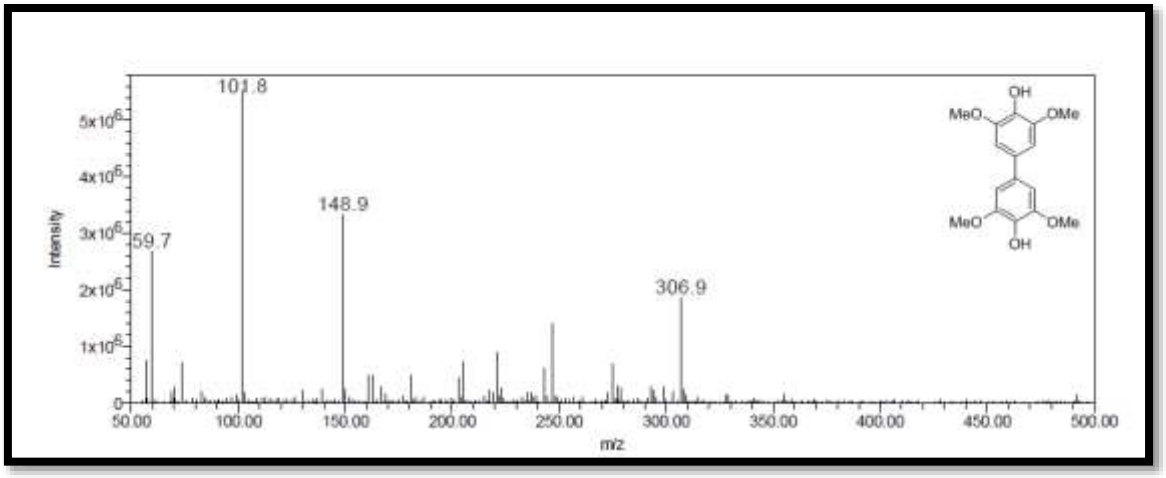


Figure F2.6.18 ESI-MS spectra of 2ee

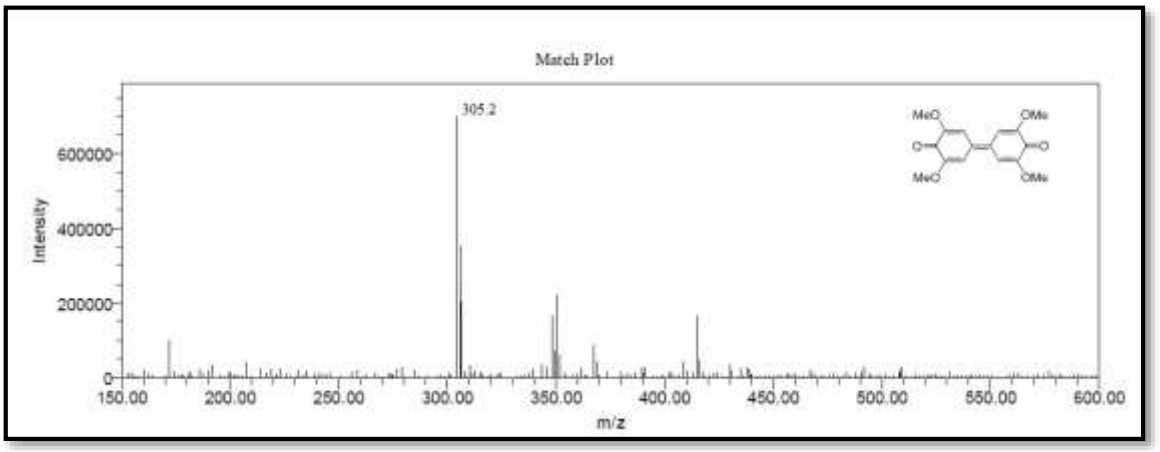


Figure F2.6.19 GC-MS spectra of 1ff

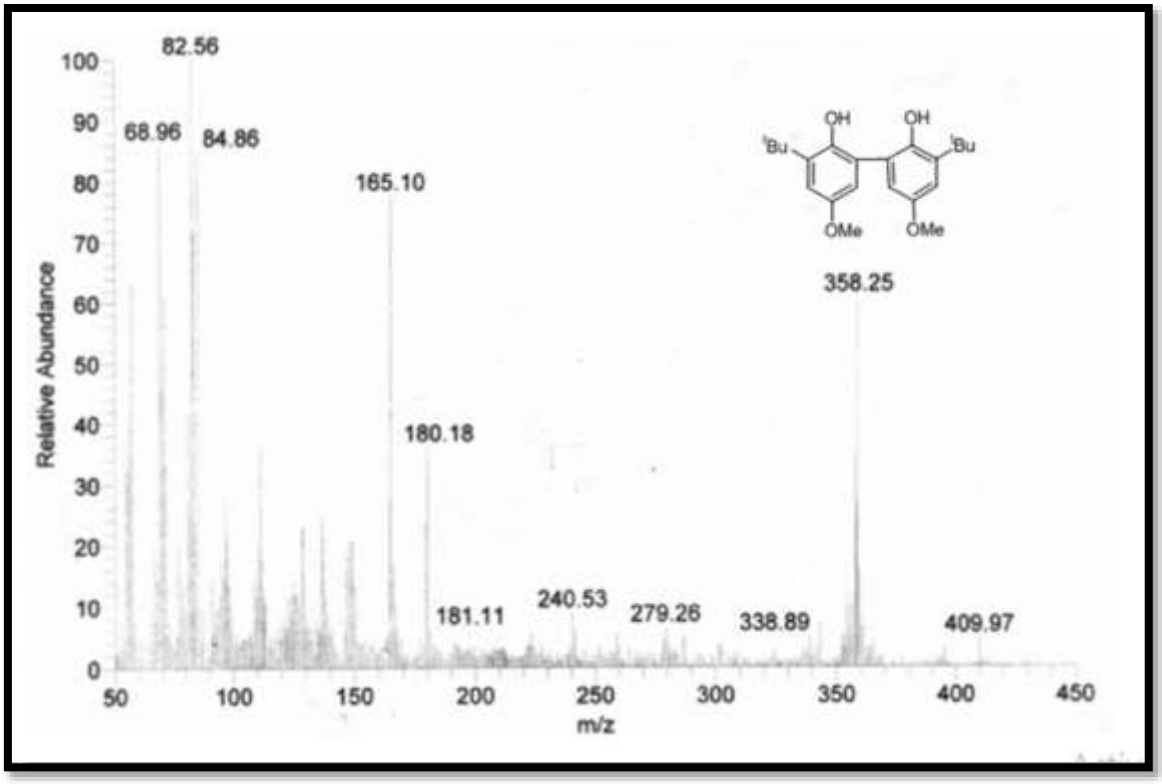


Figure F2.6.20 GC-MS spectra of 1gg

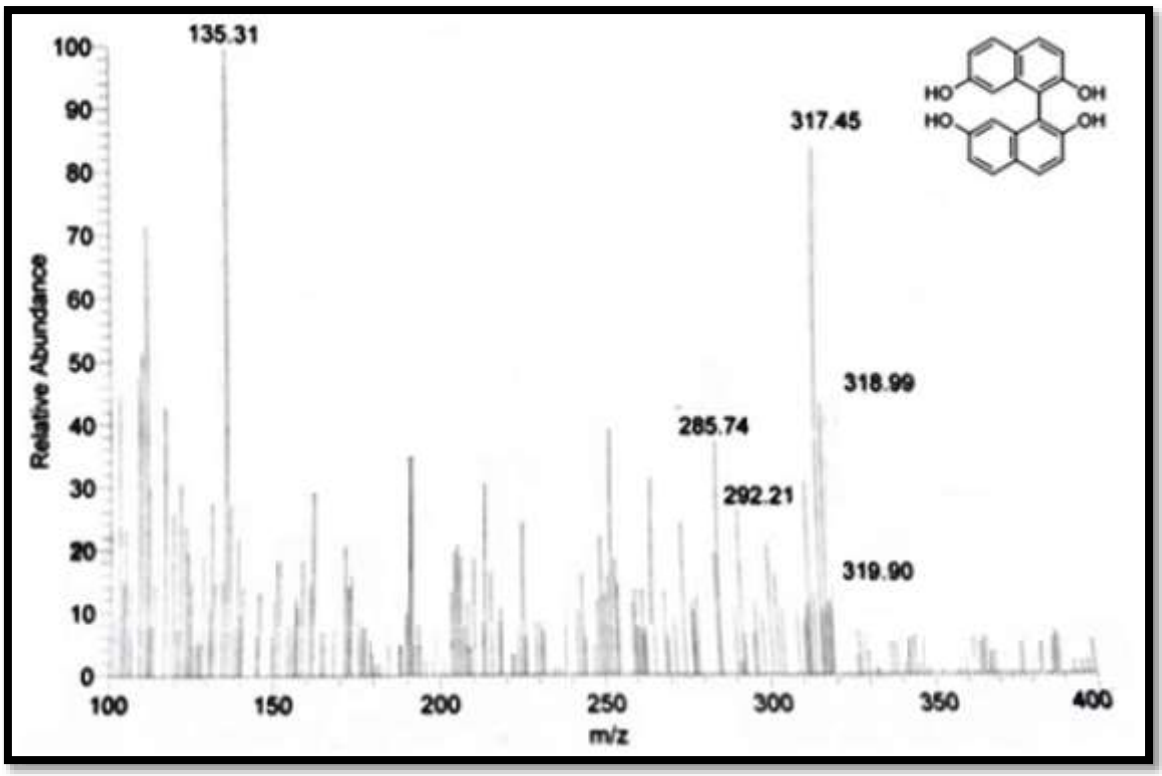


Figure F2.6.21 ESI-MS spectra of 2hh

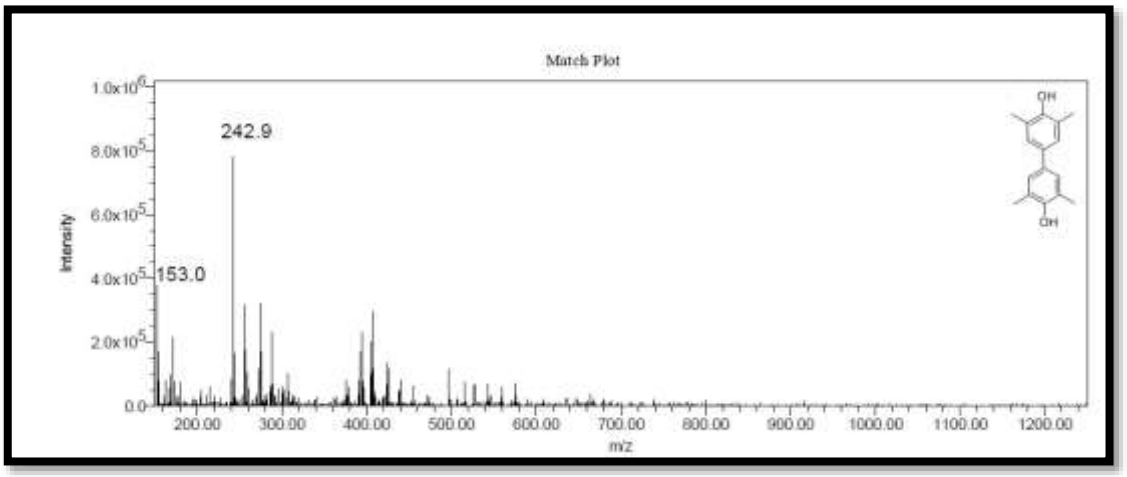
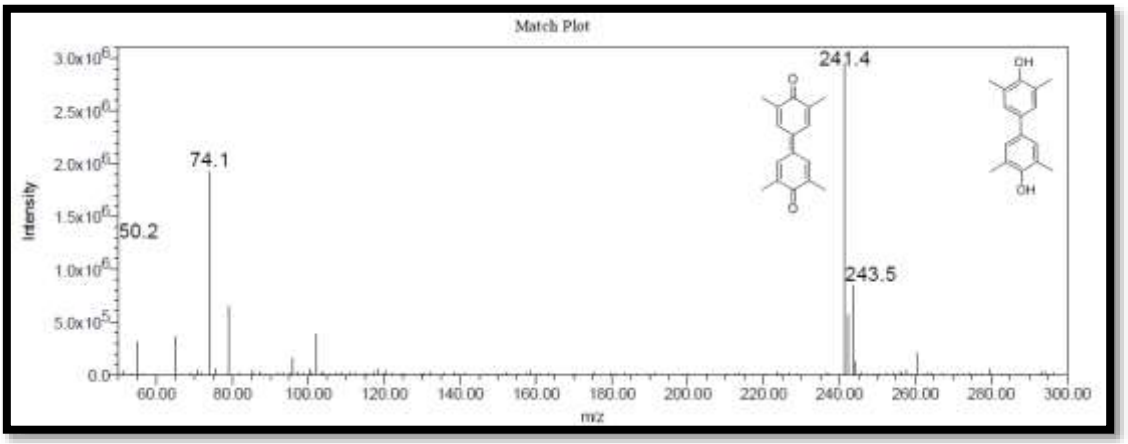


Figure F2.6.22 ESI-MS spectra of 1hh, and 2hh mixture



2.6.3 FT-IR spectral data

Figure F2.6.23 FT-IR spectra of 1aa

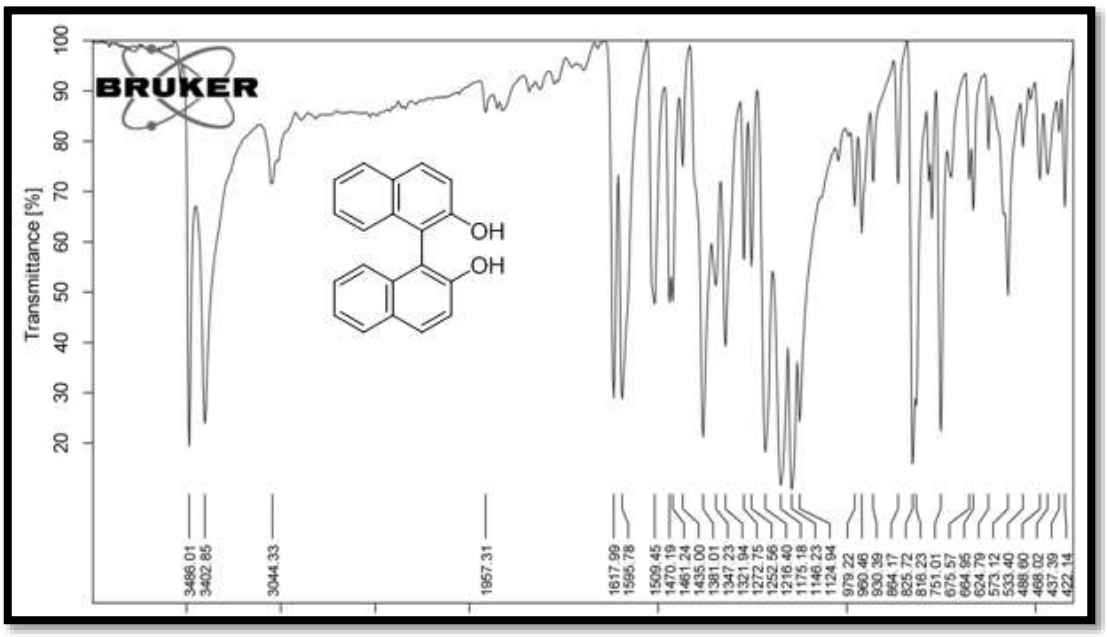


Figure F2.6.24 FT-IR spectra of 1bb

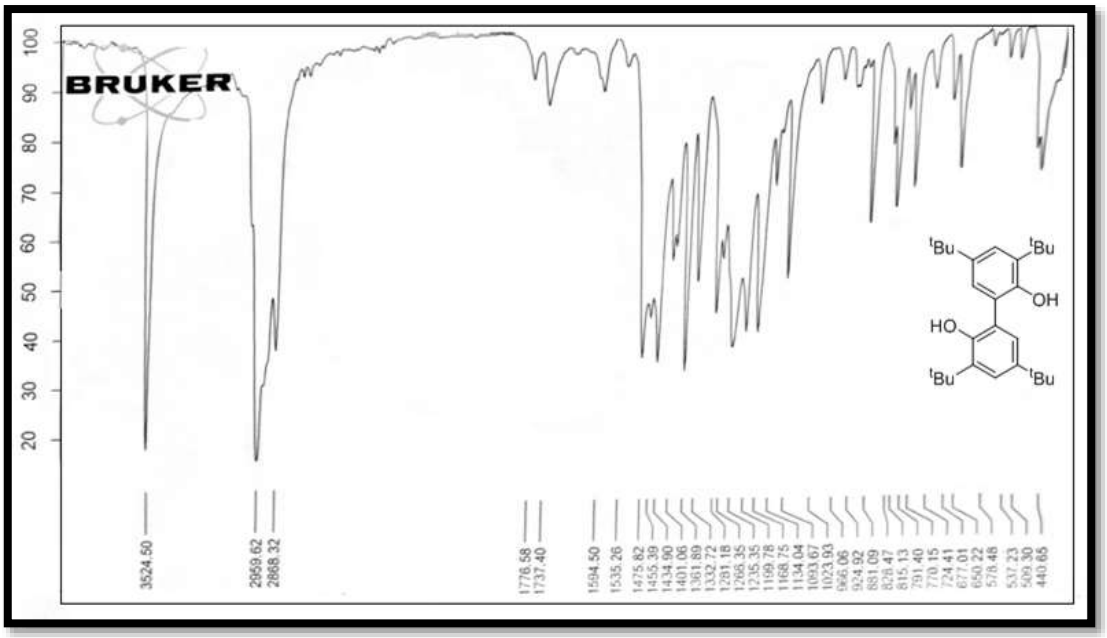


Figure F2.6.25 FT-IR spectra of 1cc

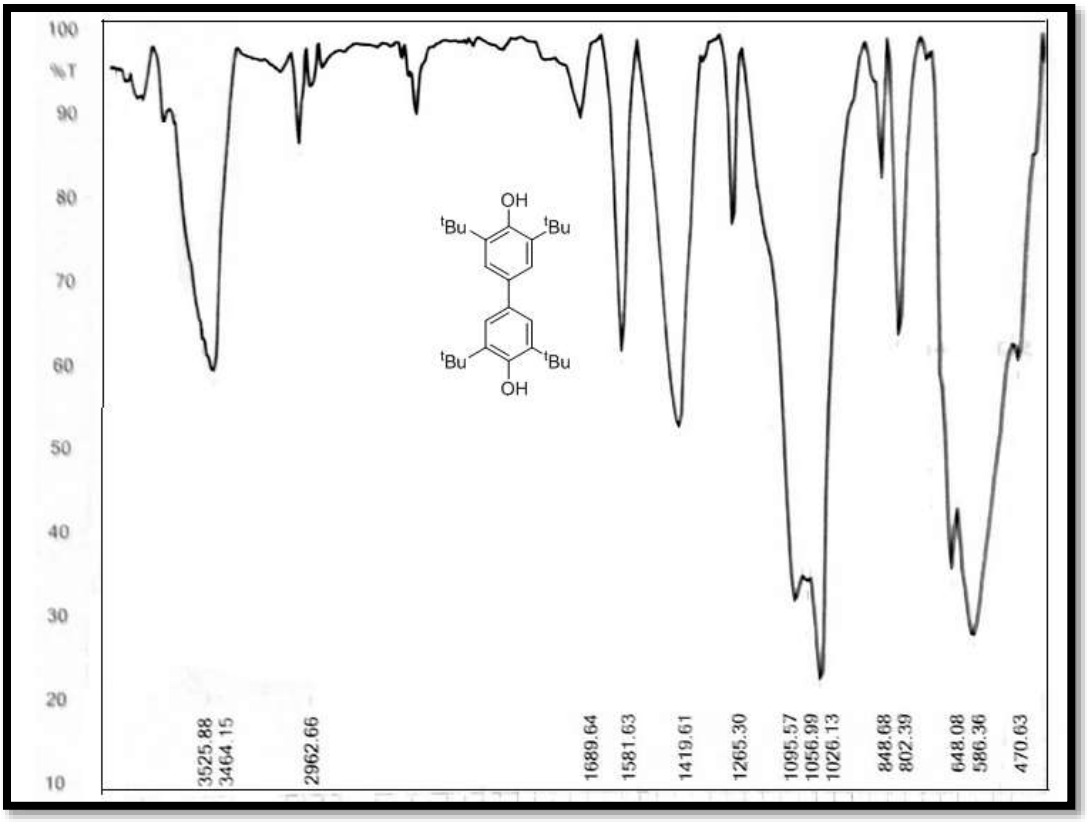


Figure F2.6.26 FT-IR spectra of 2cc

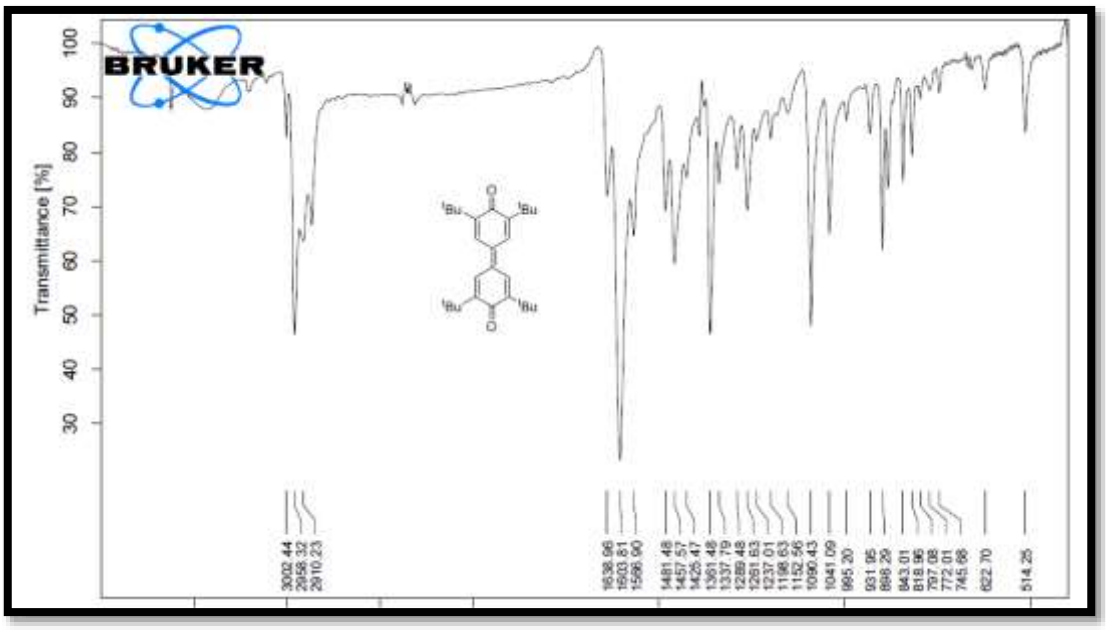


Figure F2.6.27 FT-IR spectra of 1dd

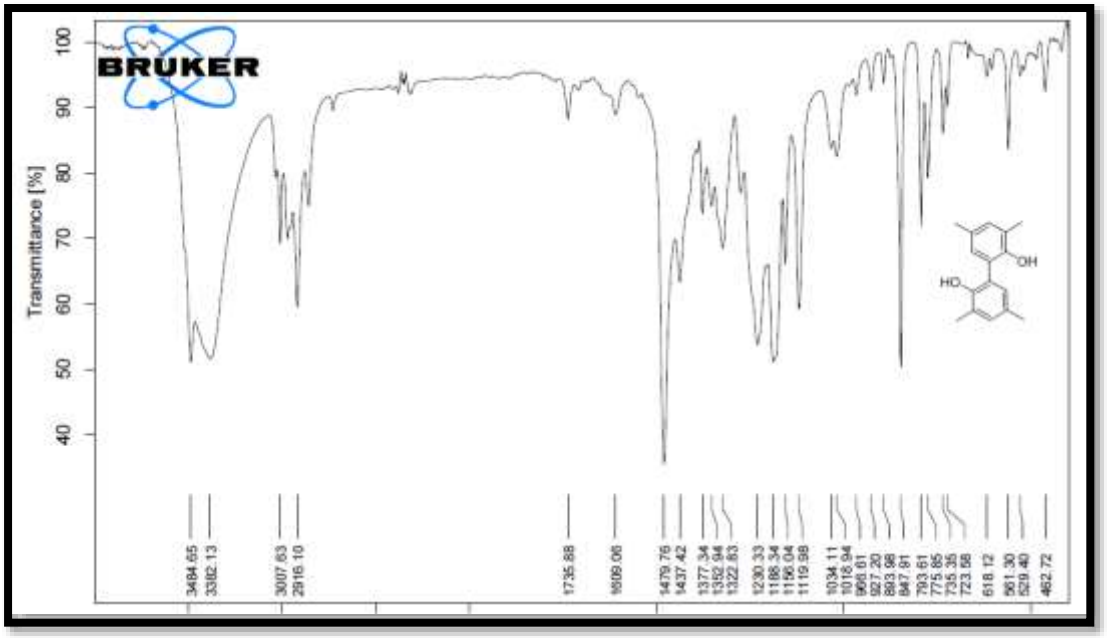


Figure F2.6.28 FT-IR spectra of 1ee

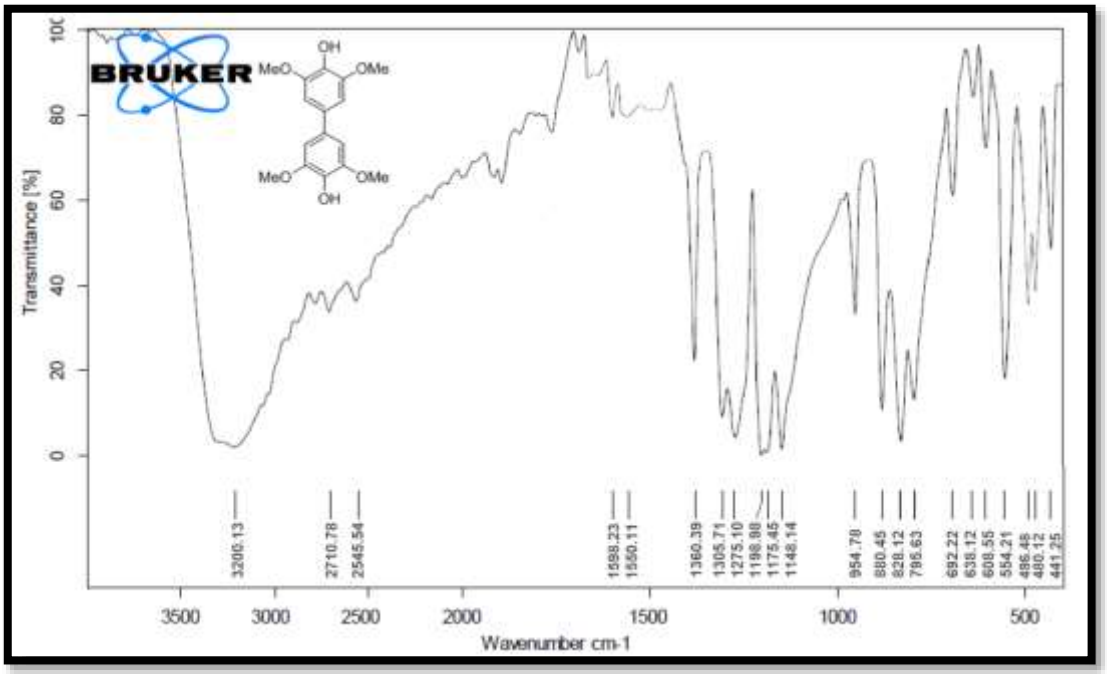


Figure F2.6.29 FT-IR spectra of 2ee

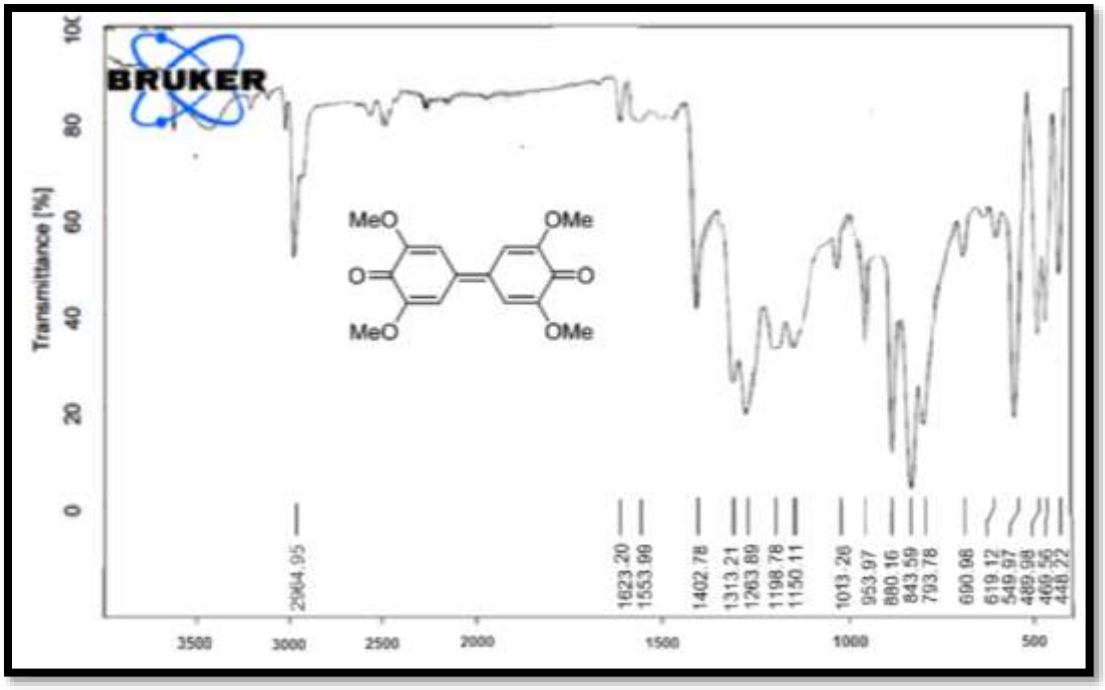


Figure F2.6.30 FT-IR spectra of 1ff

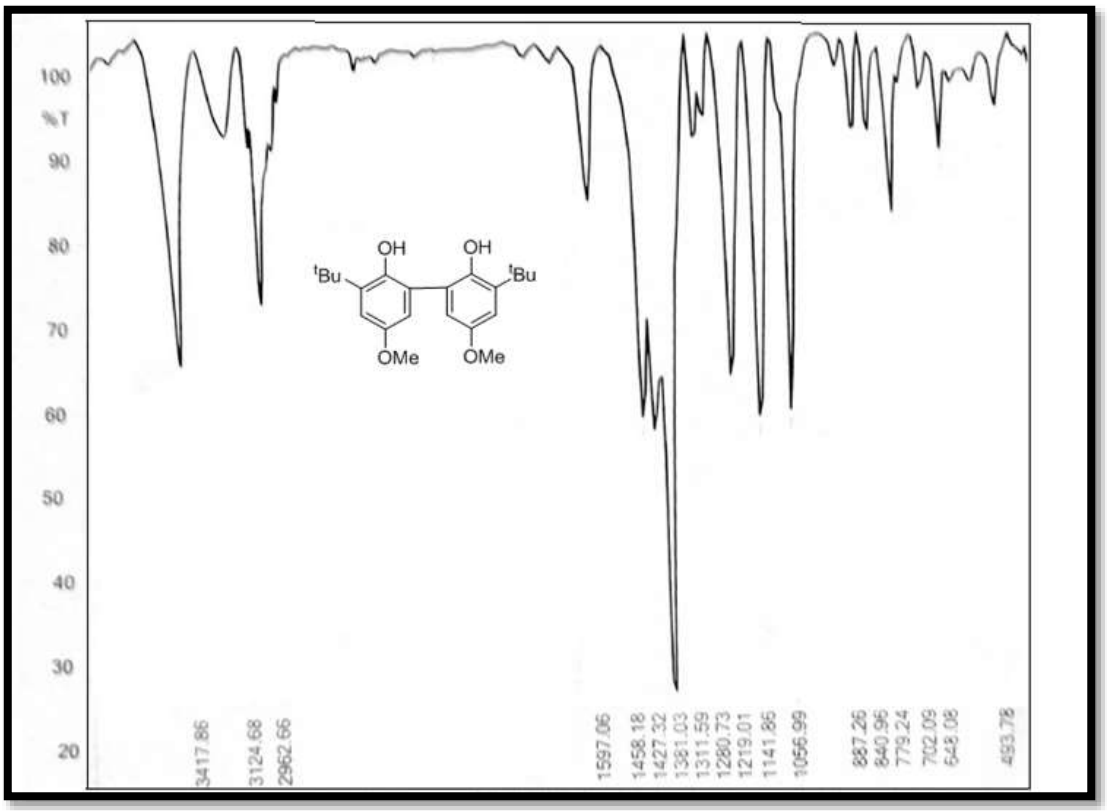


Figure F2.6.31 FT-IR spectra of 1gg

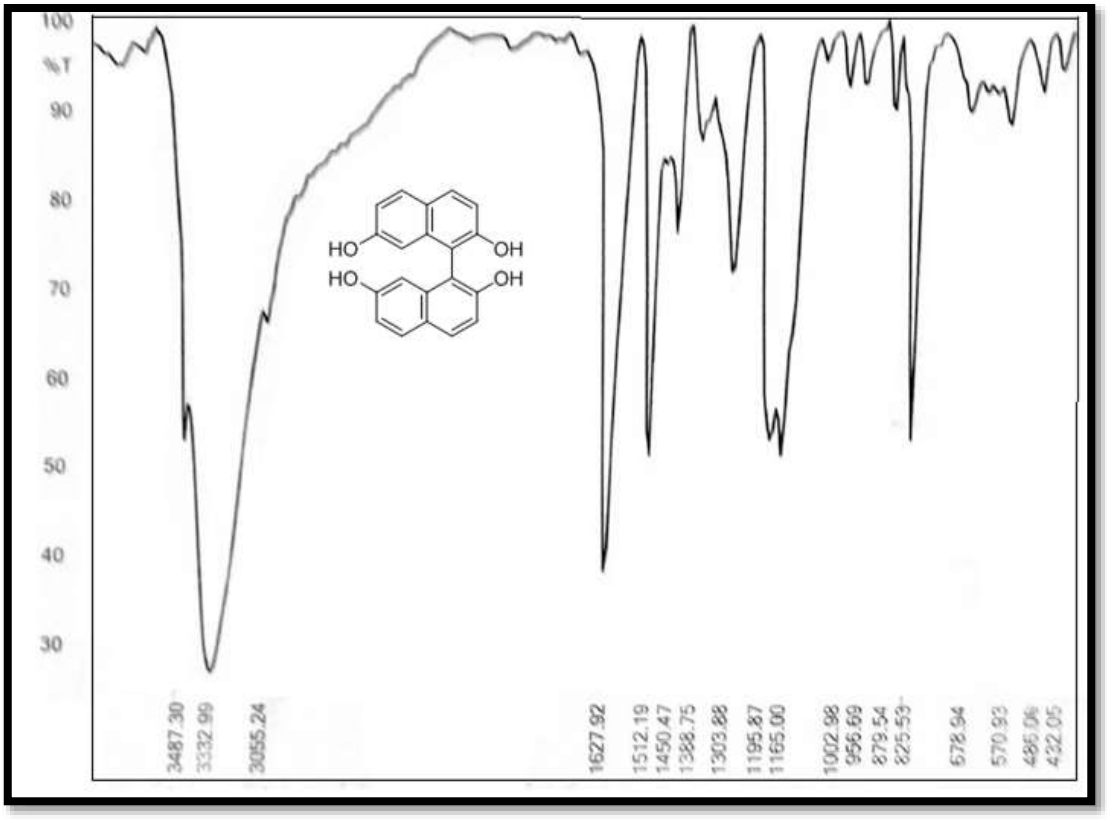


Figure F2.6.32 FT-IR spectra of 1hh

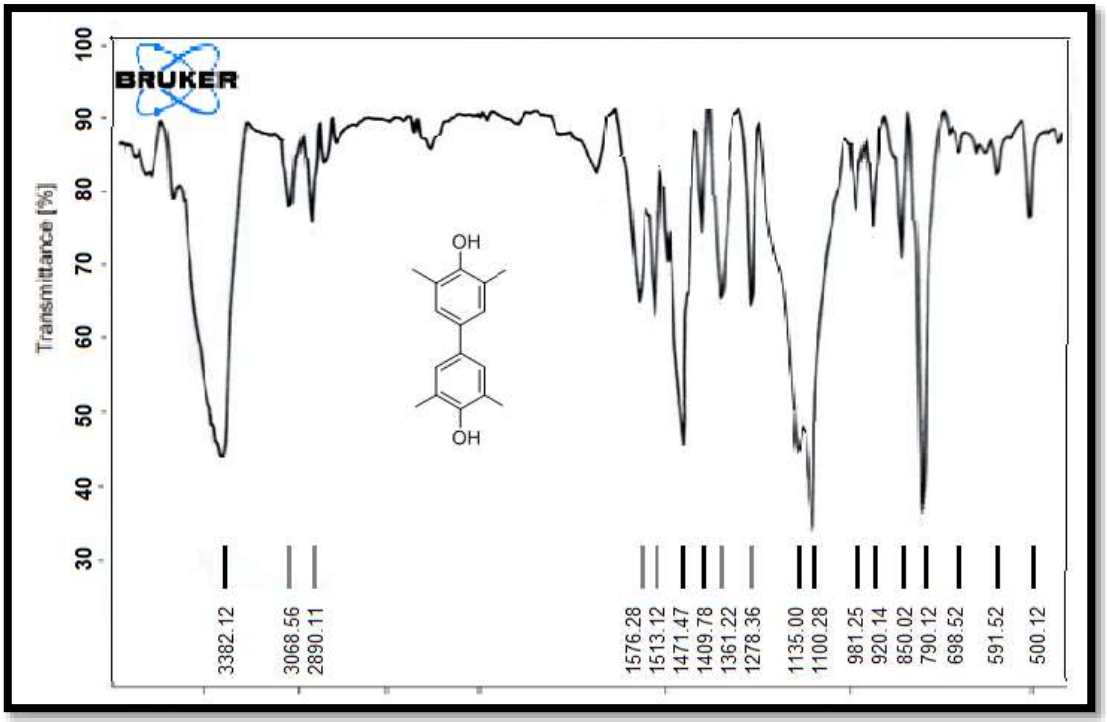
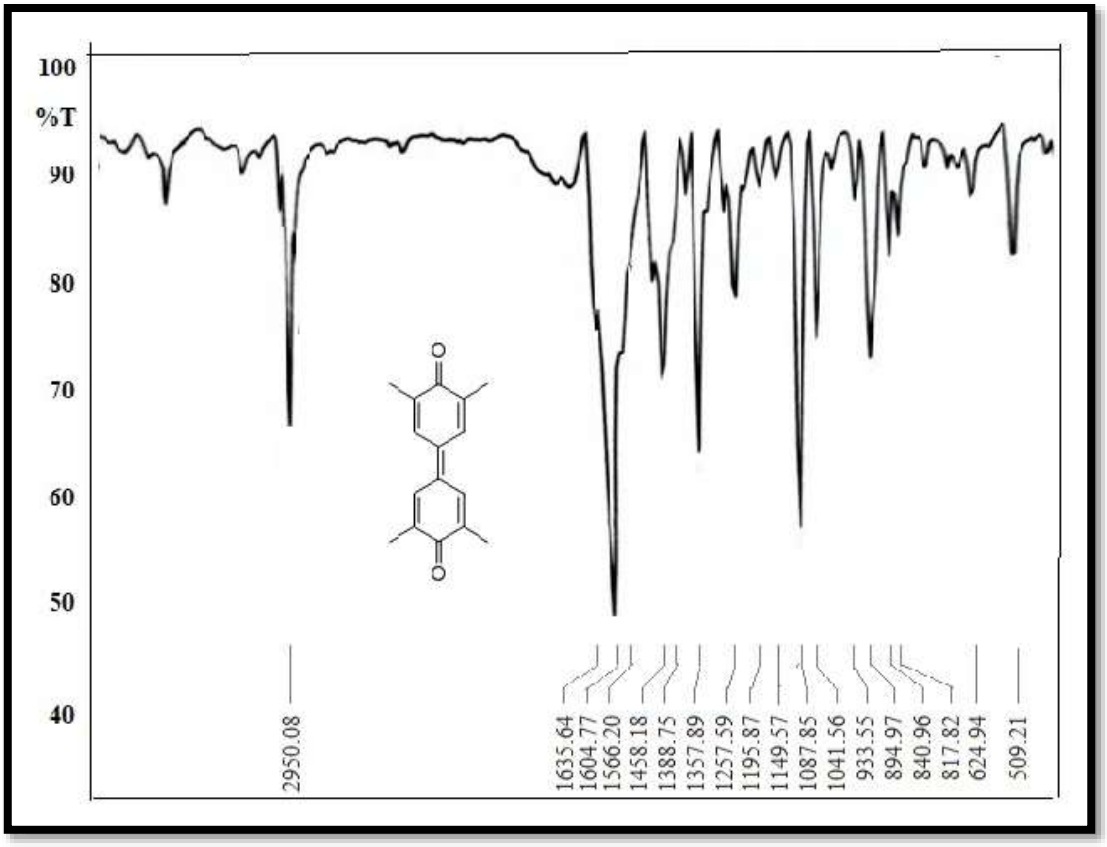


Figure F2.6.33 FT-IR spectra of 2hh



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