Thesis for the Degree of Master of Science

Facile Construction of the Benzofuran and Chromene Ring Systems via Pd^{II}-catalyzed Oxidative Cyclization

by

Jeong Im Eom

Department of Chemistry

The Graduate School

Pukyong National University

February, 2006

Facile Construction of the Benzofuran and Chromene Ring Systems via Pd^{II}-catalyzed Oxidative Cyclization

팔라듐 촉매에 의한 산화성 고리화 반응을 거친 벤조퓨란과 크로멘 고리 시스템의 용이한 합성법 개발

Advisor : Dr. So Won Youn

by
Jeong Im Eom

A thesis submitted in partial fulfillment of the requirements
for the degree of

Master of Science

in Department of Chemistry, The Graduate School,
Pukyong National University

February, 2006

Facile Construction of the Benzofuran and Chromene Ring Systems via Pd^{II}-catalyzed Oxidative Cyclization

A dissertation
by
Jeong Im Eom

Approved by :

(Chairman) : **Hyun Kwan Shim**

(Member) : **Sang Yong Pyun**

(Member) : **So Won Youn**

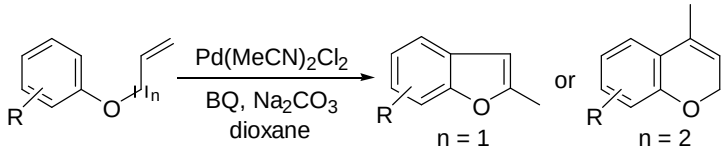
February, 2006

Facile Construction of the Benzofuran and Chromene Ring Systems via Pd^{II}-catalyzed Oxidative Cyclization

Jeong Im Eom

Department of Chemistry, The Graduate School,
Pukyong National University

Abstract



The construction of cyclic compound via transition metal catalysts is of currently considerable interest in organic chemistry. Treatment of aryl allyl ethers with $Pd(CH_3CN)_2Cl_2$, *p*-benzoquinone and Na_2CO_3 under mild condition afforded in situ the benzofurans via Claisen rearrangement and subsequent oxidative cyclization. On the other hand, aryl homoallyl ethers gave the chromenes through the direct cyclizations in the similar conditions. Pd-catalyzed intramolecular cyclizations were performed with a variety of aryl allyl ethers and aryl homoallyl ethers to provide the corresponding benzofuran and chromene derivatives. It is likely that both reactions proceed via a common Pd-catalyzed pathway involving olefin activation, nucleophilic attack, and β-hydride elimination.

Contents

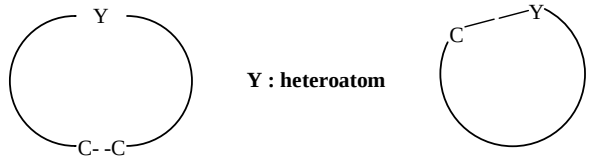
List of Scheme

List of Table

1. Introduction

Organic chemists have been making extensive efforts to produce these heterocyclic compounds by developing new and efficient synthetic transformations. Among a variety of new synthetic transformations, transition-metal-catalyzed reaction is one of the most attractive methodologies for synthesizing heterocyclic compounds, since a transition-metal-catalyzed reaction can directly construct complicated molecules from readily accessible starting materials under mild conditions. The catalytic construction of heterocyclic skeletons is classified into two major processes, as shown in Scheme 1: (1) C-C bond formation from the corresponding acyclic precursors and (2) C-Y bond formation from the corresponding acyclic precursors.

Scheme 1. Two Major Processes of Heterocycle Synthesis



(1) C-C bond formation **(2) C-Y bond formation**

Four-, five- or six-membered heterocycles can be synthesized, depending on the partner of the intra- and intermolecular reaction. The intramolecular reaction of aryl and vinyl halides via Heck-, Suzuki-, and Stille-type reactions proceeds through the C-C bond formation and that via the coupling with a heteroatom proceeds through the C-Y bond formation. Transition-metal-catalyzed intramolecular reactions of carbon-carbon unsaturated compounds tethered with N-H, O-H, C=O, and C=N groups

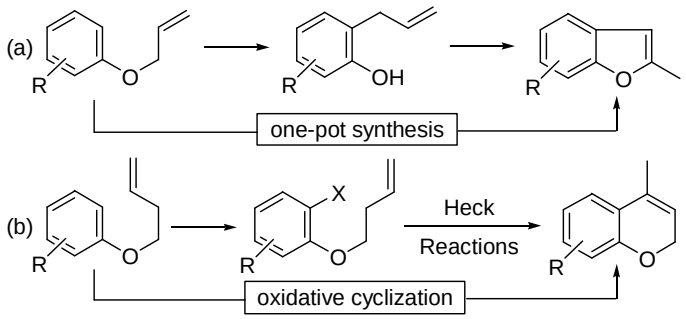
have been extensively studied and have become a powerful tool for the synthesis of heterocycles. Alkenes, allenes, methylenecyclopanes, and alkynes have been utilized as a carbon-carbon unsaturated compound, and a wide variety of transition-metal complexes, such as palladium, platinum, gold, copper, titanium, tungsten, and organolanthanides, have been used as a catalyst. In these reactions the heterocyclic compounds are produced via carbon-heteroatom (C-Y) bond formation.[1]

Among the various synthesis of heterocycles, palladium-catalyzed oxidative cyclizations have had a significant impact upon organic synthesis and are now reliable and well-used processes. Intramolecular variants of these reactions, leading to the synthesis of a variety of heterocyclic structures, have also received considerable attention. In this paper, we demonstrate that palladium-catalyzed intramolecular cyclization of allyl aryl ethers and aryl homoallyl ethers is an efficient process and can be used to prepare a variety of substituted benzofurans and chromenes.

Benzofurans and chromenes have attracted considerable attention due to their biological activity and their presence in a variety of significant natural products.[2] Consequently, a number of synthetic strategies have been reported for the construction of benzofurans[3,4] and chromenes[5]. A common approach to the benzofuran ring system consists of Claisen rearrangement[6] of an allyl aryl ether followed by Pd-catalyzed intramolecular oxidative cyclization[4c-f] of the corresponding 2-allylphenol, accomplishing the overall transformation in two discrete reactions (Scheme 2). Chromenes are also constructed by a two step sequence, typically involving prefunctionalization of the arene (*e.g.*, halogenation at the 2-position) followed by Heck-type cyclization.[5d-f] We were interested in developing a one-pot synthesis of benzofurans from allyl aryl ethers whereby a single catalytic system would invoke sequential Claisen rearrangement and oxidative cyclization.[7] Similarly, we proposed that the direct oxidative coupling of unactivated arene and olefin components of aryl homoallyl ethers would be an efficient

route to the chromene core, obviating the need for prehalogenation. Herein we report simple, convenient methods for the one-pot synthesis of benzofurans by Claisen rearrangement and subsequent oxidative cyclization of allyl aryl ethers and for the synthesis of chromenes by direct oxidative cyclization of aryl homoallyl ethers.

Scheme 2. General Methods for Synthesis of Benzofurans and Chromenes



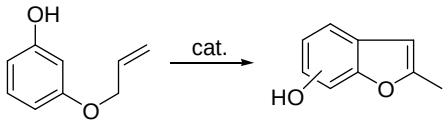
2. Results and Discussion

2.1. Palladium-Catalyzed Intramolecular Cyclizations of Allyl Aryl Ethers for the Synthesis of Benzofuran Derivatives

We focused our initial efforts in this area on the one-pot synthesis of benzofuran **2** from allyl aryl ether **1**. Transition metal complexes that were previously reported to either promote Claisen rearrangement[6] or facilitate the oxidative cyclization of 2-allylphenols[4c-f] were included in the screen (Table 1). Metal complexes were examined in a variety of solvents and the effects of oxidants and bases were studied. When the reaction was carried out with a stoichiometric amount of $Pd(CH_3CN)_2Cl_2$ at room temperature, **1** was completely consumed in 4 h and benzofuran **2** was formed in 30% yield, presumably as a result of Pd-catalyzed Claisen rearrangement followed by oxidative cyclization (Table 1, entry 1). Analysis of the crude reaction mixture by ^1H NMR showed the remainder of the material to be either products of ether cleavage or uncyclized Claisen products, reaffirming our initial worries that these side reactions would be problematic. The formation of benzofuran instead of dihydrobenzofuran suggested that β-hydride elimination had occurred, followed by isomerization of the initially formed exocyclic olefin to the thermodynamically preferred benzofuran. This indicated that a stoichiometric oxidant would be required for the catalytic conversion of **1** to **2**. In accord with this hypothesis, treatment of **1** with a catalytic amount of $Pd(CH_3CN)_2Cl_2$ and a stoichiometric amount of 1,4-benzoquinone in 1,4-dioxane at room temperature for 5 h led to **2** in 54% yield (Table 1, entry 8). In addition to $Pd(CH_3CN)_2Cl_2$, $Pd(PhCN)_2Cl_2$ served as an effective catalyst for this reaction (Table 1, entry 10). Conversely, $PtCl_2$, $RuCl_3$, and other Pd(II) sources were not effective (Table 1, entries 9-14). It was also found that 1,4-benzoquinone was the optimal oxidant in this reaction system (Table 1, entries 17 & 21-22). We supposed

that the addition of base would promote the cyclization of the Claisen-derived intermediate allylphenol, since the phenolic hydroxyl should be deprotonated in order to act as nucleophile toward the olefin fragment, either directly or through coordination to Pd.[4b-f,8] As expected, the inclusion of Na_2CO_3 provided increased yield (Table 1, entry 17). Finally, increasing the temperature to 65 ^oC led to the optimal result in the presence of 5 mol% $Pd(CH_3CN)_2Cl_2$, 1,4-benzoquinone, and Na_2CO_3, providing benzofuran **2** in 66% yield (Table 1, entry 26).

Table 1. Optimization Studies for the Cyclization of Compound **1**[a]



1 **2**

Entry	Catalyst (mol%)	Oxidant	Base	Solvent	Temp (^oC)	Time (h)	Yield (%)[b]
1	$Pd(MeCN)_2Cl_2$ (100)	-	-	dioxane	rt	4	30
2	$Pd(MeCN)_2Cl_2$ (100)	-	Cs_2CO_3	dioxane	rt	4	54
3	$Pd(MeCN)_2Cl_2$ (100)	-	Cs_2CO_3	MeCN	rt	4	3
4	$Pd(MeCN)_2Cl_2$ (100)	-	Cs_2CO_3	THF	rt	4	13
5	$Pd(MeCN)_2Cl_2$ (100)	-	Cs_2CO_3	Toluene	rt	4	-
6	$Pd(MeCN)_2Cl_2$ (100)	-	Cs_2CO_3	CH_2Cl_2	rt	4	43
7	$Pd(MeCN)_2Cl_2$ (20)	-	-	dioxane	rt	24	18
8	$Pd(MeCN)_2Cl_2$ (20)	BQ	-	dioxane	rt	5	54
9	$Pd(OAc)_2$ (20)	BQ	-	dioxane	rt	5	-
10	$Pd(PhCN)_2Cl_2$ (20)	BQ	-	dioxane	rt	5	50
11	$Pd(PPh_3)_2Cl_2$ (20)	BQ	-	dioxane	rt	5	-
12	$PdCl_2$ (20)	BQ	-	dioxane	rt	5	trace
13	$PtCl_2$ (20)	BQ	-	dioxane	rt	5	-
14	$RuCl_3$ (20)	BQ	-	dioxane	rt	5	-

15	$Pd(MeCN)_2Cl_2$ (20)	BQ	NaOAc	dioxane	rt	5	trace
16	$Pd(MeCN)_2Cl_2$ (20)	BQ	Li_2CO_3	dioxane	rt	5	21
17	$Pd(MeCN)_2Cl_2$ (20)	BQ	Na_2CO_3	dioxane	rt	5	60
18	$Pd(MeCN)_2Cl_2$ (20)	BQ	K_2CO_3	dioxane	rt	5	48
19	$Pd(MeCN)_2Cl_2$ (20)	BQ	Cs_2CO_3	dioxane	rt	5	-
20	$Pd(MeCN)_2Cl_2$ (20)	BQ	NEt_3	dioxane	rt	5	-
21	$Pd(MeCN)_2Cl_2$ (20)	$CuCl_2$	Na_2CO_3	dioxane	rt	5	trace
22	$Pd(MeCN)_2Cl_2$ (20)	$Cu(OAc)_2$	Na_2CO_3	dioxane	rt	5	5
23	$Pd(MeCN)_2Cl_2$ (10)	BQ	Na_2CO_3	dioxane	rt	24	37
24	$Pd(MeCN)_2Cl_2$ (10)	BQ	Na_2CO_3	dioxane	80	0.5	52
25	$Pd(MeCN)_2Cl_2$ (5)	BQ	Na_2CO_3	dioxane	80	1	53
26	$Pd(MeCN)_2Cl_2$ (5)	BQ	Na_2CO_3	dioxane	65	5	66
27	$Pd(MeCN)_2Cl_2$ (2)	BQ	Na_2CO_3	dioxane	80	12	trace

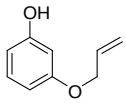
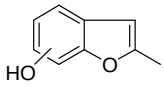
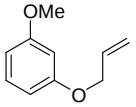
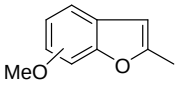
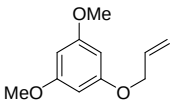
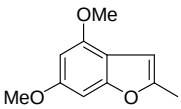
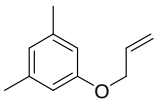
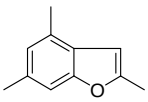
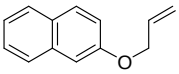
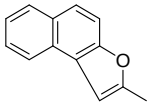
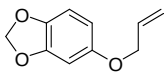
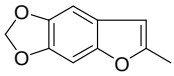
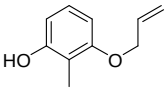
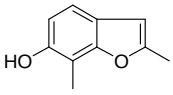
[a] All reactions were carried out with catalyst, base (1 equiv), and oxidant (1 equiv) in dioxane (0.015 M). [b] Determined by ^1H NMR using trichloroethylene as an internal standard.

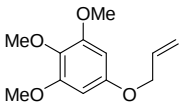
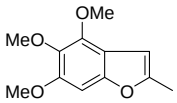
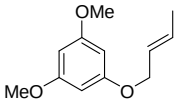
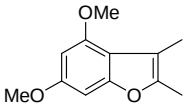
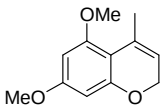
With the establishment of a viable one-pot reaction system, we set out to explore the scope of this sequential process. As shown in Table 2, a variety of allyl aryl ethers underwent tandem Claisen rearrangement/ oxidative cyclization in the presence of $Pd(CH_3CN)_2Cl_2$ to form the corresponding benzofurans.

This method was compatible with functional groups such as methoxy, methylenedioxy, and free hydroxyl. While reactions of electron rich arenes were facile, higher catalyst loading and increased temperatures were required for relatively electron deficient arenes (Table 2, entry 2 and entries 4-5). It should be noted that in addition to producing the desired benzofuran product **18,** aryl crotyl ether **17** yielded a small amount of chromene product **19**, which could have formed through either direct oxidative coupling of the arene to the alkene or 6-*endo* cyclization of the Claisen-derived 2-(α-methylallyl)phenol. The former seems more plausible,

since 5-*exo* cyclization occurs predominantly over 6-*endo* in the Pd^{II}-catalyzed oxidative cyclization of 2-allylphenols.[4c-f,9] This result prompted us to extend the application of our catalytic system to the formation of chromenes from aryl homoallyl ethers via direct oxidative cyclization.

Table 2. Pd-Catalyzed Benzofuran Synthesis.[a]

Entry	Substrate	Product (%)[b]
1[c]	 **1**	 **2** (54) (p - : o - = 84 : 16)[h]
2[d]	 **3**	 **4** (51) (p - : o - = 84 : 16)[h]
3[c]	 **5**	 **6** (60)
4[e]	 **7**	 **8** (49)
5[d]	 **9**	 **10** (57)
6[f]	 **11**	 **12** (62)
7[g]	 **13**	 **14** (49)

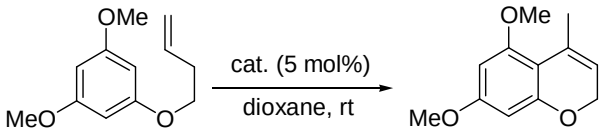
8 [c]	 **15**	 **16** (66)	
9 [e]	 **17**	 **18** (31)	 **19** (12)

[a] All reactions were performed with $Pd(MeCN)_2Cl_2$, Na_2CO_3 (1 equiv), and BQ (1 equiv) in dioxane (0.015 M) for 1-5 hours. [b] Isolated yields. [c] Performed with 5 mol % $Pd(MeCN)_2Cl_2$ at 65 °C. [d] Performed with 20 mol % $Pd(MeCN)_2Cl_2$ at 80 °C. [e] Performed with 25 mol % $Pd(MeCN)_2Cl_2$ at 80 °C. [f] Performed with 10 mol % $Pd(MeCN)_2Cl_2$ at 80 °C. [g] Performed with 10 mol % $Pd(MeCN)_2Cl_2$ at 65 °C. [h] The ratios were determined by ^1H NMR of the mixture.

2.2. Palladium-Catalyzed Intramolecular Cyclizations of Aryl Homoallyl Ethers for the Synthesis of Chromene Derivatives

Since palladium dichloride complexes are known to catalyze olefin isomerization,[10] we worried that, upon exposure to the catalytic system we had developed for the tandem Claisen rearrangement/oxidative cyclization, an aryl homoallyl ether such as **20** might simply isomerize to the aryl crotyl ether **17**, and then undergo conversion to a similar mixture of products **18** and **19**. To our delight, cyclization of **20** at room temperature in the presence of $Pd(CH_3CN)_2Cl_2$ gave chromene **19** in 77% yield without any detectable amount of benzofuran **18** (Table 3, entry 4).

Table 3. Optimization Studies for the Cyclization of Compound **20**.[a]



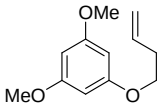
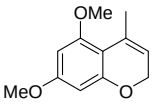
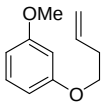
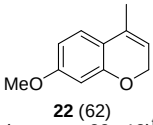
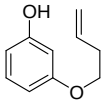
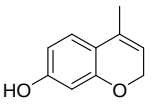
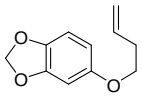
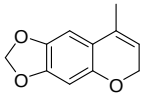
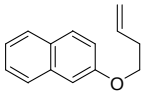
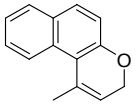
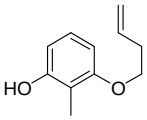
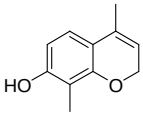
20 **19**

Entry	Catalyst	Oxidant	Base	Time (h)	Yield (%)[b]
1	$Pd(MeCN)_2Cl_2$	BQ	-	0.5	16
2	$Pd(MeCN)_2Cl_2$	-	Na_2CO_3	24	-
3	-	BQ	Na_2CO_3	24	-
4	$Pd(MeCN)_2Cl_2$	BQ	Na_2CO_3	3	77
5	$Pd(OAc)_2$	BQ	Na_2CO_3	24	-
6	$PdCl_2$	BQ	Na_2CO_3	24	28

[a] All reactions were carried out with catalyst (5 mol%), Na_2CO_3 (1 equiv), and BQ (1 equiv) in dioxane (0.015 M) at rt. [b] Determined by ^1H NMR using trichloroethylene as an internal standard.

We proceeded to explore the substrate scope of this new method (Table 4). Several chromene derivatives could be prepared from their corresponding aryl homoallyl ethers. Higher catalyst loadings were required in similarly substituted systems relative to the analogous benzofuran formation; variations in the nucleophilicity of the arenes are reflected in the catalytic demands, with less nucleophilic arenes requiring higher catalyst loadings (Table 4, entries 2-6). The oxidative cyclization occurred with excellent regioselectivity for unsymmetrically substituted substrates (Table 4, entries 2-5), and only the homoallyl naphthyl ether **27** gave a significant amount of the regioisomeric *exo*- olefin.

Table 4. Pd-Catalyzed Chromene Synthesis.[a]

Entry	Substrate	Product (%)[b]
1[c]	 **20**	 **19** (72)
2[d]	 **21**	 **22** (62) (*p* - : *o* - = 88 : 12)[f]
3[e]	 **23**	 **24** (40) (*p* - : *o* - = 88 : 12)[f]
4[e]	 **25**	 **26** (59)
5[d]	 **27**	 **28** (42)
6[e]	 **29**	 **30** (39)

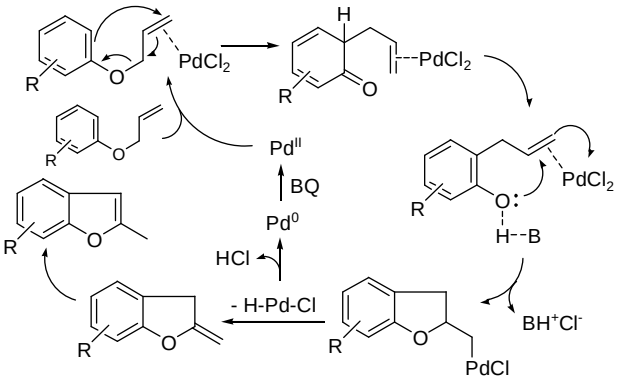
[a] All reactions were performed with $Pd(MeCN)_2Cl_2$, Na_2CO_3 (1 equiv), and BQ (1 equiv) in dioxane (0.015 M) for 3-5 hours. [b] Isolated yields. [c] Performed with 5 mol% $Pd(MeCN)_2Cl_2$ at rt. [d] Performed with 25 mol% $Pd(MeCN)_2Cl_2$ at 80 °C. [e] Performed with 20 mol% $Pd(MeCN)_2Cl_2$ at 80 °C. [f] The ratios were determined by ^1H NMR of the mixture.

Plausible mechanisms for both Pd-catalyzed cyclizations presented herein are outlined in Scheme 3 and are based on the Wacker oxidation mechanism.[11] For allyl aryl ethers, the Pd-complexed olefin first undergoes Claisen rearrangement[6] to form the corresponding 2-allylphenol intermediate. Subsequently, intramolecular cyclization proceeds via oxypalladation.[4c-f] Coordination of the C-C π-bond by palladium activates the olefin toward intramolecular nucleophilic attack[4] by the phenolic oxygen, which is readily deprotonated by the stoichiometric quantity of base.[4b-f,8] Subsequent β-hydride elimination produces Pd(H)Cl and the 2,3-dihydro-2-methylene benzofuran, which isomerizes to the thermodynamically stable 2-methylbenzofuran.[4] Pd(H)Cl eliminates HCl and forms Pd^0, which is reoxidized by BQ to regenerate the catalytically active Pd(II) species (Scheme 3a).

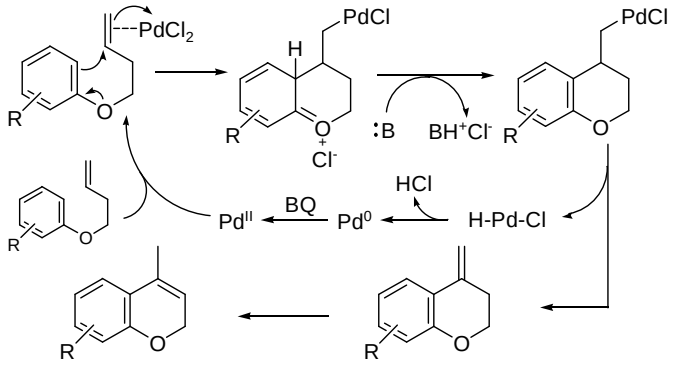
Cyclization of the aryl homoallyl ether most likely proceeds via carbopalladation, wherein activation of the olefin by coordination to Pd(II) is followed by intramolecular nucleophilic attack by the arene. Subsequent β-hydride elimination forms Pd(H)Cl and the 4-methylenechromane, which isomerizes to the thermodynamically favored 4-methylchromene.[5e] Since no products derived from initial olefin isomerization were detected in any of the reactions in Table 4, it is likely that attack of the arene on the Pd-complexed olefin is fast relative to Pd-mediated olefin isomerization[10] (Scheme 3b).

Scheme 3. Possible Mechanism for the Pd-Catalyzed Cyclizations.

(a) For Allyl Aryl Ethers : Claisen Rearrangement and Subsequent Intramolecular Oxidative Cyclizations



(b) For Aryl Homoallyl Ethers



3. Conclusion

We have developed both a one-pot procedure for the conversion of allyl aryl ethers to 2-methylbenzofurans and a direct oxidative cyclization of aryl homoallyl ethers to afford chromenes. Because a diverse range of allyl and homoallyl aryl ethers can be easily prepared, these Pd-catalyzed oxidative cyclizations represent an attractive means for the facile construction of benzofuran and chromene ring systems, which are pervasive motifs in biologically active natural products and pharmaceutical drug targets. While the method is currently limited to electron rich substrates, we are exploring ways to broaden the scope of the reaction to include other arenes, as well as acyclic substrates for the synthesis of monocyclic heterocycles.

4. Experiment Section

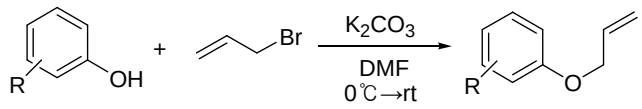
4.1. General

Nuclear Magnetic Resonance spectra were recorded on JEOL 400 Fourier transform NMR spectrometers. Spectra were recorded in $CDCl_3$ solutions referenced to TMS or solvent residual peak. IR spectra were taken as neat for liquids on NaCl plates using a Perkin-Elmer Spectrum 2000 FT-IR Spectrophotometer. High Resolution Mass Spectra were obtained on a JEOL JMS-700 mass spectrometer. Flash chromatography was performed on MERCK silica gel 60(230-400 mesh). All catalysts bought from Strem or Aldrich and used as received. Unless otherwise noted, all commercially obtained reagents were used as received. THF was distilled from sodium benzophenone ketyl immediately prior to use. Toluene and CH_2Cl_2 were all distilled from CaH_2 immediately prior to use. Reaction temperatures were controlled by an IKAmag temperature modulator. TLC was conducted with E. Merck silica gel 60 F254 precoated plates (0.25 mm) and visualized via UV and anisaldehyde staining.

4.2. Systematic Screen

Reactions were conducted at 0.015 M concentration in sealed vials under argon. To a solution of **1** (or **20**) in solvent were added catalyst, base (1 equiv.), and oxidant (1 equiv.). The resulting mixture was heated with stirring for the reported time at the reported temperature. After the reaction was completed (by TLC), the mixture was cooled, quenched with distilled water, extracted with CH_2Cl_2 (three times), dried over $MgSO_4$, and concentrated in vacuo. Yields were determined by ^1H NMR using trichloroethylene as an internal standard.

4.3. General procedure for the preparation of allyl aryl ethers



To a solution of the corresponding phenol in DMF were added K_2CO_3 (2 equiv.) and allyl bromide (1.1 equiv.) at 0 ^oC. The resulting homogeneous solution was warmed up to rt. After the reaction was completed, the reaction mixture was quenched with distilled water, extracted with ether (three times), washed with brine, dried over $MgSO_4$, and concentrated in vacuo. The residue was purified by column chromatography on silica gel by eluting EtOAc-Hexane (1:3 for **1**, 1:5 for **13**, 1:20 ~ 1:50 for others) to afford the corresponding product (31-88%).

Spectral data for 3-allyloxyphenol (**1**),[12] 3-allyloxyanisole (**3**),[12-13] 3,5-dimethoxyallyloxybenzene (**5**),[13] 3,5-dimethylallyloxybenzene (**7**),[13] 2-allyloxynaphthalene (**9**),[12] 3,4-methylenedioxyallyloxybenzene (**11**),[13-14] and 3,4,5-trimethoxyallyloxybenzene (**15**)[13] were consistent with data reported in the literature.

3-Allyloxy-2-methylphenol (13)

an orange oil (43%, EtOAc:Hexane = 1:5).

δ_H ($CDCl_3$, 400MHz) 2.15 (s, 3H), 4.53 (td, *J* = 1.5, 5.1, 2H), 4.65 (s, 1H), 5.27 (qd, *J* = 1.4, 10.6, 1H), 5.42 (qd, *J* = 1.7, 17.3, 1H), 6.07 (m, 1H), 6.45 (d, *J* = 4.1, 1H), 6.47 (d, *J* = 4.1, 1H), 7.00 (t, *J* = 8.2, 1H). δ_C ($CDCl_3$, 100MHz) 8.07, 69.09, 104.42, 108.12, 112.53, 116.92, 126.33, 133.56, 154.47, 157.63. ν_{max} (NaCl)/cm^{-1} 3419, 3084, 2926, 1595, 1471, 1362, 1096, 925, 769. HREIMS *m/z* 164.0840 $(M)^+$, calcd for $C_{10}H_{12}O_2$ 164.0837.

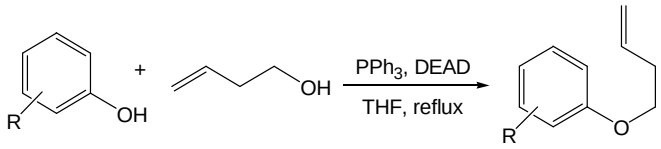
(3,5-Dimethoxyphenoxy)-2-butene (17)

a pale brown oil (31%, olefin isomer mixture 3:1, EtOAc:Hexane = 1:30).

Signals corresponding to the major isomer: δ_H ($CDCl_3$, 400MHz) 1.75 (d, *J*

= 6.5, 3H), 3.76 (s, 6H), 4.41 (d, *J* = 5.8, 2H), 5.72 (m, 1H), 5.85 (m, 1H), 6.10 (m, 3H). Representative signals corresponding to the minor isomer: δ_H ($CDCl_3$, 400MHz) 1.60 (d, *J* = 6.5, 3H), 3.78 (s, 3H), 3.79 (s, 3H), 4.55 (d, *J* = 6.5, 2H), 5.43 (m, 1H), 5.53 (m, 1H). δ_C ($CDCl_3$, 100MHz) 17.84, 55.29, 68.74, 92.98, 93.56, 125.89, 130.73, 160.57, 161.45. ν_{max} (NaCl)/cm^{-1} 2938, 1606, 1457, 1379, 1204, 1064, 967, 818. HREIMS *m/z* 208.1096 $(M)^+$, calcd for $C_{12}H_{16}O_3$ 208.1099.

4.4. General procedure for the preparation of aryl homoallyl ethers.



A solution of the 3-buten-1-ol, the corresponding phenol (3 equiv.) and PPh_3 (1.3 equiv.) in THF (0.3 M) was treated with DEAD (1.3 equiv.) at rt. The resulting homogeneous solution was heated at reflux for 1-3 hours, cooled at rt, and concentrated in vacuo. The residue was purified by column chromatography on silica gel by eluting EtOAc-Hexane (1 : 5 ~ 1 : 30) to afford the corresponding product. (47~86%)

Spectral data for 1-(3-methoxyphenoxy)-3-butene (**21**),[15] 1-(3-hydroxyphenoxy)-3-butene (**23**),[15] 1-(3,4-methylenedioxyphenoxy)-3-butene (**25**)[15] and 1-(2-naphthoxy)-3-butene (**27**)[16] were consistent with data reported in the literature.

1-(3,5-Dimethoxyphenoxy)-3-butene (20)

a colorless oil (70%, EtOAc:Hexane = 1:30).

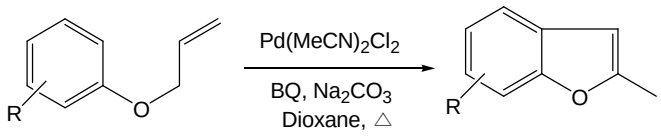
δ_H ($CDCl_3$, 400MHz) 2.53 (qt, *J* = 1.4, 6.8, 2H), 3.77 (s, 6H), 3.98 (t, *J* = 6.7, 2H), 5.10 (dq, *J* = 10.3, 1.4, 1H), 5.17 (dq, *J* = 17.2, 1.7, 1H), 5.90 (qt, *J* = 6.8, 10.3, 1H), 6.09 (s, 3H). δ_C ($CDCl_3$, 100MHz) 33.54, 55.29, 67.19, 92.99, 93.41, 116.99, 134.40, 160.79, 161.47. ν_{max} (NaCl)/cm^{-1} 3078, 2937, 1601, 1471, 1387, 1204, 1152, 1066, 918, 818. HREIMS *m/z* 208.1100 $(M)^+$, calcd

for $C_{12}H_{16}O_3$ 208.1099.

1-(3-Hydroxy-2-methylphenoxy)-3-butene (29)

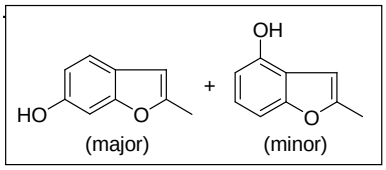
a yellow oil (47%, EtOAc:Hexane = 1:10).
δ_H ($CDCl_3$, 400MHz) 2.12 (s, 3H), 2.55 (qt, *J* = 1.4, 6.6, 2H), 4.00 (t, *J* = 6.7, 2H), 4.64 (s, 1H), 5.10 (qt, *J* = 1.5, 10.2, 1H), 5.17 (qt, *J* = 1.6, 17.2, 1H), 5.92 (m, 1H), 6.44 (d, *J* = 6.8, 1H), 6.46 (d, *J* = 7.1, 1H), 7.00 (t, *J* = 8.2, 1H). δ_C ($CDCl_3$, 100MHz) 7.96, 33.82, 67.63, 104.18, 107.98, 112.46, 116.86, 126.35, 134.69, 154.45, 157.90. ν_{max} (NaCl)/cm^{-1} 3433, 3079, 2926, 1595, 1466, 1380, 1272, 1098, 917, 769, 707. HREIMS *m/z* 178.0996 $(M)^+$, calcd for $C_{11}H_{14}O_2$ 178.0994.

4.5. General procedure for the conversion of allyl aryl ethers to 2-methylbenzofurans



To a solution of allyl aryl ether in 1,4-dioxane (0.015 M) were added $Pd(MeCN)_2Cl_2$, Na_2CO_3 (1 equiv.) and BQ (1 equiv.). The resulting mixture was heated with stirring for the reported temperature. After the reaction was completed,[17] the mixture was cooled, quenched with distilled water, extracted with CH_2Cl_2 (three times), dried over $MgSO_4$, and concentrated in vacuo. The residue was purified by column chromatography on silica gel (EtOAc:Hexane = 1:10 ~ 1:50) to afford the corresponding product.

6-Hydroxy-2-methylbenzofurans & 4-Hydroxy-2-methylbenzofurans (2)

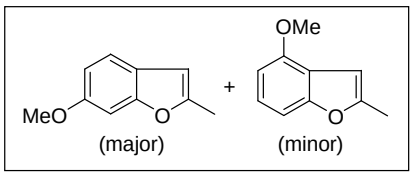


5 mol % $Pd(MeCN)_2Cl_2$ at 65 ^oC.

The mixture of isomers was obtained as a brown oil (6- : 4- = 84:16, EtOAc : Hexane = 1:10).

Spectral data were consistent with data reported in the literature.[18]

6-Methoxy-2-methylbenzofurans & 4-Methoxy-2-methylbenzofurans (2)

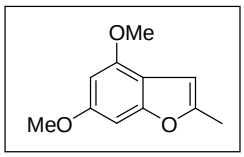


20 mol % $Pd(MeCN)_2Cl_2$ at 80 ^oC.

The mixture of isomers was obtained as a pale yellow oil (6- : 4- = 88:12, EtOAc:Hexane = 1:20).

Spectral data were consistent with data reported in the literature.[19]

4,6-Dimethoxy-2-methylbenzofuran (6)

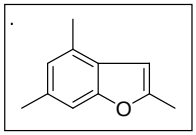


5 mol % $Pd(MeCN)_2Cl_2$ at 65 ^oC.

a white solid (EtOAc : Hexane = 1:20).

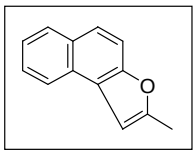
δ_H ($CDCl_3$, 400MHz) 2.40 (s, 3H), 3.82 (s, 3H), 3.88 (s, 3H), 6.29 (d, *J* = 1.7, 1H), 6.35 (s, 1H), 6.59 (d, *J* = 1.7, 1H). δ_C ($CDCl_3$, 100MHz) 13.91, 55.51, 55.75, 88.16, 93.85, 99.55, 112.63, 152.67, 152.73, 156.29, 158.15. ν_{max} (NaCl)/cm^{-1} 3119, 2955, 1601, 1501, 1457, 1370, 1216, 1155, 1104, 1043, 949, 814. HREIMS *m/z* 192.0786 $(M)^+$, calcd for $C_{11}H_{12}O_3$ 192.0786.

2,4,6-Trimethylbenzofuran (8)



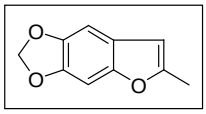
25 mol % $Pd(MeCN)_2Cl_2$ at 80 ^oC.
a pale yellow oil (EtOAc : Hexane =1:20).
Spectral data were consistent with data reported in the literature.[20]

2-Methylnaphtho[2,1-b]furan (10)



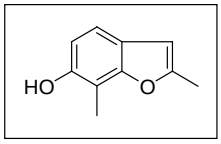
20 mol % $Pd(MeCN)_2Cl_2$ at 80 ^oC.
a pale yellow solid (EtOAc : Hexane = 1:30).
Spectral data were consistent with data reported in the literature.[21]

2-Methyl-5,6-methylenedioxybenzofuran (12)



10 mol % $Pd(MeCN)_2Cl_2$ at 80 ^oC.
a white solid (EtOAc : Hexane = 1:20).
δ_H ($CDCl_3$, 400MHz) 2.39 (d, *J* = 1.0, 3H), 5.95 (s, 2H), 6.24 (m, 1H), 6.84 (s, 1H), 6.91 (s, 1H). δ_C ($CDCl_3$, 100MHz) 14.03, 93.20, 98.85, 101.00, 102.82, 122.18, 144.06, 145.01, 149.58, 154.69. ν_{max} (NaCl)/cm^{-1} 3110, 2962, 2894, 1600, 1463, 1367, 1318, 1279, 1159, 1038, 942, 850. HREIMS *m/z* 176.0475 $(M)^+$, calcd for $C_{10}H_8O_3$ 176.0473.

2,7-Dimethyl-6-hydroxybenzofuran (14)

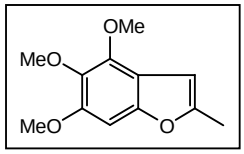


10 mol % $Pd(MeCN)_2Cl_2$ at 65 ^oC.

a pale yellow solid (EtOAc : Hexane = 1:10).

δ_H ($CDCl_3$, 400MHz) 2.39 (s, 3H), 2.43 (s, 3H), 4.66 (s, 1H), 6.26 (s, 1H), 6.69 (d, *J* = 8.2, 1H), 7.12 (d, *J* = 8.2, 1H). δ_C ($CDCl_3$, 100MHz) 8.31, 14.04, 102.52, 107.12, 111.00, 116.84, 122.27, 150.33, 154.41, 154.58. ν_{max} (NaCl)/cm^{-1} 3285, 2922, 1605, 1508, 1427, 1277, 1154, 1080, 1038, 935, 810. HREIMS *m/z* 162.0677 $(M)^+$, calcd for $C_{10}H_{10}O_2$ 162.0681.

2-Methyl-4,5,6-trimethoxybenzofuran (16)

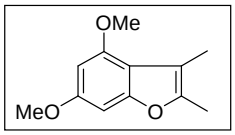


5 mol % $Pd(MeCN)_2Cl_2$ at 65 ^oC.

an orange oil (EtOAc : Hexane = 1:5).

δ_H ($CDCl_3$, 400MHz) 2.39 (d, *J* = 1.4, 3H), 3.85 (s, 3H), 3.87 (s, 3H), 4.06 (s, 3H), 6.42 (m, 1H), 6.73 (s, 1H). δ_C ($CDCl_3$, 100MHz) 13.86, 56.32, 60.31, 61.35, 90.28, 100.45, 114.01, 136.78, 145.28, 151.17, 151.63, 153.32. ν_{max} (NaCl)/cm^{-1} 3117, 2936, 1621, 1469, 1383, 1200, 1039, 933, 896, 795. HREIMS *m/z* 222.0892 $(M)^+$, calcd for $C_{12}H_{14}O_4$ 222.0892.

4,6-Dimethoxy-2,3-dimethylbenzofuran (18)



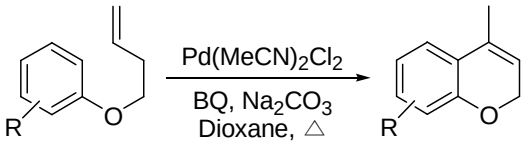
25 mol % $Pd(MeCN)_2Cl_2$ at 80 ^oC.

a colorless oil (EtOAc : Hexane = 1:50).

δ_H ($CDCl_3$, 400MHz) 2.23 (s, 3H), 2.29 (s, 3H), 3.81 (s, 3H), 3.84 (s, 3H),

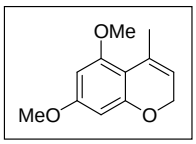
6.25 (d, *J* = 1.7, 1H), 6.53 (d, *J* = 2.0, 1H). δ_C ($CDCl_3$, 100MHz) 9.72, 11.36, 55.33, 55.68, 87.93, 93.50, 93.78, 109.42, 147.54, 154.31, 155.49, 157.96. ν_{max} (NaCl)/cm^{-1} 2927, 1606, 1501, 1455, 1214, 1148, 1112, 815. HREIMS *m/z* 206.0946 $(M)^+$, calcd for $C_{12}H_{14}O_3$ 206.0943.

4.6. General procedure for a direct oxidative cyclization of aryl homoallyl ethers to afford chromenes



To a solution of aryl homoallyl ether in 1,4-dioxane (0.015 M) were added $Pd(MeCN)_2Cl_2$, Na_2CO_3 (1 equiv.) and BQ (1 equiv.). The resulting mixture was heated with stirring for the reported temperature. After the reaction was completed,[17] the mixture was cooled, quenched with distilled water, extracted with CH_2Cl_2 (three times), dried over $MgSO_4$, and concentrated in vacuo. The residue was purified by column chromatography on silica gel (EtOAc : Hexane = 1:10 ~ 1:30) to afford the corresponding product.

5,7-Dimethoxy-4-methyl-2*H*-chromene (19)



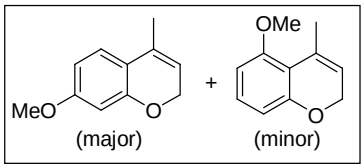
5 mol % $Pd(MeCN)_2Cl_2$ at rt.

a yellowish oil (EtOAc : Hexane = 1:20).

δ_H ($CDCl_3$, 400MHz) 2.15 (dt, *J* = 1.7, 3H), 3.77 (s, 3H), 3.78 (s, 3H), 4.49 (dq, *J* = 4.4, 1.5, 2H), 5.40 (tq, *J* = 4.3, 1.5, 1H), 6.08 (d, *J* = 2.4, 1H), 6.11 (d, *J* = 2.4, 1H). δ_C ($CDCl_3$, 100MHz) 21.73, 55.28, 55.38, 64.97, 92.92,

93.78, 107.99, 115.21, 131.64, 157.22, 158.23, 160.53. ν_{max} (NaCl)/cm^{-1} 2962, 1615, 1470, 1213, 1046, 949, 820,740. HREIMS *m/z* 206.0942 $(M)^+$, calcd for $C_{12}H_{14}O_3$ 206.0943.

7-Methoxy-4-methyl-2*H*-chromene & 5-Methoxy-4-methyl-2*H*-chromene (22)

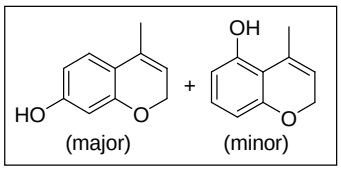


25 mol % $Pd(MeCN)_2Cl_2$ at 80 °C.

The mixture of isomers was obtained as a yellow oil (7- : 5- = >99:1, EtOAc : Hexane = 1:30).

Spectral data were consistent with data reported in the literature.[22]

7-Hydroxy-4-methyl-2*H*-chromene & 5-Hydroxy-4-methyl-2*H*-chromene (24)



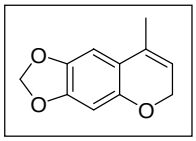
20 mol % $Pd(MeCN)_2Cl_2$ at 80 °C.

The mixture of isomers was obtained as a colorless oil (7- : 5- = 94:6, EtOAc : Hexane = 1:10).[23]

Signals corresponding to the major isomer: δ_H ($CDCl_3$, 400MHz) 1.98 (dt, *J* = 1.7, 3H), 4.71 (dq, *J* = 3.6, 1.7, 2H), 5.24 (br, 1H), 5.43 (tq, *J* = 3.6, 1.6, 1H), 6.33 (d, *J* = 2.7, 1H), 6.39 (dd, *J* = 8.3, 2.6, 1H), 7.00 (d, *J* = 8.2, 1H). δ_C ($CDCl_3$, 100MHz) 17.95, 65.68, 103.14, 107.93, 115.45, 117.73, 124.57, 130.02, 155.39, 156.29. Representative signals corresponding to the minor isomer: δ_H ($CDCl_3$, 400MHz) 2.24 (dt, *J* = 1.7, 3H), 4.53 (dq, *J* = 4.2, 1.7, 2H), 5.12 (br, 1H), 5.56 (tq, *J* = 4.1, 1.7, 1H), 6.49 (d, *J* = 8.2, 1H), 6.95 (t, *J* = 7.9, 1H). δ_C ($CDCl_3$, 100MHz) 21.61, 64.78, 108.96, 109.68, 118.36, 128.82. ν_{max} (NaCl)/cm^{-1} 3376, 2969, 1616, 1506, 1466, 1381, 1160, 1066,

1011, 942, 813. HREIMS *m/z* 162.0680 $(M)^+$, calcd for $C_{10}H_{10}O_2$ 162.0681.

4-Methyl-6,7-methylenedioxy-2*H*-chromene (26)

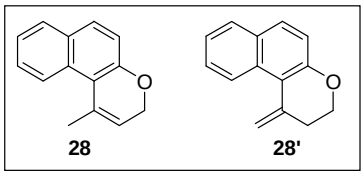


20 mol % $Pd(MeCN)_2Cl_2$ at 80 °C.

a pale yellow oil (EtOAc : Hexane = 1:30).

δ_H ($CDCl_3$, 400MHz) 1.97 (dt, *J* = 1.6, 1.7, 3H), 4.64 (dq, *J* = 3.8, 1.7, 2H), 5.47 (tq, *J* = 3.8, 1.7, 1H), 5.90 (s, 2H), 6.41 (s, 1H), 6.66 (s, 1H). δ_C ($CDCl_3$, 100MHz) 18.27, 65.41, 98.44, 100.99, 103.34, 115.65, 117.63, 130.54, 141.82, 147.24, 149.64. ν_{max} (NaCl)/cm^{-1} 2923, 1624, 1485, 1404, 1341, 1265, 1166, 1038, 937, 858, 753. HREIMS *m/z* 190.0631 $(M)^+$, calcd for $C_{11}H_{10}O_3$ 190.0630.

1-Methyl-3*H*-benzo[*f*]chromene (28) & 1-Methylene-2,3-dihydro-1*H*-benzo[*f*]chromene (28')



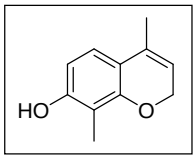
25 mol % $Pd(MeCN)_2Cl_2$ at 80 °C.

The mixture of **28** and **28'** was obtained as an orange oil (**28**:**28'**= 2:1, EtOAc : Hexane = 1:30).

Signals corresponding to **28**[24]: δ_H ($CDCl_3$, 400MHz) 2.42 (dt, *J* = 1.5, 3H), 4.55 (dq, *J* = 6.2, 1.4, 2H), 5.76 (tq, *J* = 6.2, 1.6, 1H), 7.15 (d, *J* = 8.9, 1H), 7.35 (m, 1H), 7.45 (m, 1H), 7.68 (d, *J* = 8.9, 1H), 7.78 (d, *J* = 8.2, 1H), 8.11 (d, *J* = 8.6, 1H). δ_C ($CDCl_3$, 100MHz) 22.52, 64.41, 114.03, 117.78, 118.07, 123.26, 125.38, 125.89, 128.83, 129.57, 129.99, 130.70, 132.59, 154.07. Representative signals corresponding to **28'**: δ_H ($CDCl_3$, 400MHz) 2.75 (t, *J* = 6.0, 2H), 4.47 (t, *J* = 5.8, 2H), 5.38 (m, 1H), 5.66 (s, 1H), 7.02 (d, *J* = 8.9,

1H), 7.35 (m, 1H), 7.45 (m, 1H), 7.64 (d, *J* = 8.5, 1H), 7.78 (d, *J* = 8.2, 1H), 8.45(d, *J* = 8.6, 1H). δ_C ($CDCl_3$, 100MHz) 33.24, 68.44, 118.49, 123.16, 124.01, 126.54, 128.52, 129.35, 130.28, 130.96, 139.48, 152.31. ν_{max} (NaCl)/cm^{-1} 3056, 2926, 1633, 1595, 1513, 1466, 1395, 1340, 1231, 1214, 1079, 1028, 996, 816, 747. HREIMS *m/z* 196.0884 $(M)^+$, calcd for $C_{14}H_{12}O$ 196.0888.

4,8-Dimethyl-7-hydroxy-2*H*-chromene (30)



20 mol % $Pd(MeCN)_2Cl_2$ at 80 ^oC.
a white solid (EtOAc : Hexane = 1:10).[23]
δ_H ($CDCl_3$, 400MHz) 1.98 (d, *J* = 1.0, 3H), 2.09 (s, 3H), 4.72 (m, 2H), 4.79 (s, 1H), 5.45 (m, 1H), 6.37 (d, *J* = 8.2, 1H), 6.89 (d, *J* = 8.2, 1H). δ_C ($CDCl_3$, 100MHz) 7.99, 18.06, 65.58, 107.14, 111.23, 115.25, 117.58, 121.24, 130.56, 153.22, 154.41. ν_{max} (NaCl)/cm^{-1} 3430, 2968, 1615, 1505, 1456, 1379, 1101, 808. HREIMS *m/z* 176.0832 $(M)^+$, calcd for $C_{11}H_{12}O_2$ 176.0837.

5. References

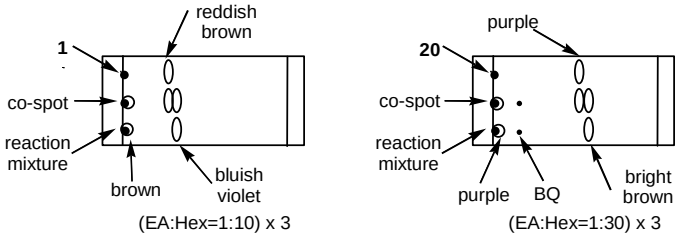
1. Nakamura, I.; Yamamoto, Y. *Chem. Rev*. **2004**, *104*, 2127
2. (a) Zeni, G.; Larock, R. C. *Chem. Rev.* **2004**, *104*, 2285. (b) Keay, B. A. *Comprehensive Heterocyclic Chemistry II*; Katritzky, A. R., Rees, C. W., Scriven, E. F. V., Eds.; Pergamon: Oxford, 1996; Vol. 2. p 395. (c) Cagniant, P.; Cagniant, D. In *Advances in Heterocyclic Chemistry*; Katritzky, A. R., Boulton, A. J., Eds.; Academic Press: New York, 1975; Vol.18, p 337. (d) Nicolaou, K. C.; Pfefferkorn, J. A.; Roecker, A. J.; Cao. G. Q.; Barluenga, S.; Mitchell, H. J. *J. Am. Chem. Soc.* **2000**, *122*, 9939.
3. For recent examples, see: (a) Zhang, J.; Zhang, Y.; Zhang, Y.; Herndon, J. W. *Tetrahedron* **2003**, *59*, 5609. (b) Cruz, M. del C.; Tamariz, J. *Tetrahedron Lett.* **2004**, *45*, 2377. (c) Xie, X.; Chen, B.; Lu, J.; Han, J.; She, X.; Pan, X. *Tetrahedron Lett.* **2004**, *45*, 6235. (d) Konno, T.; Chae, J.; Ishihara, T.; Yamanaka, H. *Tetrahedron* **2004**, *60*, 11695. (e) Bellur, E.; Freifeld, I.; Langer, P. *Tetrahedron Lett.* **2005**, *46*, 2185.
4. For a review, see: (a) Cacchi, S.; Fabrizi, G.; Goggiomani, A. *Hetereocycles* **2002**, *56*, 613.; For intramolecular oxidative arene-olefin cyclizations, see: (b) Zhang, H.; Ferreira, E. M.; Stoltz, B. M. *Angew. Chem., Int. Ed.* **2004**, *43*, 6144 and references therein.; For oxidative cyclizations of 2-allylphenols, see: (c) Hosokawa, T.; Maeda, K.; Koga, K.; Moritani, I. *Tetrahedron Lett.* **1973**, *14*, 739. (d) Hosokawa, T.; Ohkata, H.; Moritani, I. *Bull. Chem. Soc. Jpn.* **1975**, *48*, 1533. (e) Hosokawa, T.; Murahashi, S.-I. *Acc. Chem. Res.* **1990**, *23*, 49. (f) Roshchin, A. I.; Kel'chevski, S. M.; Bumagin, N. A. *J. Organomet. Chem.* **1998**, *560*, 163 and references therein.
5. (a) Pastine, S. J.; Youn, S. W.; Sames, D. *Org. Lett.* **2003**, *5*, 1055. (b) Youn, S. W.; Pastine, S. J.; Sames, D. *Tetrahedron* **2003**, *59*,

8859. (c) Hardouin, C.; Burgaud, L.; Valleix, A.; Doris, E. *Tetrahedron Lett.* **2003**, *44*, 435. (d) Caddick, S.; Kofie, W. *Tetrahedron Lett.* **2002**, *43*, 9347. (e) Shezad, N.; Clifford, A. A.; Rayner, C. M. *Tetrahedron Lett.* **2001**, *42*, 323. (f) Shi, L.; Narula, C. K.; Mak, K. T.; Kao, L.; Xu, Y.; Heck, R. F. *J. Org. Chem.* **1983**, *48*, 3894.

6. For a review, see: (a) Castro, A. M. M. *Chem. Rev.* **2004**, *104*, 2939. (b) Hiersemann, M.; Abraham, L. *Eur. J. Org. Chem.* **2002**, 1461.; For Claisen rearrangement of allyl aryl ethers with catalytic amount of metal catalysts, see: $IrCl_3$/AgOTf: (c) Grant, V. H.; Liu, B. *Tetrahedron Lett.* **2005**, *46*, 1237 and references therein.; $Yb(OTf)_3$: (d) Sharma, G. V. M.; Ilangovan, A.; Sreenivas, P.; Mahalingam, A. K. *Synlett* **2000**, 615.; $Pd(MeCN)_2Cl_2$: (e) Anjaneyulu, A. S. R.; Isaa, B. M. *J. Chem. Soc., Perkin Trans. 1* **1991**, 2089.
7. For one-pot synthesis of benzofurans from β-haloallyl aryl ethers: (a) Tao, Z.-F.; Qian, X.; Fan, M. *Tetrahedron* **1997**, *53*, 13329. (b) Mali, R. S.; Pandhare, N. A.; Sindkhedkar, M. D. *Tetrahedron Lett.* **1995**, *36*, 7109. (c) Saisi, M. R. *Hetereocycles* **1982**, *19*, 1473.
8. (a) Trend, R. M.; Ramtohul, Y. K.; Ferreira, E. M.; Stoltz, B. M. *Angew. Chem., Int. Ed.* **2003**, *42*, 2892. (b) Beccalli, E. M.; Broggini, G.; Paladino, G.; Pennoni, A.; Zoni, C. *J. Org. Chem.* **2004**, *69*, 5627.
9. For a specific example of a 6-*endo* cyclization of 2-allylphenols, see: Larock, R. C.; Wei, L.; Hightower, T. R. *Synlett* **1998**, 522.
10. (a) Han, X.; Widenhoefer, R. A. *J. Org. Chem.* **2004**, *69*, 1738 and references therein. (b) Ref. 3(d) and references therein.
11. Bäckvall, J. E.; Åkermark, B.; Ljunggren, S. O. *J. Am. Chem. Soc.* **1979**, *101*, 2411.
12. Gozzo, F. C.; Fernandes, S. A.; Rodrigues, D. C.; Eberlin, M. N.; Marsaioli, A. J. *J. Org. Chem.* **2003**, *68*, 5493.
13. Taskinen., E. *J. Chem. Soc., Perkin Trans. 2* **2001**, 1824.

14. Baxendale, I. R.; Lee, A.-L.; Ley. S. V. *J. Chem. Soc., Perkin Trans. 1* **2002**, 1850
15. Hoffmann, N.; Pete, J.-P. *J. Org. Chem.* **1997**, *62*, 6952.
16. Youn, S. W.; Pastine, S. J.; Sames, D. *Org. Lett.* **2004**, *6*, 581.
17. In TLC diagram, the spots of both starting material and corresponding product are very close in every reaction. After developing TLC with nonpolar solvent (such as EtOAc:Hexane = 1:10~1:50) a few times, visualization with anisaldehyde stain shows color differences between starting material and product.

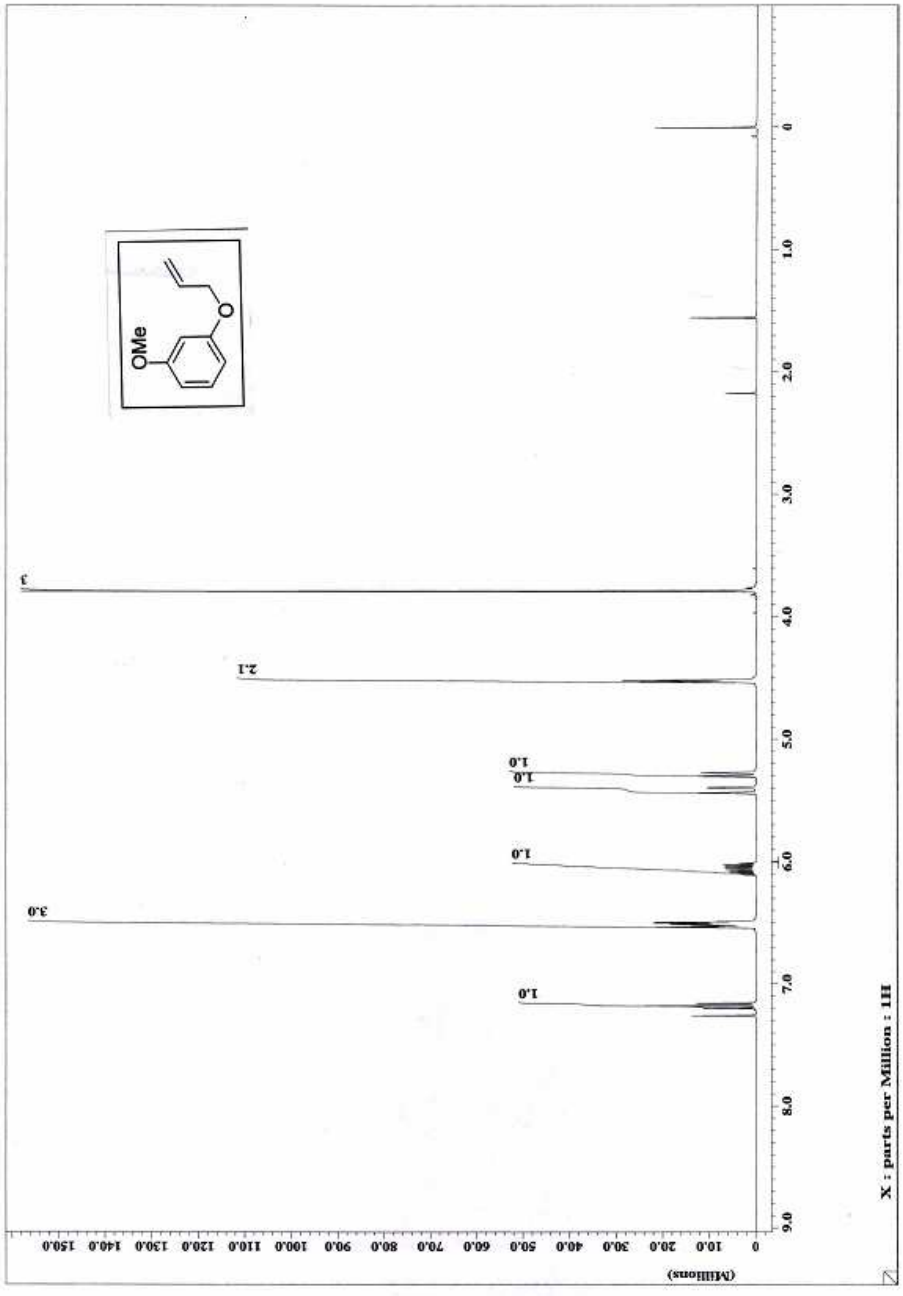
    For examples, TLC diagrams with regards to reactions of **1** and **20** are as follows.

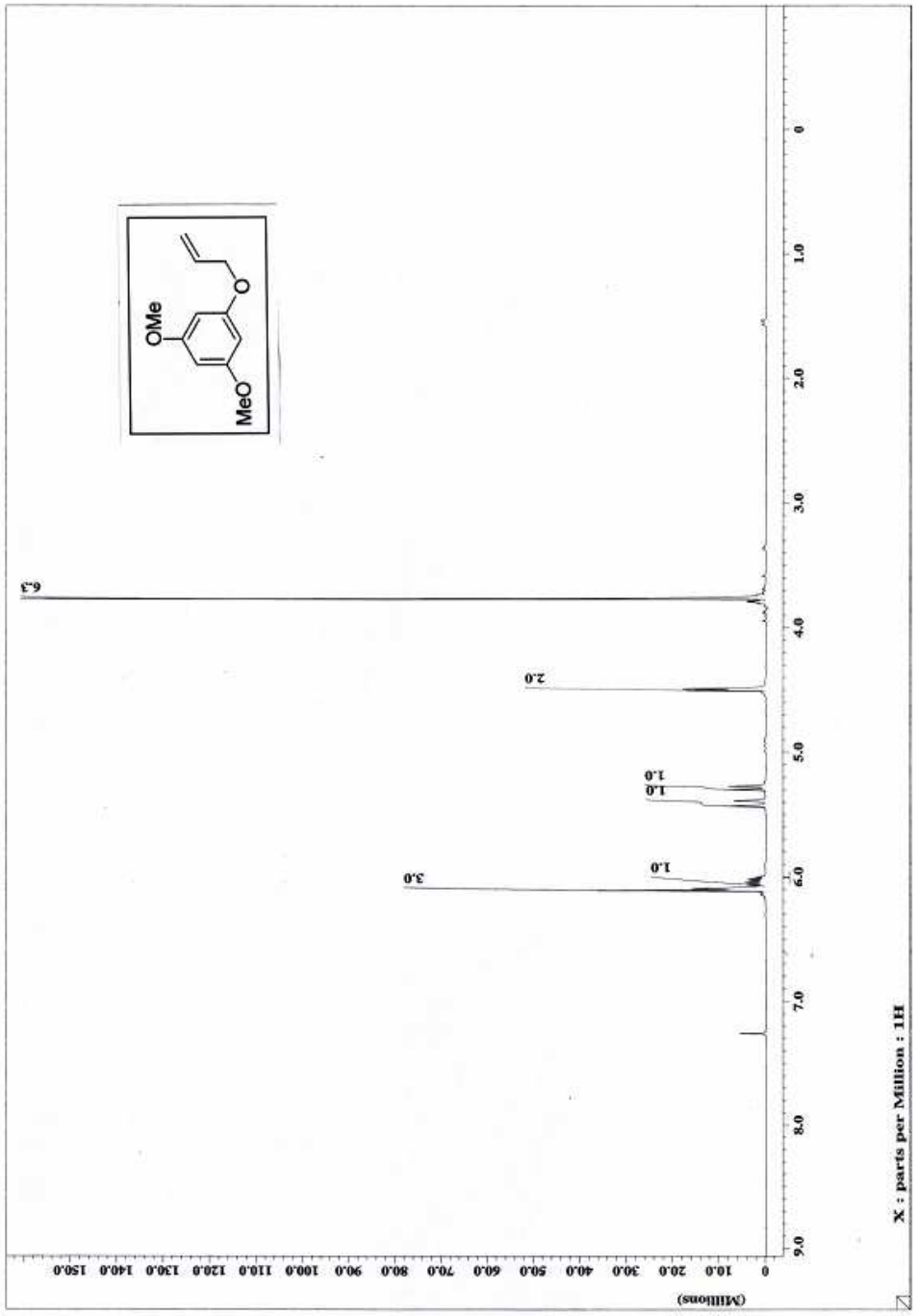


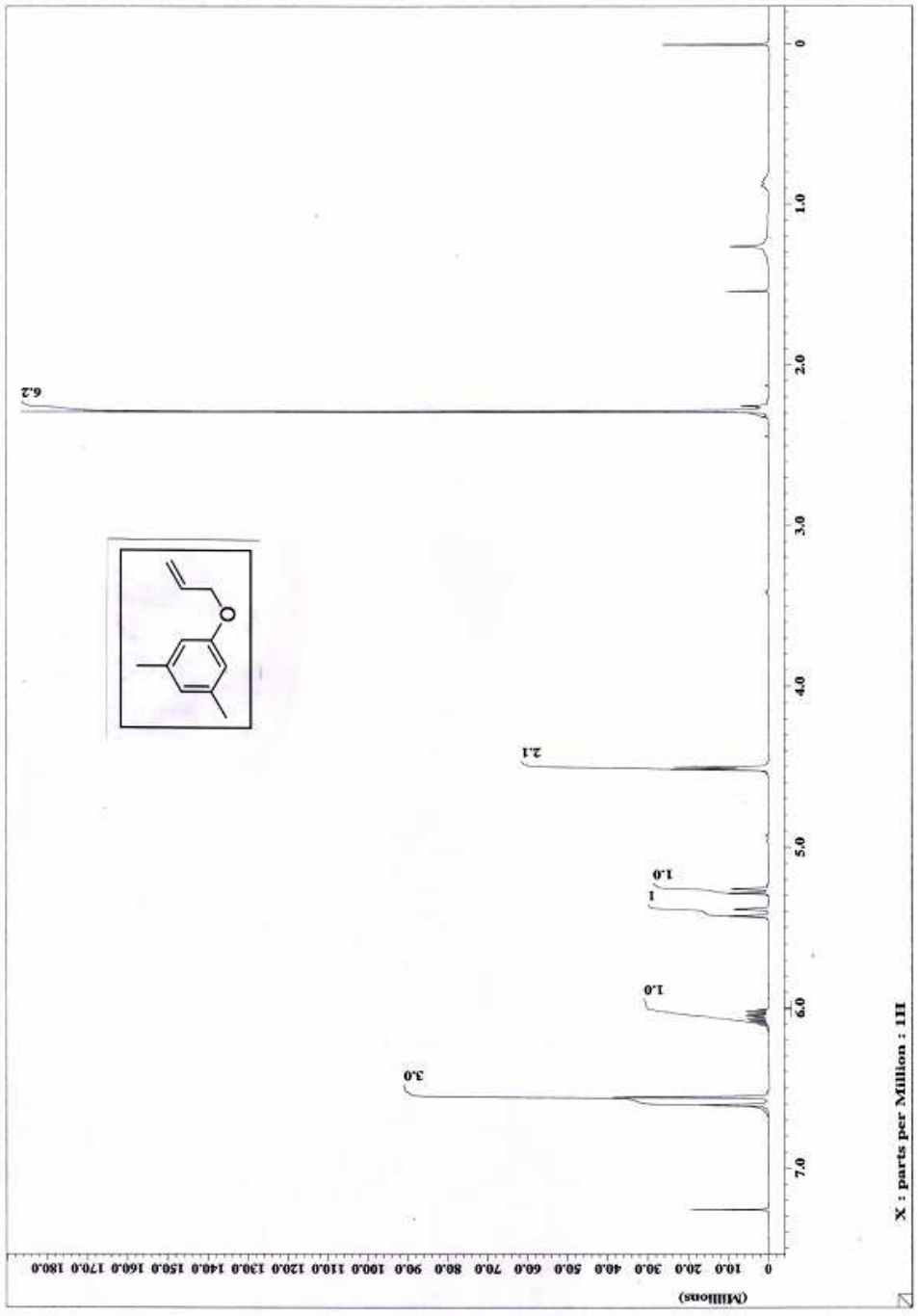
18. (a) For spectral data of *p*-isomer, see: Dupont, R.; Cotelle, P. *Synthesis* **1999**, 1651. (b) For spectral data of *o*-isomer, see: Demerseman, P.; Lechartier, J.-P.; Pène, C.; Cheutin, A.; Royer, R. *Bull. Soc. Chim. Fr.* **1965**, 1473.
19. Alemagna, A.; Baldoli, C.; Del Buttero, P.; Licandro, E.; Maiorana, S. *Synthesis* **1987,** 192.
20. Choi, H.-D.; Seo, P.-J.; Son, B.-W. *J. Kor. Chem. Soc.* **1999**, *43*, 237.
21. (a) Chow, Y. L.; Zhou, X. M.; Gaitan, T. J.; Wu, Z. Z. *J. Am. Chem. Soc.* **1989**, *111*, 3813. (b) Black, M.; Cadogan, J. I. G.; McNab, H.; MacPherson, A. D.; Roddam, V. P.; Smith, C.; Swenson, H. R. *J. Chem. Soc., Perkin Trans. 1* **1997**, 2483.
22. (a) Engler, T. A.; LaTessa, K. O.; Iyengar, R.; Chai, W.; Agrios, K. *Bioorg. Med. Chem*. **1996**, *4*, 1755. (b) Anderson, W. K.; LaVoie, E. J.; Whitkop, P. G.. *J. Org. Chem.* **1974**, *39*, 881.

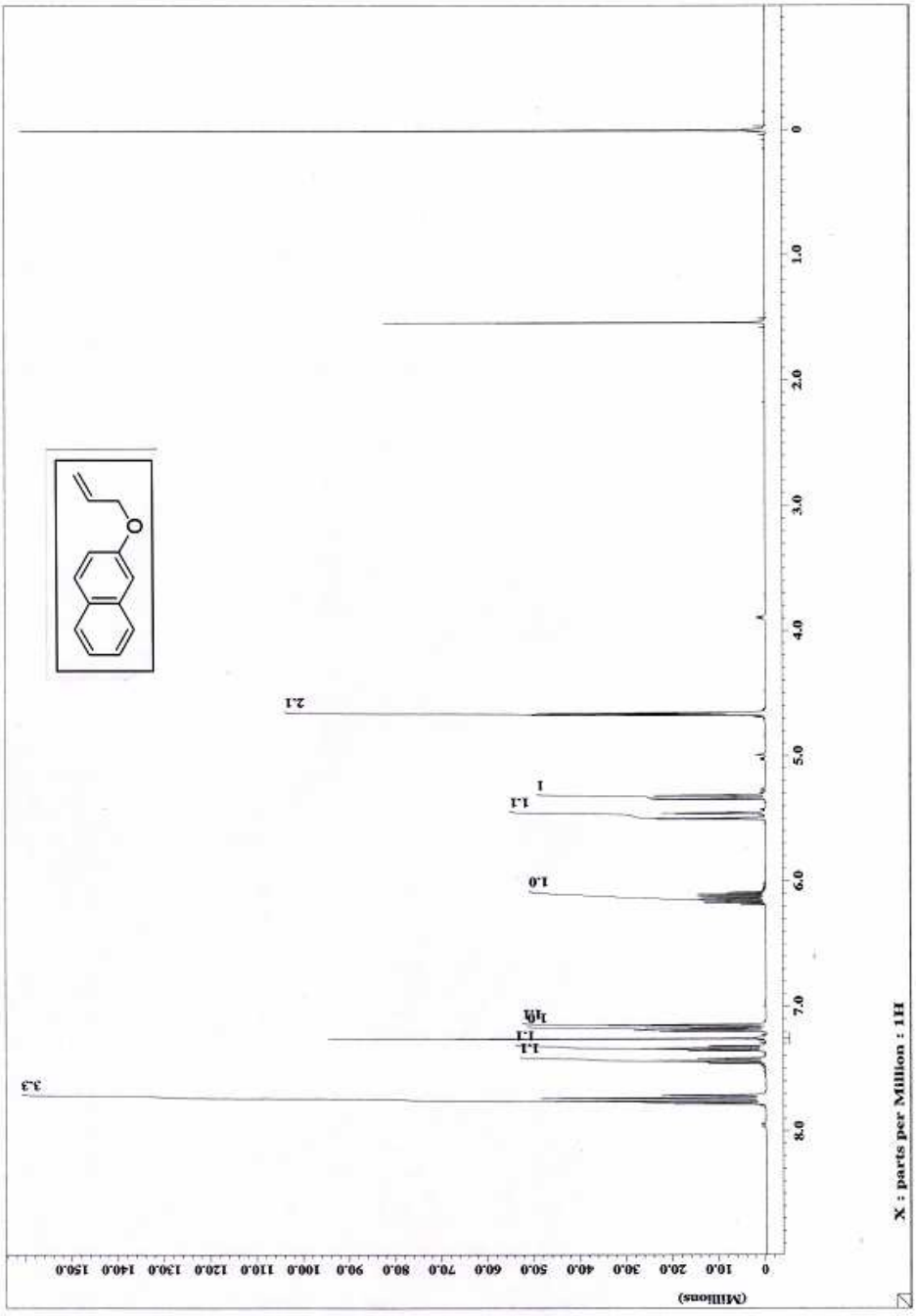
23. This compound is too unstable to store even for 1 day in the freezer. Therefore, spectral data for this compound should be obtained immediately after purification.
24. For spectral data of **28**, see: (a) Muljiani, Z.; Tilak, B. D. *Indian J. Chem.* **1969**, *7*, 28 & 30. (b) Iwai, I.; Ide, J. *Chem. Pharm. Bull.* **1962**, 926.

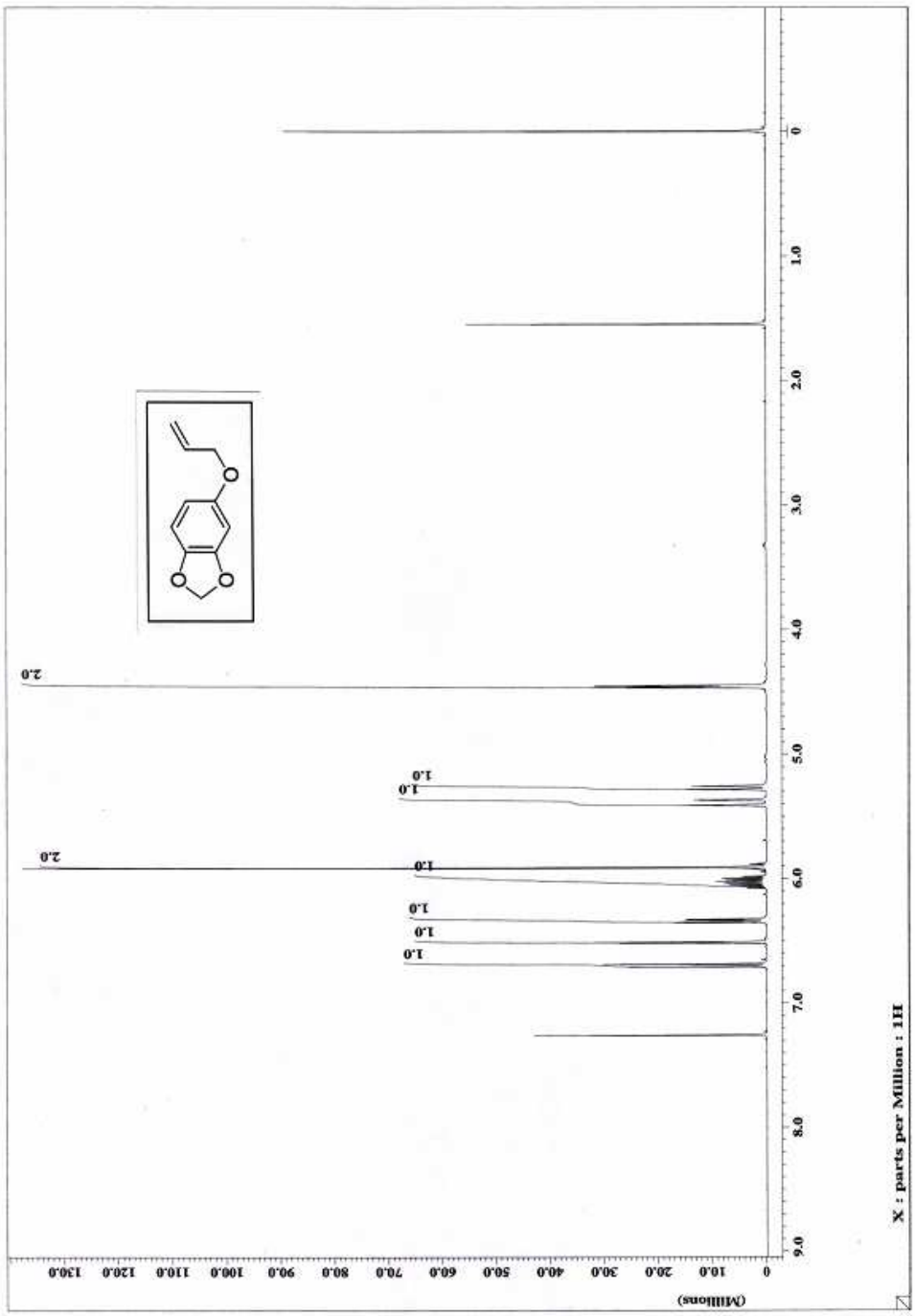
6. Spectral Data

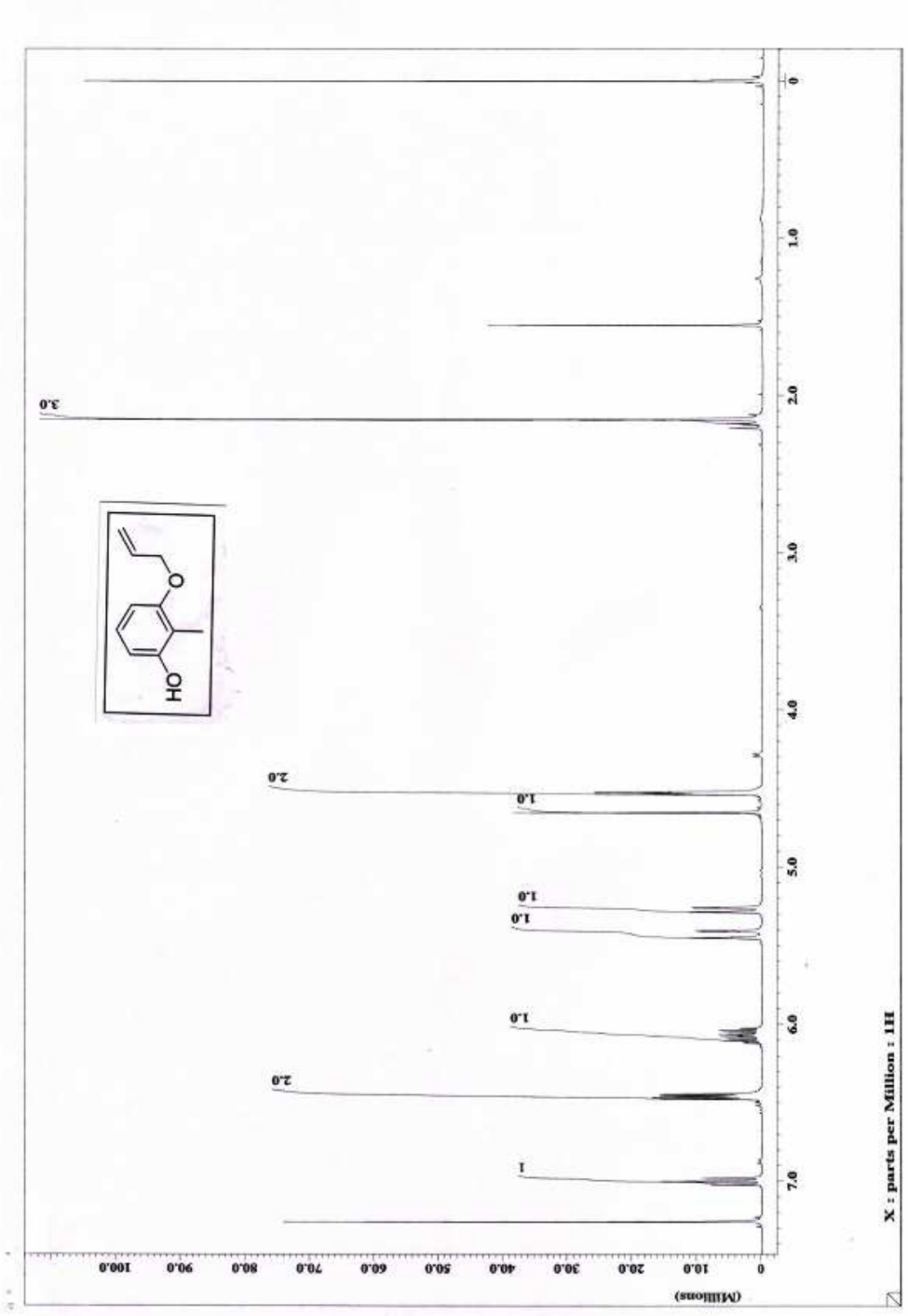


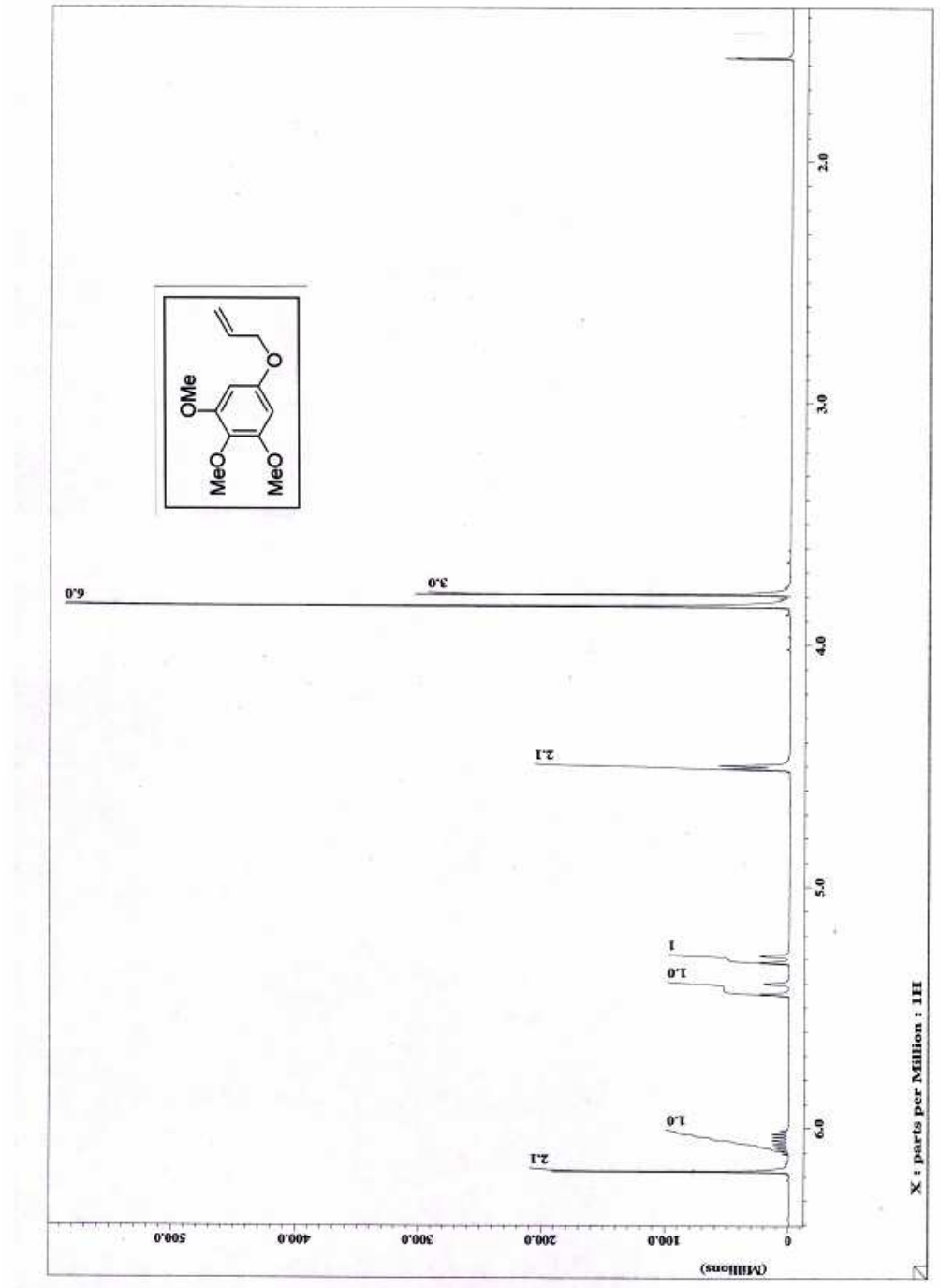

OMe
MeO
6.3
2.0
1.0
1.0
1.0
3.0
X : parts per Million : 1H
(Millions)

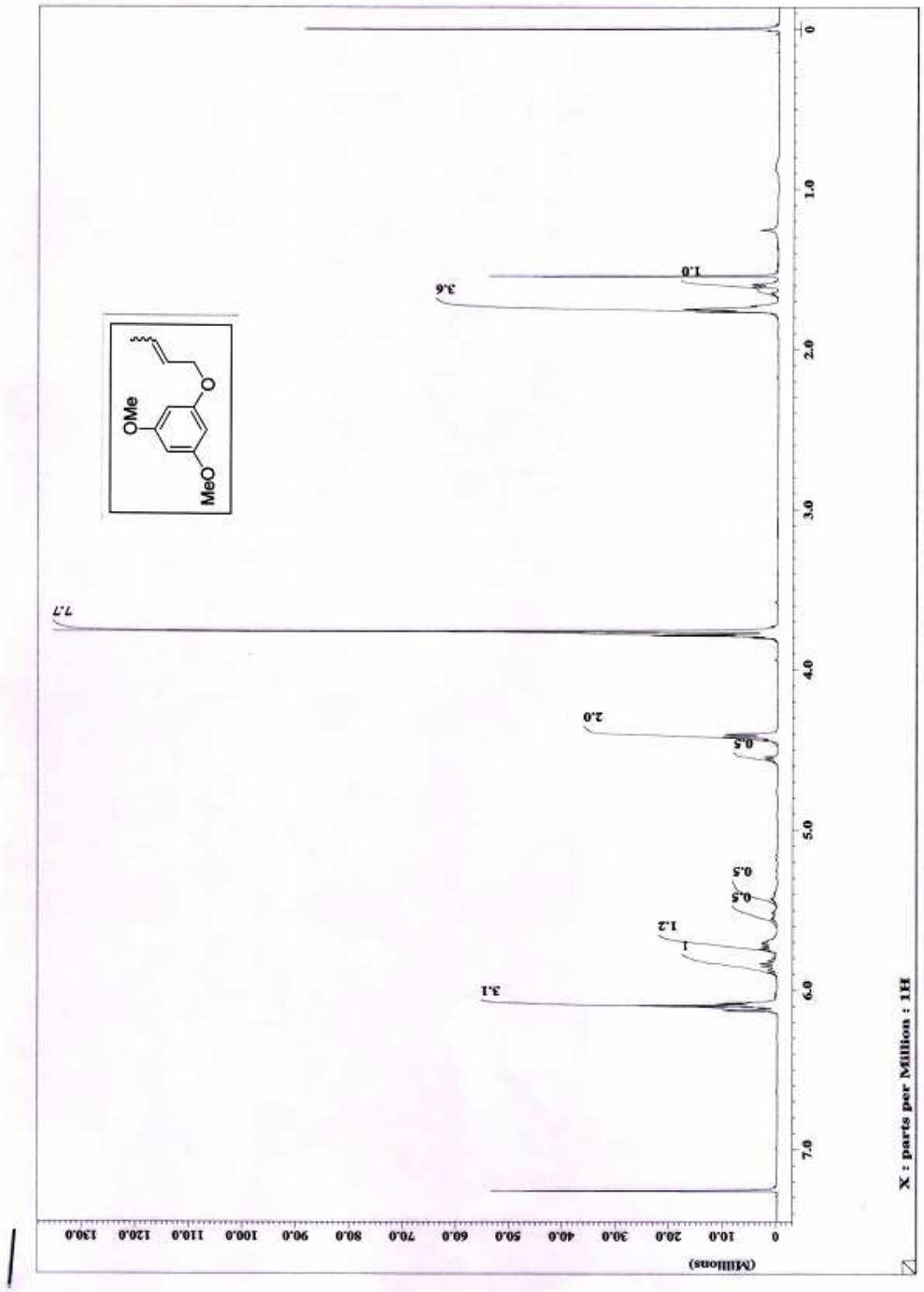

6.2
2.1
1.0
1
1.0
1.0
3.0
X : parts per Million : 1H
(Millihons)

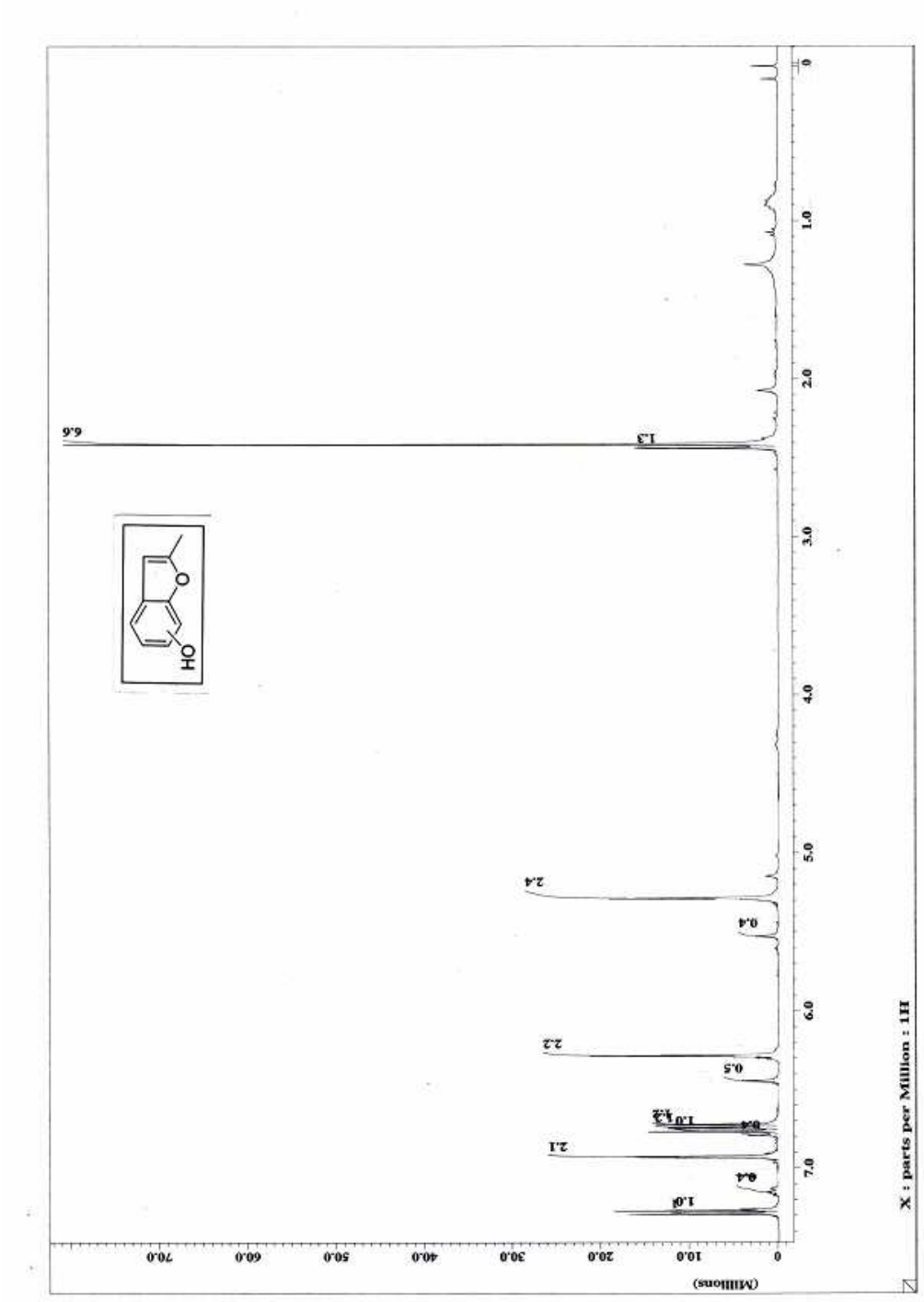

X : parts per Million : 1H
(Millions)
3.3
2.1
1.1
1.0

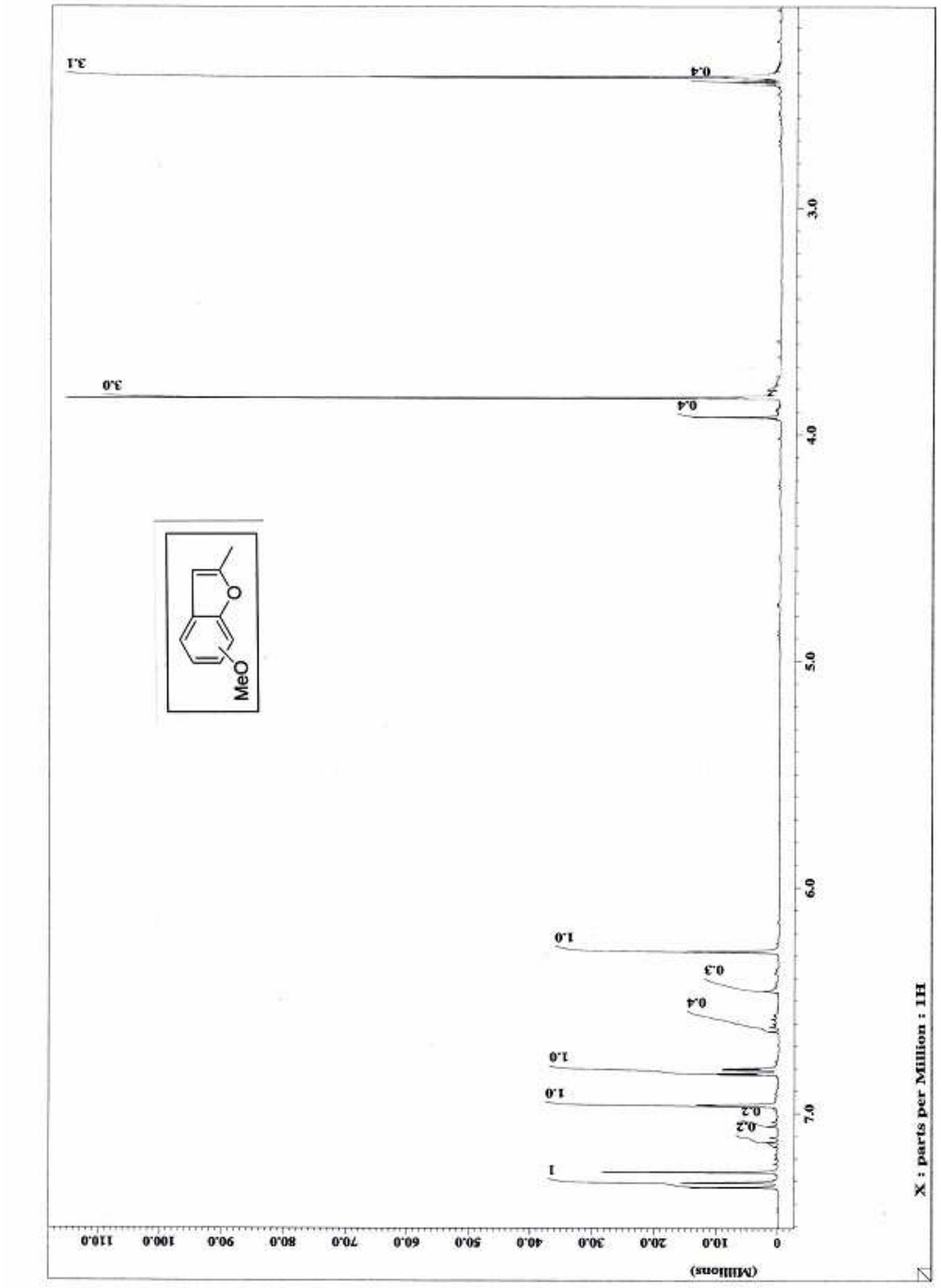

(Millions)
X : parts per Million : 1H
2.0
1.0
1.0
2.0
1.0
1.0
1.0

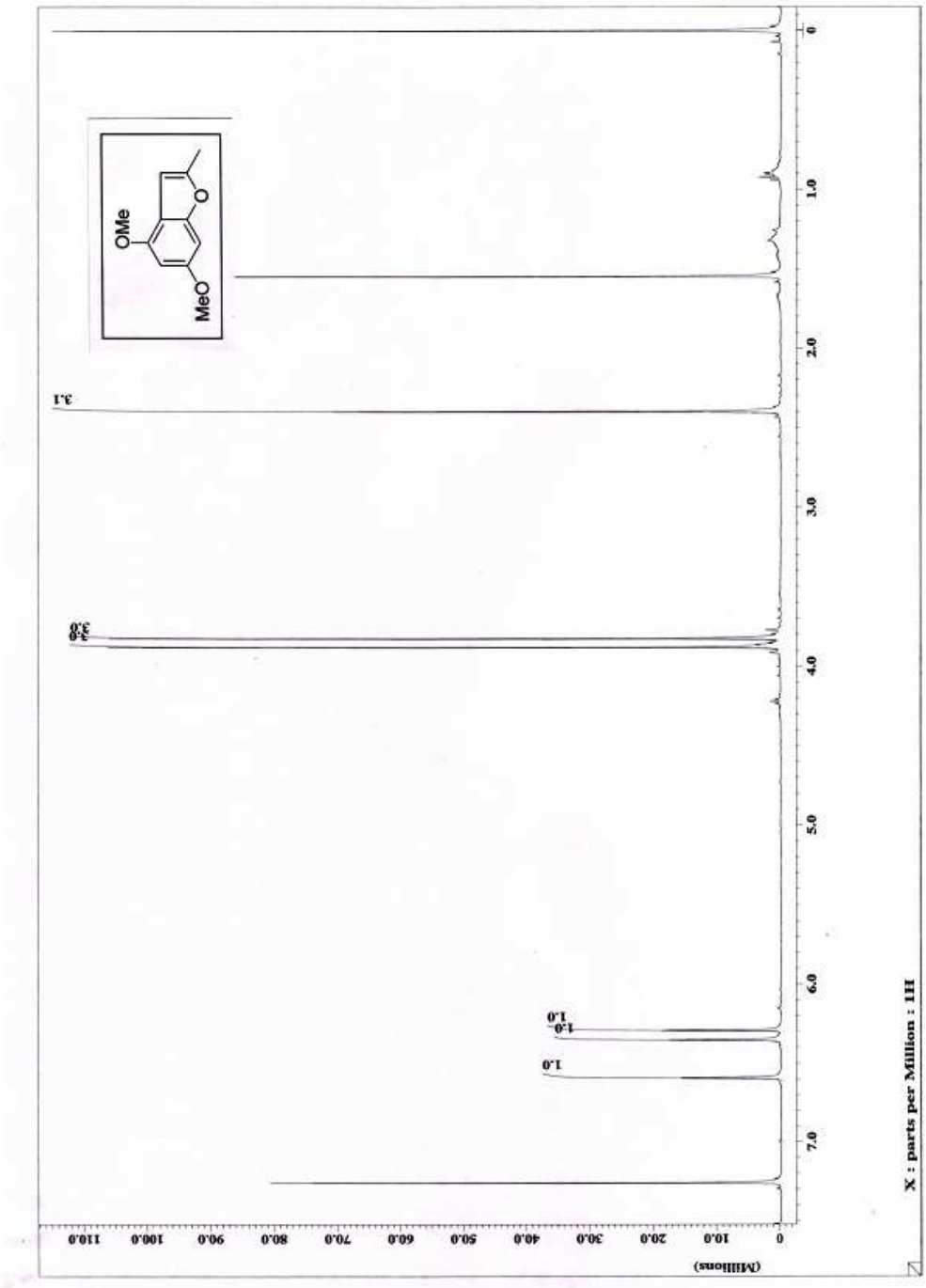

X : parts per Million : 1H
(Millions)
3.0
2.0
1.0
1.0
1.0
1.0
2.0
1.0
2.0
1
HO
O

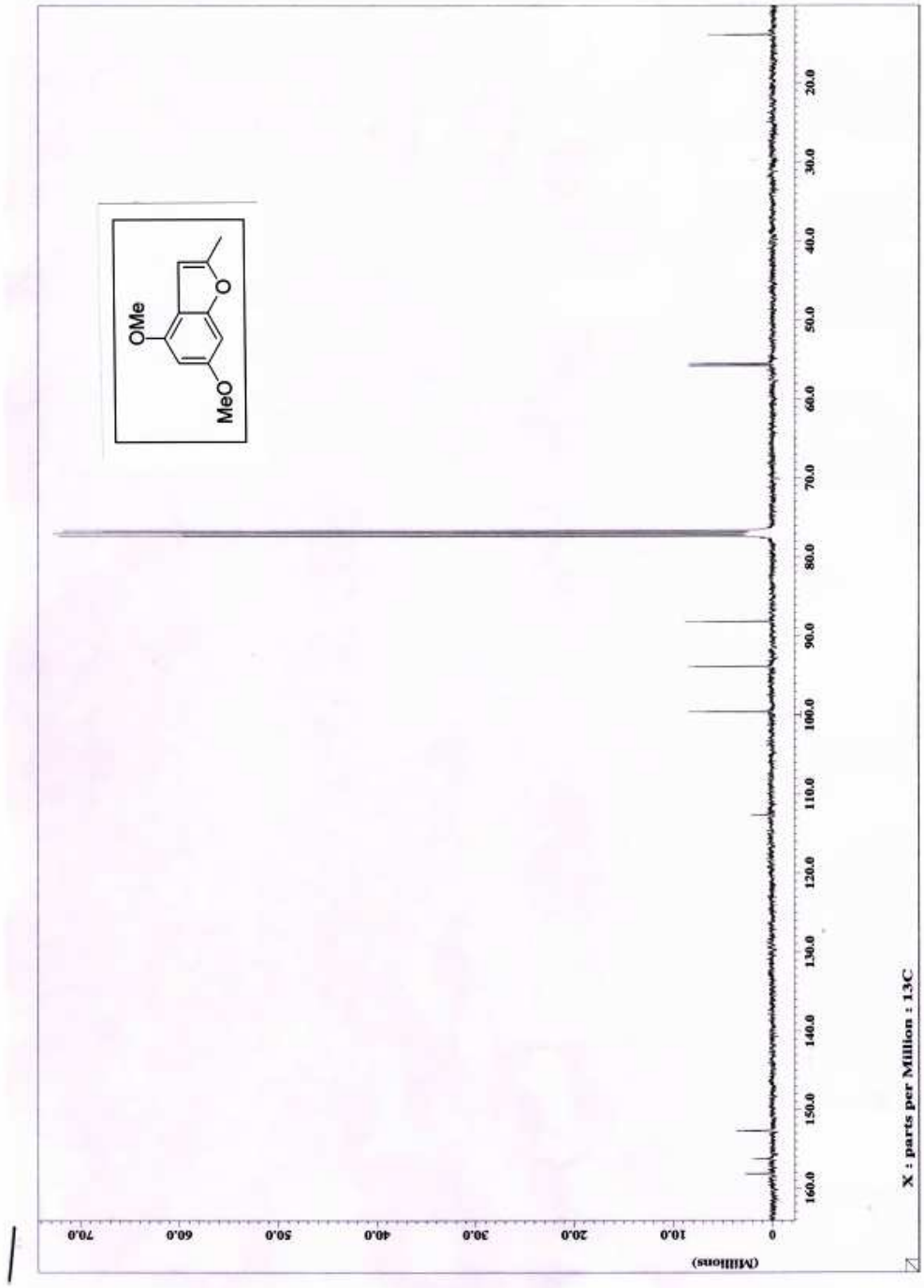

OMe
MeO
MeO
3.0
6.0
2.1
1
1.0
1.0
2.1
(Millions)
X : parts per Million : 1H

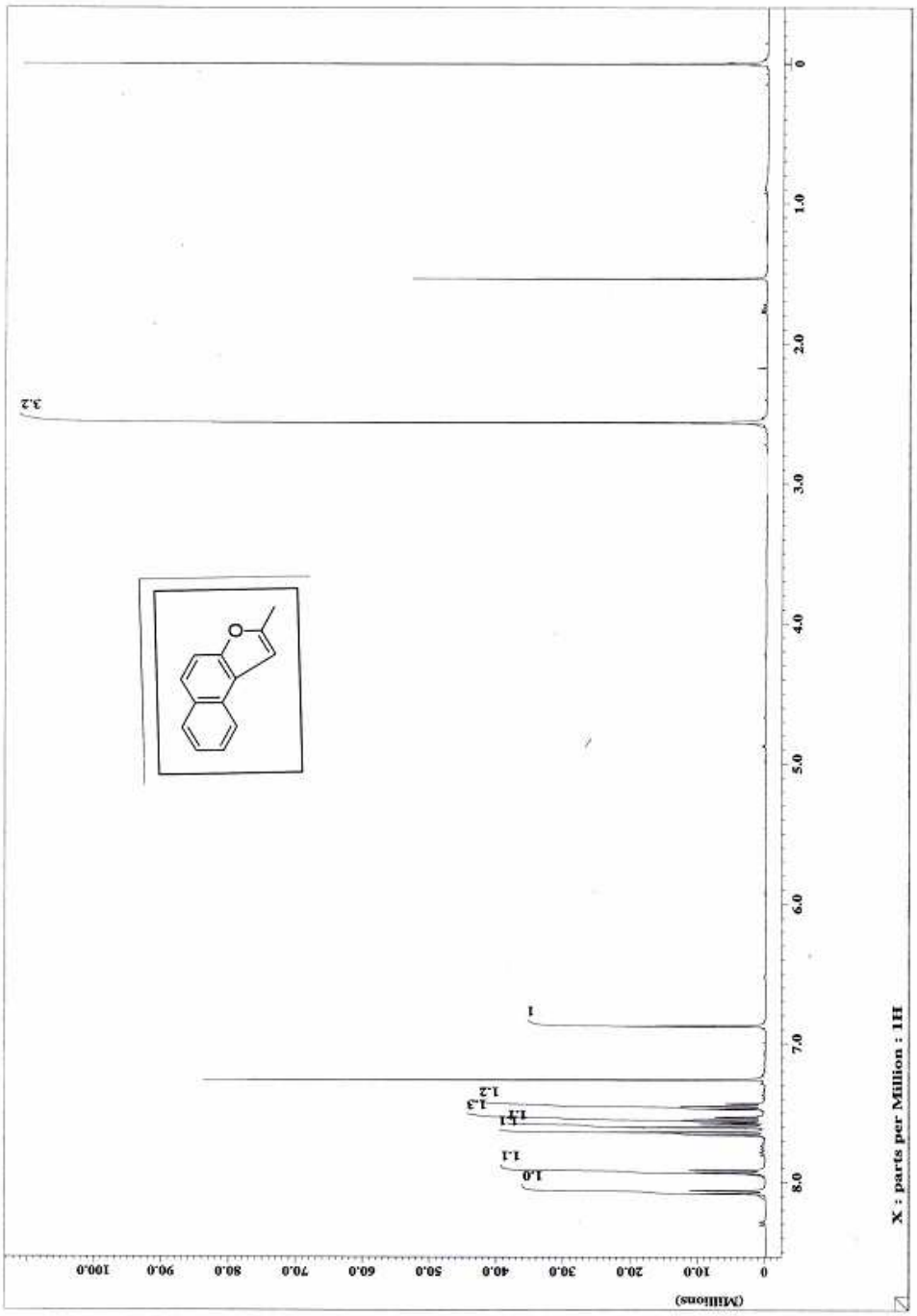

X : parts per Million : 1H
(Millions)
7.7
3.6
3.1
2.0
1.2
1.0
0.5
0.5
0.5
OMe
MeO
O

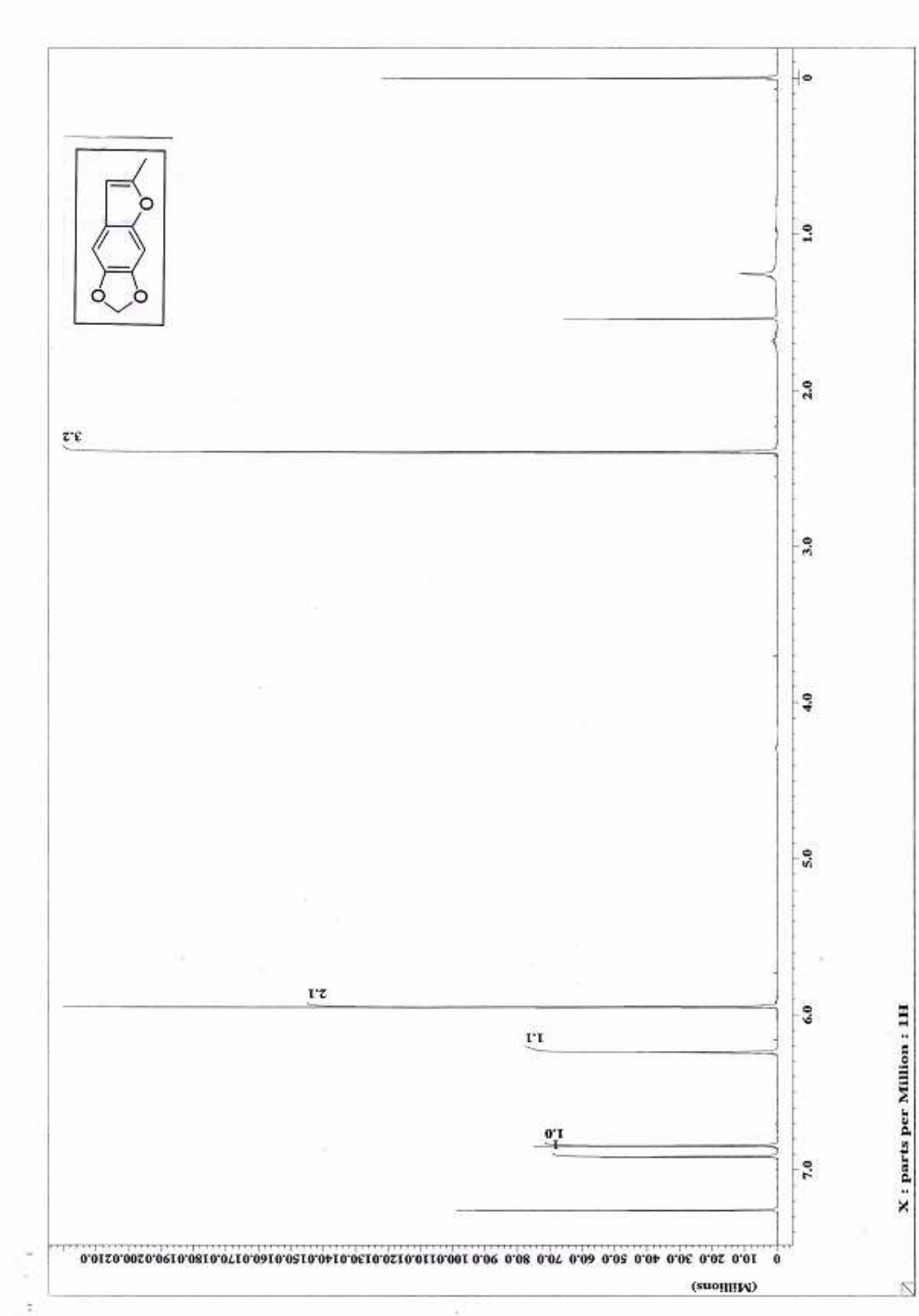

6.6
1.3
2.4
0.4
2.2
0.5
2.1
1.0
1.3
0.4
0.4
1.0
OH
X : parts per Million : 1H
(Millions)

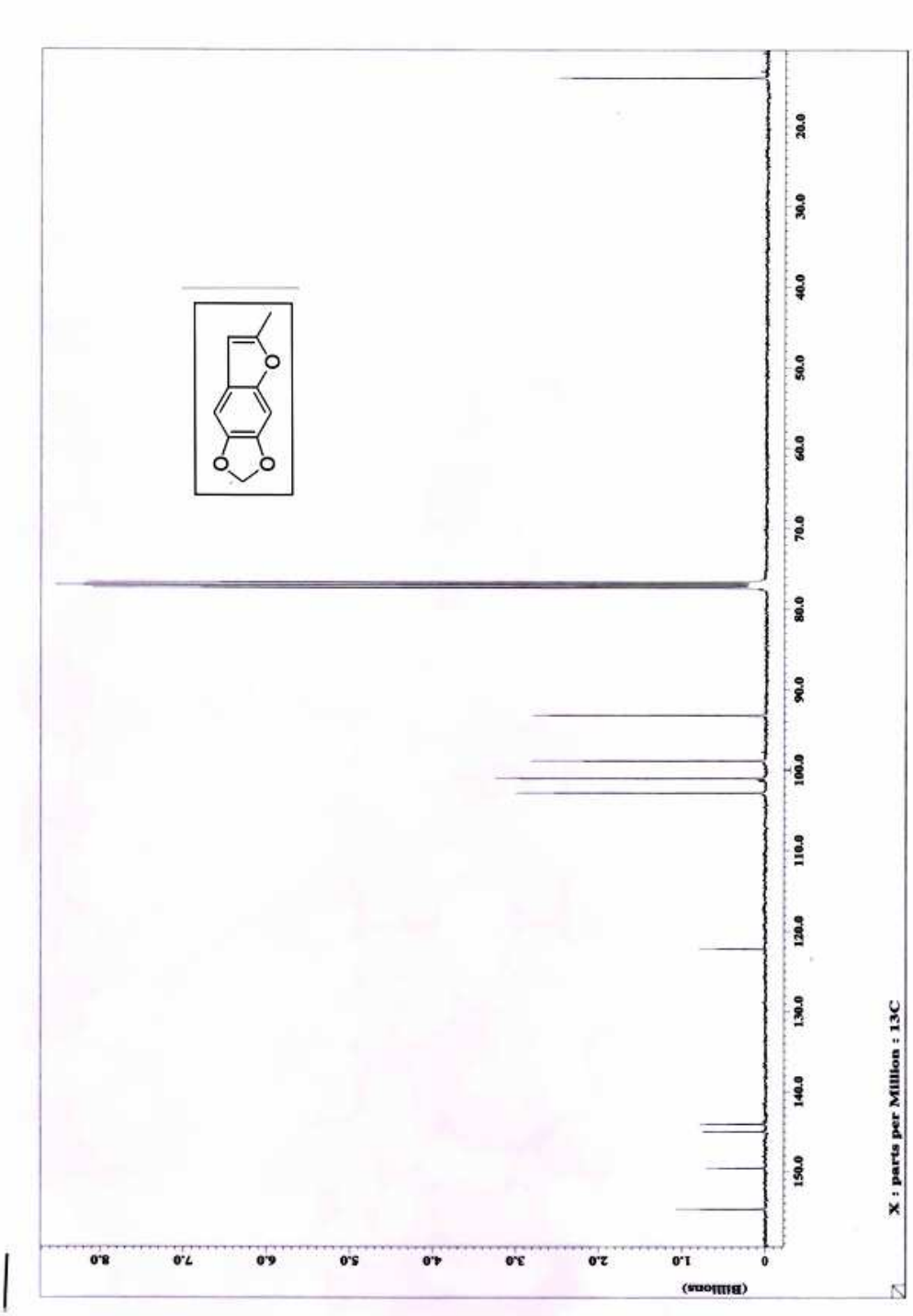

MeO
3.1
0.4
3.0
0.4
1.0
0.3
0.4
1.0
1.0
0.2
0.2
1
X : parts per Million : 1H
(Millions)

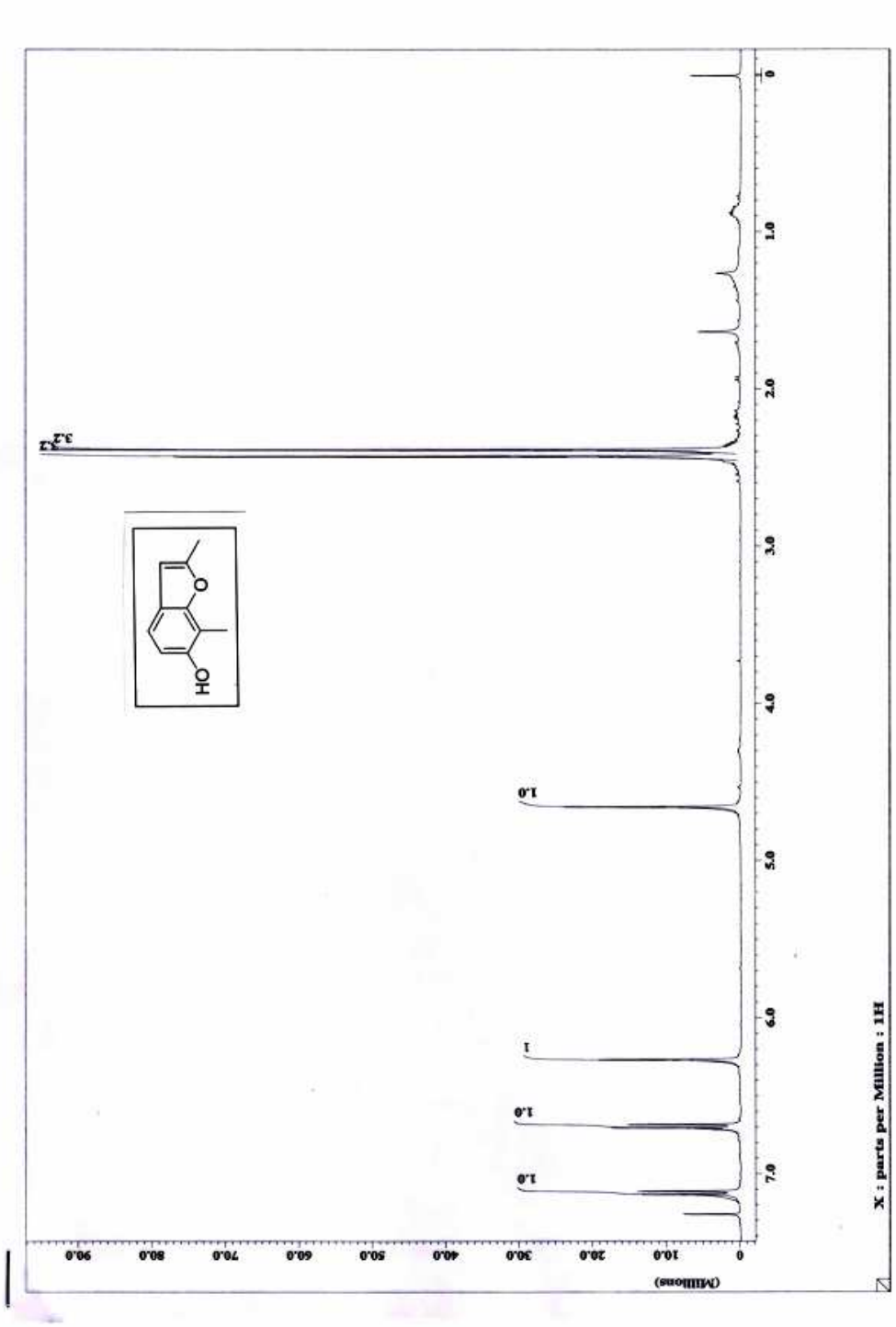

OMe
MeO
3.1
3.0
3.0
1.0
1.0
1.0
X : parts per Million : 1H
(Millions)

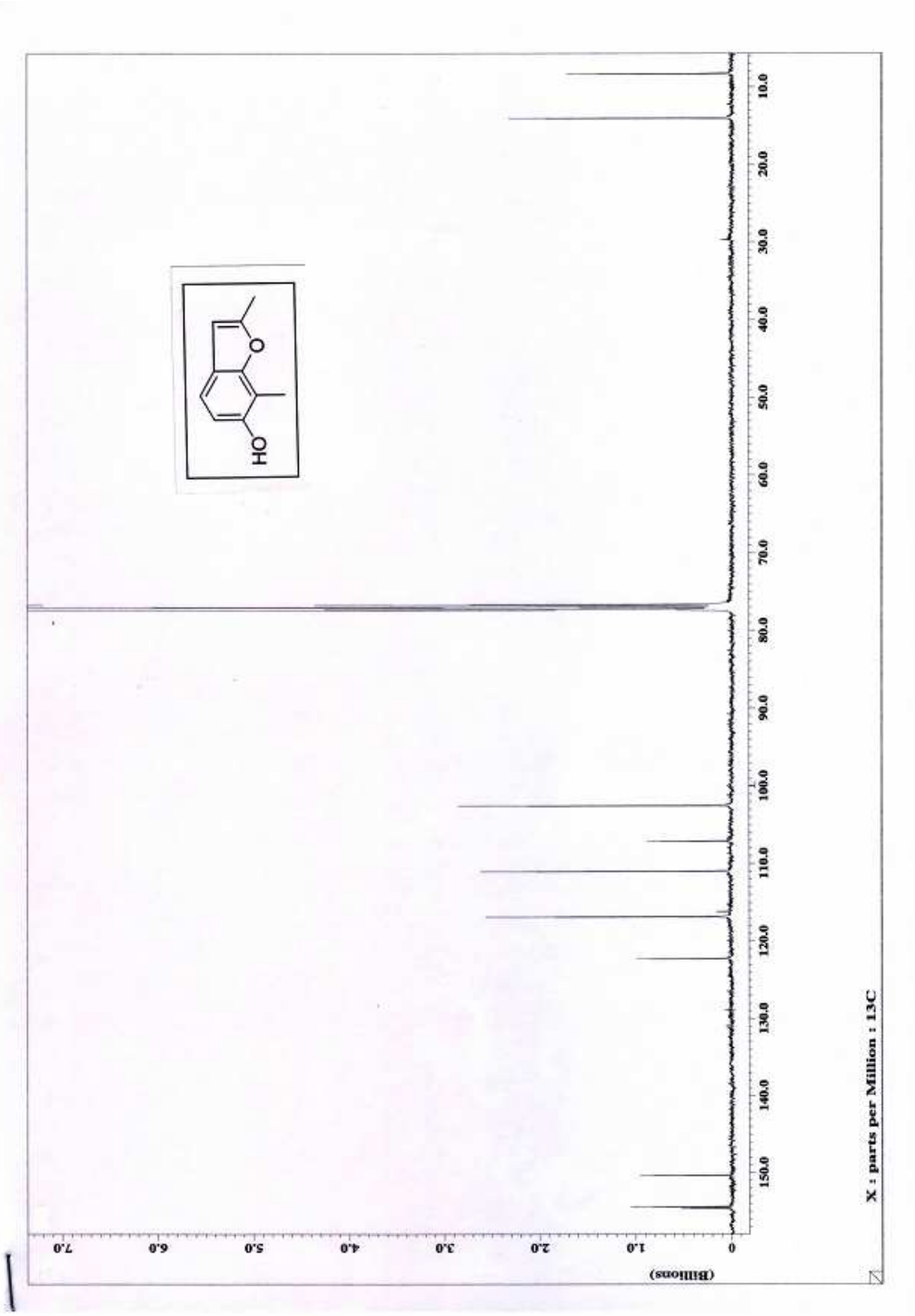

OMe
MeO
O
(Millions)
0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
160.0
150.0
140.0
130.0
120.0
110.0
100.0
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
X : parts per Million : 13C

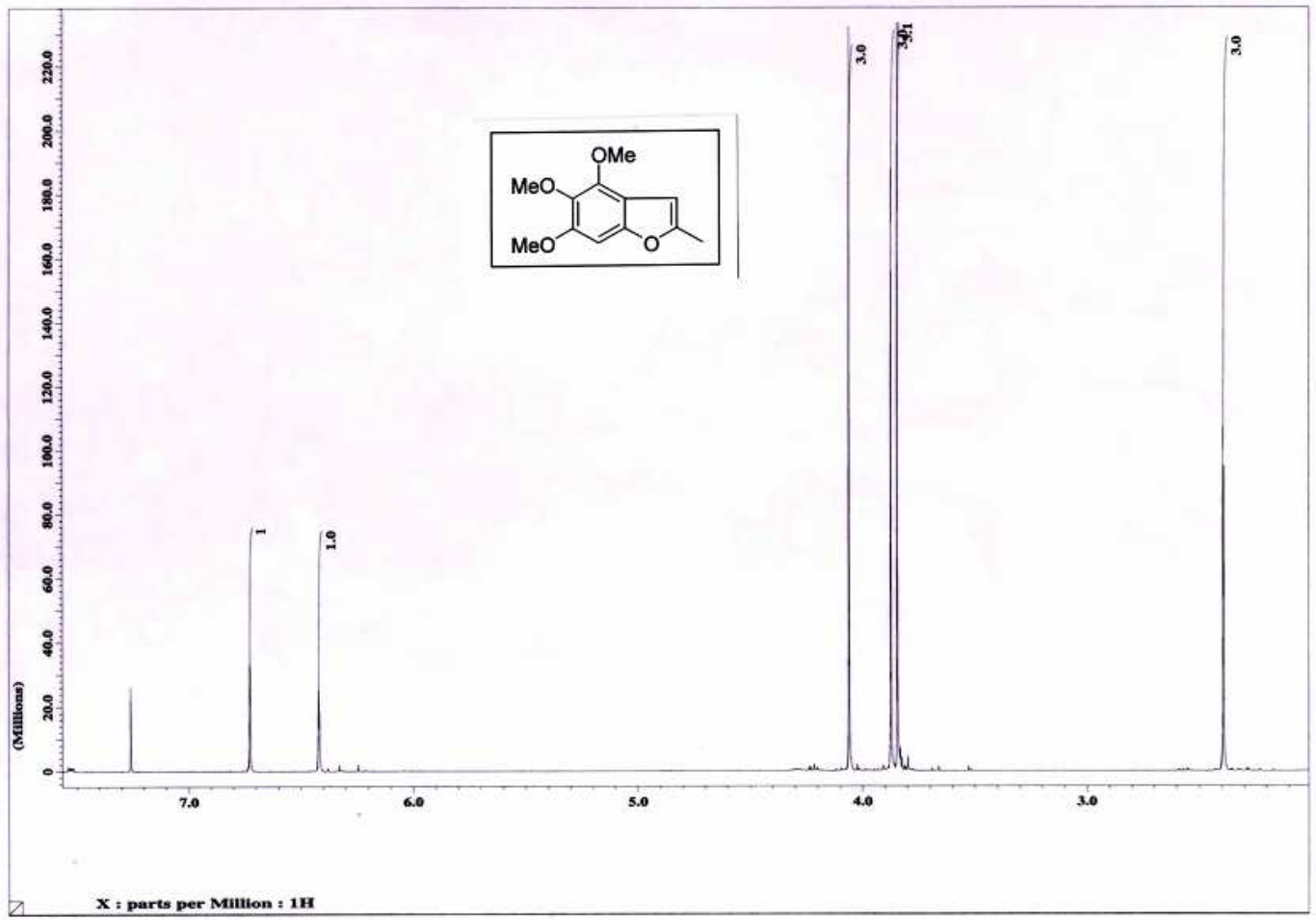

3.2
1
1.2
1.3
1.4
1.1
1.0
(Millions)
X : parts per Million : 1H

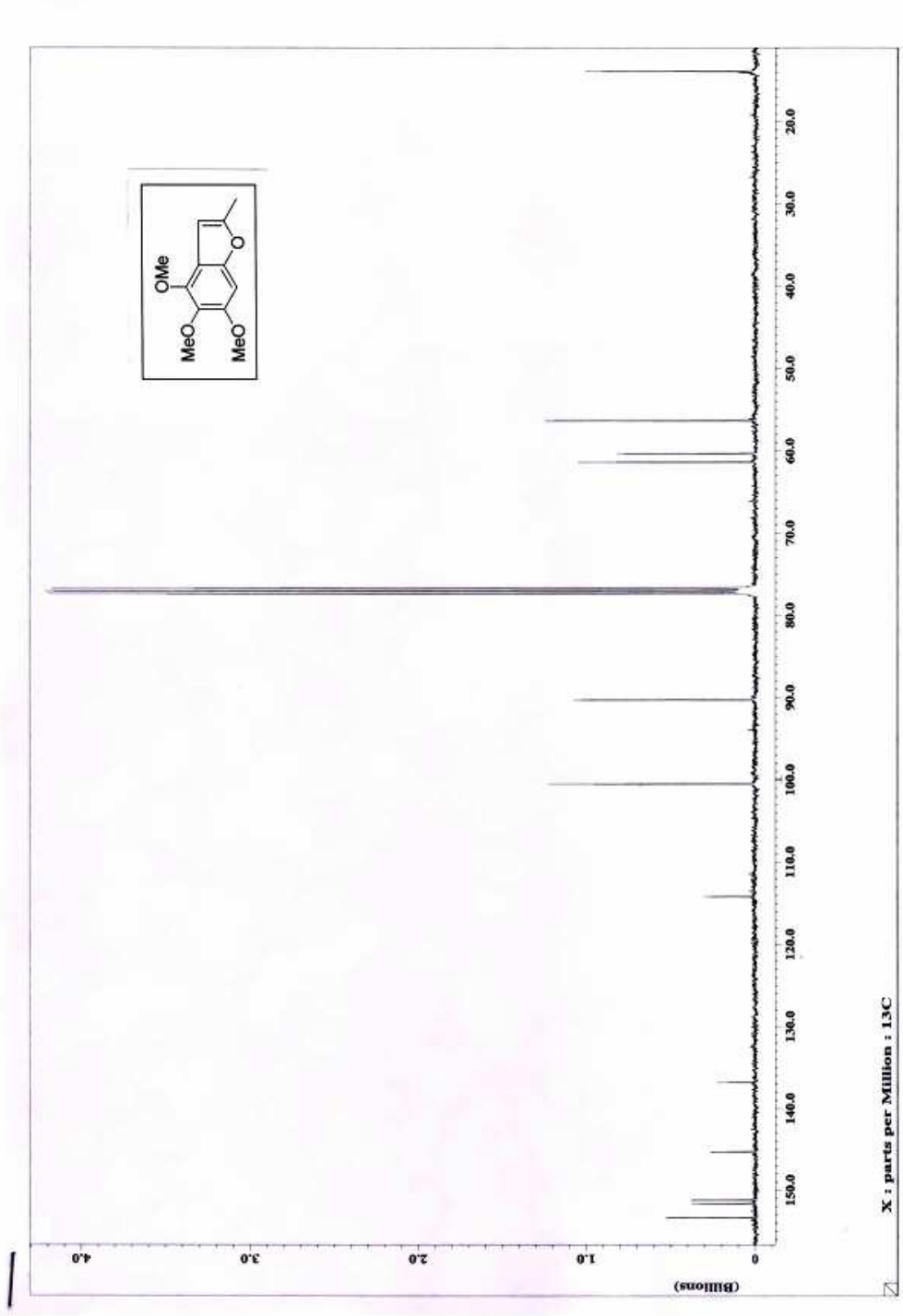

X : parts per Million : 1H
(Millions)
0 10.0 20.0 30.0 40.0 50.0 60.0 70.0 80.0 90.0 100.0 110.0 120.0 130.0 140.0 150.0 160.0 170.0 180.0 190.0 200.0 210.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0
1.0
1.1
2.1
3.2

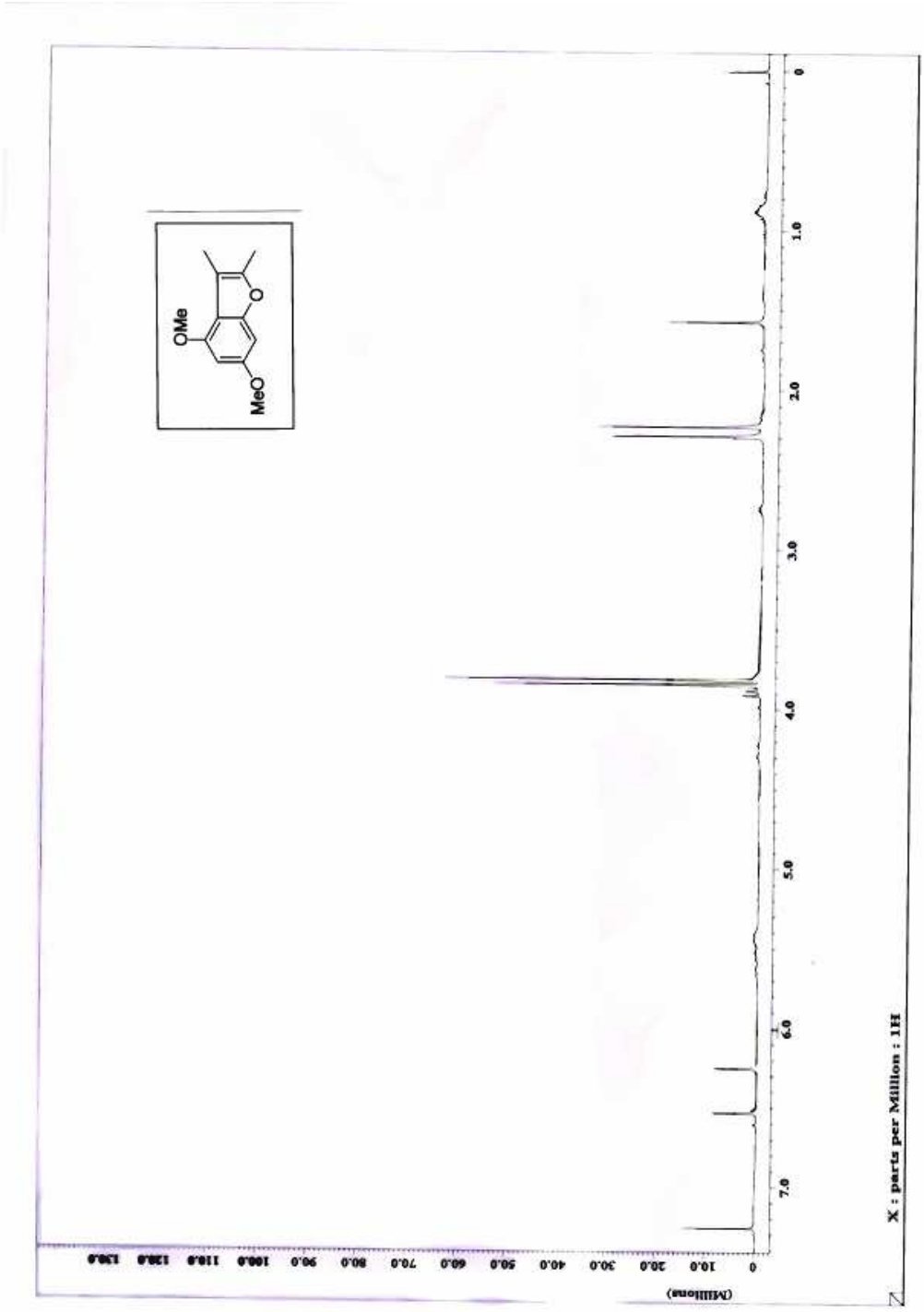

X : parts per Million : 13C
(Billions)

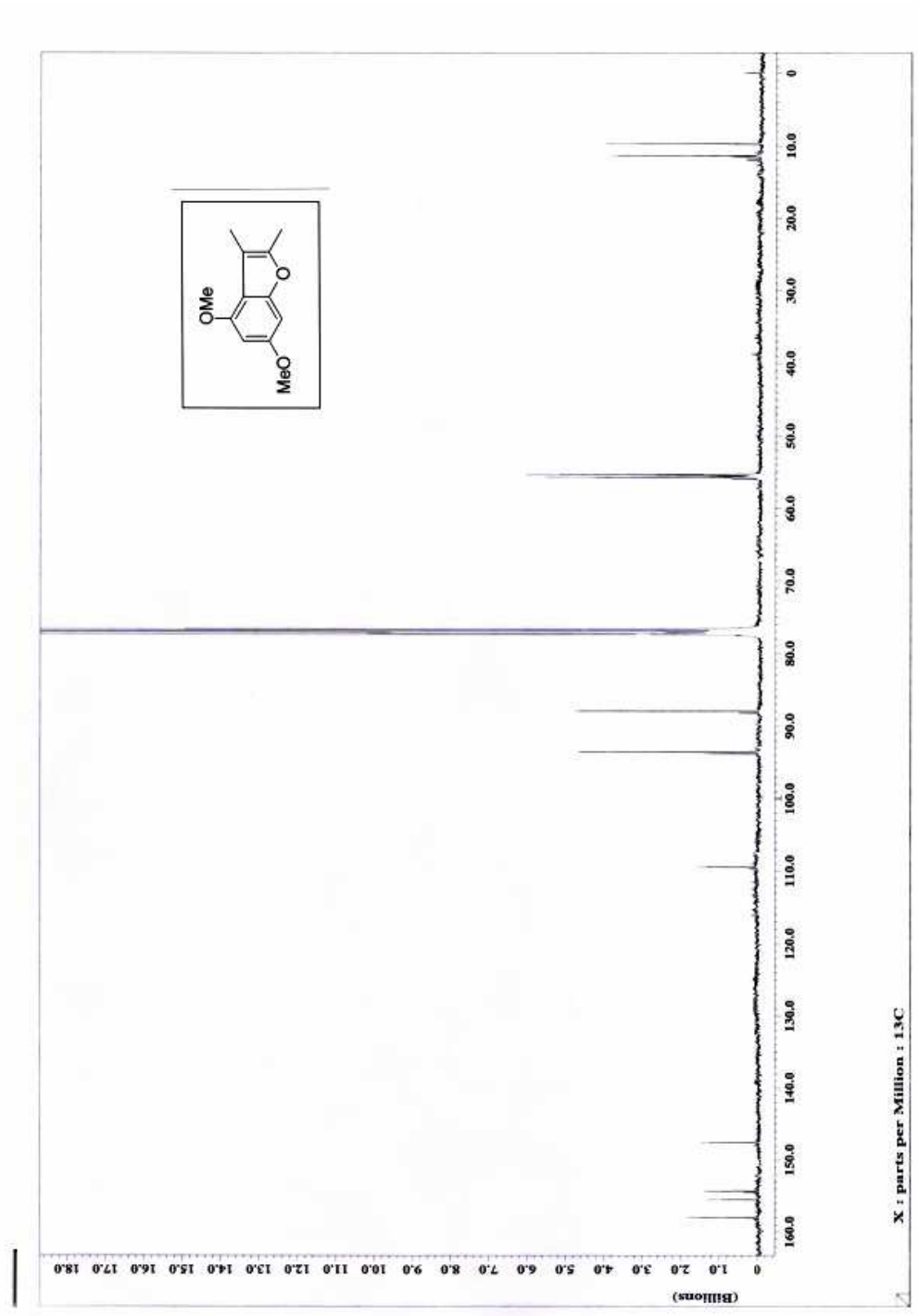

3.2
1.0
1
1.0
1.0
OH
(Millions)
X : parts per Million : 1H

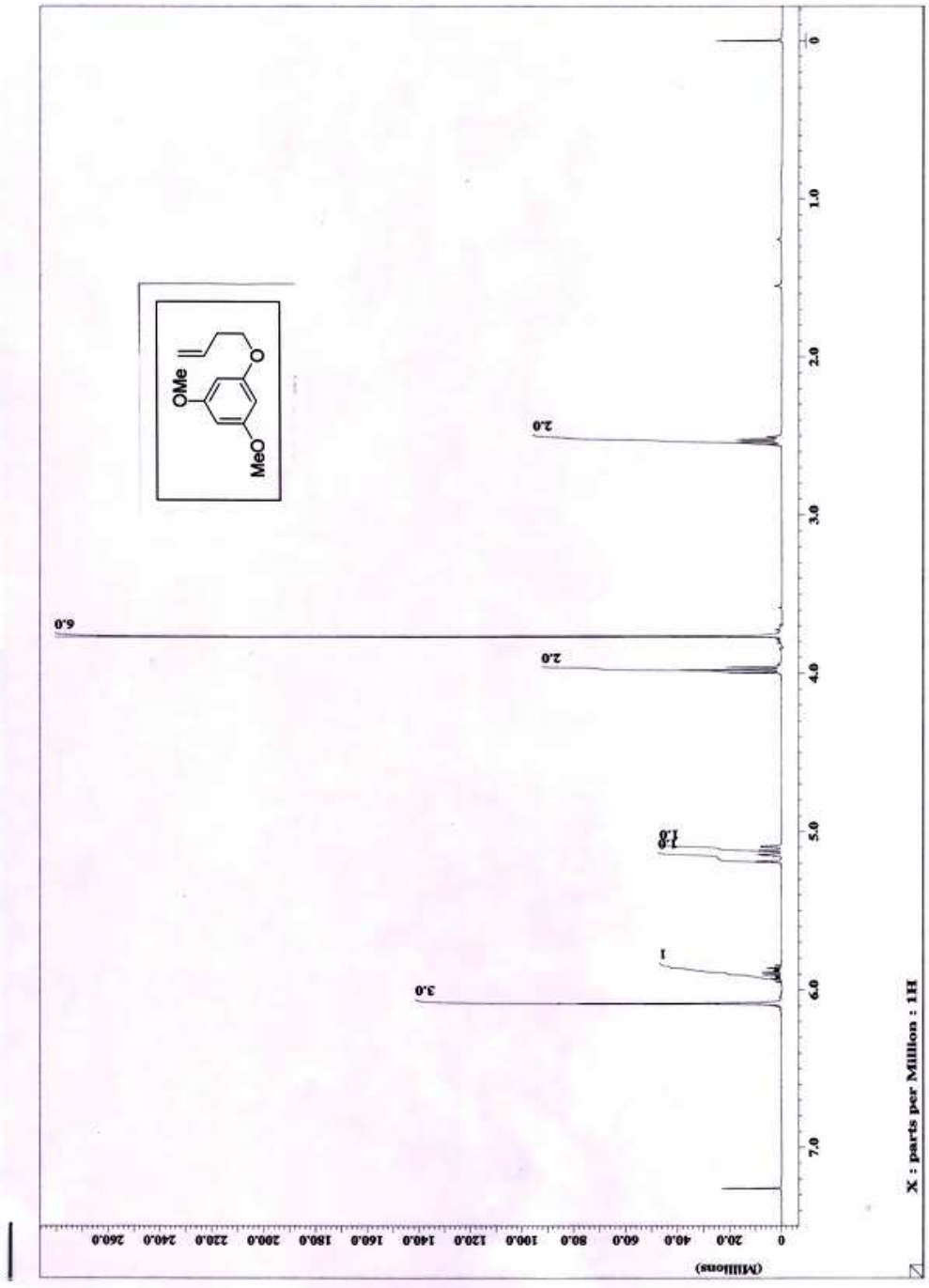

OH
X : parts per Million : 13C
(Billions)

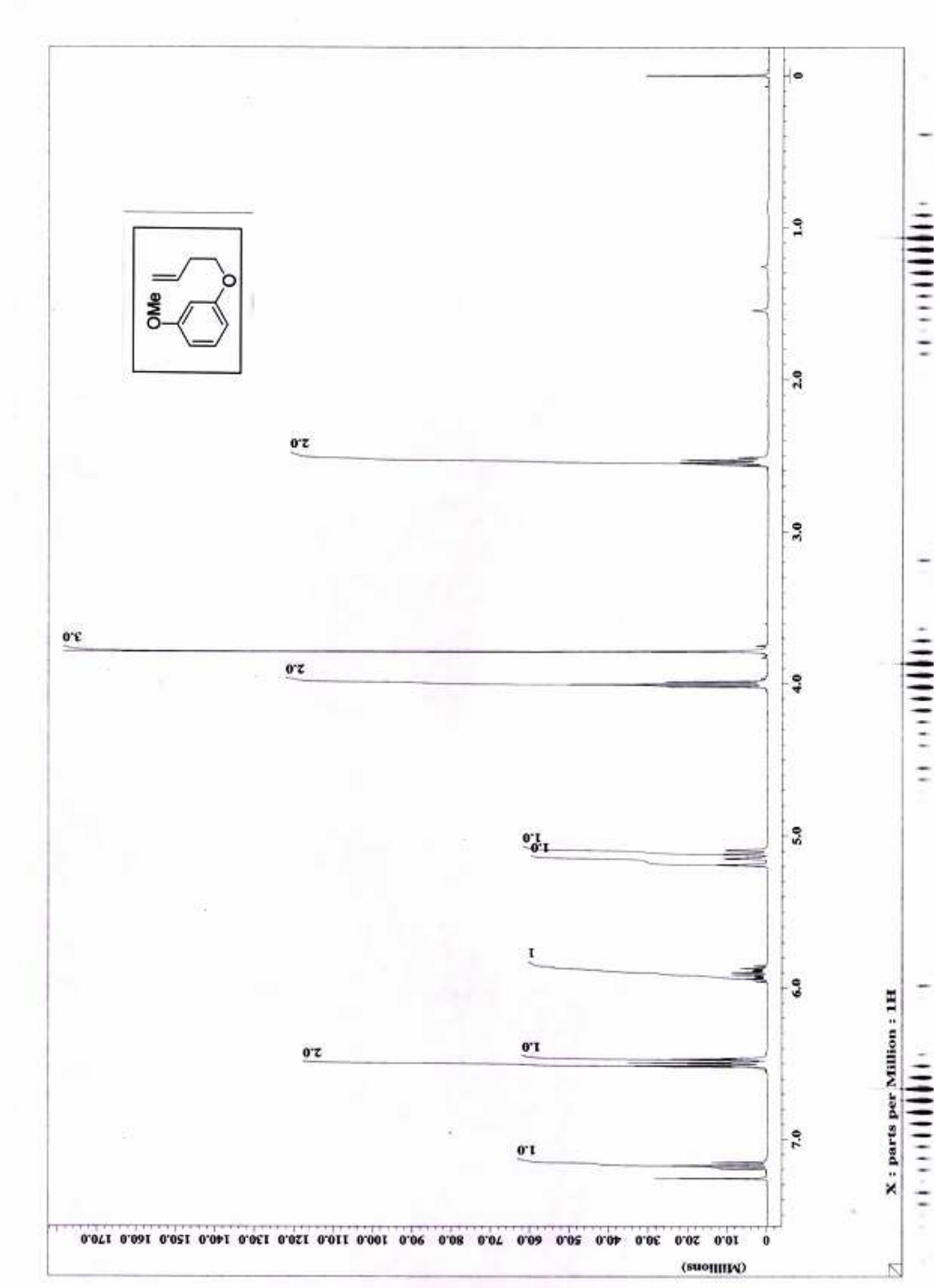

OMe
MeO
MeO
O
(Millions)
220.0
200.0
180.0
160.0
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0
1
1.0
3.0
3.0
3.0
7.0
6.0
5.0
4.0
3.0
X : parts per Million : 1H

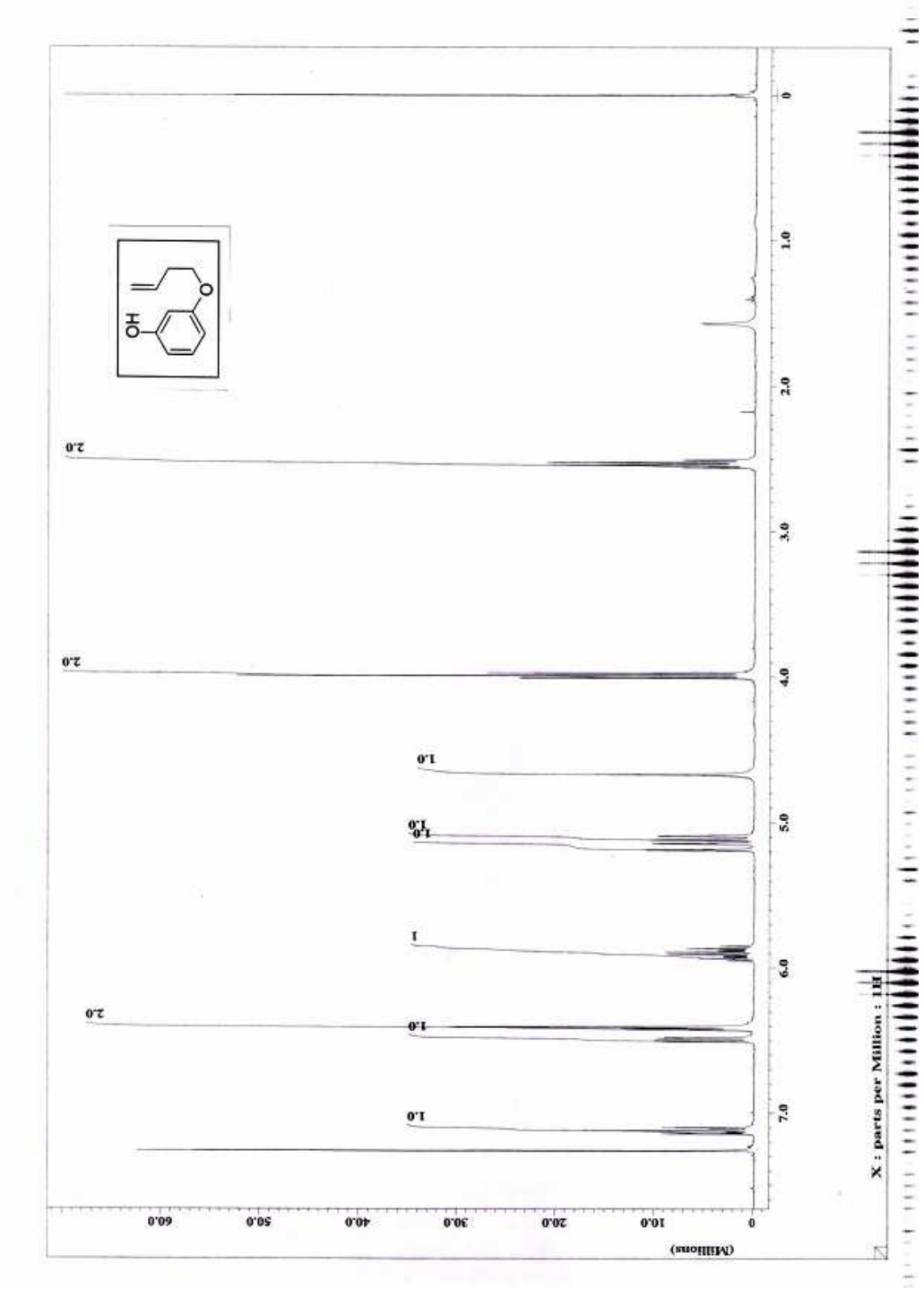

OMe
MeO
MeO
(Billions)
0
1.0
2.0
3.0
4.0
150.0
140.0
130.0
120.0
110.0
100.0
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
X : parts per Million : 13C

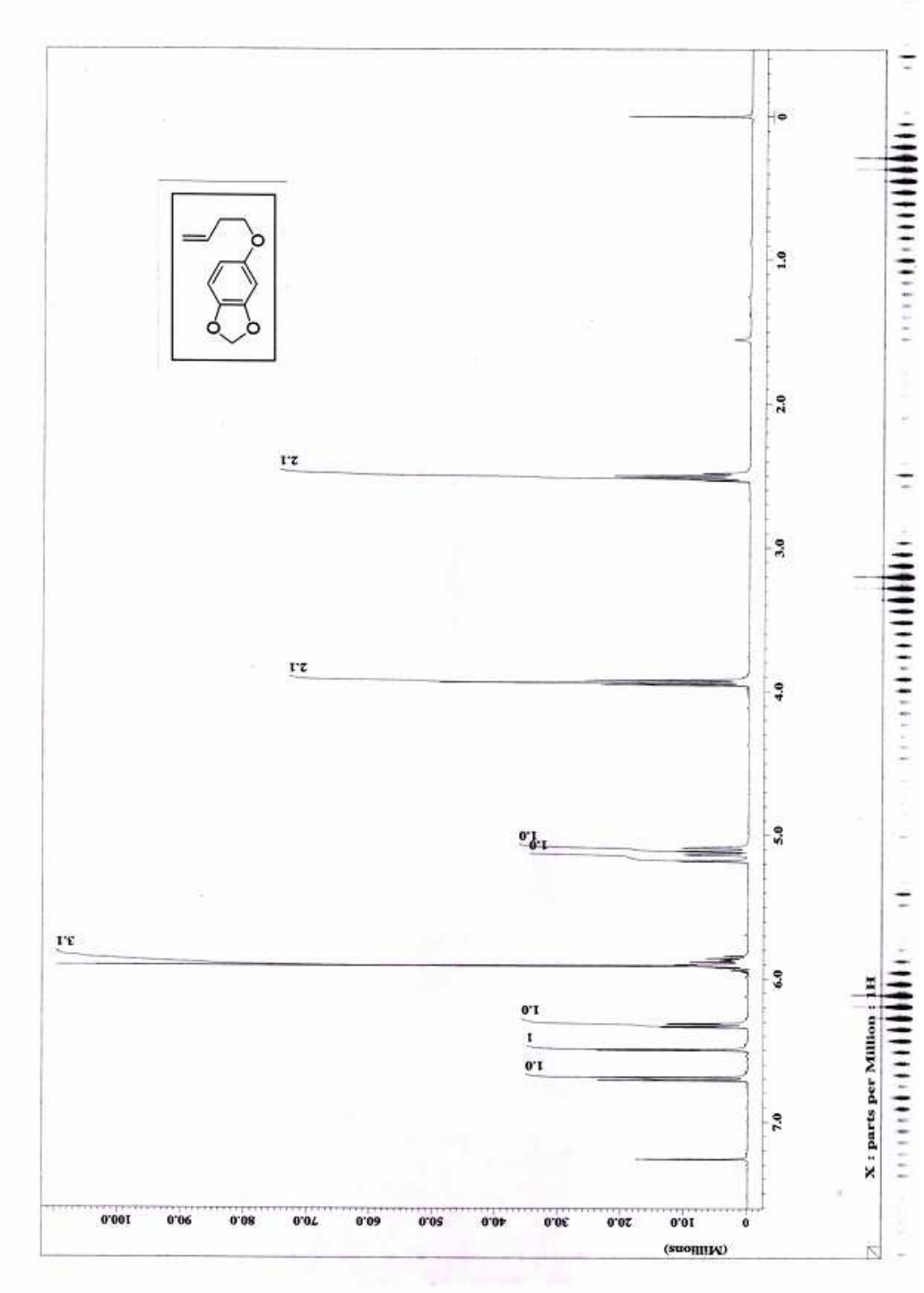

OMe
O
MeO
X : parts per Million : 1H

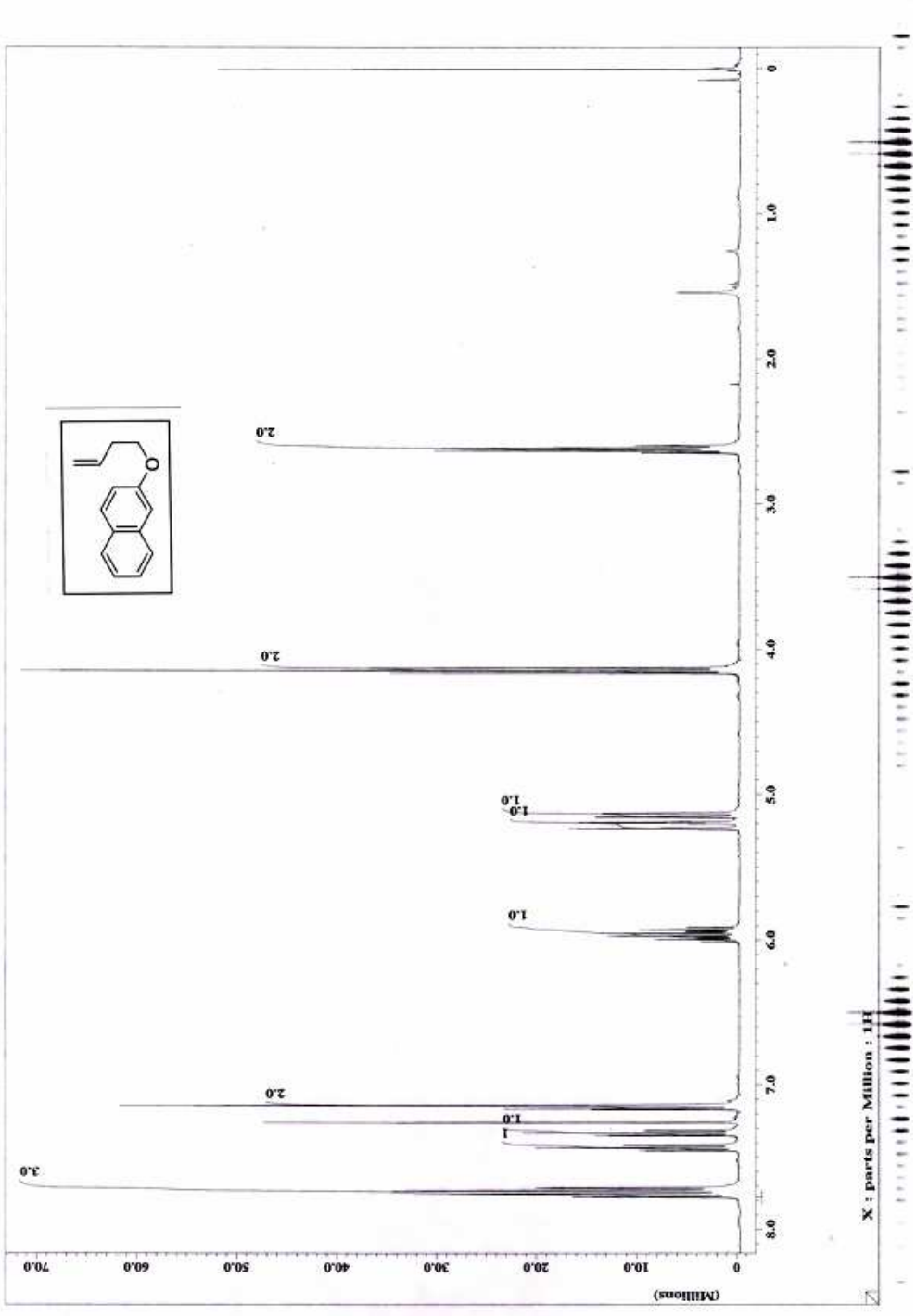

OMe
MeO
(Billions)
X : parts per Million : 13C

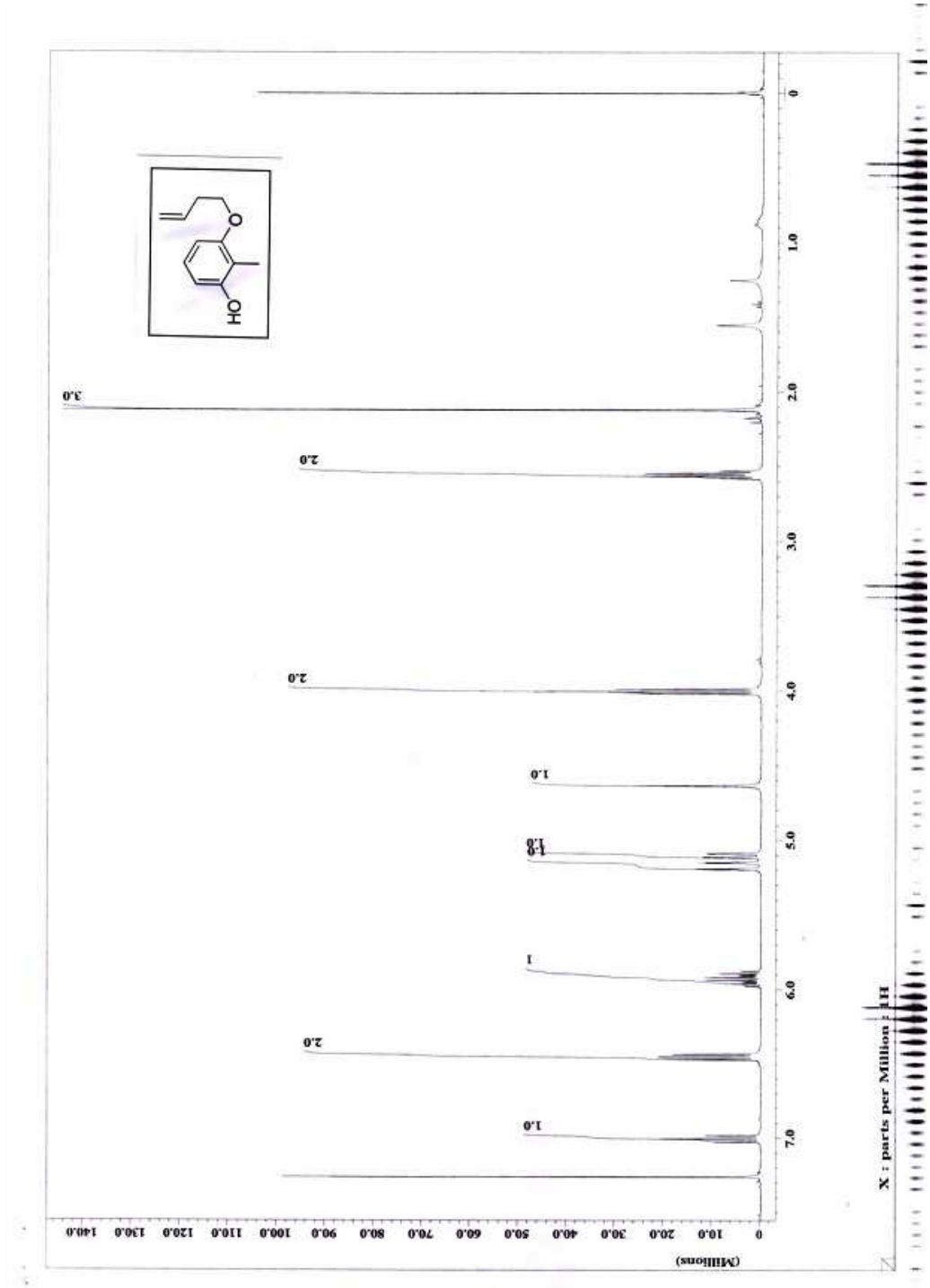

OMe
O
MeO
6.0
2.0
2.0
1.8
1
3.0
X : parts per Million : 1H
(Millions)

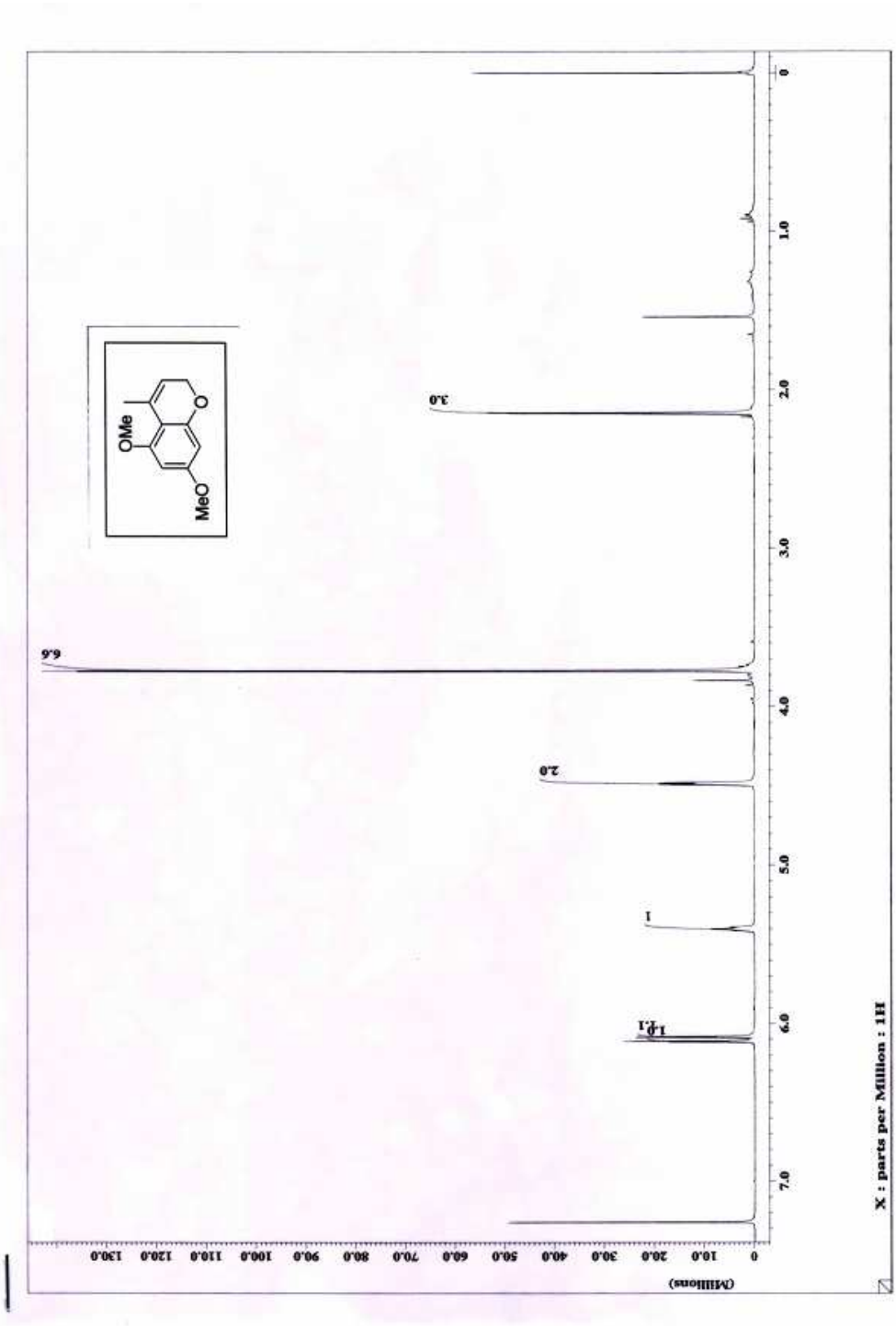

OMe
X : parts per Million : 1H
(Millions)
1.0
2.0
1.0
1
1.0
1.0
2.0
3.0
2.0

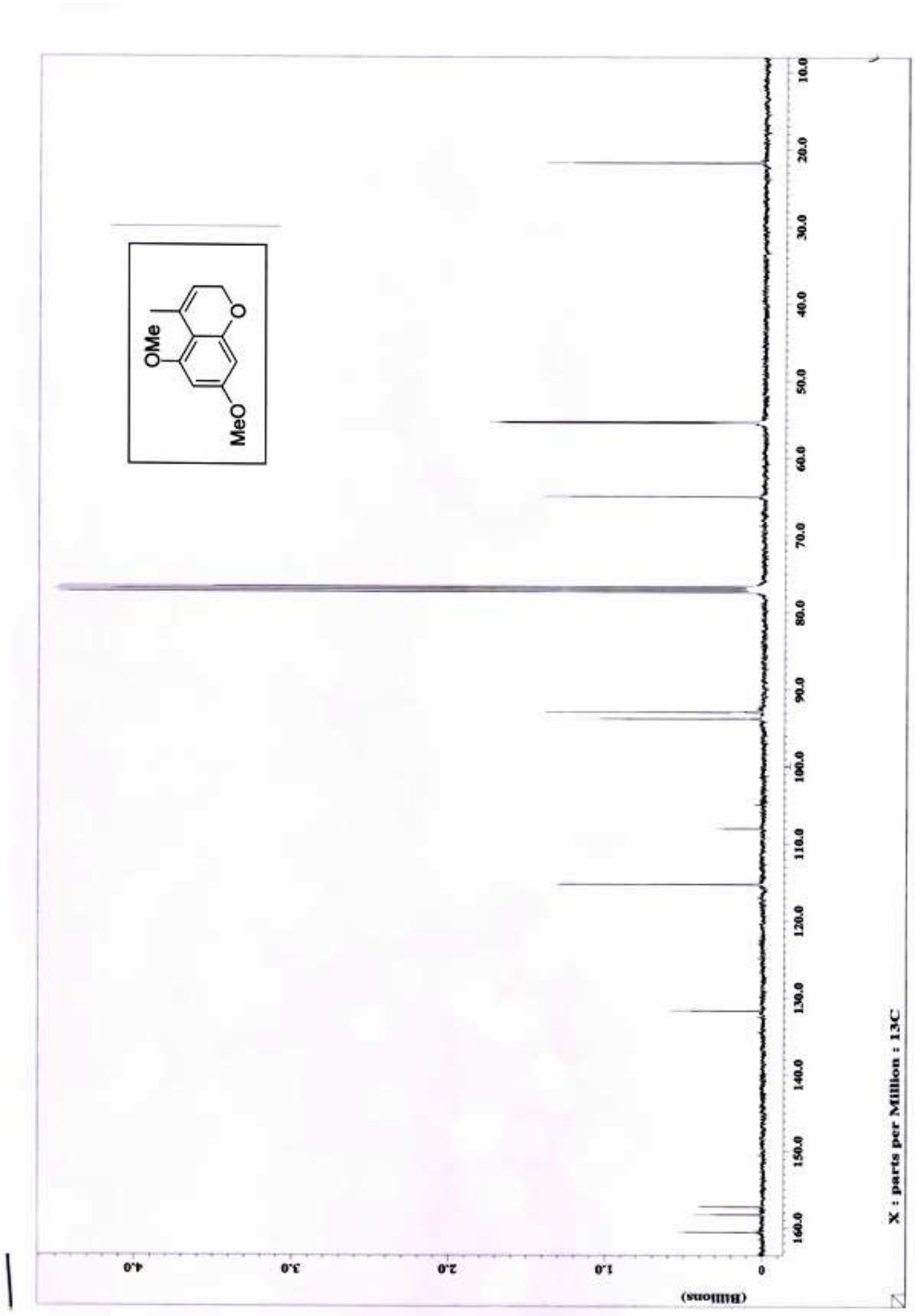

OH
O
2.0
2.0
1.0
1.0
1.0
1
1.0
2.0
1.0
X : parts per Million : 1H
(Millions)

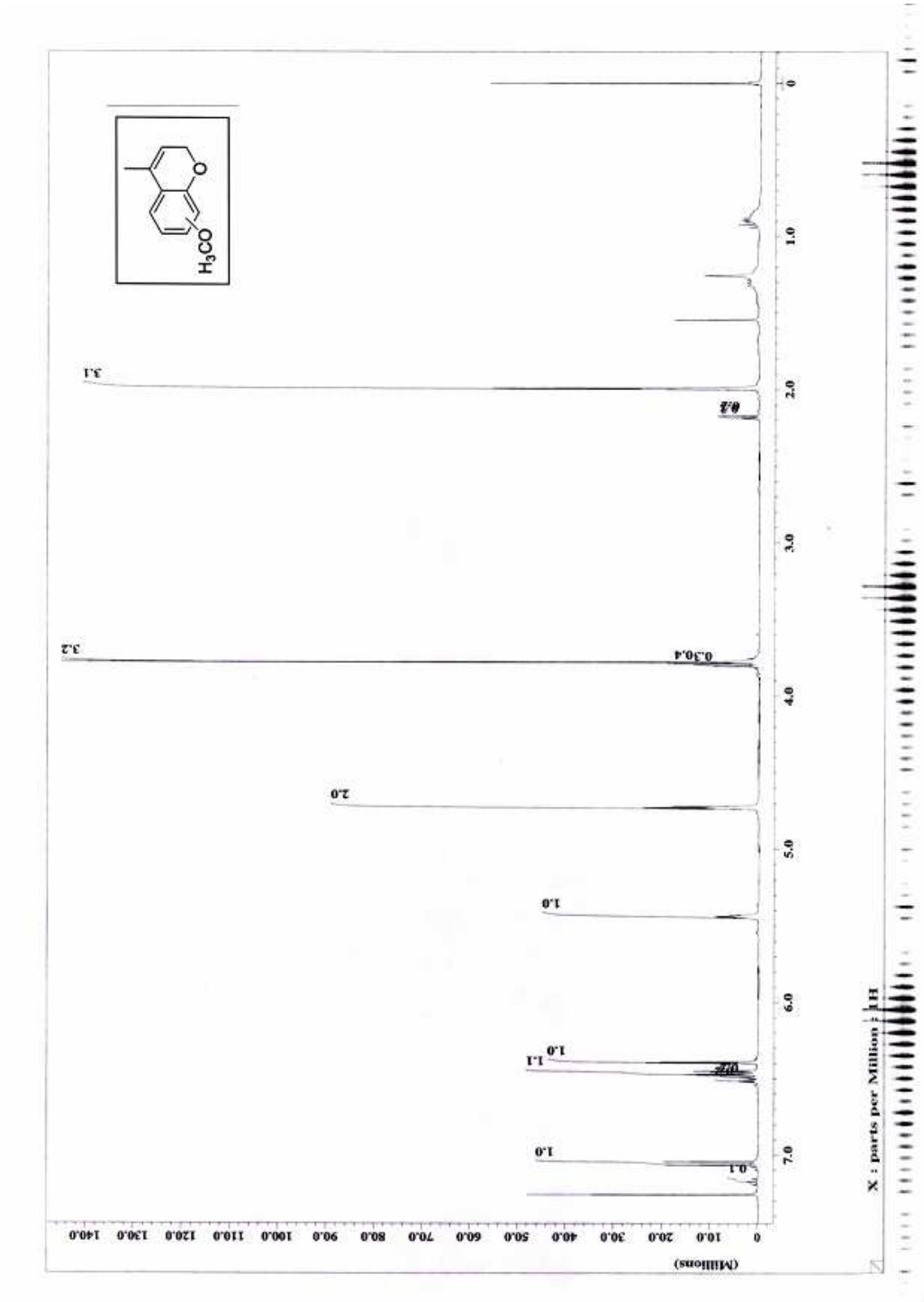

X : parts per Million : 1H
(Millions)
3.1
1.0
1
1.0
1.0
1.0
2.1
2.1


(Millions)
X : parts per Million : 1H

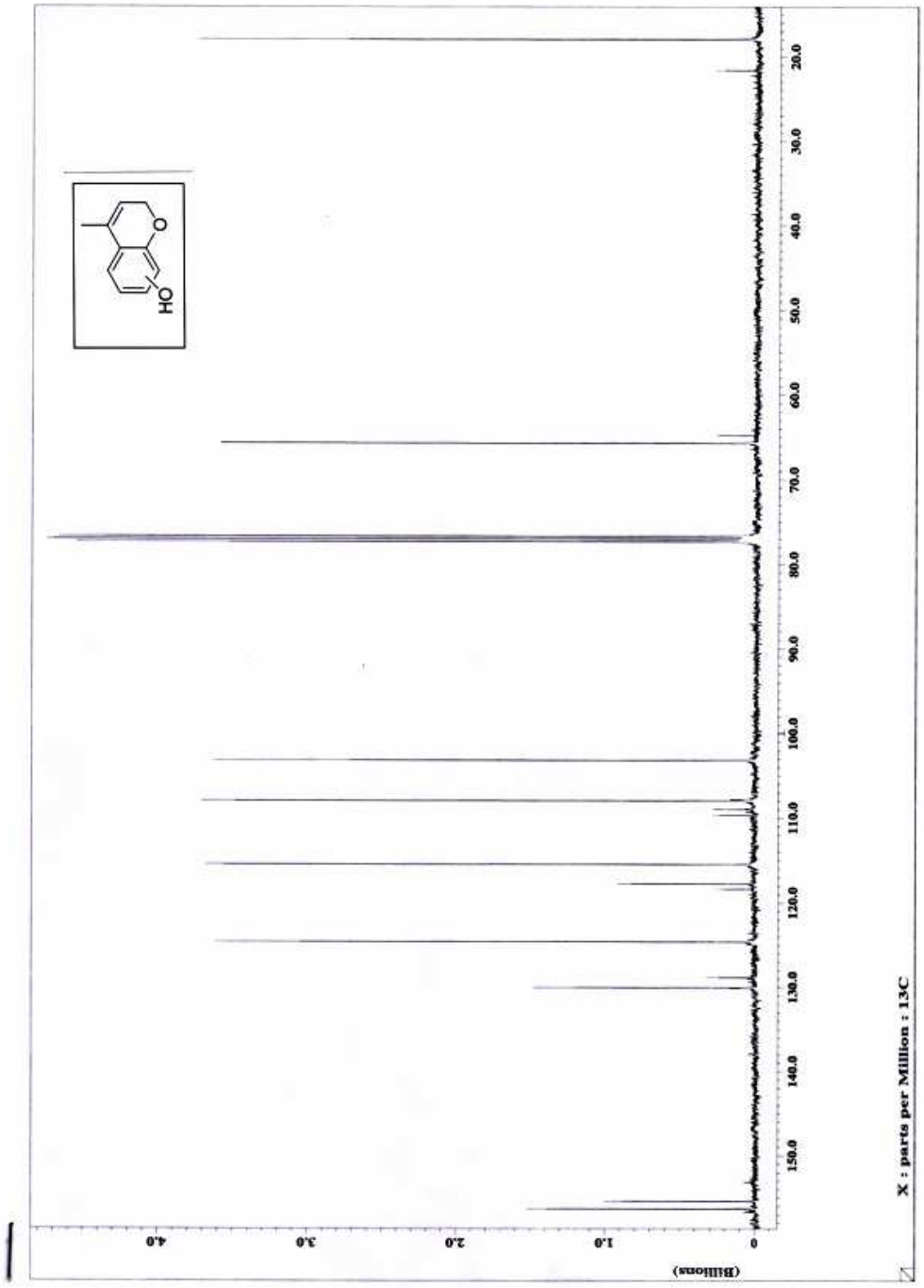

X : parts per Million : 1H
(Millions)
HO
O
3.0
2.0
2.0
1.0
1.0
1.0
1.0
2.0
1.0

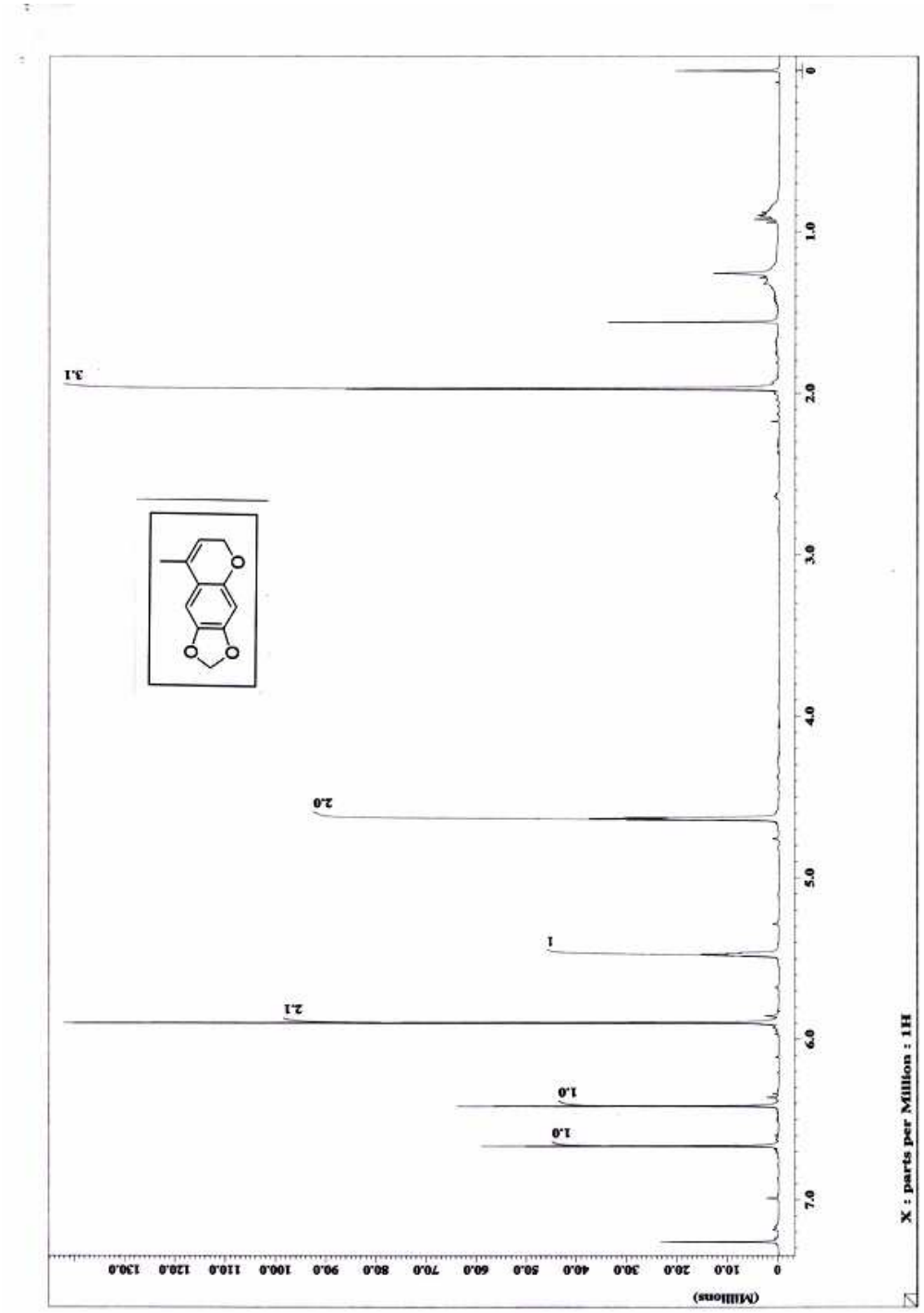

OMe
MeO
6.6
3.0
2.0
1
1.0
2.1
X : parts per Million : 1H
(Millions)

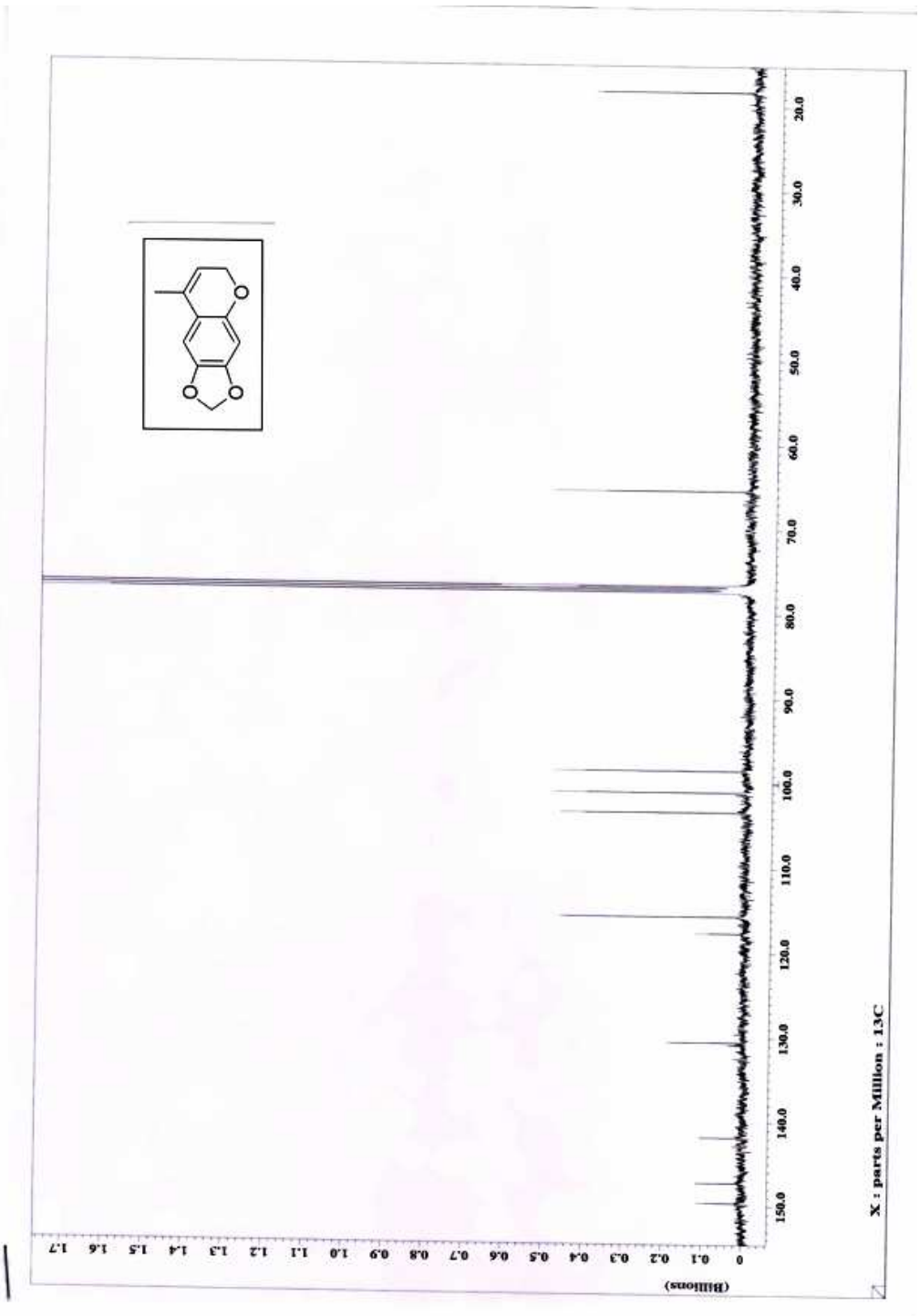

OMe
MeO
O
(Billions)
0
1.0
2.0
3.0
4.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
90.0
100.0
110.0
120.0
130.0
140.0
150.0
160.0
X : parts per Million : 13C

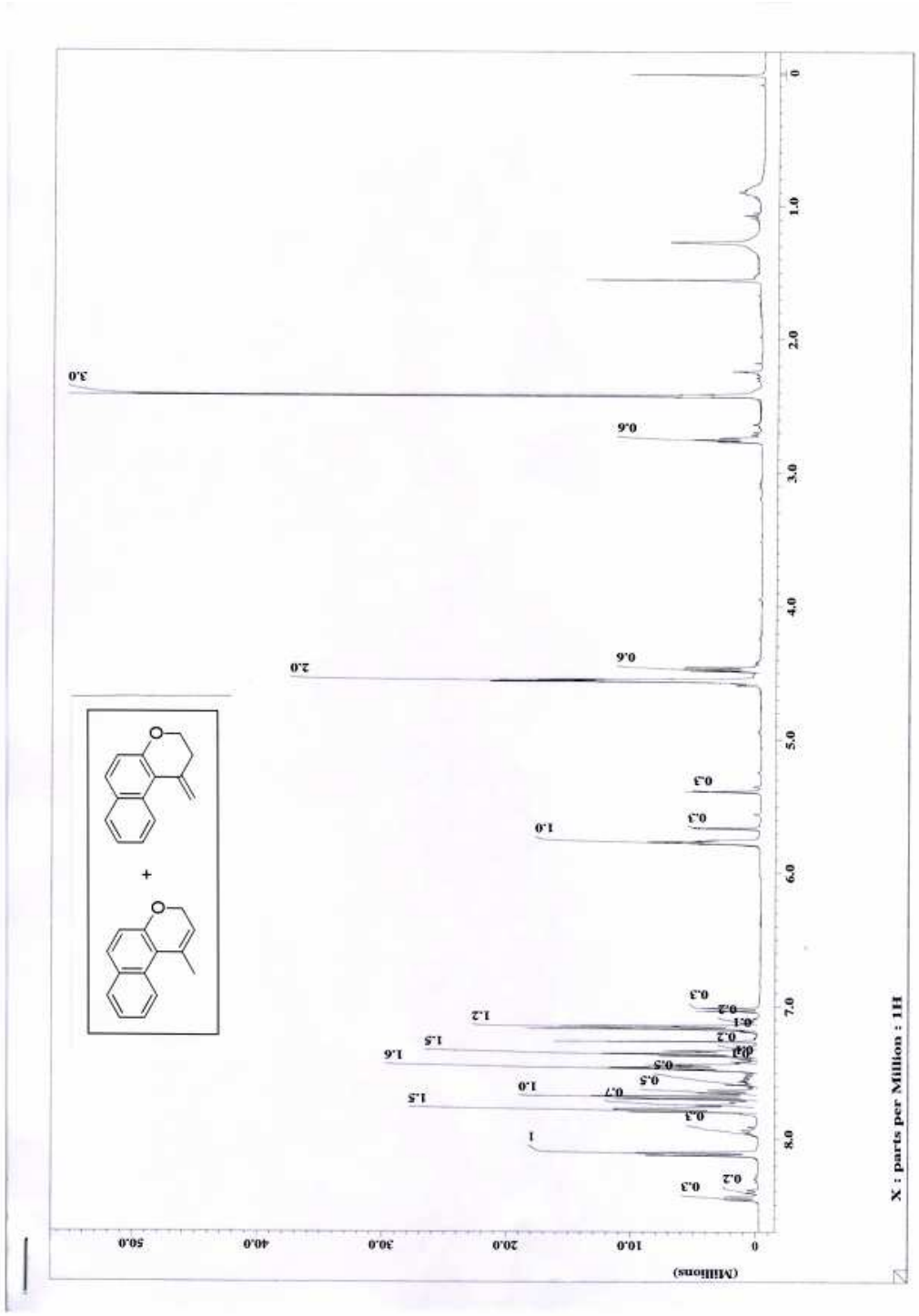

H3CO
X : parts per Million : 1H
(Millihons)
0.1
1.0
1.1
1.0
2.0
1.0
2.0
3.2
0.3
0.4
0.2
3.1

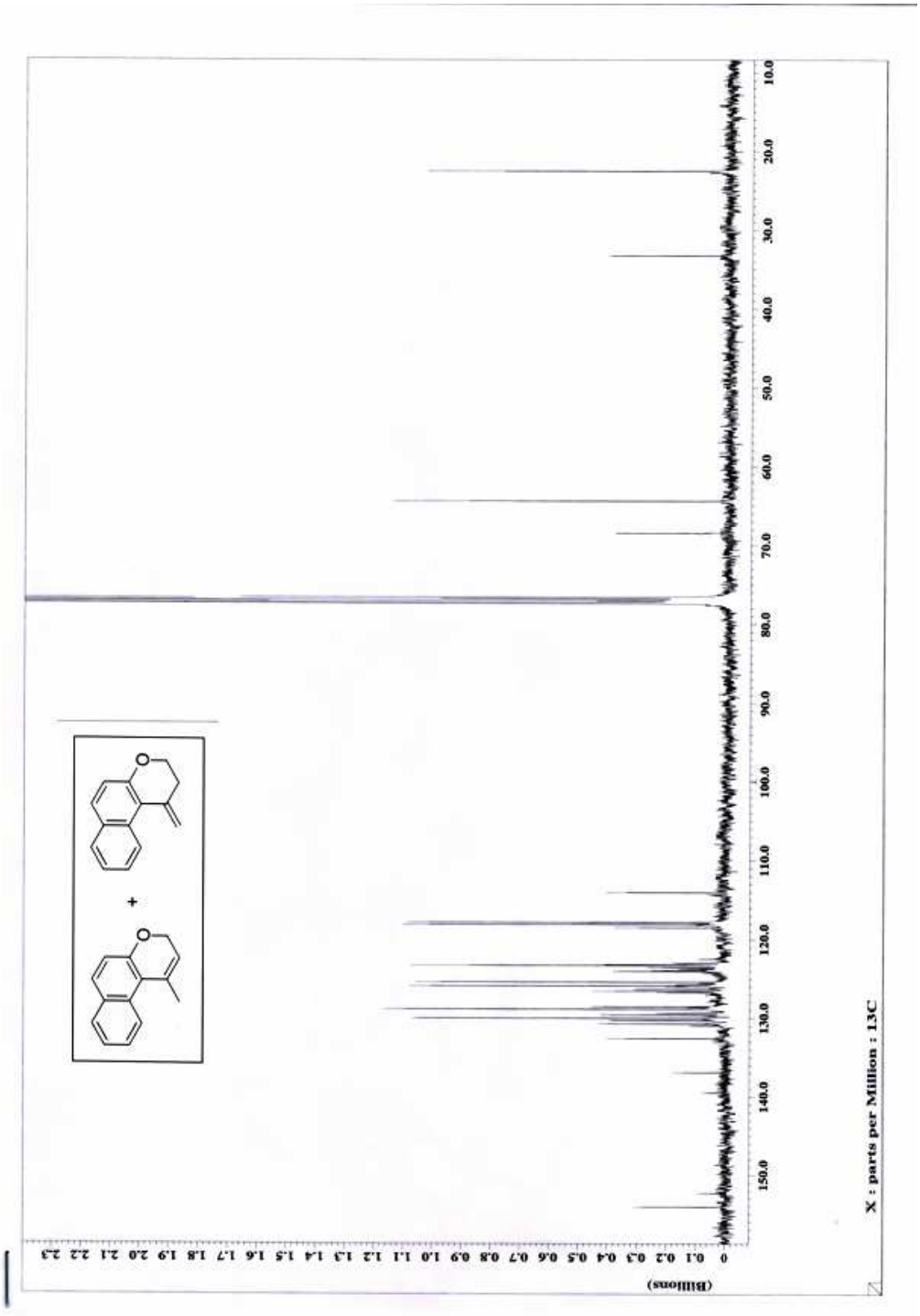
X : parts per Million : 1H
3.1
0.2
2.0
0.1
1.0
1.0
1.0
1.0
1
OH
O

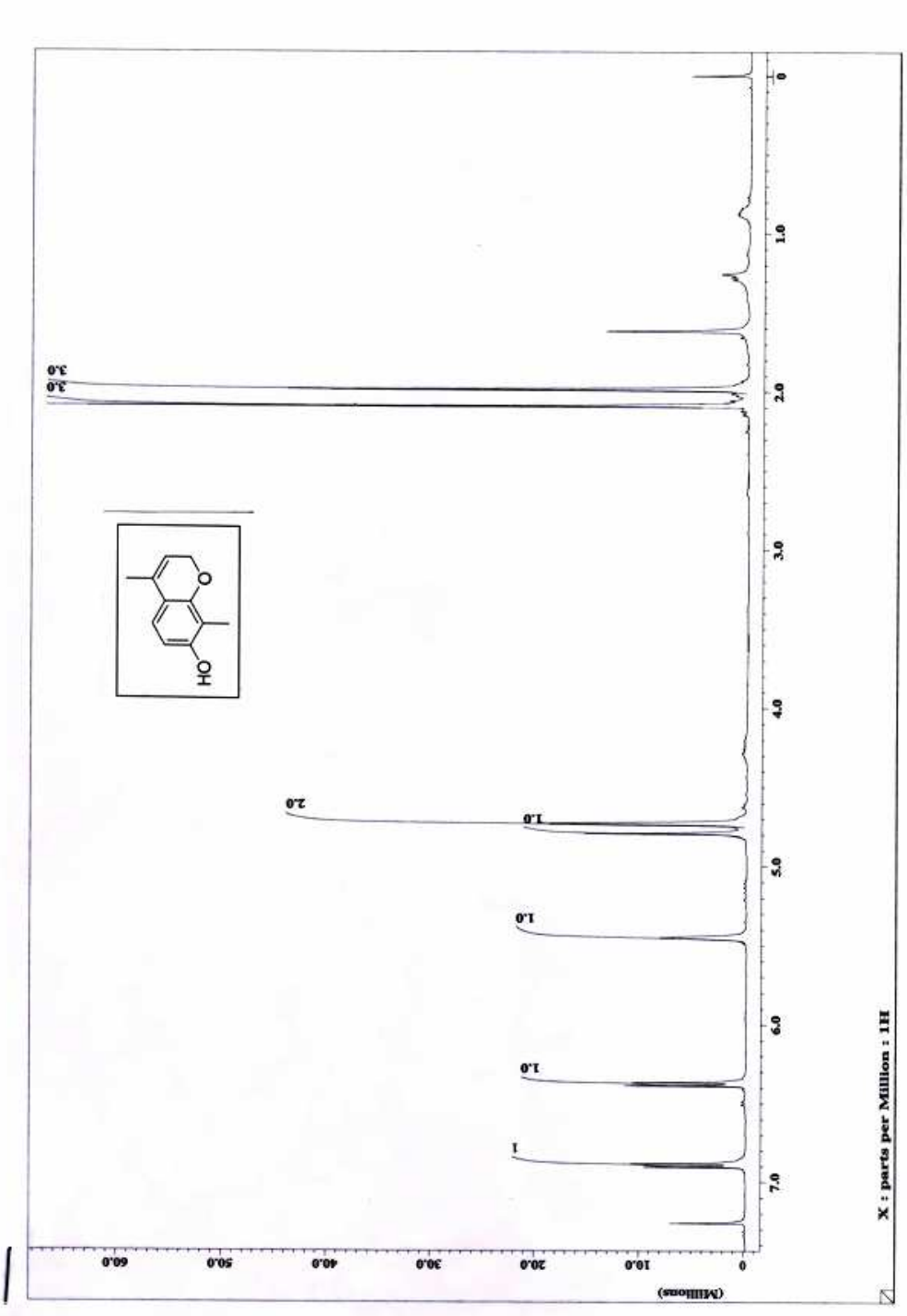

HO
O
(Billions)
0
1.0
2.0
3.0
4.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
90.0
100.0
110.0
120.0
130.0
140.0
150.0
X : parts per Million : 13C

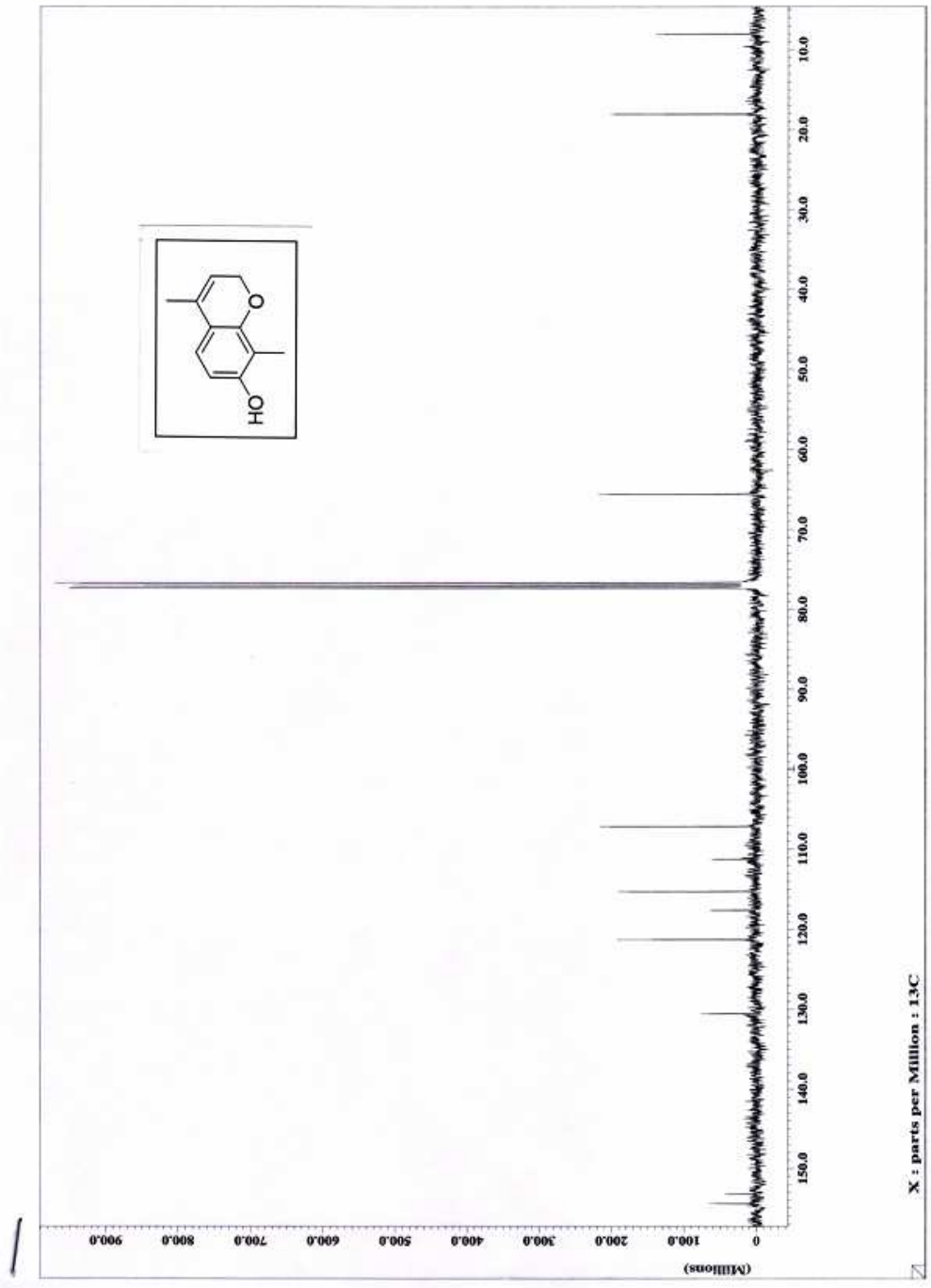

X : parts per Million : 1H
(Millionths)
3.1
2.0
1
2.1
1.0
1.0


X : parts per Million : 13C
(Billions)

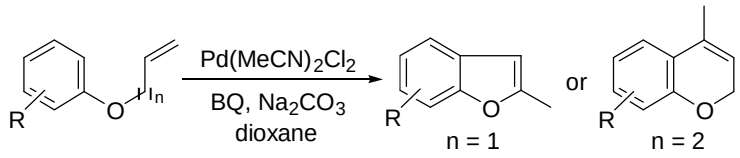

X : parts per Million : 1H
(Millions)
0
10.0
20.0
30.0
40.0
50.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0
0.3
0.2
1
0.3
1.5
0.7
1.0
0.5
0.5
1.6
1.5
0.2
0.1
1.2
0.3
1.0
0.3
0.3
2.0
0.6
0.6
3.0
+


(Billions)
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8 1.9 2.0 2.1 2.2 2.3
10.0 20.0 30.0 40.0 50.0 60.0 70.0 80.0 90.0 100.0 110.0 120.0 130.0 140.0 150.0
X : parts per Million : 13C


X : parts per Million : 1H
(Millions)
3.0
3.0
2.0
1.0
1.0
1.0
1.0
1
OH
O


HO
O
(Millions)
X : parts per Million : 13C

7. Korean Abstract



본 연구에서는 전이금속 촉매인 $Pd(MeCN)_2Cl_2$를 사용하여, 알릴 아릴 에터로부터 연속적인 Claisen 자리 옮김 반응과 산화성 고리화 반응을 통한 2-메틸벤조퓨란의 합성 및 아릴 호모알릴 에터로부터 직접적인 산화성 고리화 반응을 통해 크로멘을 합성하는 한 단계 반응을 개발하였다.

Pd 촉매에 의한 분자내 산화성 고리화 반응은 $Pd(MeCN)_2Cl_2$, *p*-benzoquinone, Na_2CO_3, 그리고 용매인 dioxane 존재 하에서 다양한 알릴 아릴 에터 또는 아릴 호모알릴 에터를 사용하면서 수행되어졌고, 그 결과 벤조퓨란과 크로멘이 합성되어졌다. 이 반응은 올레핀 활성화, 친전자성 공격, β-수소 제거반응을 통하여 진행되어진다.