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Brønsted acidic magnetic nano-Fe_3O_4-adorned calix[n]arene sulfonic acids: Synthesis and application in the nucleophilic substitution of alcohols

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ABSTRACT

Three magnetically recoverable Brønsted acidic calix[n]arene derivatives were successfully constructed by immobilizing calix[n]arene sulfonic acids onto silica-coated magnetic nanoparticles, a process which allows calix[n]arene derivatives to acquire magnetic properties. All of the magnetically recoverable Brønsted acidic calix[n]arenes efficiently catalyze the coupling of electron-rich arenes with some alcohols in water. After separation and recovery from the reaction mixture by a simple magnet, these Brønsted acidic calix[n]arenes can be recycled many times without losing their catalytic activity.

Keywords: Calix[n]arene sulfonic acids, magnetic nanoparticles, Brønsted acid catalysis, alkylation of aromatic compounds, green chemistry.

1. Introduction

Recently, the formation of C-C bonds derived from reactions between nucleophiles, such as arenes and heteroarenes, and halide/alcohols or related derivatives has attracted the attention of researchers.[1,2] The popularity of examining these reactions derives largely from

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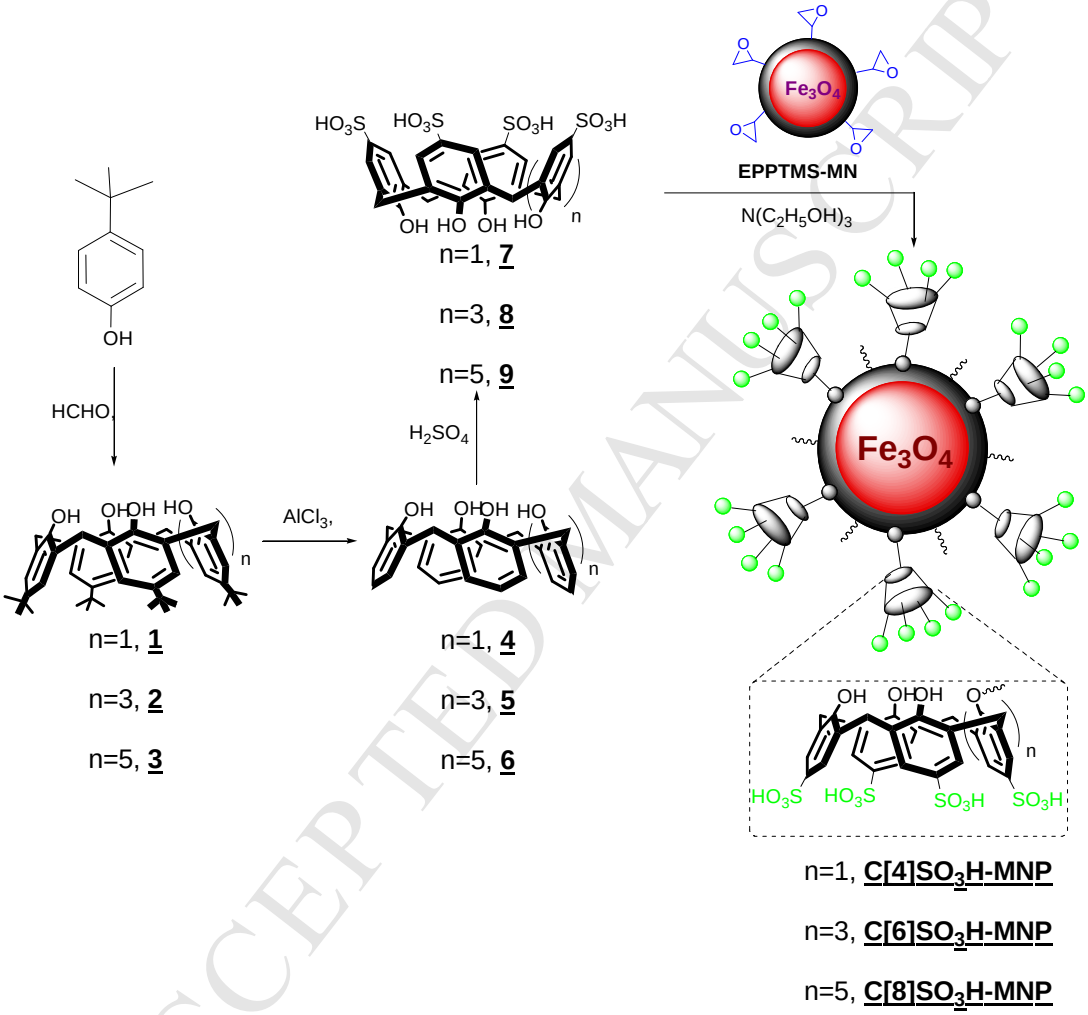
their common application in the preparation of compounds used to prepare dyestuffs, perfumes, flavors, agricultural aids, and pharmaceuticals.[3] Performing the reaction between an alcohol as an electrophile and reactive nucleophiles in particularly attractive because preparing the reactive materials is not required, plus, only H_2O is depends how the alcohol is activated generated as a byproduct. Indeed, this process can provide significant and environmentally friendly ways to save energy.[4] This kind of reaction requires a catalyst to activate either the alcohol or nucleophile to allow the process to proceed not just in water. Several catalysts suitable for this kind of reaction have been developed, including Lewis acids, Brønsted acids, and transition metal reagents, among others.[4-9] Although some of these catalysts seem promising for this reaction, designing a new efficient catalyst is necessary.

Calixarenes, derived from the condensation reaction of phenol and formaldehyde, represent very useful building blocks in supramolecular chemistry.[10-12] Their easy preparation, unlimited functionalization, and variously sized cavities make them unique macrocyclic compounds,[13,14] which have been widely used in sensors, enzyme-mimics, ion carriers, solid-phase support materials, ion selective electrodes, drug-delivery agents, and in catalysis studies, among others.[15-17] Despite their wide employment, the separating the calixarenes from the reaction product can be difficult and time consuming. To address these disadvantages, efforts have recently focused on immobilizing the calixarenes onto magnetic Fe_3O_4 nanoparticles to facilitate their separation & recovery. [18]

More recently, calix[6]arenes, which act similarly to surfactant-type Brønsted acids were used to catalyse nucleophilic substitutions in water. This study found that some of these Brønsted acidic-calix[6]arene derivatives were effective catalysts for the alkylation of aromatic compounds with allyl alcohols in water.[5] The results from this study encouraged us to develop a new catalyst for the alkylation of aromatic compounds with alcohols in water. To the best of our knowledge, there are no examples of Brønsted acidic magnetic Fe_3O_4-grafted calix[n]arene sulfonic acids being employed as catalysts. In this study, we report the synthesis

of magnetic Fe_3O_4-grafted calix[n]arene sulfonic acids (C[4]SO_3H-MNP, C[6]SO_3H-MNP, and C[8]SO_3H-MNP) and an evaluation of their ability to catalyse catalytic affinities toward the coupling of electron-rich arenes with alcohols in aqueous media, along with facile recovery.



Scheme 1. Preparation of **C[4]SO_3H-MN**, **C[6]SO_3H-MN** and **C[8]SO_3H-MN**

2. Results and discussion

2.1. Synthesis and characterizations of Brønsted acidic calix[n]arene derivatives

The aim of this study was the synthesis of Brønsted acidic calix[n]arene derivatives (**7**, **8**, **9**) and their magnetic nanoparticles (**C[4]SO$_3$H-MN**, **C[6]SO$_3$H-MN**, **C[8]SO$_3$H-MN**) and evaluation of their catalytic abilities for coupling electron-rich arenes with some alcohols in water without co-solvents. For this purpose, we synthesized calix[4]arene-*p*-tetrasulfonic acid (**7**), calix[6]arene-*p*-hexasulfonic acid (**8**) and calix[8]arene-*p*-octasulfonic acid (**9**) starting from *p-tert*- butylcalix[4]arene (**1**), *p-tert*-butylcalix[6]arene (**2**), and *p-tert*-butylcalix[8]arene (**3**) (Scheme 1).[19,20] All compounds were characterized by using FTIR, ^{1}H-NMR, ^{13}C-NMR spectroscopy and elemental analysis (see Supporting information).

Fe_3O_4 nanoparticles and [3-(2,3-epoxypropoxy)-propyl]-trimethoxysilane-coated Fe_3O_4 nanoparticles (EPPTMS-MN) were prepared according to the literature.[21] **C[n]SO$_3$H-MNP**s (n= 4, 6 and/or 8) were prepared by the immobilization of the calix[n]arene sulfonic acids (**7**, **8** and/ or **9**) onto [3-(2,3-epoxypropoxy)-propyl]-trimethoxysilane-coated Fe_3O_4 nanoparticles (EPPTMS-MN) (Scheme 1, 2, and 3). The structures of these calix[n]arene-grafted magnetic nanoparticles (**C[4]SO$_3$H-MN**, **C[6]SO$_3$H-MN**, **C[8]SO$_3$H-MN**) were determined by a combination of FTIR spectroscopy, TEM and elemental analysis.

FT-IR spectroscopy was used to elaborate the structure of **C[4]SO$_3$H-MNP**, **C[6]SO$_3$H-MNP**, and **C[8]SO$_3$H-MNP**. Characteristic peaks appeared at 1518, 1447, and 1414 cm^{-1} for **C[4]SO$_3$H-MNP**; 1508 and 1447 cm^{-1} for **C[6]SO$_3$H-MNP**; and, 1466 and 1411 cm^{-1} for **C[8]SO$_3$H-MNP**, all of which are stretching vibrations of the aromatic C=C bonds of the calix[n]arene derivatives.[19,20] It is then possible to distinguish the vibration bend of S-O, which derives from the calix[n]arene sulfonic acids by appearing at 867 cm^{-1} for **C[4]SO$_3$H-MNP**, 867 cm^{-1} for **C[6]SO$_3$H-MNP**, and 855 cm^{-1} for **C[8]SO$_3$H-MNP**. However, additional peaks of all compounds centered at 1200, 1078, 955, and 796 cm^{-1} for **C[4]SO$_3$H-MNP**; 1038, 952, and 790 cm^{-1} for **C[6]SO$_3$H-MNP**; and 1088, 958, and 800 cm^{-1} for **C[8]SO$_3$H-MNP**. These additional peaks were due to the symmetric and asymmetric

vibrations of the SO_2 bands of the calix[n]arene sulfonic acids and the Si-O groups of the silica part of EPPTMS-MN (Fig. 1).

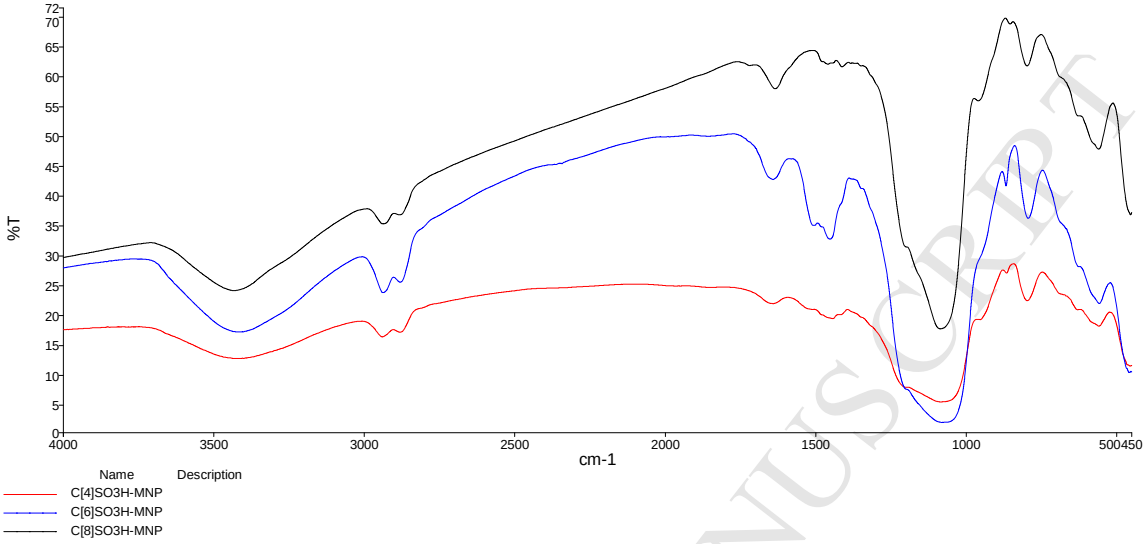


Figure 1. FTIR (KBr) spectra of **C[4]SO_3H-MNP**, **C[6]SO_3H-MNP**, and **C[8]SO_3H-MNP**.

Transmission electron microscopy (TEM) of the Fe_3O_4 magnetic nanoparticles (Fig. 2a), **C[4]SO_3H-MNP** (Fig. 2b), **C[6]SO_3H-MNP** (Fig. 2c), and **C[8]SO_3H-MNP** (Fig. 2d), respectively, was used to obtain more direct information regarding particle size and morphology (Fig. 2). TEM images of the calixarene-adorned magnetic nanoparticles show that the morphologies of the magnetic core has a uniform-size with a typical size range of 8±3 nm surrounded by calixarene units that are approximately 8-10 nm thick. After the **C[n]SO_3H-MNP** immobilization, the particle dispersion was improved due to the electrostatic repulsion force and steric hindrance between the **C[n]SO_3H-MNP** on the surface of Fe_3O_4 nanoparticles. In addition TG and dTG curves can indicate that the anchoring of **C[n]SO_3H** on EPPTMS-MN (Fig. 3). Upon heating, the weight loss of EPPTMS-MN was observed about 5 % within a broad temperature range of 250 and 650 ^oC. Thermal

degradation between 300-900 ^{o}C temperature ranges, the decompositions of **C[6]SO$_3$H-MNP** and **C[8]SO$_3$H-MNP** were found as 20% and 21.1%, respectively (see Fig. 3.).

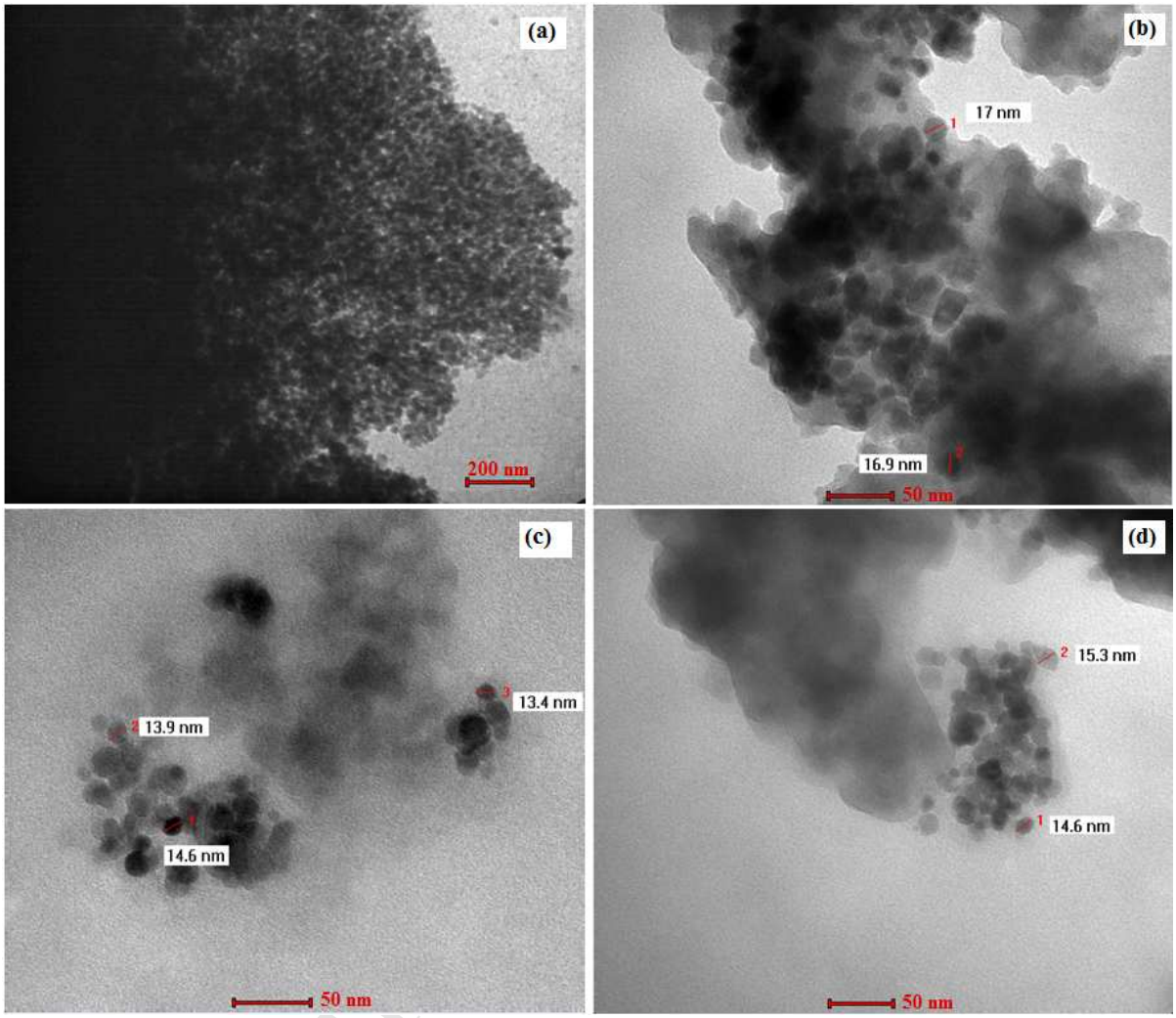


Figure 2. TEM images of (a); Fe_3O_4 magnetic nanoparticles, (b); **C[4]SO$_3$H-MNP**, (c); **C[6]SO$_3$H-MNP**, and (d); **C[8]SO$_3$H-MNP**.

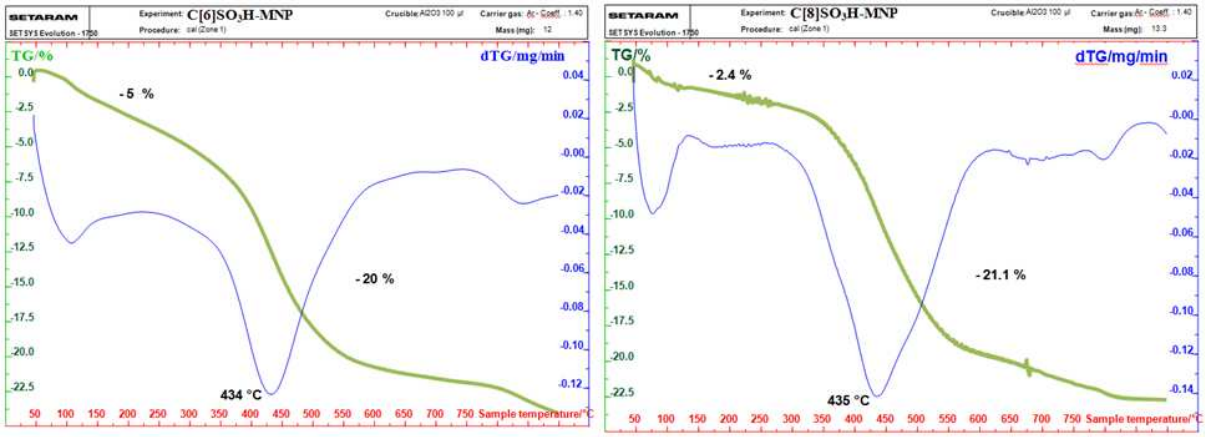


Figure 3. TGA curves of **C[6]SO$_3$H-MNP** and **C[8]SO$_3$H-MNP**

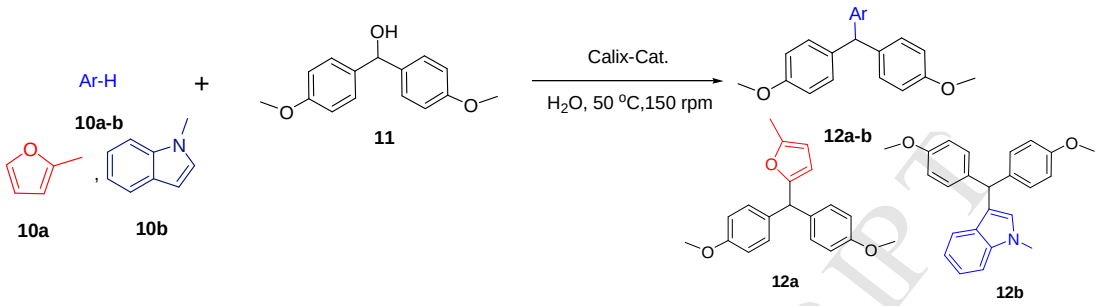
Table 1. Elemental analysis results of **C[4]SO$_3$H-MNP**, **C[6]SO$_3$H-MNP**, and **C[8]SO$_3$H-MNP**

	C(%)	H(%)	S(%)	Bounded amount of calixarene (mmol/g)[a]
C[4]SO$_3$H-MNP	8.29	1.84	0.35	0.44
C[6]SO$_3$H-MNP	13.1	2.94	0.47	0.88
C[8]SO$_3$H-MNP	14.0	3.03	0.82	2.06
EPPTMS-MN	13.20	2.61	-	-

[a]Calculated according to the S content.

Elemental analysis was performed to characterize the amount of grafted calixarene on the nanoparticles (EPPTMS-MN) by measuring the amount of sulfur the calix[n]arene sulfonic acids provided sulfur with 035, 0.47, and 0.82% sulfur corresponding to 0.44, 0.88, and 2.06 mmol of **C[4]SO$_3$H-MNP**, **C[6]SO$_3$H-MNP**, and **C[8]SO$_3$H-MNP**/g of support, respectively to iron oxide nanoparticle (Table 1).

Table 2. The coupling reaction of **10a-b** with **11** in H_2O

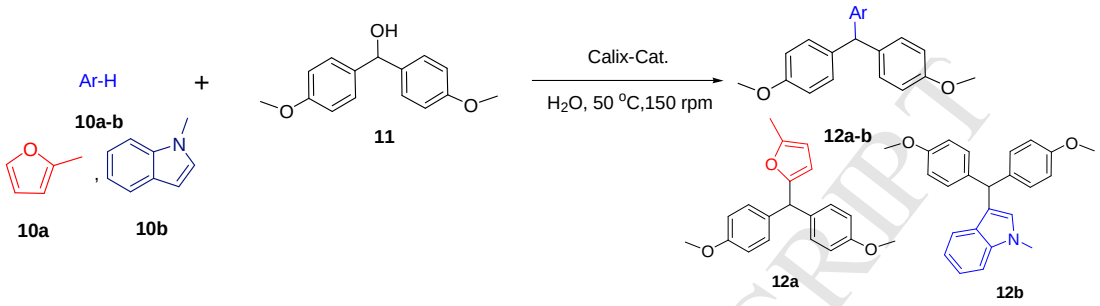


Entry	Catalyst	Catalyst loading	Ar-H	*sec*-Alcohol	Time /h	H_2O /mL	Product	Yield (%)[a]
1	**7**	5 mol%	**10a**	**11**	15	0.5	**12a**	47
2	**7**	5 mol%	**10a**	**11**	15	1	**12a**	50
3	**7**	5 mol%	**10a**	**11**	15	2	**12a**	86
4	**7**	5 mol%	**10a**	**11**	30	1	**12a**	99.9
5	**8**	5 mol%	**10a**	**11**	15	0.5	**12a**	40
6	**8**	5 mol%	**10a**	**11**	15	1	**12a**	62
7	**8**	5 mol%	**10a**	**11**	15	2	**12a**	40
8	**8**	5 mol%	**10a**	**11**	30	1	**12a**	70
9	**9**	5 mol%	**10a**	**11**	15	0.5	**12a**	45
10	**9**	5 mol%	**10a**	**11**	15	1	**12a**	97
11	**9**	5 mol%	**10a**	**11**	15	2	**12a**	63
12	**7**	5 mol%	**10b**	**11**	24	1	**12b**	63
13	**7**	5 mol%	**10b**	**11**	24	2	**12b**	56
14	**8**	5 mol%	**10b**	**11**	24	1	**12b**	63
15	**8**	5 mol%	**10b**	**11**	24	2	**12b**	58
16	**9**	5 mol%	**10b**	**11**	24	1	**12b**	28
17	**9**	5 mol%	**10b**	**11**	24	2	**12b**	12
18	none	-	**10a**	**11**	48	1 or 2	**12a**	0
19	none	-	**10b**	**11**	48	1 or 2	**12b**	0

[a]Reaction conditions: **10a-b** (0.18 mmol), **11** (22 mg, 0.09 mmol); isolated yield.

2.2. Catalysis efficiencies of Brønsted acid type calix[n]arene derivatives

Table 3. The coupling reaction of **10a-b** with 11 in H_2O in the presence of **C[n]SO_3H-MNP** catalysts



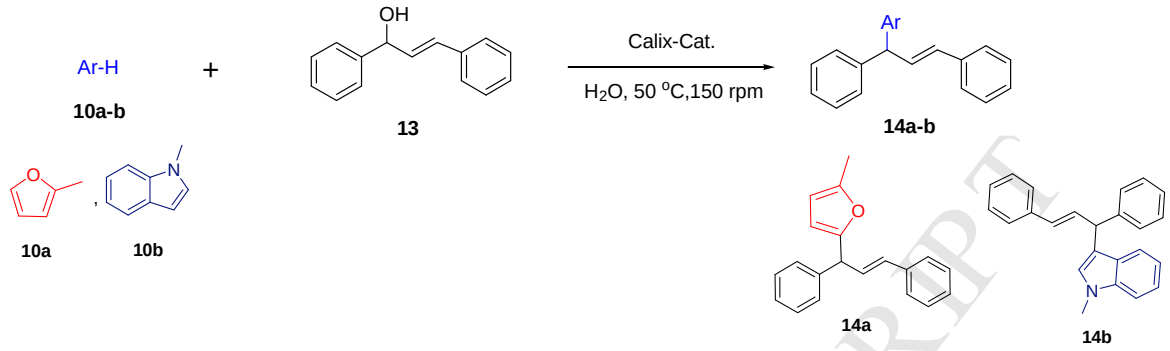
Entry	Catalyst	Catalyst loading	Ar-H	*sec*-Alcohol	Time /h	H_2O /mL	Product	Yield (%)[a]
1	C[4]SO_3H-MNP	5 mg	**10a**	**11**	48	1	**12a**	63
2	C[4]SO_3H-MNP	5 mg	**10a**	**11**	48	2	**12a**	85
3	C[6]SO_3H-MNP	5 mg	**10a**	**11**	48	1	**12a**	73
4	C[6]SO_3H-MNP	5 mg	**10a**	**11**	48	2	**12a**	67
5	C[8]SO_3H-MNP	5 mg	**10a**	**11**	6	1	**12a**	68
6	C[8]SO_3H-MNP	5 mg	**10a**	**11**	48	1	**12a**	82
7	C[8]SO_3H-MNP	5 mg	**10a**	**11**	48	2	**12a**	86
8	C[4]SO_3H-MNP	5 mg	**10b**	**11**	6	1	**12b**	98
9	C[4]SO_3H-MNP	5 mg	**10b**	**11**	24	1	**12b**	99.9
10	C[4]SO_3H-MNP	5 mg	**10b**	**11**	24	2	**12b**	99.8
11	C[6]SO_3H-MNP	5 mg	**10b**	**11**	24	1	**12b**	96.6
12	C[6]SO_3H-MNP	5 mg	**10b**	**11**	24	2	**12b**	95
13	C[8]SO_3H-MNP	5 mg	**10b**	**11**	24	1	**12b**	96
14	C[8]SO_3H-MNP	5 mg	**10b**	**11**	24	2	**12b**	84
15	C[4]SO_3H-MNP	5 mg	**10a**	**11**	48	1	**12a**	62.4[a], 62.3[b], 62.3[c]
16	C[4]SO_3H-MNP	5 mg	**10b**	**11**	24	1	**12b**	99.8[a], 99.8[b], 98.9[c]
17	C[6]SO_3H-MNP	5 mg	**10a**	**11**	48	1	**12a**	73.2[d], 72.8[e], 72.7[f]
18	C[6]SO_3H-MNP	5 mg	**10b**	**11**	24	1	**12b**	96.6[d], 96.4[e], 95.8[f]
19	C[8]SO_3H-MNP	5 mg	**10a**	**11**	48	1	**12a**	82.1[g], 82[h], 81.8[i]
20	C[8]SO_3H-MNP	5 mg	**10b**	**11**	24	1	**12b**	96.2[g], 95.4[h], 95.5[i]

[a]Reaction conditions: **10a-b** (0.18 mmol), **11** (22 mg, 0.09 mmol); isolated yield. [b]Second reuse of **C[4]SO_3H-MNP**. [c]Third reuse of **C[4]SO_3H-MNP**. [d]Fourth reuse of **C[4]SO_3H-MNP**. [e]Second reuse of **C[6]SO_3H-MNP**. [f]Third reuse of **C[6]SO_3H-MNP**. [g]Fourth reuse of **C[6]SO_3H-MNP**. [h]Second reuse of **C[8]SO_3H-MNP**. [i]Third reuse of **C[8]SO_3H-MNP**. [j]Fourth reuse of **C[8]SO_3H-MNP**.

As shown in Tables 2, 3, 4 and 5, the catalytic abilities of calix[n]arene sulfonic acids and their magnetic nanoparticles for coupling of various hetero-aromatic compounds (**10a-b**) with two activated *sec*-alcohols (**11** and **13**) at 50 ^{o}C in water were investigated. The corresponding products (**12a-b** and **14a-b**) were isolated in good to excellent yields (up to 99%) (Supporting information). It is clear that the yields are affected dramatically when the water amount used is changed (see Fig. 2). The reason may depend upon on the formation of micelle capability of Brønsted-type calix[n]arene sulfonic acids and their magnetic nanoparticles.

Easy and rapid separation of the preferred product from organic reaction mixture by magnetism promise a very attractive method for the C-C bond-forming reaction. It was, nevertheless, a very time-consuming task to complete the separation of desired products **12a-b** and/or **14a-b** from micelle mixture when calix[n]arene sulfonic acids (**7-9**) were employed as catalysts for the coupling reaction of 4,4'-dimethoxybenzhydrol and/or (E)-trans-1,3-diphenyl-2-propen-1-ol with 2-methyl furan and/or 1-methylindole. Therefore, providing magnetic properties for calix[n]arene sulfonic acids (**7-9**) would allow them to receive increased attention due to their easy separation. In order to see any changes on yield of **12a-b** and/or **14a-b**, various amounts of magnetic calix[n]arene sulfonic acid nanoparticles (**C[4]SO$_3$H-MNP**, **C[6]SO$_3$H-MNP**, and **C[8]SO$_3$H-MNP**) were employed as catalysts (Tables 3 and 5). All three, magnetic calix[n]arene sulfonic acid nanoparticles (**C[4]SO$_3$H-MNP**, **C[6]SO$_3$H-MNP**, and **C[8]SO$_3$H-MNP**) exhibited excellent catalytic ability with yields up to 99% for all products **12a-b** and/or **14a-b**. In the absence of the catalyst, no product was obtained.

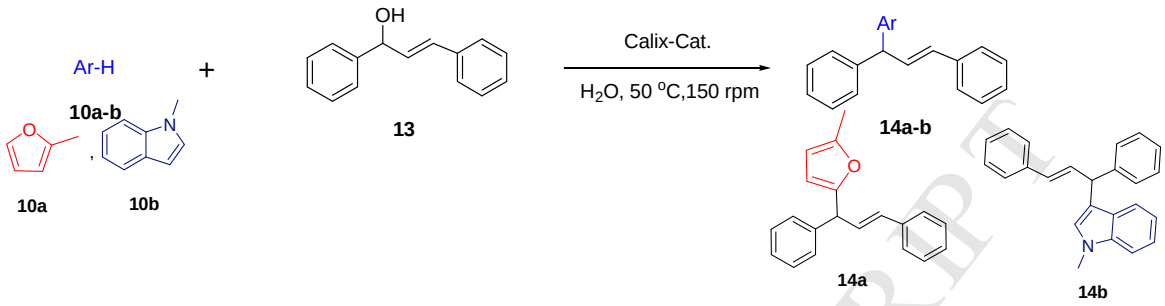
Table 4. The coupling reaction of **10a-b** with **13** in H_2O



Entry	Catalyst	Catalyst loading	Ar-H	*sec*-Alcohol	Time/h	H_2O/mL	Product	Yield (%)[a]
1	**7**	5 mol%	**10a**	**13**	61	1	**14a**	53
2	**7**	5 mol%	**10a**	**13**	61	2	**14a**	81
3	**7**	5 mol%	**10a**	**13**	86	1	**14a**	81
4	**8**	5 mol%	**10a**	**13**	61	1	**14a**	89
5	**8**	5 mol%	**10a**	**13**	61	2	**14a**	86
6	**8**	5 mol%	**10a**	**13**	86	1	**14a**	69
7	**9**	5 mol%	**10a**	**13**	61	1	**14a**	42
8	**9**	5 mol%	**10a**	**13**	61	2	**14a**	61
9	**9**	5 mol%	**10a**	**13**	86	1	**14a**	57
10	**7**	5 mol%	**10b**	**13**	15	1	**14b**	96
11	**7**	5 mol%	**10b**	**13**	61	1	**14b**	99.9
12	**7**	5 mol%	**10b**	**13**	61	2	**14b**	99.8
13	**8**	5 mol%	**10b**	**13**	15	1	**14b**	23
14	**8**	5 mol%	**10b**	**13**	61	1	**14b**	99
15	**8**	5 mol%	**10b**	**13**	61	2	**14b**	98
16	**9**	5 mol%	**10b**	**13**	15	1	**14b**	74
17	**9**	5 mol%	**10b**	**13**	61	1	**14b**	99.8
18	**9**	5 mol%	**10b**	**13**	61	2	**14b**	99.8
19	None	-	**10a**	**13**	86	1 or 2	**14a**	0
20	None	-	**10b**	**13**	86	1 or 2	**14b**	0

[a]Reaction conditions: **10a-b** (0.18 mmol), **13** (19 mg, 0.09 mmol). Isolated yield.

Table 5. The coupling reaction of **10a-b** with **13** in H_2O in the presence of **C[n]SO_3H-MNP** catalysts



Entry	Catalyst	Catalyst loading	Ar-H	*sec*-Alcohol	Time/h	H_2O/mL	Product	Yield (%)[a]
1	C[4]SO_3H-MNP	5 mg	**10a**	**13**	6	1	**14a**	73
2	C[4]SO_3H-MNP	5 mg	**10a**	**13**	48	1	**14a**	88
3	C[4]SO_3H-MNP	5 mg	**10a**	**13**	48	2	**14a**	86
4	C[6]SO_3H-MNP	5 mg	**10a**	**13**	48	1	**14a**	63
5	C[6]SO_3H-MNP	5 mg	**10a**	**13**	48	2	**14a**	89
6	C[8]SO_3H-MNP	5 mg	**10a**	**13**	6	1	**14a**	77
7	C[8]SO_3H-MNP	5 mg	**10a**	**13**	48	1	**14a**	92
8	C[8]SO_3H-MNP	5 mg	**10a**	**13**	48	2	**14a**	98
9	C[4]SO_3H-MNP	20 mg	**10b**	**13**	61	1	**14b**	92
10	C[4]SO_3H-MNP	10 mg	**10b**	**13**	61	1	**14b**	98
11	C[4]SO_3H-MNP	5 mg	**10b**	**13**	61	1	**14b**	98.9
12	C[4]SO_3H-MNP	5 mg	**10b**	**13**	24	1	**14b**	80
13	C[4]SO_3H-MNP	5 mg	**10b**	**13**	24	2	**14b**	93
14	C[6]SO_3H-MNP	20 mg	**10b**	**13**	61	1	**14b**	83
15	C[6]SO_3H-MNP	10 mg	**10b**	**13**	61	1	**14b**	98.9
16	C[6]SO_3H-MNP	5 mg	**10b**	**13**	61	1	**14b**	84
17	C[6]SO_3H-MNP	5 mg	**10b**	**13**	24	1	**14b**	93
18	C[6]SO_3H-MNP	5 mg	**10b**	**13**	24	2	**14b**	99.9
19	C[8]SO_3H-MNP	20 mg	**10b**	**13**	61	1	**14b**	89
20	C[8]SO_3H-MNP	10 mg	**10b**	**13**	61	1	**14b**	87
21	C[8]SO_3H-MNP	5 mg	**10b**	**13**	61	1	**14b**	81
22	C[8]SO_3H-MNP	5 mg	**10b**	**13**	24	1	**14b**	83
23	C[8]SO_3H-MNP	5 mg	**10b**	**13**	24	2	**14b**	72

[a]Reaction conditions: **10a-b** (0.18 mmol), **13** (19 mg, 0.09 mmol). Isolated yield.

3. Conclusion

In summary, three Brønsted acidic calix[n]arene derivatives were synthesized and immobilized onto the silica-based magnetic nanoparticles surface (EPPTMS-MN) to impact both rigid structural properties and to provide easy separation capability from reaction mixture by using an external magnet. Additionally, the catalytic properties of these new calix[n]arene sulfonic acid-grafted magnetic nanoparticles for coupling of various hetero-aromatic compounds with two activated *sec*-alcohols in water were investigated. Results reflect that not only calix[n]arene sulfonic acid but also these calix[n]arene sulfonic acid-grafted magnetic nanoparticles were effective catalysts for the substitution reactions. In addition, allowing calixarene compounds to acquire magnetic properties would attract new insight into the catalytic C-C bond-formation reactions due to their easy separation from the reaction system by using an external magnet, as well as the sustained catalytic activity in recyclable processes.

4. Experimental

4.1. General Remarks

A Ez-Melt apparatus in a sealed capillary was used to determine all melting points of the synthesized compounds. NMR spectra were recorded on a Varian 400 MHz spectrometer, indicating chemical shifts as ppm that are relative to an internal standard tetramethylsilane (δ= 0.0). FT-IR spectra were recorded with a Perkin-Elmer 100 spectrometer. Elemental analyses were performed on a Leco CHNS-932 analyzer.

4.2. Synthesis

p-tert-Butylcalix[4]arene (**1**), *p-tert*-butylcalix[6]arene (**2**), *p-tert*-butylcalix[8]arene (**3**), calix[4]arene (**4**), calix[6]arene (**5**), calix[8]arene (**6**), and calix[n]arene-*p*-sulfonates (**7**, **8**, **9**) were synthesized according to the literature procedure.[19,20] Silica-based magnetic Fe_3O_4-

nanoparticles (**EPPTMS-MN**) were prepared as described in our previously study.[21] Calixarene-adorned magnetic nanoparticles (**C[4]SO_3H-MNP**, **C[6]SO_3H-MNP** and **C[8]SO_3H-MNP**) are reported for the first time.

*4.2.1. Calix[4]arene-p-tetrasulfonic acid (**7**).*[19] White solid. Yield: 95%, m.p. > 350 ^oC. FTIR (ATR) cm^{-1}: 3133 (ν_{OH}), 1682 (ν_{H2O}), 1597, 1459 ve 1377 ($\nu_{C=C}$), 1151, 1105 (ν_{SO2} asymmetric), 1023 (ν_{SO2} symmetric) and 784 (ν_{S-O}). ^{1}H-NMR (400 MHz, D_2O): δ 3.86 (s, 8H, Ar-CH_2-Ar), 7.43 (s, 8H, ArH). ^{13}C-NMR (100 MHz, D_2O): δ 31.96 (Ar-CH_2-Ar), 125.97 (C-Ar), 126.10 (C-Ar), 130.71 (C-Ar), 133.36 (C-Ar), 156.21 (ArC-O). Anal. Calcd. For $C_{28}H_{24}O_{16}S_4 \cdot 6H_2O$ (%): C, 39.43; H, 4.25; S, 15.04. Found (%); C, 39.38; H, 4.32; S, 15.00.

*4.2.2. Calix[6]arene-p-hexasulfonate (**8**).*[19] White solid. Yield: 40%; M.p.: >350 ^oC. FTIR (ATR) cm^{-1}: 3154 (ν_{OH}), 1685 (ν_{H2O}), 1591, 1472 and 1340 ($\nu_{C=C}$), 1273 (ν_{C-O-C}), 1151, 1108 (ν_{SO2} asymmetric), 1020 (ν_{SO2} symmetric), and 870 (ν_{S-O}). ^{1}H-NMR (400 MHz, D_2O): δ 3.82 (s, 12H, Ar-CH_2-Ar), 7.35 (s, 12H, ArH). ^{13}C-NMR (100 MHz, D_2O): δ 32.63 (Ar-CH_2-Ar), 125.71 (C-Ar), 125.80 (C-Ar), 129.05 (C-Ar), 132.01 (C-Ar), 157.95 (ArC-O). Anal. Calcd. For $C_{42}H_{28}O_{24}S_6Na_8 \cdot 9H_2O$ (%): C, 34.67; H, 3.19; S, 13.22. Found (%); C, 34.55; H, 3.09; S, 13.31.

*4.2.3. Calix[8]arene-p-octasulfonate (**9**).*[19] White solid. Yield: 39%; M.p.: >350 ^oC. FTIR (ATR) cm^{-1}: 3435 (ν_{OH}), 1649 (ν_{H2O}), 1420 ($\nu_{C=C}$), 1211 (ν_{C-O-C}), 1172, 1114 (ν_{SO2} asymmetric), 1047 (ν_{SO2} symmetric), and 879 (ν_{S-O}). ^{1}H-NMR (400 MHz, D_2O): δ 3.78 (s, 16H, Ar-CH_2-Ar), 7.21 (s, 16H, ArH). ^{13}C-NMR (100 MHz, D_2O): δ 32.35 (Ar-CH_2-Ar), 125.34 (C-Ar), 129.30 (C-Ar), 130.61 (C-Ar), 159.66 (ArC-O). Anal. Calcd. For $C_{56}H_{35}O_{32}S_8Na_{13} \cdot 18H_2O$ (%): C, 32.04; H, 3.41; S, 12.22. Found (%); C, 32.08; H, 3.38; S, 12.16.

4.2.4. General procedure for the preparation of Brønsted acidic magnetic calix[4]arene derivatives ***C[4]SO$_3$H-MNP****,* ***C[6]SO$_3$H-MNP****, and* ***C[8]SO$_3$H-MNP****.* A mixture of the calix[n]arene-*p*-sulfonate derivative (**7**, **8** or **9**) (0.3 g) and $N(C_2H_5OH)_3$ (10 M, 25 mL) in DMSO (10 mL) was stirred at 30 ^oC for 17 h then EPPTMS-MN (0.3 g) was added, and the solution heated at 50 ^oC for 4 days. After magnetic separation, the residue was washed with water three times to remove excess of calix[n]arene-*p*-sulfonate derivative, and then treated with 0.1 M HCl and dried under vacuum.

4.2.4.1. ***C[4]SO$_3$H-MNP****.* FTIR (KBr) cm^{-1}: 3424 (V_{OH}), 1644 (V_{H2O}), 1524, 1447, 1418 ($V_{C=C}$), 1078 (V_{Si-O}, V_{SO2} asymmetric and symmetric), 864 (V_{S-O}), 796 (V_{Si-O}), and 560 (V_{Fe-O}).

4.2.4.2. ***C[6]SO$_3$H-MNP****.* FTIR (KBr) cm^{-1}: 3408 (V_{OH}), 1508, 1453 ($V_{C=C}$), 1075 (V_{Si-O}, V_{SO2} asymmetric and symmetric), 867 (V_{S-O}), 793 (V_{Si-O}), and 557 (V_{Fe-O}).

4.2.4.3. ***C[8]SO$_3$H-MNP****.* FTIR (KBr) cm^{-1}: 3421 (V_{OH}), 1460, 1411 ($V_{C=C}$), 1081 (V_{Si-O}, V_{SO2} asymmetric and symmetric), 855 (V_{S-O}), 799 (V_{Si-O}), and 560 (V_{Fe-O}).

4.3. General procedure for Brønsted acidic calix[n]arene derivatives catalyzed nucleophilic substitutions of two *sec*-alcohols in water

Method 1.

The reaction was carried out according to the literature procedure.[5,22] Typically, the alcohol (**11** or **13**) and a hetero-aromatic compound (**10a-b**) were added to a solution of the catalysis in water (as listed in the tables of main text). The mixture was stirred at 50 ^oC for the

period of time given in the tables (see main text), after that the mixture was centrifuged to separate water-soluble calixarene-based catalysts. Et_2O and $NaHCO_3$ aq. were added to the organic layer, and the ether phase was separated and washed with H_2O to adjust pH 7, and dried over $MgSO_4$. The solvent was evaporated under reduced pressure, the crude product was purified by column chromatography to obtain the desired substitution product (**12a**, **12b**, **14a** or **14b**).

Method 2.

To a mixture of calixarene-grafted magnetic nanoparticles (**C[4]SO_3H-MNP**, **C[6]SO_3H-MNP**, and/or **C[8]SO_3H-MNP**) in H_2O was added a sec-alcohol (**11** or **13**) and a hetero-aromatic compound (**10a-b**). The mixture was stirred at 50 ^oC for a period of time given in the tables of the main text. Then, catalyst was easily separated from the mixture by using a simple magnet. The remaining residue was treated with Et_2O and $NaHCO_3$ aq., and the ether phase was separated and washed with water to neutral pH, and dried over $MgSO_4$. The solvent was removed under reduced pressure, the crude was purified by column chromatography to obtain desired product (**12a**, **12b**, **14a** or **14b**).

*4.3.1. 2-[Bis(4-methoxyphenyl)methyl]-5-methylfuran (**12a**).*[22] Purified by column chromatography (SiO_2, hexane/ethyl acetate= 3/1 (v/v)). FTIR (ATR) cm^{-1}: 2928, 1645, 1602, 1511, 1251, 1031, 833, 769. ^{1}H-NMR (400 MHz, $CDCl_3$): δ 2.24 (s, 3H, Ar-C**H$_3$**), 3.78 (s, 6H, O-C**H$_3$**), 5.29 (s, 1H, -C**H**), 5.71 (d, 1H, J= 3.2 Hz, Ar**H** (furan)), 5.86 (dd, 1H, J_1= 0.8 Hz, J_2= 2.0 Hz, Ar**H** (furan)), 6.83 (d, 4H, J= 8.8 Hz, Ar**H**), 7.08 (d, 4H, J= 8.8 Hz, Ar**H**). ^{13}C-NMR (100 MHz, $CDCl_3$): δ 13.69 (-**C**H_3, furan), 49.25 (-**C**H), 55.23 (O-**C**H_3), 105.84 (Ar**C**, furan), 108.74 (Ar**C**, furan), 113.69 (Ar**C**), 129.61 (Ar**C**), 132.25 (Ar**C**), 151.35 (Ar**C**, furan), 155.50 (Ar**C**, furan), 158.16 (Ar**C**-O) (see Supporting information). Anal. Calcd. For $C_{20}H_{20}O_3$ (%): C, 77.90; H, 6.54. Found (%); C, 77.84; H, 6.62.

*4.3.2. 1-Methyl-3-(di(4-methoxyphenyl)methyl)-1H-indole (**12b**).*[22] Purified with column chromatography (SiO_2, petroleum ether/ethyl acetate= 98/2 (v/v)). FTIR (ATR) cm^{-1}: 3019, 2928, 1605, 1505, 1239, 1028, 744. ^{1}H-NMR (400 MHz, $CDCl_3$): δ 3.70 (s, 3H, N-C**H$_3$**), 3.79 (s, 6H, O-C**H$_3$**), 5.57 (s, 1H, -C**H**), 6.40 (s, 1H, C=C**H**), 6.82 (d, 4H, *J*= 8.8 Hz, Ar**H**), 6.98 (t, 1H, *J*= 8.0, Ar**H**), 7.14 (d, 4H, *J*= 8.4 Hz, Ar**H**), 7.17-7.24 (m, 2H, Ar**H**), 7.29 (d t, 1H, J_1= 8.0 Hz, J_2= 1.2 Hz, Ar**H**). ^{13}C-NMR (100 MHz, $CDCl_3$): δ 32.73 (N-**C**H$_3$), 47.07 (-**C**H), 55.26 (O-**C**H$_3$), 109.10 (Ar**C**), 113.57 (Ar**C**), 118.74 (Ar**C**), 120.10 (Ar**C**), 121.56 (Ar**C**), 127.30 (Ar**C**), 128.65 (Ar**C**), 129.82 (Ar**C**), 132.27 (Ar**C**), 136.66 (Ar**C**), 137.44 (Ar**C**), 157.84 (Ar**C**-O) (see Supporting information). Anal. Calcd. For $C_{24}H_{23}NO_2$ (%): C, 80.64; H, 6.49; N, 3.92. Found (%); C, 80.49; H, 6.34; N, 4.02.

*4.3.3. (E)-2-(1,3-Diphenyl allyl)-5-methylfuran (**14a**).*[5] Purified with column chromatography (SiO_2, petroleum ether/ethyl acetate= 12/1 (v/v)). FTIR (ATR) cm^{-1}: 3029, 2922, 1709, 1599, 1453, 1218, 964, 747, 695. ^{1}H-NMR (400 MHz, $CDCl_3$): δ 2.26 (s, 3H, -C**H$_3$**), 4.84 (d, 1H, *J*= 7.6 Hz, -C**H**), 5.89-5.90 (m, 1H, Ar**H** (furan)), 5.96 (d, 1H, *J*= 3.2 Hz, Ar**H** (furan)), 6.39 (d, 1H, *J*= 16 Hz, ArC**H**=C), 6.56 (dd, 1H, J_1= 7.2 Hz, J_2= 15.8 Hz, C=C**H**), 7.19-7.38 (m, 10H, Ar**H**). ^{13}C-NMR (100 MHz, $CDCl_3$): δ 13.64 (-**C**H$_3$), 48.42 (-**C**H), 105.98 (Ar**C**), 107.45 (Ar**C**), 126.37, 126.63, 127.07, 127.67, 128.26, 128.53, 130.13, 131.56, 137.15, 141.42, 151.43, 154.22 (see Supporting information). Anal. Calcd. For $C_{20}H_{18}O$ (%): C, 87.56; H, 6.61. Found (%); C, 87.47; H, 6.74.

*4.3.4. (E)-3-(1,3-Diphenyl allyl)-1-methyl-1H-indole (**14b**).*[5] Purified with column chromatography (SiO_2, petroleum ether/ethyl acetate= 12/1 (v/v)). FTIR (ATR) cm^{-1}: 3053, 2925, 1709, 1465, 1239, 1013, 735, 699. ^{1}H-NMR (400 MHz, $CDCl_3$): δ 3.75 (s, 3H, -C**H$_3$**),

5.12 (d, 1H, *J*= 7.2 Hz, -C**H**), 6.45 (d, 1H, *J*= 15.6 Hz, Ar-C**H**=C-), 6.70-6.76 (m, 2H, -C**H**=C- ve N-C**H**=C-), 7.18-7.44 (m, 14H, Ar**H**). ^{13}C-NMR (100 MHz, $CDCl_3$): δ 32.75 (-**C**H_3), 48.20 (-**C**H), 109.23, 118.90, 119.97, 121.65, 126.34, 127.17, 127.42, 128.51, 130.42, 132.71, 137.51, 143.55 (see Supporting information). Anal. Calcd. For $C_{24}H_{21}N$ (%): C, 89.12; H, 6.54; N, 4.33. Found (%); C, 88.99; H, 6.58; N, 4.45.

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Supplementary data

TEM images, TGA thermograms, FTIR spectra, ^{1}H-NMR and ^{13}C-NMR data.

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Figure captions:

Figure 1. FTIR (KBr) spectrums of **C[4]SO_3H-MNP**, **C[6]SO_3H-MNP**, and **C[8]SO_3H-MNP**.

Figure 2. TEM images of (a); Fe_3O_4 magnetic nanoparticles, (b); **C[4]SO_3H-MNP**, (c); **C[6]SO_3H-MNP**, and (d); **C[8]SO_3H-MNP**.

Figure 3. TGA curves of **C[6]SO_3H-MNP** and **C[8]SO_3H-MNP**

Scheme 1. Preparation of **C[4]SO_3H-MN**

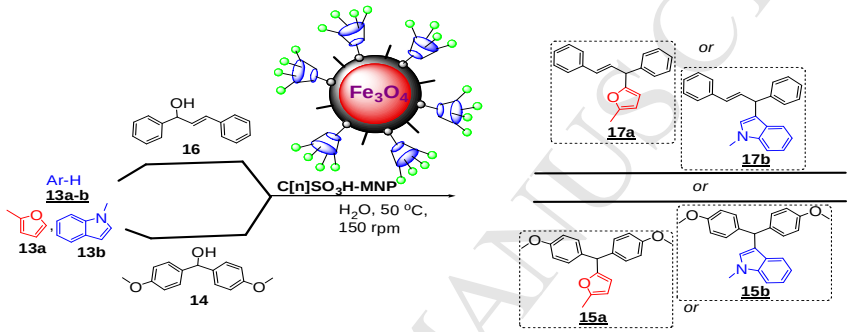
Scheme 2. Preparation of **C[6]SO_3H-MNP**

Scheme 3. Preparation of **C[8]SO_3H-MNP**

Graphical Abstract

Brønsted acidic magnetic nano-Fe_3O_4-adorned calix[n]arene sulfonic acids: Synthesis and application in the nucleophilic substitution of alcohols

Serkan Sayin, Mustafa Yilmaz



Supporting information

Brønsted Acidic Magnetic Nano-Fe_3O_4-Adorned Calix[n]arene Sulfonic Acids: Synthesis and Application in the Nucleophilic Substitution of Alcohols

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1. FTIR spectrums:

Figure 1S. FTIR (KBr) spectrums of C[4]SO_3H-MNP, C[6]SO_3H-MNP, and C[8]SO_3H-MNP

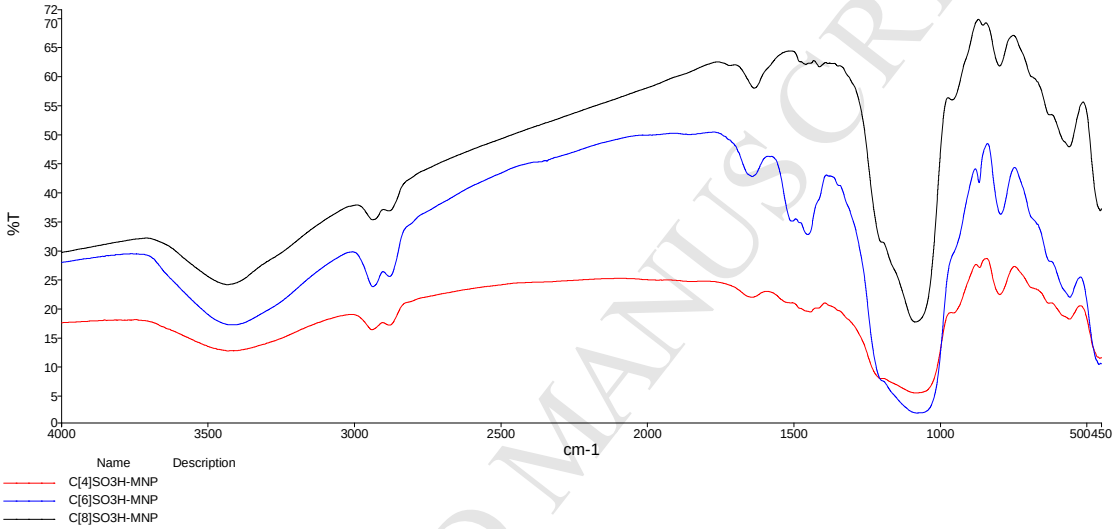
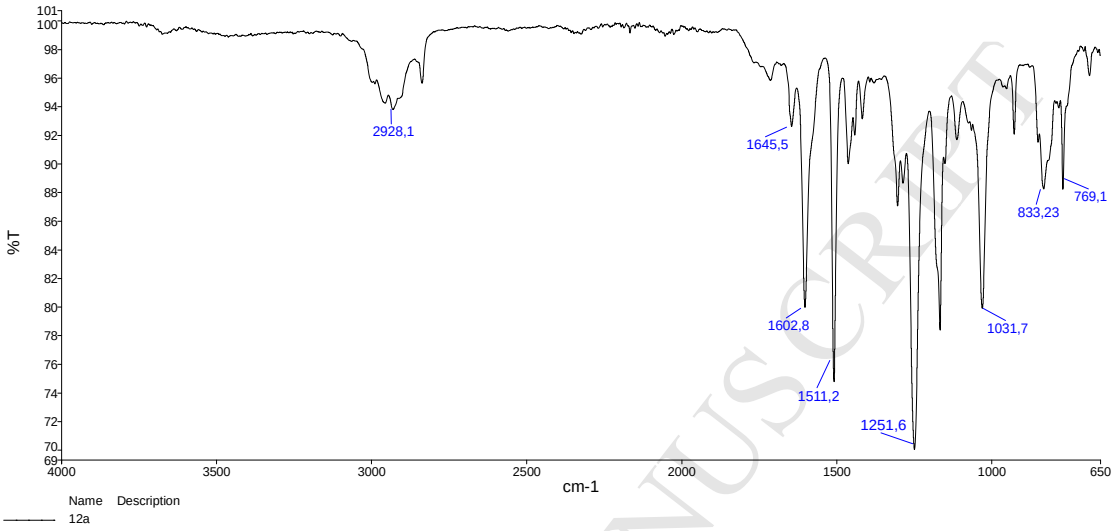


Figure 2S. FTIR (ATR) spectrums of **12a** and **12b**:



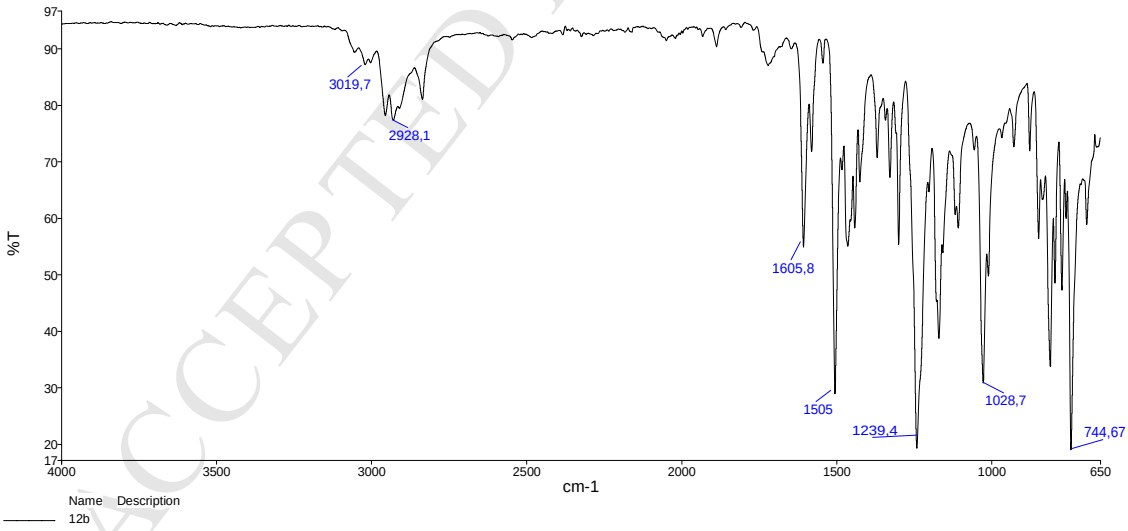
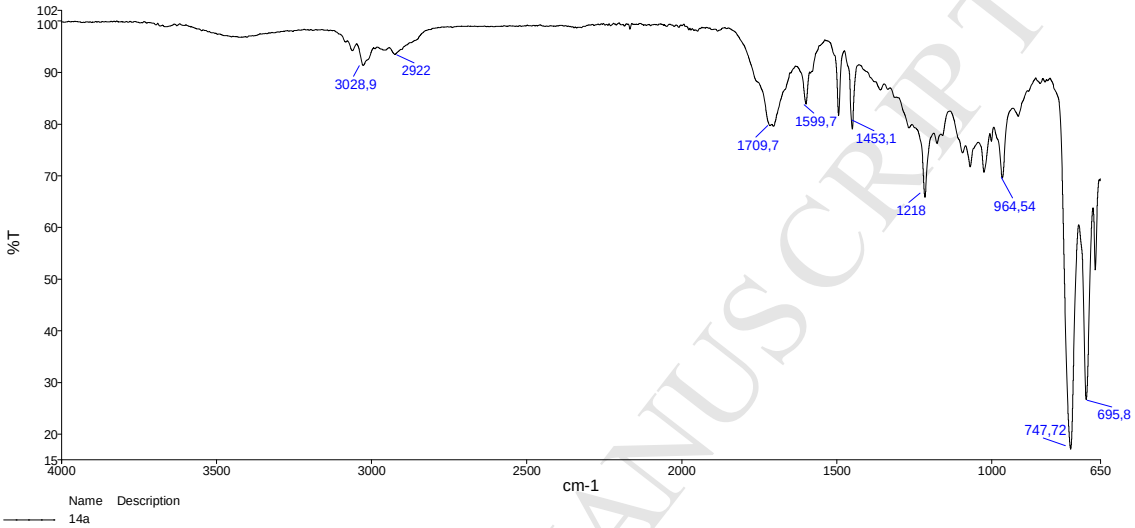
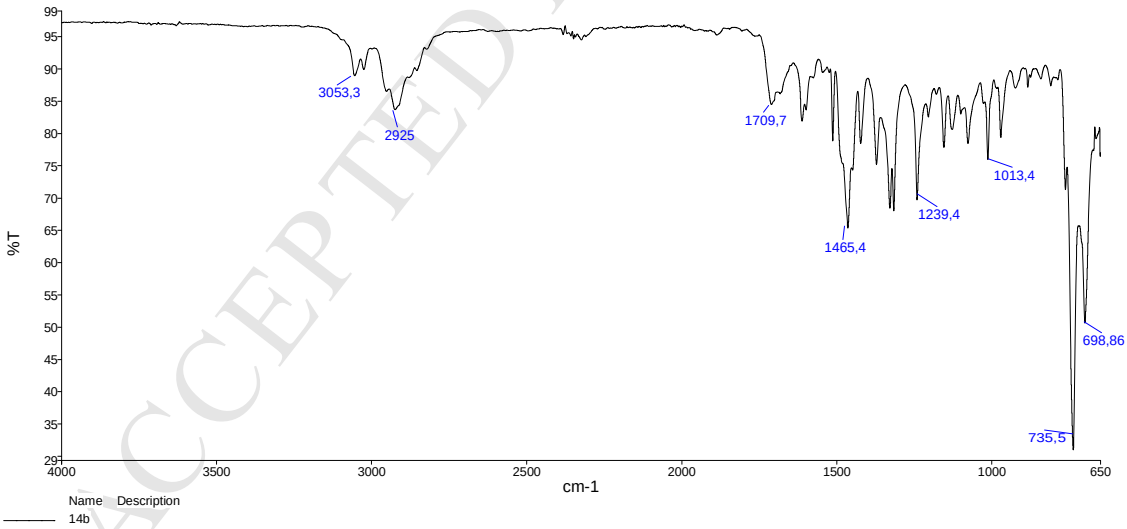


Figure 3S. FTIR (ATR) spectrums of **14a** and **14b**:





2. ^{1}H-NMR and ^{13}C-NMR data:

Figure 4S. ^{1}H-NMR spectrum of **12a**:

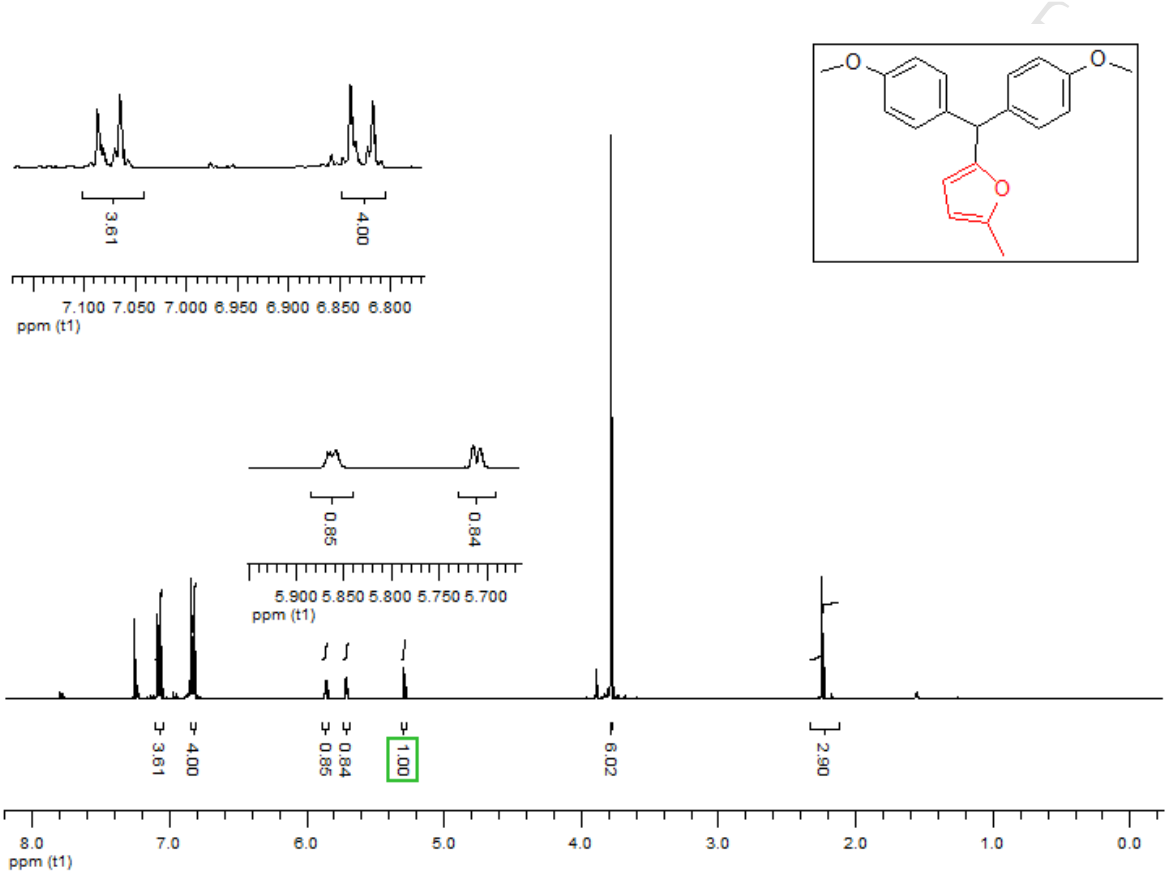


Figure 5S. ^{13}C-NMR spectrums of **12a**:

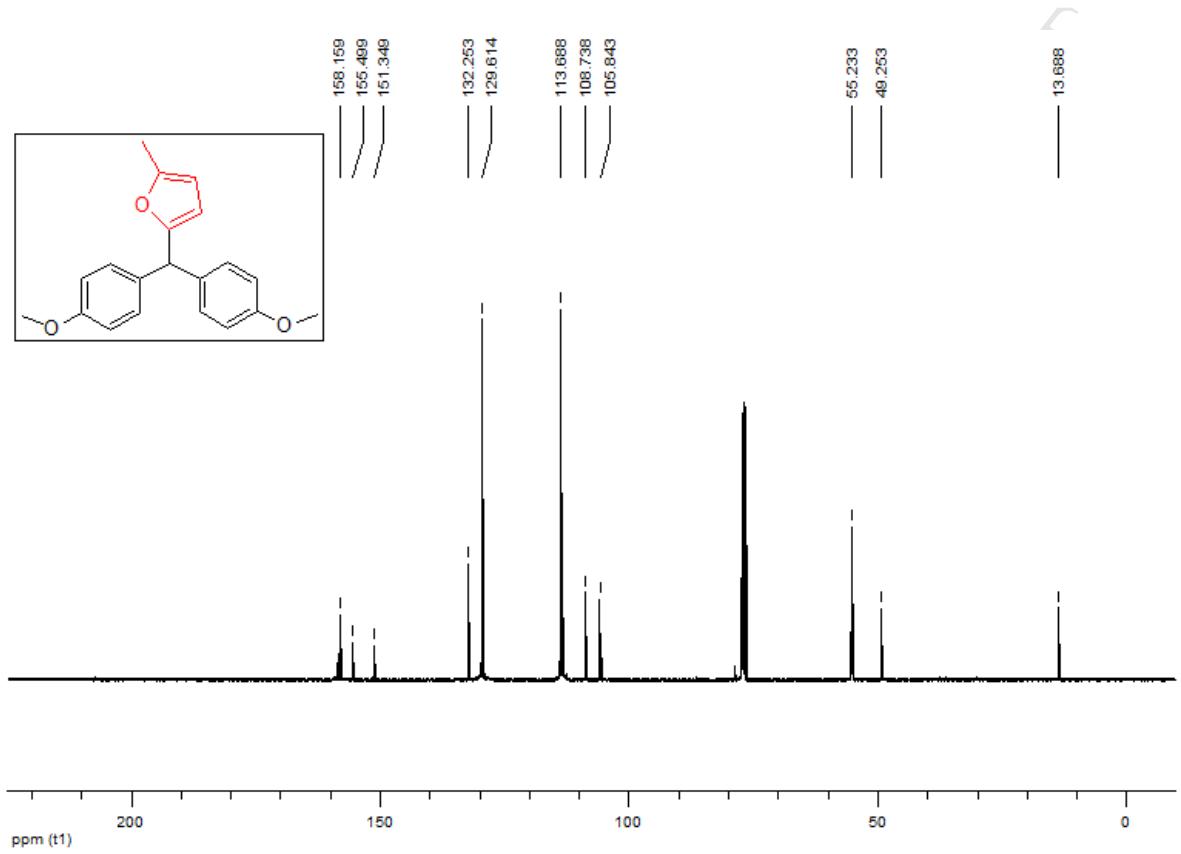


Figure 6S. ^{1}H-NMR spectrums of **12b**:

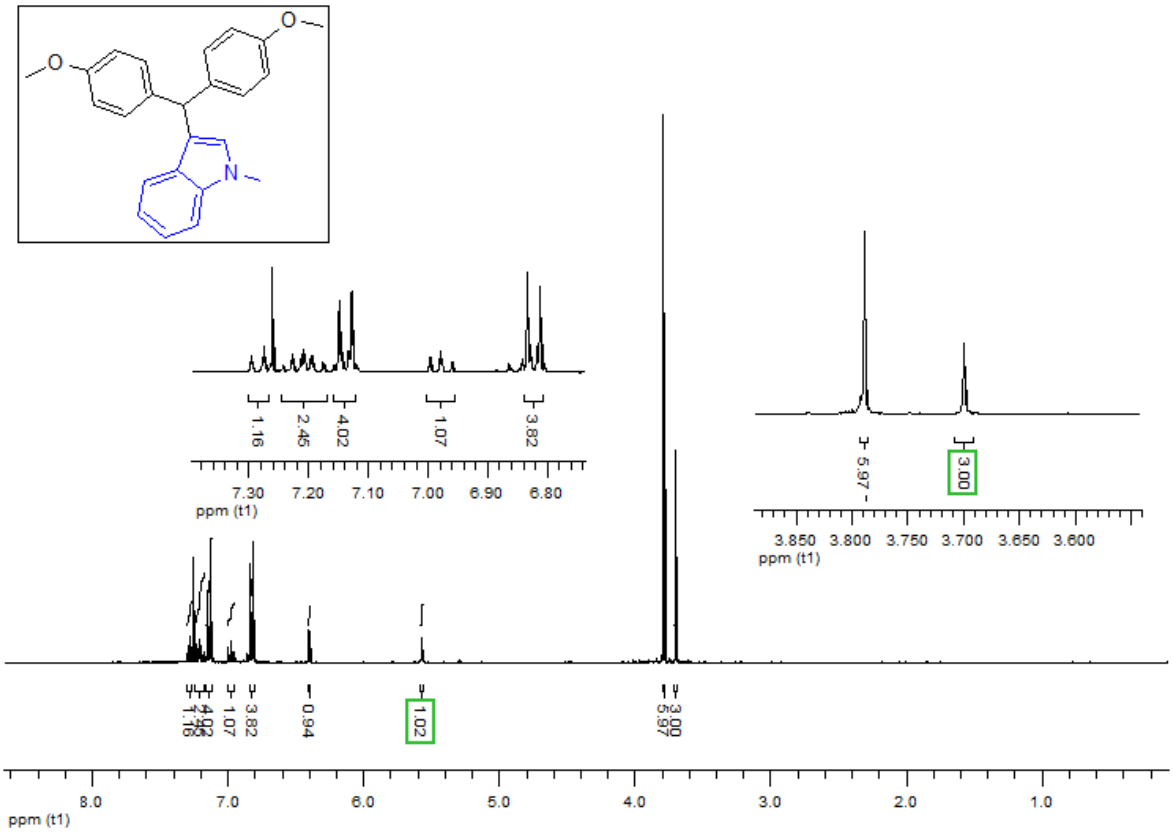


Figure 7S. ^{13}C-NMR spectrum of **12b**:

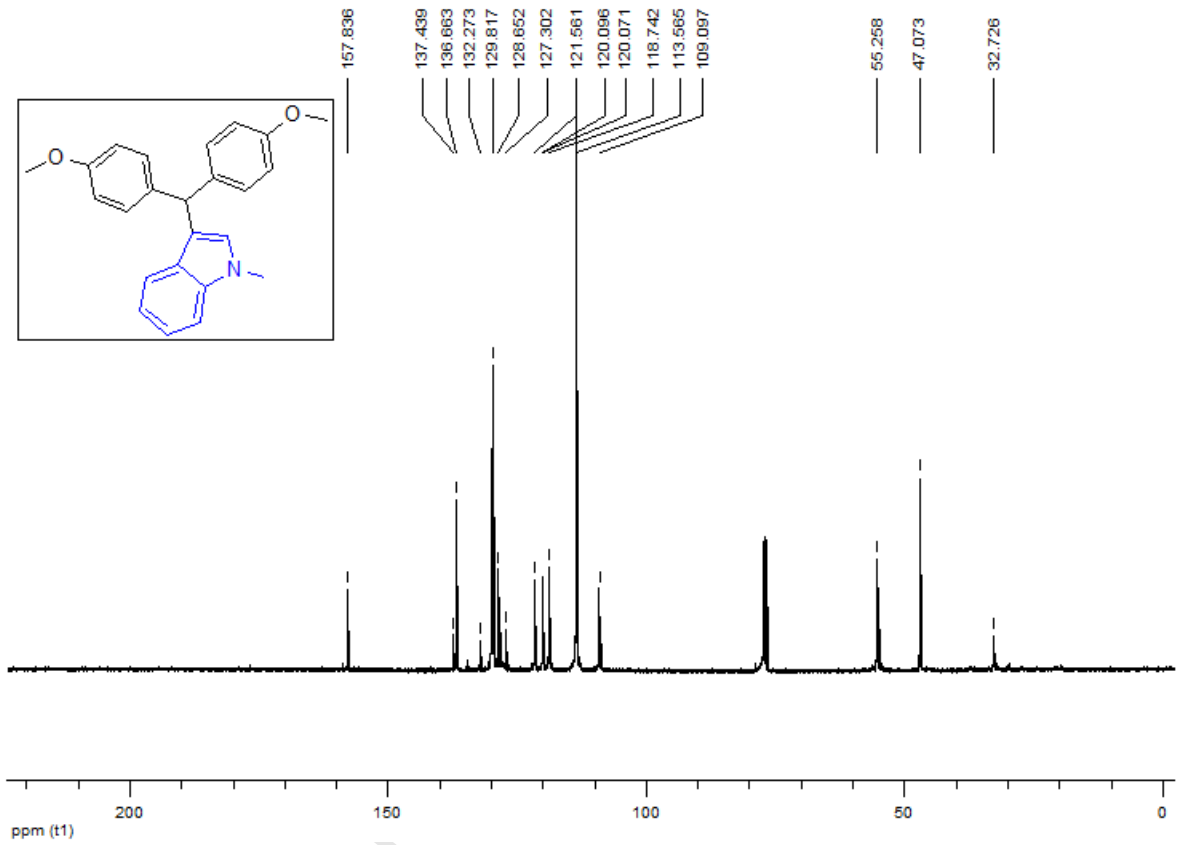


Figure 8S. ^{1}H-NMR spectrum of **14a**:

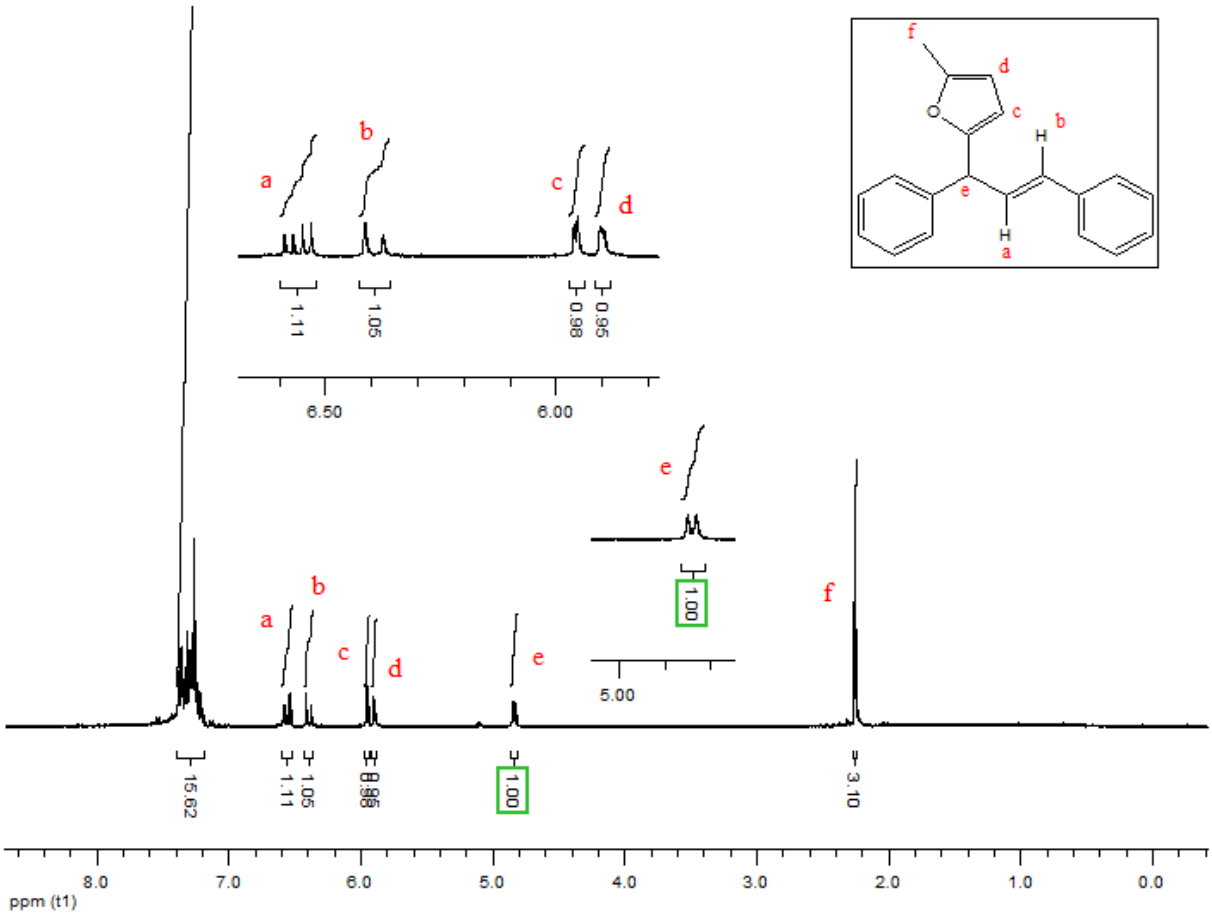


Figure 9S. ^{13}C-NMR spectrum of **14a**:

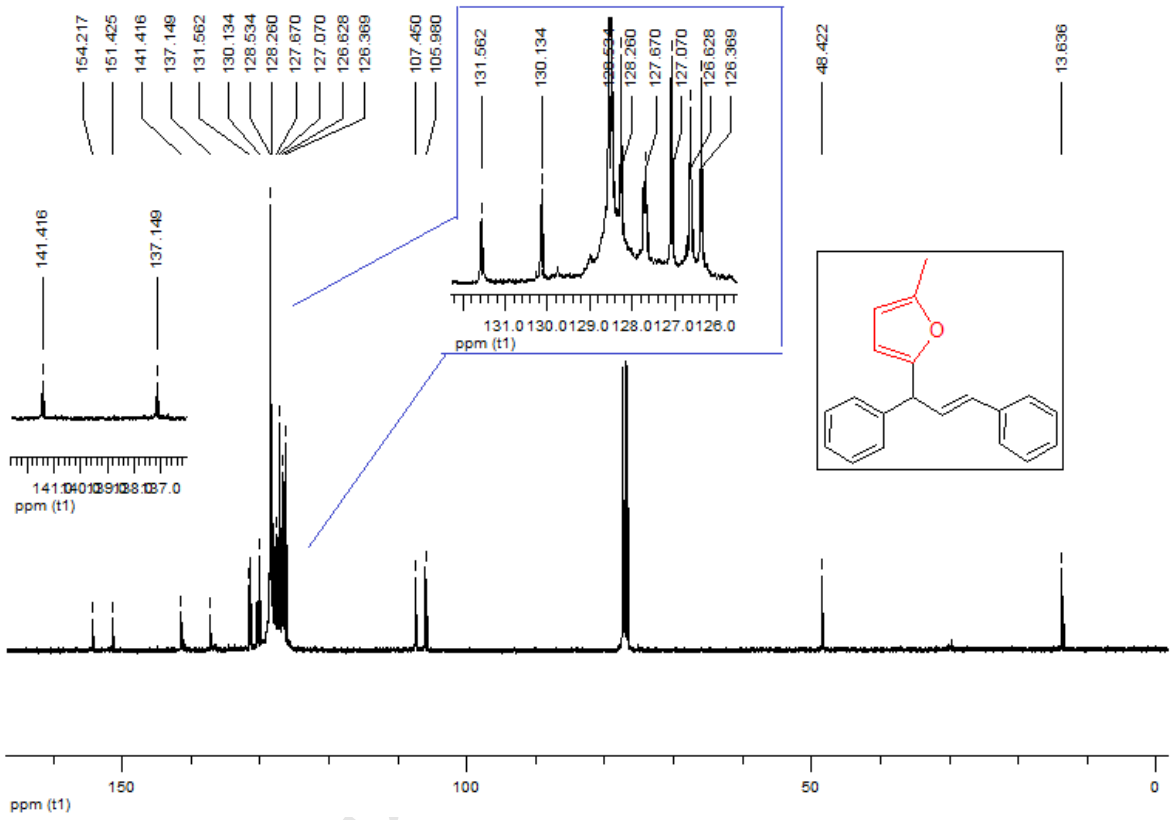


Figure 10S. ^{1}H-NMR spectrum of **14b**:

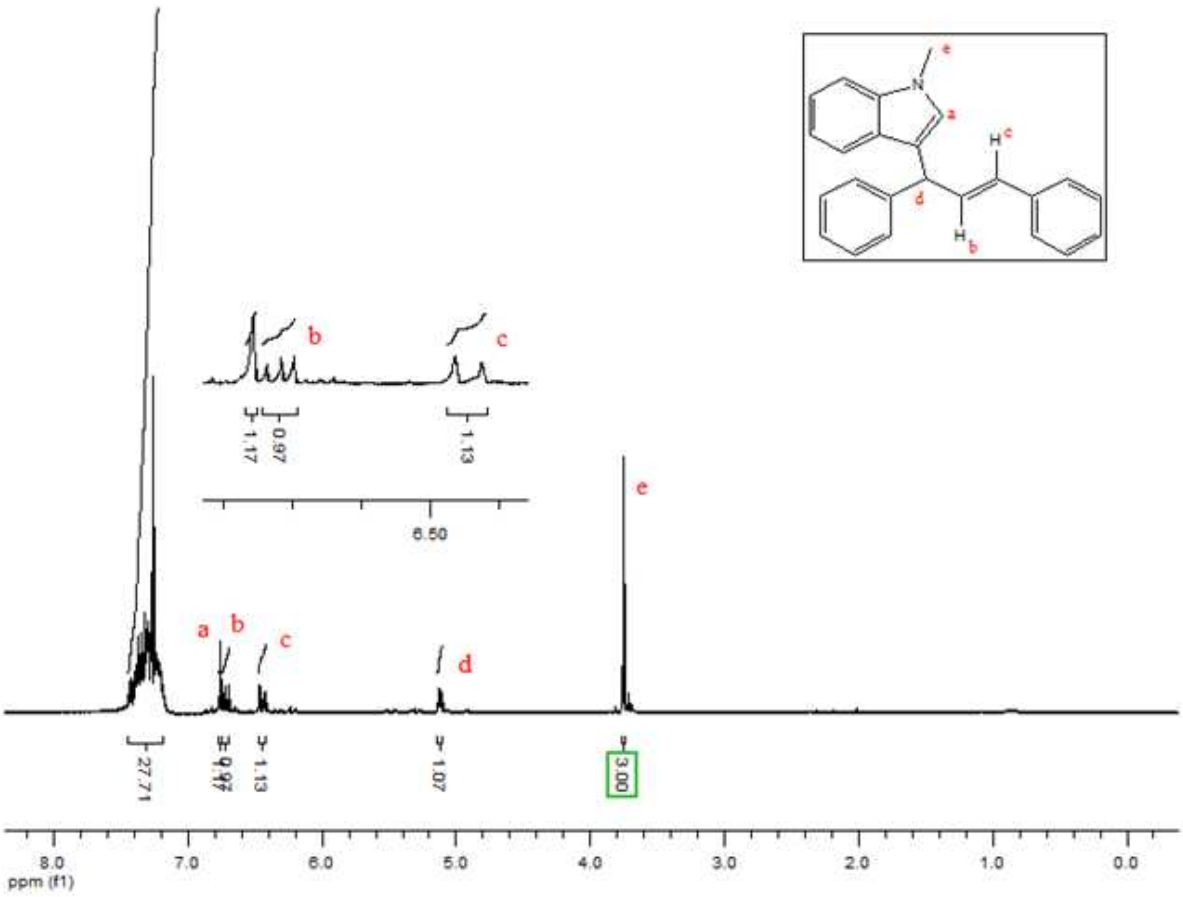


Figure 11S. ^{13}C-NMR spectrum of **14b**: