Supplemental Material

Green asymmetric synthesis of binol *via* oxidative cross-coupling in the presence of L-cysteine@Fe_3O_4 nanoparticles

Akram Ashouri*, Behzad Nasiri, Somayeh Pourian, Hazhir Moghaddami Fard#, Omid Mohammadi#, Arezu Moradi#

# Equal contribution (in alphabetic order)

Department of Chemistry, Faculty of Science, University of Kurdistan, 66177-15175, Sanandaj, Iran.

Email: a.ashouri@uok.ac.ir

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1. Characterization of the L-cysteine@Fe_3O_4

1.1. FT-IR spectrum

The FT-IR analyses were conducted to confirm the presence of L-cysteine on Fe_3O_4 after immobilization. In Figure 1, a broad absorption around 3400 cm^{-1} confirms the presence of the -NH and -OH functional groups in the L-cysteine@Fe_3O_4 nanoparticles. Two peaks observed at 1623 and 1184 cm^{-1} indicate the stretching vibrations of COO– groups. A very weak absorption at 1290 cm^{-1} is attributed to the C-N stretching. The disappearance of the S-H group absorption at 2555 cm^{-1} in the spectra of L-cysteine@Fe_3O_4 nanoparticles suggests the attachment of L-cysteine molecules to the Fe_3O_4 magnetic nanoparticles occurs via the S-H group, forming a covalent Fe-S bond on the Fe_3O_4 substrate (586 cm^{-1}) [1].

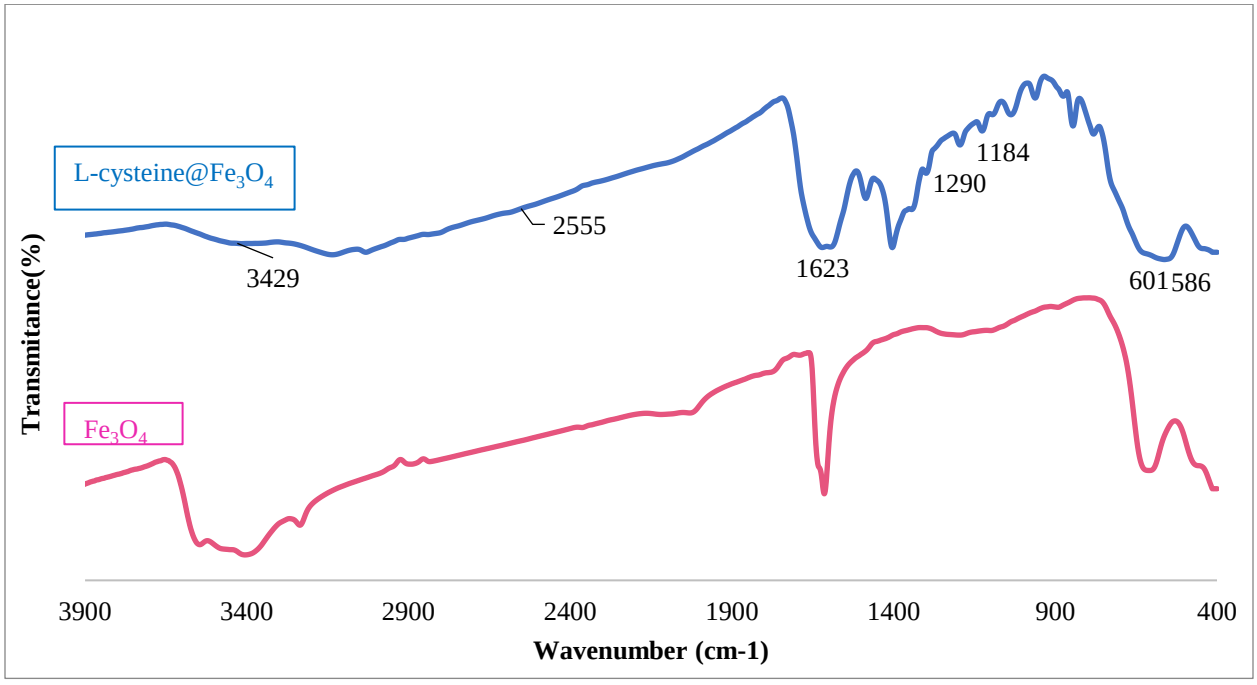

Figure 1. FT-IR spectrum of Fe_3O_4 and L-cysteine@Fe_3O_4 nano catalyst

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1.2. EDAX spectrum

In the next step, to confirm the elements present in L-cysteine@Fe_3O_4 nanoparticles, the EDAX spectrum was examined, indicating the presence of carbon, oxygen, nitrogen, iron, and sulfur. This was also confirmed by the elemental map (Figure 2) [2].

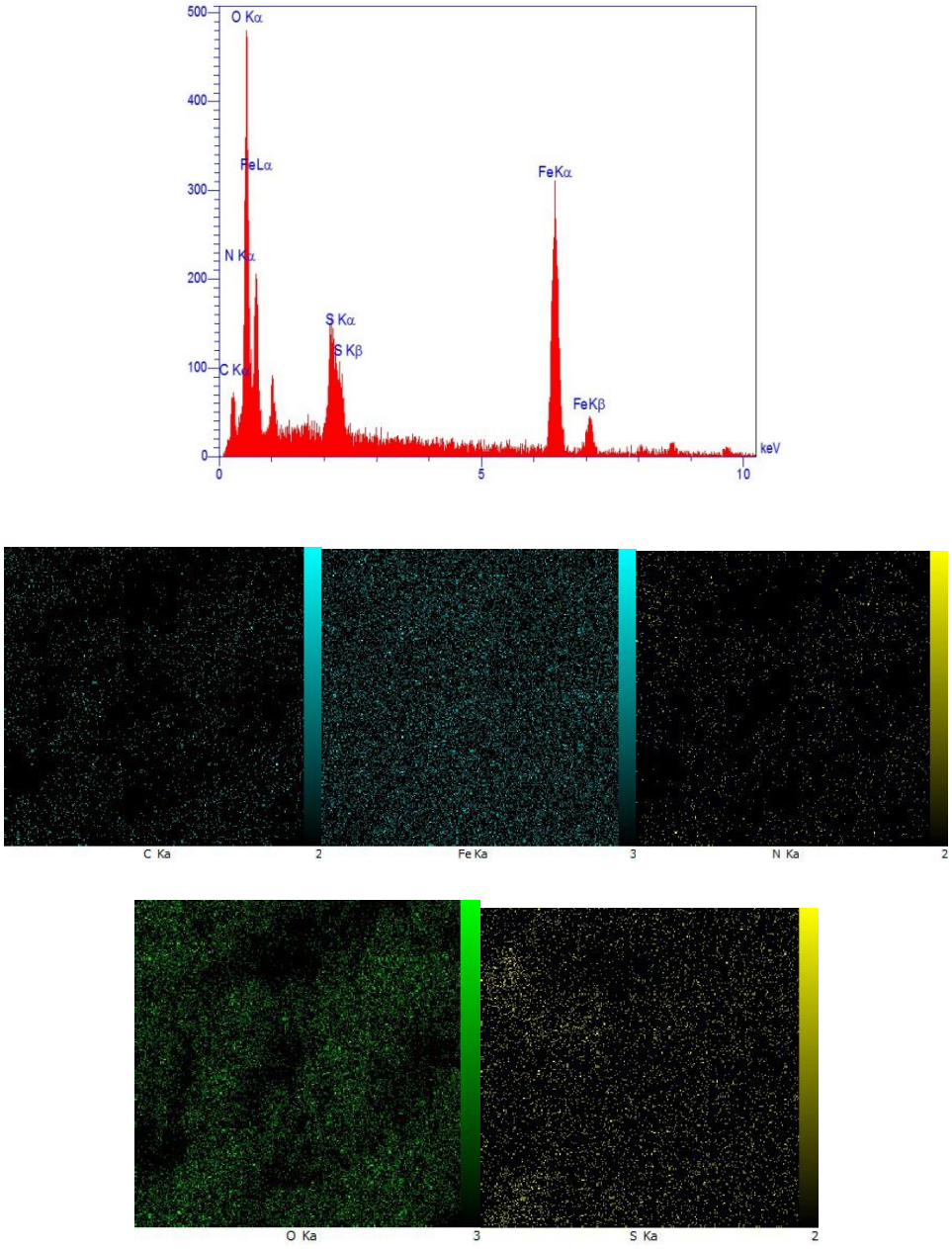

Figure 2. EDAX spectrum of L-cysteine@Fe_3O_4 nanoparticles

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1.3. SEM images

The morphology of Fe_3O_4 and L-cysteine@Fe_3O_4 magnetic nanoparticles was investigated by SEM technique (Figure 3a and 4b). Based on the images, the spherical and uniform dispersion of magnetic nanoparticles in three dimensions is observed. When L-cysteine is deposited onto the Fe_3O_4 nanoparticles, the morphology does not change significantly but is more aggregated.

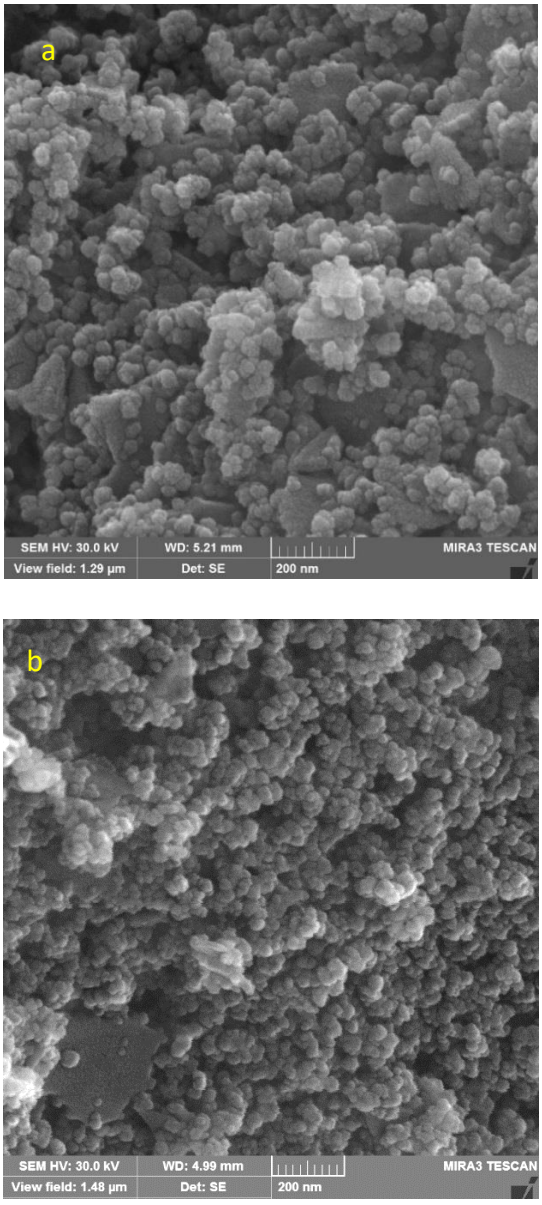

Figure 3. SEM image of synthesized (a)Fe_3O_4 and (b)L-cysteine@Fe_3O_4 nanoparticles

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1.4. XRD spectrum

The XRD technique was used to identify the crystal properties, phase, and size of synthesized L-cysteine@Fe_3O_4 nanoparticles. According to Figure 5, diffraction peaks at 2θ values of 30.4°, 35.7°, 43.3°, 54.8°, 57.5°, and 62.8° corresponded to crystal planes (220), (311), (400), (422), (511), and (440), which are attributed to the structure of Fe_3O_4. This aligns with the reported pattern for Fe_3O_4 nanoparticles (JCPDS No. 79-0418) [3], indicating that the surface coating of magnetite with L-cysteine did not alter its composition after the grafting of L-cysteine. The calculated crystalline size from the Scherrer equation is about 22.8 nm for L-cysteine@Fe_3O_4 (Figure 4) [2].

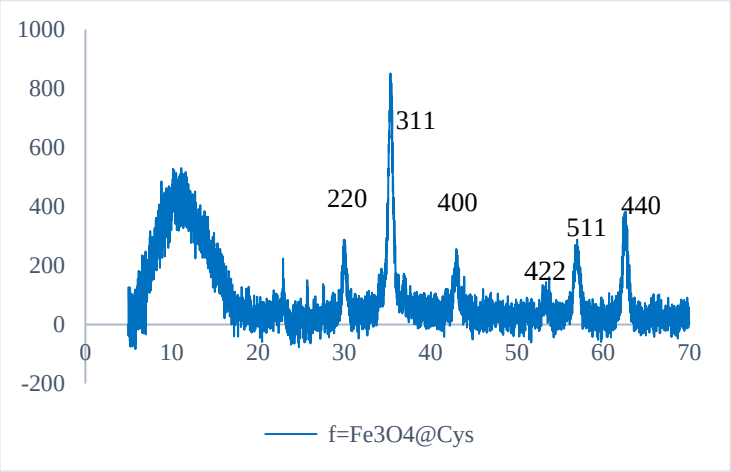

Figure 4. XRD spectrum of L-cysteine@Fe_3O_4 nanoparticles

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1.5. TGA Spectrum

The thermal behavior of the catalysts was studied using the TGA technique. The curve in Figure 5 shows a significant weight loss of L-cysteine@Fe_3O_4 nanoparticles, indicating their high thermal instability. The first and second weight losses below 250°C are due to water evaporation on the surface and trapped water in the catalyst's crystalline structure. The third weight loss between 250 and 450°C is attributed to the decomposition of the organic layer of L-cysteine. According to TGA, the total weight loss was around 10%, indicating the loading percentage of cysteine on Fe_3O_4 [2].

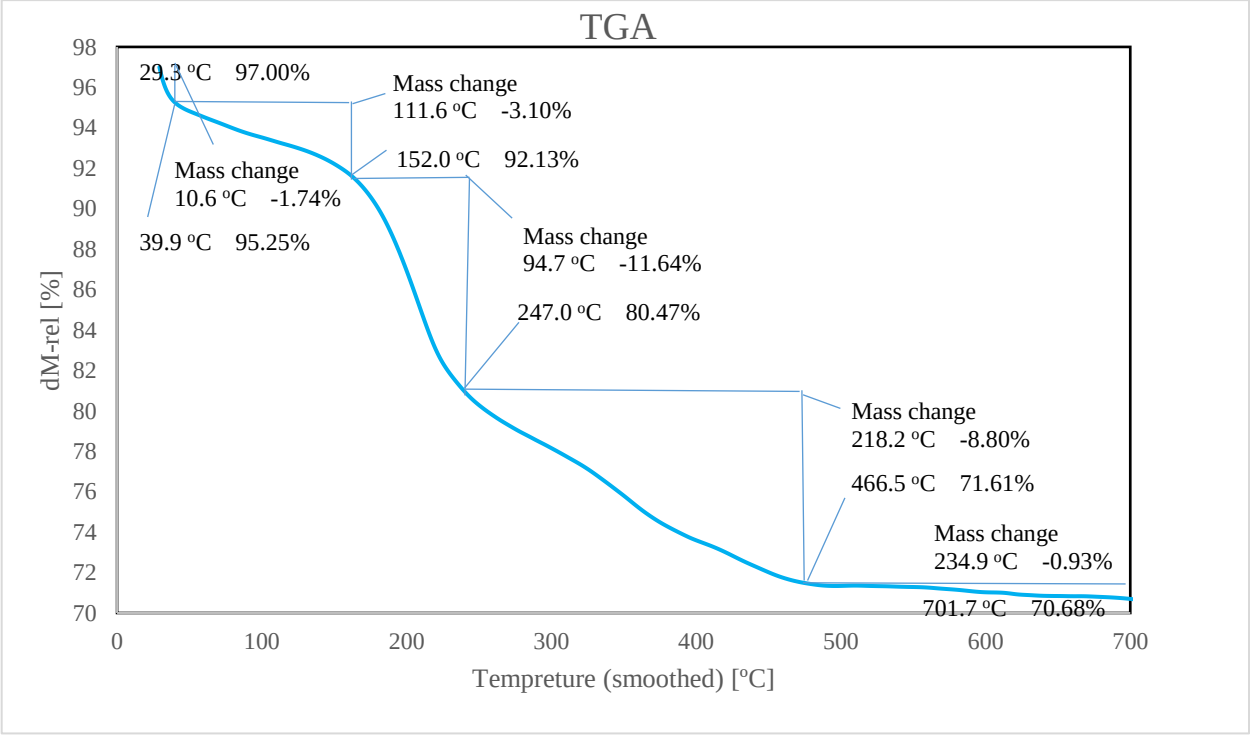

Figure 5. TGA Spectrum of L-cysteine@Fe_3O_4 nanoparticles

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1.6. VSM curves

The magnetization curves of nanocatalysts at 300 K measured the magnetic properties of L-cysteine@Fe_3O_4 nanoparticles. The saturation magnetization (σs) of the nanoparticles was found to be 43.6 emu/g and 39.4 emu/g, respectively, confirming the magnetic nature of the prepared nanoparticles (see Figure 6). Therefore, the obtained results confirm that L-cysteine was successfully grafted onto the surface of Fe_3O_4.

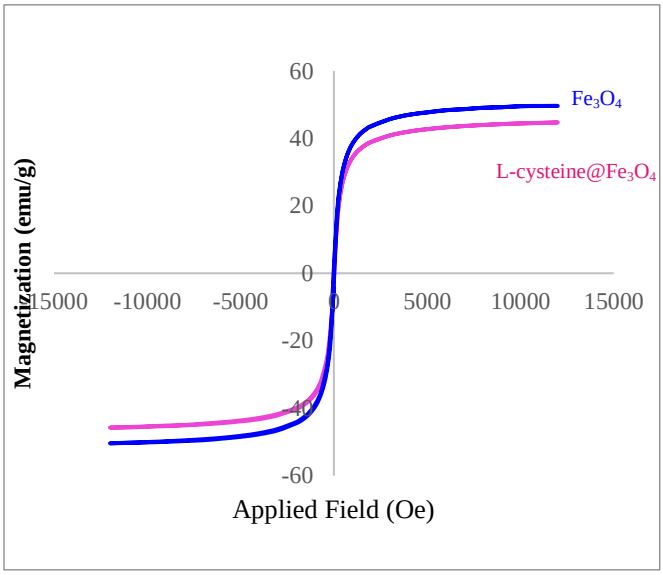

Figure 6. VSM curves of L-cysteine@Fe_3O_4 nanoparticles

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1.7. ^{1}H NMR Spectrum

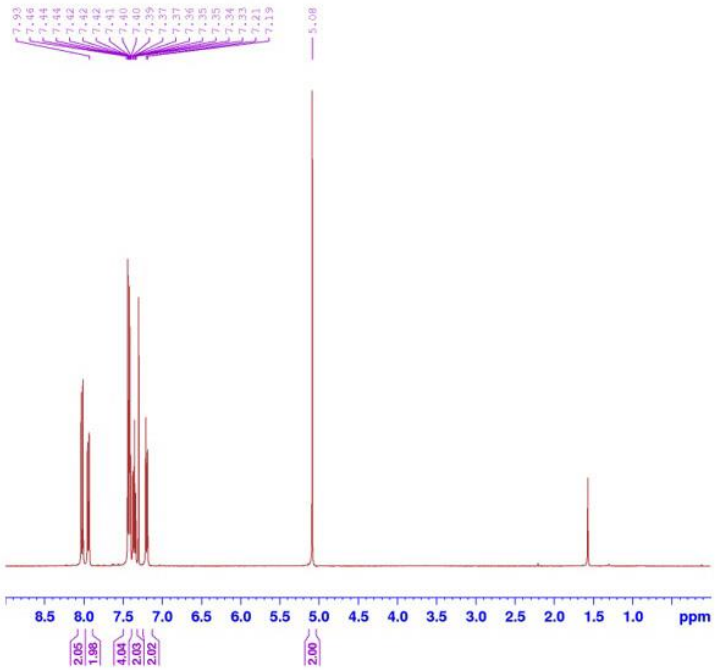

Figure 7. ^{1}H NMR of (*S*)-2,2'-dihydroxy-1,1'-binaphthyl

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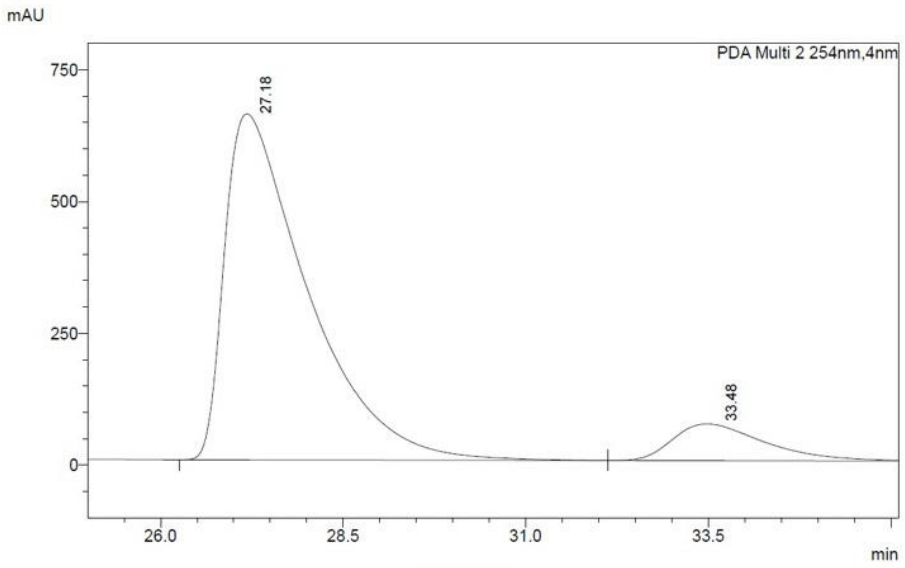
1.8. HPLC chromatogram



Peak Table

PDA Ch2 254nm

Peak#	Ret. Time	Area	Area%
1	27.18	51886568	89.40
2	33.48	6154351	10.60
Total		58040920	100.00

Figure 8. The HPLC chromatogram of obtained *S*-binol

2. References

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