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Synthesis and characterization of γ-Fe_2O_3/polyaniline-curcumin composites

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Superparamagnetic nanomaterials are showing great prospects in medical treatment with targeted medicine. A new conductive superparamagnetic nanocomposite, γ-Fe_2O_3/polyaniline-curcumin (γ-Fe_2O_3/PANI-curcumin), has been synthesized using the interaction between amino group in polyaniline and ketone group in curcumin. The γ-Fe_2O_3/PANI-curcumin composite has the superparamagnetism (30 $emu\cdot g^{-1}$) and electrochemical activity based on the results of magnetization curve and cyclic voltammetry (CV). Transmission electron microscope (TEM) shows that the particle size of γ-Fe_2O_3/PANI-curcumin is about 50 nm. Fourier transform infrared spectra (FTIR) and X-ray diffraction (XRD) have been used to characterize the γ-Fe_2O_3/PANI-curcumin composite and to confirm that curcumin is immobilized into γ-Fe_2O_3/PANI chains. The study provides an academic foundation for developing some new material for immobilizing drugs of anticancer.

Keywords: Curcumin, Fe_2O_3/polyaniline-curcumin Maghemite, Nanocomposites, Polyaniline, Superparamagnetism

Since the 1980s, conductive polymer has broken the traditional concept that polymer was only nonconductor[1]. Magnetic composites have become an extremely attractive research field because of their unique and intriguing properties and potential applications in industrial processes[2-7], such as electrical and magnetic shielding, nonlinear optics, molecular electronics, electrochemical power source[8], drug[9], sensor and microwave absorbent[10-12].

Polyaniline (PANI) nanoparticles containing γ-Fe_2O_3 (thereafter written as γ-Fe_2O_3/PANI) is a novel nanomaterial exhibiting good application prospect in medical treatment as target drug carrier. The γ-Fe_2O_3/PANI not only can diminish particle size, but also the polyaniline can provide functional group to load drug. The γ-Fe_2O_3/PANI nanoparticles show core-shell structure and superparamagnetism combined with high environmental and thermal stability[13]. Up to date, γ-Fe_2O_3/PANI has been most commonly prepared by chemical methods[14-16], showing good conductivity and novel prospect as drug carrier. The main ingredient of γ-Fe_2O_3/PANI, polyaniline (PANI), known for more than 150 years, is the oldest and potential one of the most useful conducting polymers due to its ease of synthesis, environmental stability, and unique doping/dedoping and reversible redox mechanism[17]. In particular, polyaniline has good biological compatibility. MacDiarmid *et al*.[18] observed that the conductivity of polyaniline can last about 100 h in human body and currents through the conductor surfaces can control the shape and function of anchorage-dependent cells. Mattioli-Belmonte used the potential of polyaniline as an electroactive polymer in the culture of excitable cells opens the possibility of using this material as an electroactive scaffold in cardiac and neuronal tissue engineering applications, and demonstrated that PANI is biocompatible in vitro and in long-term animal studies in vivo[19].

The another main ingredient of γ-Fe_2O_3/PANI, γ-iron sesquioxide (γ-Fe_2O_3), has been especially attractive due to its non-toxicity, thermal and chemical stability, low cost and is regarded as a valuable material for mollifying biologically active compounds, bio-tagging of drug molecules, hysteretic heating of maligned cells etc. Their magnetism allows manipulation with external fields besides biocompatibility and nontoxicity to humans[20-22]. Therefore, γ-Fe_2O_3 is viewed as a valuable material for drug delivery, information storage, bioseparation, magnetic sensors, catalysts, etc.

Curcumin from zingiberaceae, curcuma longa, is a kind of phenolic pigment extracted from the rhizome of curcuma longa, which as a inartificial medical material has various derivants in nature. Curcumin with antineoplastic, anti-oxidation, and anti-inflammation functions is the main composition of curcuma longa, a kind of traditional Chinese medicine, which can also adjust immunity and has extensive value both in economic and medical aspects.

In this article, we have developed a new process for the synthesis of γ-Fe_2O_3/PANI- curcumin. And its electrical, magnetic properties are investigated. The curcumin can be immobilized into polyaniline chains based on the interaction between amino group in polyaniline and ketone group in curcumin. The results of FT-IR, XRD and so on confirm that curcumin is immobilized into γ-Fe_2O_3/PANI chains. CV and magnetization studies show that γ-Fe_2O_3/PANI-curcumin composite has both superparamagnetism and electrochemical activity.

Experimental Section

All chemicals used were analytical grade. The monomer aniline and ammonium persulphate (APS, for short) were offered by Shanghai Chemical Reagent Co., Ltd. The monomer aniline was distilled under reduced pressure and stored in refrigerator (about 4°C) before use. Ferrous sulfate heptahydrate ($FeSO_4 \cdot 7H_2O$), ferric chloride hexahydrate ($FeCl_3 \cdot 6H_2O$), ethanol and ammonium hydroxide (30% NH_3 in water) were all of analytical grade and obtained from Sinopharm Chemical Reagent Co., Ltd. Curcumin was purchased from Shanghai Aladdin Reagent Co., Ltd. Other chemicals were used as received without further treatment. All of the aqueous solutions were prepared with double distilled water.

Preparation of γ-Fe_2O_3 nanoparticles

The γ-Fe_2O_3 was prepared according to published procedures[23-27] with some modifications. A typical example of the preparation of γ-Fe_2O_3 nanoparticles is as follows. 5.4 g of $FeCl_3 \cdot 6H_2O$ (20 mmol) and 2.8 g of $FeSO_4 \cdot 7H_2O$ (10 mmol) were dissolved in 20 mL and 10 mL of doubly distilled water, respectively. The two iron-salt solutions were combined and added to 400 mL of 0.6 mol·dm^{-3} aqueous ammonia solution for over 20 min with constant stirring. The *p*H values of the reaction mixture were kept between 11 and 12 with the addition of a concentrated ammonium hydroxide solution. The resulting products were separated by a magnet, repeatedly washed with doubly distilled water, and then air dried at 80°C for 12 h.

Preparation of γ-Fe_2O_3/PANI

A typical procedure for the preparation of γ-Fe_2O_3/PANI is as follows[23]. 1.9 mL of aniline monomer (20 mmol) was dissolved in 200 mL of 0.5 mol·dm^{-3} HCl with suspended γ-Fe_2O_3. Then 0.5 mol·dm^{-3} APS (20 mmol) was added slowly into the given solution and stirred for 5 h. γ-Fe_2O_3/PANI was obtained by centrifugation (Model 80-2, 4000 r·min^{-1}), washed successively with double-distilled water and ethanol, and finally vacuum dried at 70°C for 12 h. In order to obtain the γ-Fe_2O_3/PANI base, the synthesized γ-Fe_2O_3/PANI was immersed in 0.2 mol·dm^{-3} aqueous ammonium with magnetic stirring for 24 h, filtrated and washed with double-distilled water to a *p*H of 6-7, and then vacuum dried at 80°C for 12 h.

Preparation of a γ-Fe_2O_3/PANI–curcumin composite

Adjusting the different ratio of γ-Fe_2O_3/PANI and curcumin, curcumin was dissolved in ethanol, and then γ-Fe_2O_3/PANI was added into the curcumin solution. The mixed solution reacted under an ultrasonic water bath for hours. The γ-Fe_2O_3/PANI-curcumin was washed with ethanol and vacuum dried at 70°C for 12 h, then pulverized after being dried, and characterized by different test methods.

Characterization of γ-Fe_2O_3/PANI–Curcumin

FTIR spectra of the samples on pressed KBr pellets were recorded on a Bruker Tensor 27 FTIR spectrometer (Germany) in the range of 4000-400 cm^{-1}. X-ray diffraction patterns of the powder samples were taken on an XD-3A powder diffractometer using Cu-K_α radiation (λ = 1.5406 Å), which was employed to ascertain the degree of crystallinity. The applied magnetic field dependence of magnetization was obtained on a vibrating sample magnetometer (VSM) (ADE Co., USA) in fields ranging from -8000 to 8000 Oe at room temperature. The size and morphology of the resulting particles were measured using a Tecnai-12 (Philips) transmission electron microscope. The cyclic voltammogram (CV) was taken on a CHI 660 electroanalysis workstation. The cell consists of a working electrode (6×6 mm^2), a platinum sheet (10×10 mm^2) counter electrode and a saturated calomel electrode (SCE) as reference electrode in a Britton-Robinson (B-R) buffer (*p*H 7.0). The working electrode was prepared by dispersing the samples in DMF and then dripping the resultant suspension onto the platinum sheet, which was then dried in atmosphere.

Results and Discussion

It is well know that aldehydes and ketones can react readily with equimolar amounts of primary amines, yielding imines[28] .Curcumin and the end groups of Polyaniline contain ketones and primary amines, respectively. We envision the synthetic route of γ-Fe_2O_3/PANI-curcumin (Fig.1).

Step 1: preparation of skeleton material, basing on the synthesized γ-Fe_2O_3, we make the γ-Fe_2O_3 coat with a layer of polyaniline by solution polymerization method, and form the γ-Fe_2O_3/PANI magnetic nanomaterials with core-shell structures.

Step 2: immobilization of curcumin, basing on the synthesized superparamagnetism nano particles γ-Fe_2O_3/PANI, curcumin is immobilized into γ-Fe_2O_3/PANI chains, which is due to the interaction between carbanyl group of curcumin and surface amino group of polyaniline.

IR spectra of samples

Figure 2 shows the IR spectra of γ-Fe_2O_3, γ-Fe_2O_3/PANI, γ-Fe_2O_3/PANI-curcumin and curcumin. The peaks at 1590 and 1503 cm^{-1} correspond to the C=C stretching vibration of the quinoid ring and the benzene ring, respectively. The peak at 1303 cm^{-1} attributes to aromatic (C–N) stretching band of polyaniline. The absorption peak at 1128 cm^{-1} corresponds to B–NH–B, where B refers to the benzenic-type rings. The peaks of γ-Fe_2O_3/PANI-curcumin virtually overlap with that of polyaniline over 1128 cm^{-1}. Compared curve c with curve b in fig. 2, it is seen that there are two new peaks at 1029 cm^{-1} and 962 cm^{-1} in the curve c, which are same with the peaks of curcumin in the curve d. It indicates that curcumin was immobilized into γ-Fe_2O_3/PANI, forming γ-Fe_2O_3/PANI-curcumin.

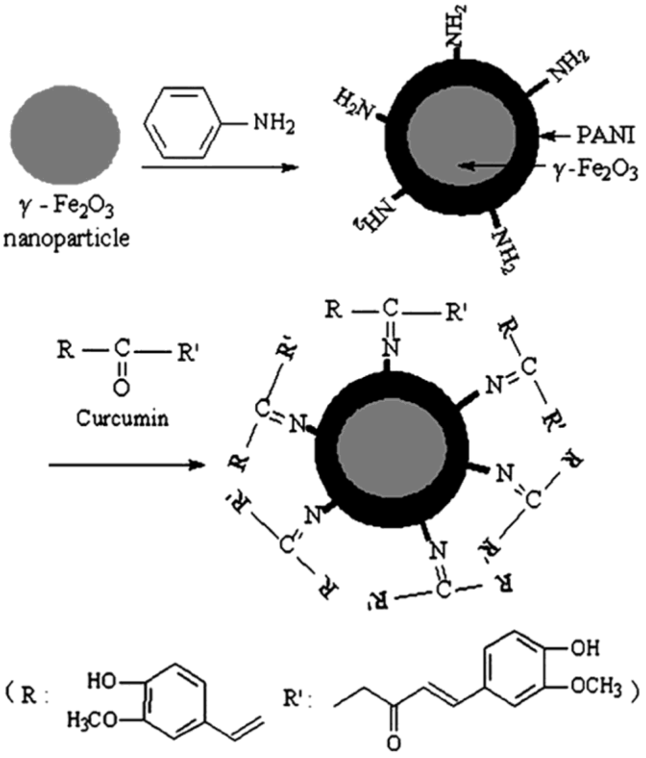

Fig. 1 — Schematic illustration for formation of γ-Fe_2O_3/PANI-Curcumin.

Figure 3 shows FT-IR spectra of γ-Fe_2O_3/PANI-curcumin with different molar ratios of γ-Fe_2O_3/PANI to curcumin at room temperature. Molar ratios of Curves a, b and c are 1:2, 1:1, 2:1, respectively. In fig. 4, three samples appear the characteristic peak of Fe-O stretching vibration at 570 cm^{-1}, this indicated that the γ-Fe_2O_3 existed in three different molar ratios sample. It can be seen from fig. 3 that the absorption peak position of γ-Fe_2O_3/PANI-curcumin with different molar ratios of γ-Fe_2O_3/PANI to curcumin is same. This indicates that the molar ratios of

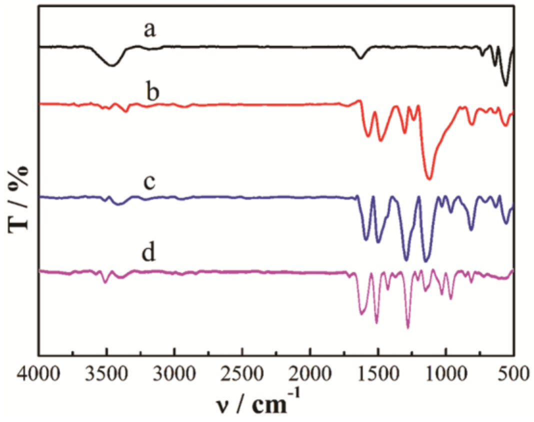

Fig. 2 — IR spectra of samples
γ-Fe_2O_3 ; b. γ-Fe_2O_3/PANI ; c. γ-Fe_2O_3/PANI-curcumin ; d. curcumin.

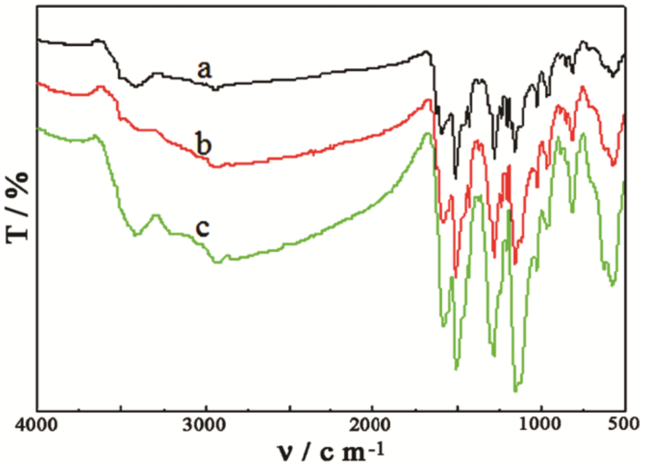

Fig. 3 — FT-IR spectra of γ-Fe_2O_3/PANI-curcumin with different molar ratios between γ-Fe_2O_3/PANI and curcumin.
n(γ-Fe_2O_3/PANI) : n(curcumin) = (a) 1:2; (b) 1:1; (c) 2:1.

γ-Fe_2O_3/PANI to curcumin hardly affect the structure of the samples.

Figure 4 shows IR spectra of samples with different reaction times at room temperature. Different reaction times have no significant effect on the structure of the samples as their absorption peak positions are roughly same.

Magnetic characterization of the samples

Figure 5 shows the applied magnetic field dependence of magnetization for γ-Fe_2O_3 (a), γ-Fe_2O_3 /PANI (b), and γ-Fe_2O_3 /PANI-curcumin (c) in the range of -8000 to 8000 Oe at room temperature. It was found from fig. 5 that the saturated magnetization (M_s) of γ-Fe_2O_3, γ-Fe_2O_3/PANI, and γ-Fe_2O_3/PANI-curcumin decreased gradually with forming PANI shell and immobilized curcumin. The following sequence was observed: γ-Fe_2O_3 (83 emu g^{-1}) > γ-Fe_2O_3/PANI (44 emu g^{-1}) > γ-Fe_2O_3/PANI-curcumin (34 emu g^{-1}). The saturated magnetization of γ-Fe_2O_3/PANI-curcumin mainly comes from that of γ-Fe_2O_3. The gradually decreasing saturated magnetization from γ-Fe_2O_3 to γ-Fe_2O_3/PANI-curcumin indicates the decrease of the γ-Fe_2O_3 content in unit mass products, which also further confirms that γ-Fe_2O_3 has been wrapped by PANI and curcumin has been immobilized into γ-Fe_2O_3/PANI. They are consistent with the result of IR (fig. 2). It can be also seen from fig. 5 that they all exhibit superparamagnetism because there is no remnant magnetization (M_r) or coercive force (H_c)[29].

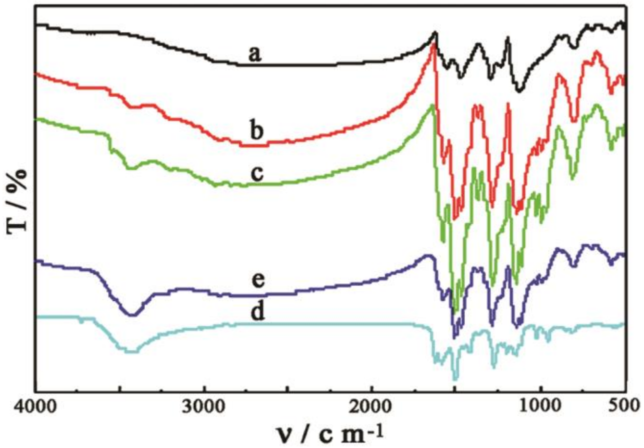

Fig. 4 — IR spectra of samples with different reaction times at room temperature.
a. 4 h; b. 8 h; c. 12 h; d.16 h; e. 20 h

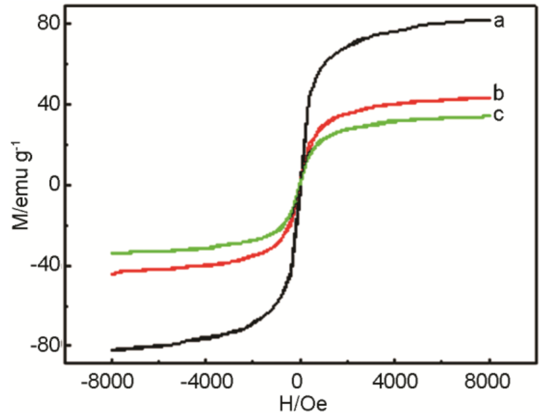

Fig. 5 — Dependence of magnetization on the applied magnetic field at room temperature for samples
a. γ-Fe_2O_3 ; b. γ-Fe_2O_3/PANI ; c. γ- Fe_2O_3/PAn/curcumin.

In order to determine the most suitable proportion of curcumin during synthesizing γ-Fe_2O_3/PANI-curcumin, γ-Fe_2O_3/PANI-curcumin have been synthesized by the different molar ratios of γ-Fe_2O_3/PANI to curcumin. Figure 6 shows the magnetizations of γ-Fe_2O_3/PANI-curcumin with different molar ratios of γ-Fe_2O_3/PANI to curcumin. Curve a is γ-Fe_2O_3/PANI, its saturated magnetization is 44 emu·g^{-1}. Curve b, c and d represent that of the different molar ratios of γ-Fe_2O_3/PANI to curcumin, which are 2 : 1, 1 : 2 and 1 : 1, respectively. It can be seen from the fig. 6 that the saturated magnetization intensity of γ-Fe_2O_3/PANI-curcumin nanoparticles reduced with increasing the molar ratios of γ-Fe_2O_3/PANI to curcumin. This may be due to that curcumin is immobilized into γ-Fe_2O_3/PANI leading to the decrease of the γ-Fe_2O_3 content in unit mass products. From the figure 6 we can also understand that the saturated magnetization intensity is various for different molar ratios synthesized products. When the molar ration between γ-Fe_2O_3/PANI and curcumin

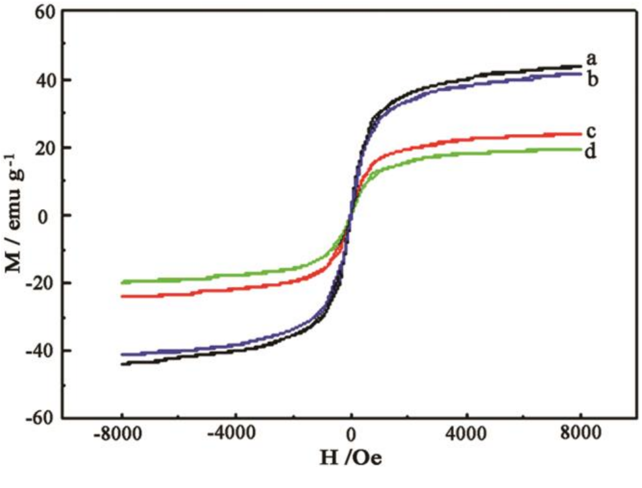

Fig. 6 — VSM of γ-Fe_2O_3/PANI-curcumin with different molar ratios between γ-Fe_2O_3/PANI and curcumin
a. γ-Fe_2O_3/PANI; b. 2 : 1; c. 1 : 2; d. 1 : 1.

is 2 : 1, the saturated magnetization (41 emu·g^{-1}) is maximum. When the molar ratios between γ-Fe_2O_3/PANI and curcumin is 1 : 2 and 1 : 1, the saturated magnetization decrease from 41 emu·g^{-1} to 24 emu·g^{-1} and 19 emu·g^{-1}, respectively. In the figure we can also obtain that all γ-Fe_2O_3/PANI-curcumin are superparamagnetism, so we can infer that the particle size of ferromagnetic samples is very small and less than 90 nm. Because when the size of the particles (d=14-90 nm) is within the critical dimension of superparamagnetic, many ferromagnetic substances will form the ferromagnetic transform into superparamagnetic[30].

Figure 7 shows VSM of γ-Fe_2O_3/PANI-curcumin under the different reaction time at room temperature, curves a~e are the hysteresis loop of γ-Fe_2O_3/PANI-curcumin correspond reaction time for 4, 8, 12, 16 and 20 h, respectively. From the Fig. 7 it is seen that γ-Fe_2O_3/PANI-curcumin are all superparamagnetic at different reaction time, indicate that particle diameter of γ-Fe_2O_3/PANI-curcumin are less than 50 nm. Figure 8 shows magnetizations of γ-Fe_2O_3/PANI-curcumin are affected by different reaction time. The reaction times are 4, 8, 12 and 16 h, the saturated magnetization is decreased with the increase of reaction time. When the reaction time is 4 h, the saturated magnetization (30 emu·g^{-1}) is the strongest, and when the reaction time is 16 h, the saturated magnetization (13 emu·g^{-1}) is minimum. This is due to the increase of curcumin percentage in γ-Fe_2O_3/PANI-curcumin with the extension of the reaction time. However, the saturated magnetization for 20 h is greater than that for 16 h, which needs to be further studied.

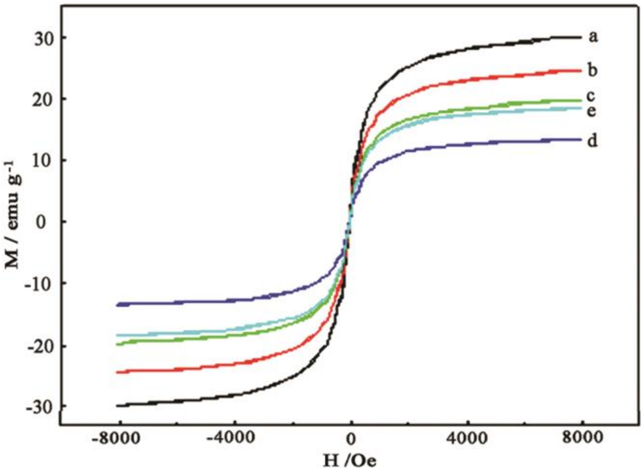

Fig. 7 — VSM of γ-Fe_2O_3/PANI /curcumin under different reaction time.
a. 4 h; b. 8 h; c. 12 h; d. 16 h; e. 20 h.

TEM mages of samples

Figure 9 shows TEM images of γ-Fe_2O_3/PANI-curcumin. It can be seen from Fig. 9 that the average particle diameter of γ-Fe_2O_3/PANI-curcumin is about 50 nm, the particle diameter is within the critical dimension of superparamagnetic (d=14-90 nm), they are consistent with the result of VSM. The conductive superparamagnetic particle with diameters less than 100 nm is highly favorable to the targeted therapies[31].

The cyclic voltammograms of samples

Figure 10 is the cyclic voltammograms of the samples, they are tested in the BR buffer solution. Curves a ~ c are the cyclic voltammograms of polyaniline, magnetic nanoparticles γ-Fe_2O_3/PANI and γ-Fe_2O_3/PANI-curcumin, respectively. It can be seen clearly from Fig. 10 that when the film mass is settled, the electrochemical activity of γ-Fe_2O_3/PANI significantly decreased, this is due to the decrease of polyaniline content in γ-Fe_2O_3/PANI. It can be seen from fig. 10 that γ-Fe_2O_3/PANI-curcumin still possess some electrochemical activity in BR buffer solution, which may be favourable to the shape and function of anchorage-dependent cells at currents through the conductor surfaces.

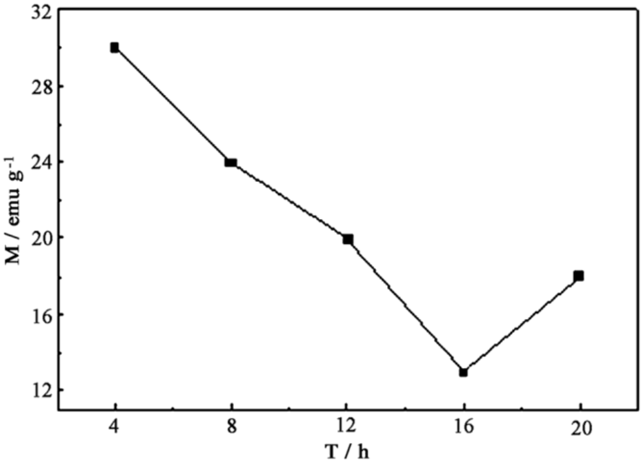

Fig. 8 — Diagram of magnetization and reaction time for γ-Fe_2O_3/PANI-curcumin.

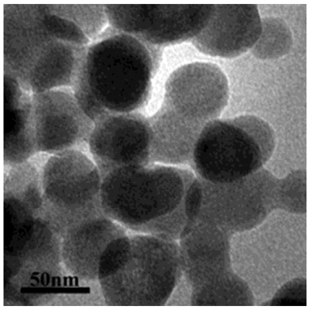

Fig. 9 — TEM of γ-Fe_2O_3/PANI-curcumin.

X-ray diffraction of samples

Figure 11 shows the X ray diffraction patterns of γ-Fe_2O_3, γ-Fe_2O_3/PANI and γ-Fe_2O_3/PANI-curcumin. As can be seen from the figure, that γ-Fe_2O_3 has a XRD pattern with an appearance of diffraction peaks at about 2θ = 30.2°, 35.6°, 43.2°, 53.8°, 57.3° and 62.9°, which shows the good crystalline structure of the γ-Fe_2O_3. Comparing curve b with curve c, γ-Fe_2O_3/PANI keeps the crystalline structure of γ-Fe_2O_3. It proved that γ-Fe_2O_3 was immobilized into polyaniline. The additional peaks at 20.4°and 25.2° in curve c are attributed to the characteristic crystalline nature of PANI. When curcumin is immobilized into γ-Fe_2O_3/PANI, the obvious crystal diffraction peaks disappear at 14–28° (curve d). It may be due to the reason that the interaction between functional groups of curcumin and polyaniline affects the crystal form of PANI. Meanwhile, the characteristic signal of γ-Fe_2O_3 becomes weak obviously, which indicates that the interaction between curcumin and polyaniline makes the content of γ-Fe_2O_3 decreased in the products.

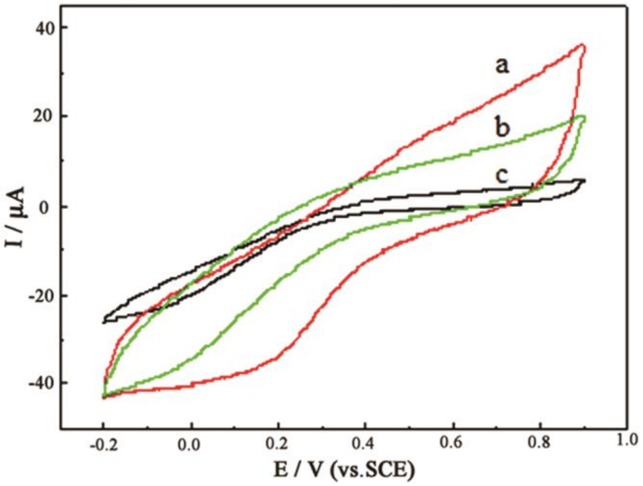

Fig. 10 —Cyclic voltammograms of samples
a. PANI; b. γ-Fe_2O_3 / PANI; c. γ-Fe_2O_3/PANI/curcumin

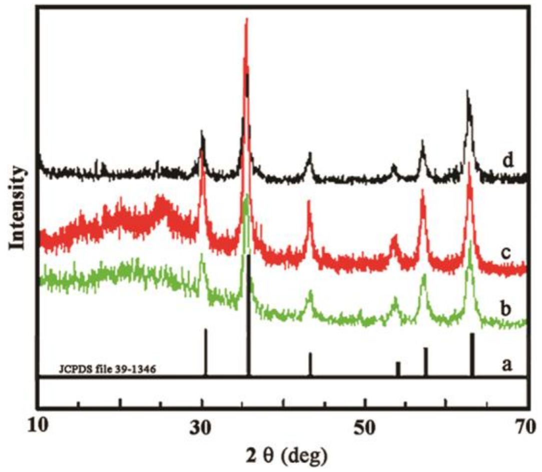

Fig. 11 — XRD patterns of samples
a. standard spectrum of γ-Fe_2O_3; b. γ-Fe_2O_3; c. γ-Fe_2O_3/PANI; d. γ-Fe_2O_3/PAIN/curcumin.

Conclusion

A conductive superparamagnetic nanocomposite (γ-Fe_2O_3/PANI-curcumin) has been synthesized. Various characterizations of γ-Fe_2O_3/PANI-curcumin have validated its good electrochemical activity and stable magnetic conductivity with the particle size of about 50 nm, which may meet the requirements of targeted drugs on particle size. Based on the effects of the reaction time and mole ratios between γ-Fe_2O_3/PANI and curcumin in γ-Fe_2O_3/PANI-curcumin, when the reaction time is 4 h and mole ratio is 2:1, the magnetization is the strongest. By farther research, some new targeted drugs may be developed.

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References

1 Galvin M E & Wnek G E, *Polym*, 23 (1982) 795.
2 Pu Z, Zhou X, Yang X, Jia K & Liu X, *J Magn Magn Mater*, 385 (2015) 368.
3 Held G A, Grinstein G, Doyle H, Sun S & Murray C B, *Phys Rev B*, 64 (2001) 012408-1.
4 Qiu Y, Ma Z & Hu P, *J Mater Chem A*, 2 (2014) 13471.
5 Urbanova V, Magro M, Gedanken A, Baratella D, Vianello F & Zboril R, *Chem Mater*, 26 (2014) 6653.
6 Jiang W, Chen X, Wu J, Xu S & Tian R, *J Mater Eng Perform*, 24 (2015) 1237.
7 Fang F F, Liu Y D & Choi H J, *Colloid Polym Sci*, 291 (2013) 1781.
8 Ma Z & Kan J, *Synth Met*, 174 (2013) 58.
9 Wuang S C, Neoh K G, Kang E T, Pack D W & Leckband D E, *Biomaterials*, 29 (2008) 2270.
10 Kawaguchi H, *Prog Polym Sci*, 25 (2000) 1171.
11 Gomez-Romero P, *Adv Mater*, 13 (2001) 163.
12 Xiao H M, Zhang W D, Wan M X & Fu S Y, *J Polym Sci Polym Chem*, 47 (2009) 4446.
13 Deng J, Ding X, Zhang W, Peng Y, Wang J, Long X, Li P & Chan A S C, *Polym*, 43 (2002) 2179.
14 Huang H, Zhang L & Kan J, *Mater Chem Phys*, 145 (2014) 27.
15 Gao R, Li J, Han S, Wen B, Zhang T, Miao H & Zhang Q, *J Exp Nanosci*, 7 (2012) 282.
16 Shen Q, Lang J & Kan J, *Asian J Chem*, 26 (2014) 6492.
17 Li D, Huang J X & Kaner R B, *Acc Chem Res*, 42 (2009) 135.

18 Bidez P R, Li S, MacDiarmid A G, Venancio E C, Wei Y & Lelkes P I, *J Biomat Sci Polym E*, 17 (2006) 199.

19 Mattioli-Belmonte M, Giavaresi G, Biagini G, Virgili L, Giacomini M, Fini M, Giantomassi F, Natali D, Torricelli P & Giardino R, *Int J Artificial Organs*, 26 (2003) 1077.

20 Layek S, Pandey A, Pandey A & Verma H C, *Int J Environ Sci Te*, 2 (2010) 33.

21 Pankhurst Q A, Connolly J, Jonesa S K & Dobson J, *Appl Phys*, 36 (2003) 167.

22 Levy M, Wilhelm C, Siaugue J M, Horner O, Bacri J C & Gazeau F, *J Phys Condens Matter*, 20 (2008) 1.

23 Tang B Z, Geng Y, Lam J W Y & Li B, *Chem Mater*, 11 (1999) 1581.

24 Tang B Z, Geng Y H, Sun Q H, Zhang X X & Jing X B, *Pure Appl Chem*, 72 (2000) 157.

25 Tang R, Liu M & Kan J, *Polym Renew Resources*, 3 (2012) 1.

26 Morales M P, Veintemillas-Verdaguer S, Montero M I & Serna C J, *Chem Mater*, 11 (1999) 3058.

27 Cao S W, Zhu Y J, Ma M Y, Li L & Zhang L, *J Phys Chem C*, 112 (2008) 1851.

28 Vancik H, *Basic Organic Chemistry for the Life Sciences* (Springer International Publishing, New York), 2014, 94.

29 Bean C P & Livingston J D, *J Appl Phys*, 30 (1959) S120.

30 Liu J & Wan M X, *J Polym Sci Polym Chem*, 38 (2000) 2734.

31 Olivier Jean-Christophe, *NeuroRx*, 2 (2005) 108.