

**A magnetic biocatalyst based on mussel-inspired polydopamine and its acylation of dihydromyricetin**

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1                   **Preparation of a magnetic nanobiocatalyst based on**  
2                   **mussel-inspired polydopamine and its efficient application to**  
3                   **acylation of dihydromyricetin**

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1    **ABSTRACT**

2    A mussel-inspired polydopamine-coated magnetic iron oxide nanoparticles (PD-MNPs)  
3    hybrid composite was successfully prepared and structurally characterized in detail. A  
4    widely used *Aspergillus niger* lipase (ANL) was effectively immobilized onto  
5    PD-MNPs (ANL@PD-MNPs), with a protein loading of 138 mg/g-support and an  
6    activity recovery of 83.6% at optimal conditions. During the immobilization process,  
7    the pH and the immobilization time were investigated respectively. Meanwhile, the  
8    pH, thermal and storage stabilities of ANL@PD-MNPs significantly surpassed those  
9    of free ANL. Also, ANL@PD-MNPs manifested better solvent tolerance than free  
10    ANL and secondary structure of free ANL and ANL@PD-MNPs was analyzed by  
11    infrared spectroscopy. A kinetic study demonstrated that the as-prepared  
12    ANL@PD-MNPs had an enhanced enzyme-substrate affinity and a relatively high  
13    catalytic efficiency. Furthermore, the prepared ANL@PD-MNPs was successfully  
14    applied as an efficient nanobiocatalyst for regioselective acylation of dihydromyricetin  
15    (DMY) in DMSO with a conversion of 79.3%, which was higher than that reported  
16    previously. The as-prepared ANL@PD-MNPs remained over 55% of its initial activity  
17    after 10 cycles of consecutive reuse. Besides, the ANL@PD-MNPs was readily  
18    separated from the reaction system by magnetic forces. Clearly, PD-MNPs is a  
19    excellent support for ANL and the resulting ANL@PD-MNPs displayed great  
20    potential for efficient synthesis of dihydromyricetin-3-acetate through enzymatic  
21    regioselective acylation.

1 **Keywords:** magnetic iron oxide; nanoparticles; polydopamine; *Aspergillus niger*  
2 lipase; acylation; dihydromyricetin

## 4 **1.Introduction**

5 As an important biological catalyst, lipase (glycerol ester hydrolases E.C.3.1.1.3) is  
6 widely used in the production of biofuels, organic synthetic compounds, detergents,  
7 perfumes, cosmetics, leather, enantiopure pharmaceuticals, medical diagnostics, foods  
8 and feeds[1, 2]. *Aspergillus niger* lipase is a well known biocatalyst because of its  
9 wide application in the chemoselective, enantioselective and regioselective hydrolysis  
10 and synthesis of a broad range of non-natural esters[3]. However, the disadvantages of  
11 the free lipase, such as poor mechanical stability, unrecyclability and difficulties in  
12 separating from products, hinder its further application in industry. To overcome these  
13 problems, immobilization techniques of enzyme have been widely employed[4]. With  
14 the further development of catalytic system, the ideal immobilization methodology  
15 should meet the following requirements: (i) The enzyme carrier should manifest a high  
16 specific surface area, good biocompatibility, be easily recyclable and capable of  
17 binding large amounts of enzyme with recovery of enzymatic activity. (ii) The  
18 immobilization process should be simple, rapid and facile. (iii) The immobilized  
19 enzyme should exhibit good stability in the reaction system[5].

20 In recent years, magnetic iron oxide nanoparticles (MNPs) have attracted great  
21 interest owing to its properties, such as biocompatibility, superparamagnetism, high

1 surface-to-volume ratios and low toxicity[6]. It has been used as enzyme supports due  
2 to its high specific surface area and easy separation from the reaction mixture by an  
3 external magnetic field[7]. In most cases, the MNPs require further modification or  
4 functionalization to introduce catalyst on the surface.

5 Polydopamine, a polymer inspired by the composition of adhesive protein in  
6 mussels, is one of the most commonly used biomimetic materials[8]. The primary  
7 advantage of polydopamine is that, it can be easily deposited on virtually all types of  
8 inorganic and organic materials by the self-polymerization of its monomer  
9 dopamine[9-11]. Furthermore, polydopamine could graft some macromolecules (such  
10 as enzyme) containing thiol or amine via Michael addition or Schiff base reaction  
11 between catechols (a moiety of polydopamine or dopamine) and amines or thiols[12].  
12 Therefore, it is of great interest to make use of polydopamine to surface modify  
13 MNPs, and the polydopamine-coated MNPs (PD-MNPs) can be an excellent carrier for  
14 enzyme immobilization[13] due to these advantages: polydopamine exhibits good  
15 biocompatibility; the enzyme immobilization process is simple and mild [14, 15]; the  
16 as-prepared immobilized enzyme could be easily and rapidly recycled from the  
17 reaction system through the magnetic force.

18 Dihydromyricetin (DMY), a natural aglycone flavonoid, has been found to  
19 possess numerous bioactivities with potential beneficial effects to the human body,  
20 such as anti-inflammatory, analgesic, antitussive, expectorant, antibacterial,  
21 anti-thrombotic and anti-tumor activities[16]. However, DMY is poorly soluble in

1 both aqueous and nonaqueous systems, which limits its processability and application  
2 potential. Lately, Hou et al[17] in our research group firstly reported the lipase  
3 catalytic acylation of DMY, and the solubility of product in organic solvents and lipid  
4 systems was significantly improved. Nevertheless, to meet the requirements in  
5 industrial production, the reusability of the lipase needed to be significantly improved.

6 In this study, the MNPs were successfully prepared and surface modified with  
7 polydopamine coating. Then, the polydopamine-coated MNPs (PD-MNPs) were  
8 structurally characterized in detail. Furthermore, the lipase from *Aspergillus niger*  
9 (ANL) was successfully immobilized onto the PD-MNPs with relatively high  
10 recovery activity and protein loading for the first time. Also, the enzymatic properties  
11 of the resulting immobilized lipase (ANL@PD-MNPs) were investigated  
12 systematically. Finally, for the first time, the as-prepared ANL@PD-MNPs was used  
13 as a magnetically recyclable biocatalyst for the kinetic regioselective acylation of  
14 dihydromyricetin (DMY).

## 15 **2. Experimental Section**

### 16 **2.1. Materials**

17 Dopamine hydrochloride was purchased from Aladdin. Ferric chloride  
18 hexahydrate ( $\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$ ) and ferrous chloride tetrahydrate ( $\text{FeCl}_2 \cdot 4\text{H}_2\text{O}$ ) were from  
19 the Guangzhou Chemical Reagent Co. Ltd. *Aspergillus niger* lipase was purchased  
20 from Shenzhen Leveking Bio-Engineering Co. Ltd (Shenzhen, China). DMY was from  
21 Aladdin (Shanghai, China). Vinyl acetate (VA), used as acyl donor, was purchased from

1 Sigma-Aldrich and TCI Co. Ltd. (Shanghai, China). All other reagents were analytical  
2 reagents and obtained from commercial sources.

### 3 **2.2. Preparation of MNPs**

4 The procedure for the preparation of MNPs is based on the conventional  
5 co-precipitation method with some modifications. In a typical experiment, 0.9 g  
6  $\text{FeCl}_2 \cdot 4\text{H}_2\text{O}$  and 2.43 g  $\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$  were dissolved in 300 mL deionized water under  
7 nitrogen at room temperature; then the pH of the solution was kept at 9.5 using 25%  
8 ammonia solution with vigorous stirring. After 1 hour, the magnetite precipitates were  
9 collected by external magnetic force and washed three times with deionized water.  
10 The precipitate was dispersed in Tris-HCl buffer (10mM, pH 8.5) to 2.7 mg MNPs per  
11 milliliter of solution.

### 12 **2.3. Preparation of PD-MNPs**

13 Firstly, the MNPs suspension prepared as described above was ultrasonicated  
14 for 20 minutes before dopamine hydrochloride (37.5 mg, 2.5 mg/mL) was added to  
15 the MNPs suspension. Then the pH of the solution was adjusted to 8.5 by addition of  
16 100 mM NaOH. After vigorous stirring for 1 hour, the PD-MNPs was separated by  
17 external magnetic field and washed three times with deionized water and then  
18 dispersed in deionized water to 4.2 mg PD-MNPs per milliliter solution.

### 19 **2.4. Immobilization of *Aspergillus niger* lipase on the PD-MNPs**

20 Before immobilization, the PD-MNPs solution was ultrasonicated for 10 minutes.  
21 In order to immobilize *Aspergillus niger* lipase (ANL), the suspension of PD-MNPs

1 was added to a buffered lipase solution. An aqueous solution of ANL (1.5 mg/mL)  
2 was prepared by dissolving the ANL powder in sodium phosphate (50mM, pH 8.0)  
3 solution. The freshly prepared PD-MNPs solution (2 mL, 4.2 mg/mL) was added to  
4 the ANL solution (1 mL, 1.5 mg/mL) at 0°C in an ice bath. After stirring at 100 rpm  
5 for 12 h (at 0°C), the ANL-loaded precipitates were washed and collected with  
6 deionized water. Then, the concentration of the residual ANL in the solution and the  
7 concentration of ANL in the washings were determined by the Bradford method [18].  
8 The amount of ANL in the prepared ANL@PD-MNPs was calculated using the  
9 following equation:

10 
$$\text{amount of ANL on ANL@PD-MNPs} = m - C_1 V_1 - C_2 V_2$$

11 where  $m$  (mg) represents the mass of ANL initially added to the solution,  $C_1$   
12 (mg/ml) represents the residual ANL concentration of the solution,  $V_1$ (ml) represents  
13 the volume of the solution,  $C_2$  (mg/ml) represents the ANL concentration of the  
14 washings,  $V_2$  (ml) represents the volume of the washings. Finally the  
15 ANL@PD-MNPs was stored at 4°C prior to use.

16 **2.5. Activity assay of free ANL or ANL@PD-MNPs**

17 The enzymatic activities of free and immobilized lipase were measured by the  
18 *para*-nitrophenyl palmitate (*p*NPP) assay[19]. The basis of this assay protocol is the  
19 colorimetric estimation of *para*-nitrophenol (*p*NP) released as a result of enzymatic  
20 hydrolysis of *p*NPP at 405 nm. In brief, a given amount of free lipase or immobilized  
21 lipase was dispersed in 0.6 mL of sodium phosphate (50 mM, pH 7.0) solution and



1 subsequently mixed with 0.1 mL of 140mM *para*-nitrophenyl palmitate (in  
2 isopropanol) as the substrate. After 5 minutes of incubation at 35°C with shaking at  
3 100 rpm, the enzymatic reaction was terminated by the addition of 5.3 mL of ethanol  
4 and the free *para*-nitrophenol was detected spectrophotometrically at 405 nm. One  
5 unit (U) of lipase activity was defined as the amount of lipase which liberated 1  $\mu$ mol  
6 of *para*-nitrophenol per minute under the assay conditions. The activity recovery of  
7 the immobilized enzyme was calculated as the ratio of immobilized lipase activity to  
8 that of the amount of lipase added initially.

## 9 **2.6. Characteristics of free ANL and ANL@PD-MNPs**

10 In order to study the optimal pH and temperature of both free and immobilized  
11 lipases, the activities were measured over the pH range from 5 to 10 and the  
12 temperature range from 20°C to 80°C.

13 The Michaelis-Menten constant ( $K_m$ ) and the maximum reaction rate ( $V_{max}$ ) of  
14 both free and immobilized lipases, as well as the reusability of the immobilized lipase,  
15 were determined as described previously[20]. In order to assay the kinetic parameters  
16 of free and immobilized lipases, the enzymatic hydrolysis of *p*NPP was used as the  
17 model reaction. The initial reaction rates were determined under optimum reaction  
18 conditions (0.063U of enzyme per mL, 35°C, pH 7.0 for the free enzyme or 40°C, pH  
19 8.0 for the immobilized enzyme). The substrate concentrations was varied from 20 to  
20 180 mM. The Michaelis-Menten equation was used to fit the data (initial reaction rate  
21 vs. substrate concentration), and the kinetic parameters ( $K_m$  and  $V_{max}$ ) of *p*NPP

1 hydrolysis with free or immobilized lipase were obtained from the fit.

2 To determine the pH stability and thermostability of the enzyme,  
3 lipase-immobilized-PD-MNPs containing 20 µg lipase or 20 µg free lipase were  
4 incubated in sodium phosphate buffer (50 mM) adjusted to various pH values (pH  
5 6-10 at 40°C) and various temperatures (40-80°C, pH 7). The incubation times to test  
6 the stability of the enzyme were 12 h and 8 h for the pH stability and thermostability,  
7 respectively. The residual activity of both free and immobilized lipases was  
8 determined as above.

9 To investigate the solvent tolerance of the free and immobilized enzymes, lipase  
10 immobilized on MNPs containing 50 U lipase or 50 U free lipase were incubated in 3  
11 mL of solvent (acetonitrile, DMSO, ethanol or [HMIm]BF<sub>4</sub>) at 30°C for 6 h and the  
12 residual activity of the enzyme was assayed via the method described above.

### 13 **2.7. Secondary structure analysis of free ANL and ANL@PD-MNPs by infrared** 14 **spectroscopy**

15 The IR spectra of free ANL and ANL@PD-MNPs were obtained through the  
16 same method described before. FTIR spectra were detected from 4000 to 400 cm<sup>-1</sup>  
17 with powder samples dispersed in the pressed KBr discs using a Tensor 37  
18 spectrometer (Bruker, Germany) equipped with a deuterated triglycine sulfate (DTGS)  
19 detector. This equipment system was managed by Bruker OPUS software. Besides,  
20 subtraction of residual vapour absorption was also performed as necessary. And the the  
21 background spectra were recorded in absence of the enzyme. The enzyme spectras

1 were corrected by subtraction of the background spectra. Curve fitting of the amide I  
2 region (1600 to 1700  $\text{cm}^{-1}$ ), were smoothed with a 13-point Savitzky-Golay and  
3 identified using the secondary derivative. Then, a multipeak fitting program with  
4 Gaussian function in PeakFit 4.2 software (Jandel Scientific) was used to quantitatively  
5 evaluate the multicomponent peak areas in protein amide I bands. The relative contents  
6 of  $\alpha$ -helix structure (1650  $\text{cm}^{-1}$ -1658  $\text{cm}^{-1}$ ),  $\beta$ -sheet structure (1610 $\text{cm}^{-1}$ -1640  $\text{cm}^{-1}$ ),  
7 random coil structure (1640  $\text{cm}^{-1}$ -1650  $\text{cm}^{-1}$ ), and  $\beta$ -turn structure (1660 $\text{cm}^{-1}$ -1700  $\text{cm}^{-1}$ )  
8 based on the multicomponent peak area were calculated according to the previous  
9 literature by the software[21].

## 10 **2.8. Application of ANL@PD-MNPs to the regioselective acylation of DMY**

11 During the regioselective acylation process of DMY, 60 U of free ANL or  
12 ANL@PD-MNPs was added to 2 mL of DMSO, followed by the addition of DMY  
13 and vinyl acetate to the final concentrations of 0.04 mM and 0.4 mM, respectively.  
14 The mixture was incubated 35°C in an orbital shaking water bath (200 rpm) for up to  
15 48 h. Aliquots were withdrawn at specified time intervals. The reaction mixtures were  
16 analyzed by RP-HPLC on a 4.6 mm  $\times$  250 mm (5  $\mu\text{m}$  coating thickness) Zorbax  
17 SB-C18 column (Agilent Technology Industries Co., Ltd.) using a Waters HPLC  
18 system consisting of two Waters 1525 pumps and a Waters 2489 UV detector set at  
19 294 nm. Elution was performed with a gradient system comprising 0.1% acetic acid  
20 and 100% methanol as solvents A and B, respectively. Elution began with 28%  
21 solvent B, which was increased to 30% between 0 and 6 min, and then to 80%

1 between 6 and 12 min, and finally returned 28% between 12 and 13 min. The peak of  
2 DMY (which eluted at 6.68 min) was detected by HPLC. The conversion (C) of DMY  
3 was calculated as per formula (1):

$$4 \qquad C (\%) = \frac{C_0 - C_s}{C_0} \times 100 \qquad (1)$$

5 where  $C_0$  and  $C_s$  were the initial and terminal concentration of DMY, respectively.

6 To study the effect of the molar ratio of vinyl acetate to DMY on the reaction,  
7 acylation reactions were conducted in 2 ml DMSO with the addition of 60 U free  
8 ANL or ANL@PD-MNPs, while the molar ratio of vinyl acetate to DMY was varied  
9 from 2.5 to 25. To investigate the effect of temperature on the reaction, acylation  
10 reactions were conducted under the same conditions as above except that the molar  
11 ratio of vinyl acetate to DMY was fixed at 1 to 10 (0.04 mM DMY and 0.4 mM vinyl  
12 acetate) while the reaction temperature was varied between 30 and 50 °C. To study the  
13 effect of enzyme concentration on the reaction, acylation experiments were conducted  
14 under the same conditions as above except that the temperature was fixed at 45 °C,  
15 the molar ratio of DMY to vinyl acetate was fixed at 1 to 10 (0.04 mM DMY and 0.4  
16 mM vinyl acetate), while the amount of enzyme was varied from 10 U to 100 U.

17 The operational stability of immobilized lipase during the regioselective acylation  
18 process of DMY was studied under the same conditions as described in the previous  
19 section. After each enzyme run, the ANL@PD-MNPs were magnetically isolated and  
20 washed with hexane and ultrapure water to remove any remaining substrate and  
21 product species before the next experiment. The residual activity of the immobilized  
22 lipase after each cycle was expressed as a percentage of the activity at the beginning of

the experiment.

All data reported in this study were averages of experiments performed at least in triplicate, with no more than 3.0% experimental error.

### **3. Results and Discussion**

#### **3.1. Synthesis and analysis of MNPs and PD-MNPs**

TEM images of MNPs and PD-MNPs are shown in Fig. 1. MNPs were spherical shape with the average diameter of 10 nm (Fig. 1A). The fact that the MNPs were aggregated was consistent with their having a large specific surface area and high surface energy. After coating with polydopamine (polymerization time 1 h), it could be clearly observed that the dark MNPs were uniformly encapsulated in light gray polydopamine layer (Fig. 1B). The MNPs showed a tendency to aggregate due to the interaction between polydopamine and MNPs. The average thickness of the polydopamine coating around the edge of the MNP aggregates in the hybrid material was about 4 nm. Fig. 1C showed the TEM image of ANL@PD-MNPs. The mean size of the aggregates of PD-MNPs with immobilized lipase is about 25 nm, which is obviously larger than that of PD-MNPs without the enzyme. Furthermore, the size of MNPs, PD-MNPs and ANL@PD-MNPs was evaluated by dynamic light scattering (DLS). The size distribution was clearly depicted in Figure 1, and the mean sizes of MNPs, PD-MNPs and ANL@PD-MNPs were 9.6, 13.8 and 26.1 nm respectively, which were consistent with those in the TEM images.

XPS was applied to investigate the chemical elements on surface of MNPs and

1 PD-MNPs. The energy scale was calibrated with the C1s peak of carbon (284.8 eV).  
2 Wide-scan XPS spectra for MNPs and PD-MNPs are shown in Figure S1A and Figure  
3 S1B of the Supporting information, respectively. The characteristic peaks of Fe2p (Fe  
4 2p<sub>1/2</sub> 724.38 eV, Fe 2p<sub>3/2</sub> 710.58 eV ) and O1s (530.08 eV) appeared in the spectrum  
5 due to Fe<sub>3</sub>O<sub>4</sub>, and the weak peak of C1s was attributed to the presence of impurities[22].  
6 After the MNPs were coated with polydopamine, the peak of C1s enhanced  
7 significantly (boxed in red in Figure S1B of the Supporting Information), and that of  
8 O1s shrank somewhat due to the high content of carbon and low content of oxygen in  
9 polydopamine. Meanwhile, the appearance of the characteristic N1s weak peaks at  
10 expected positions 399.08 eV (also boxed in red in Figure S1B of the Supporting  
11 Information) confirmed the presence of nitrogen contained within the polydopamine.  
12 The data in Figure S1B indicate that the PD-MNPs exhibited an N/C ratio of 0.106,  
13 which is close to the N/C ratio of 0.125 (dopamine). Figure S1C and Figure S1D show  
14 high-resolution scan spectra of the C1s and N1s regions, respectively, of PD-MNPs  
15 after XPS peak-differentiating and imitating. The C1s peak contains C–C (284.8 eV),  
16 C–N (285.8 eV), C–O (286.3eV) and C=O (287.8eV) peaks and the N1s region is  
17 made up of N–H (398.7 eV) and –N= (399.7 eV) peaks, which are in accordance with  
18 the previously published XPS results of polydopamine[23]. Taken together, the XPS  
19 results demonstrated that MNPs were successfully covered by polydopamine.

20 The FTIR spectra displayed in Fig. 2 were recorded to confirm the chemical  
21 composition of the PD-MNPs. A strong peak appearing at around 580 cm<sup>-1</sup> and a weak

one at approximately  $436\text{ cm}^{-1}$  in the spectra of both the MNPs and PD-MNPs (spectra a and b, respectively in Fig. 2) were related to the vibration of the Fe–O functional group. The relatively high intensity of the band at  $580\text{ cm}^{-1}$  indicated the high content of  $\text{Fe}_3\text{O}_4$ [24]. Additionally, a weak band appearing at  $1255\text{ cm}^{-1}$  in spectrum b in Fig. 2 was attributed to the phenolic hydroxyl group stretching mode of polydopamine layer. For PD-MNPs, this signal appeared showing the interaction between hydroxyl and aromatic rings. The vibrational signals at  $1610$  and  $1490\text{ cm}^{-1}$  were ascribed to C=C in aromatic rings. The peak at  $1428\text{ cm}^{-1}$  of PD-MNPs (b) was broader than that of MNPs (a), which results from the overlapping of O=C-O symmetric vibration ( $1405\text{ cm}^{-1}$ ) and the indoline peak of polydopamine ( $1438\text{ cm}^{-1}$ ) [25].

Fig. 3a shows the XRD patterns of the MNPs. Similar to the previous report[26], the XRD pattern showed six diffraction peaks in the  $2\theta$  range of  $20^\circ$ – $70^\circ$ , including a high-intensity sharp peak at  $2\theta = 35.6^\circ$ , corresponding to the (3 1 1) plane, and five additional weak peaks at  $2\theta = 30.6^\circ$ ,  $43.4^\circ$ ,  $54.4^\circ$ ,  $56.7^\circ$  and  $62.7^\circ$ , corresponding to the (2 2 0), (4 0 0), (4 2 2), (4 1 1) and (4 4 0) planes, respectively, showing the presence of the magnetite crystal with a cubic spinal structure[27]. The unit cell of cubic spinal structure consists of eight ferric ions at tetrahedral sites each with four oxide ions nearest neighbors, and eight ferric ions and eight ferrous ions at octahedral sites each with six oxide ions as the nearest neighbors[28]. The XRD spectrum of the PD-MNPs (Fig. 3b) showed that the crystal structure of  $\text{Fe}_3\text{O}_4$  was maintained after the coating process. No obvious diffraction peak for the polydopamine was observed,

1 which may be due to the relatively thin layer and amorphous crystallinity of the  
2 polydopamine prepared under this polymerization method[29].

3 The polydopamine, MNPs and PD-MNPs were analyzed via TGA analysis in a  
4 nitrogen atmosphere with a heating rate of 10 °C /min. Figure S2 of the Supporting  
5 Information illustrates the TGA curves, depicting the variations of the residual masses  
6 of the samples with temperature. The first weight loss stage (below 130 °C) in the  
7 polydopamine sample (Figure S2A(a)) can be ascribed to the evaporation of water  
8 molecules in the polymer matrix while the other stage of weight loss, beginning at  
9 about 190 °C, was due to the decomposition of polydopamine. As the polydopamine  
10 (PD) content of the materials increased (Figure S2A(c-e)), the proportion of the mass  
11 lost due to thermal decomposition of the PD increased also. As shown in Figure S2B,  
12 when the concentration of dopamine hydrochloride is up to 4mg/mL, the weight loss  
13 of the PD-MNPs upon heating was 24.4%.

14 The PD-MNPs could be separated and purified from the solvent by using a magnet  
15 (Figure S3A of the Supporting Information). Vibrating specimen magnetometer (VSM)  
16 magnetization curves of MNPs and PD-MNPs (Figure S3B) indicated no remanence or  
17 coercivity, suggesting that MNPs and PD-MNPs behaved in a superparamagnetic  
18 fashion. Saturation magnetization is defined as the maximum magnetic response of  
19 materials attained under an external magnetic field, which can be seen as a value to  
20 estimate the magnetism of materials[30, 31]. Consistent with their superparamagnetic  
21 behavior, the MNPs and PD-MNPs showed high saturation magnetization of 60.1 and



1 52.7 emu/g, respectively. The lower saturation magnetization of PD-MNPs compared  
2 with the MNPs is consistent with their lower proportion of magnetic material due to the  
3 presence of the polydopamine coating. Nonetheless, the magnetic properties of  
4 PD-MNPs are sufficient to provide an easy and effective way to isolate them from a  
5 liquid reaction system.

### 6 **3.2. Immobilization of free ANL onto PD-MNPs**

7 During the immobilization process, the activity recovery and the protein loading  
8 were found to be affected by pH and immobilization time. Therefore, these two  
9 factors were varied in order to maximize immobilization capacity and enzyme activity.  
10 As the pH was increased from 6 to 9, the amount of lipase that immobilized onto the  
11 PD-MNP support increased from 26.3 mg/g of PD-MNP to 138.1 mg/g of PD-MNP.  
12 The proportion of the enzyme activity remaining after immobilization dropped off  
13 above pH 8 (Fig. 4A). Hence, under the conditions tested pH 8 appears optimal for  
14 immobilization of the enzyme because, whilst protein immobilization continue to  
15 become more effective with increasing pH beyond this, the enzyme begins to become  
16 inactivated. Immobilization time also influenced the properties of the immobilized  
17 biocatalyst. As the immobilization time was increased, the amount of enzyme that  
18 loaded onto the PD-MNPs and the proportion of activity remaining after  
19 immobilization showed maximum values after 12 h of immobilization, with 138mg/g  
20 of enzyme immobilized and 83.6% retention of activity (Fig.4B).The decrease in  
21 retention of activity after longer immobilization time may be related to steric

1 hindrance of substrate access to the enzyme at high enzyme loading onto the solid  
2 support [32].

### 3 **3.3. Characteristics of free ANL and ANL@PD-MNPs**

4 Immobilization resulted in a change in the pH activity profile of the lipase (Fig.  
5 5A), such that the range over which the lipases retained more than 85% of enzyme  
6 activity was widened slightly from pH 7 to 8 for the free ANL to pH 7 to 8.5 for the  
7 ANL@PD-MNPs, and the optimum pH shifted from pH 7 to 8 upon immobilization.  
8 The interactions between the enzyme and the polymeric matrix, such as hydrogen  
9 bonding and electrostatic interactions, may explain the observed alkaline shift and  
10 broadening in the pH profile of the immobilized lipase[33]. Similar results upon  
11 immobilization of lipase and other enzymes have been reported previously [34]. In  
12 particular, compared with free ANL, ANL@PD-MNPs exhibited a considerably  
13 higher relative activity at pH 10 (64.3% of the maximum activity), while its free  
14 counterpart merely had 24.6% of the maximum activity at this pH. Hence, the  
15 ANL@PD-MNPs exhibited improved activity across a wider a pH range especially in  
16 weakly alkaline media.

17 Fig.5B shows the effect of temperature on the activity of free ANL and  
18 ANL@PD-MNPs. The activity obtained in a temperature range of 20-80°C were  
19 expressed as percentage of the maximum activity recorded at 35°C and 40°C for both  
20 free ANL and ANL@PD-MNPs, respectively (i.e. as a percentage of the activity at the  
21 optimum temperature for each form of the enzyme). Above 50°C, the relative activity

1 of free ANL dropped sharply and it retained only 26.7% at 80°C. In contrast,  
2 ANL@PD-MNPs retained about 54.4% of the relative activity at 80°C. The increase in  
3 the optimum temperature of the immobilized enzyme might result from the changing  
4 conformational integrity of the lipase structure by covalent bond formation between  
5 the enzyme and solid support via amino groups. During the immobilization process, if  
6 the flexibility of the enzyme molecules is decreased, the enzyme may require a higher  
7 activation energy to reorganize to the appropriate conformation for catalysis[35].  
8 ANL@PD-MNPs showed enhanced heat resistance at high temperature (>70 °C),  
9 possibly because of restricted conformational mobility of the molecules which may  
10 protect against thermal denaturation[36]. Therefore, the ANL@PD-MNPs was higher  
11 than its free counterpart under high temperatures. Similar observations of improved  
12 activity at high temperatures after enzyme immobilization have also been  
13 observed[37].

14 In order to study the pH-stability of the free ANL and ANL@PD-MNPs over a  
15 period of time, the enzyme was incubated at 40 °C for 12 h in phosphate buffer (50 mM,  
16 pH varied over the range 6–10) (Fig. 6A). The ANL@PD-MNPs retained 49.1% of its  
17 initial activity after 12 h incubation at pH 10 (Fig. 6A), while the final activity of the  
18 free ANL was only about 22.9 % of the initial value (Fig. 6A), indicating that the  
19 ANL@PD-MNPs exhibited enhanced pH stability.

20 The thermal stability of free ANL and ANL@PD-MNPs were investigated as a  
21 function of time at different temperatures between 40°C and 80°C. As seen in Fig.6B,

1 the ANL@PD-MNPs retained more than 83.5% of its initial activity after incubation  
2 for 8 h at 40 °C, while less than 71% of residual activity was detected with the free ANL  
3 after the same treatment. As mentioned above, the conformational rigidity of lipase  
4 may have been strengthened by immobilization, thus enhancing its thermal stability.

5 Both free ANL and ANL@PD-MNPs were stored at 4 °C in pH=7 phosphate  
6 buffer for 20 days in order to investigate the enzymatic storage stability. Compared to  
7 the free ANL, the ANL@PD-MNPs exhibited excellent retention of activity under  
8 these conditions, as can clearly be seen by the fact that after 20 days of storage the  
9 ANL@PD-MNPs retained 92.8% of its original activity, while the free counterpart  
10 retained only 21.5% under the same conditions (Fig.6C).

11 Compared with the free ANL, the ANL@PD-MNPs exhibited significantly better  
12 tolerance to all four solvents tested (Fig.6D). The difference in retention of activity  
13 between the free ANL and ANL@PD-MNPs increased with overall degree of  
14 inhibition caused by the solvent during the 6 h incubation period at 40°C. Hence, the  
15 least inhibitory solvent ethanol permitted retention of 90.48% and 81.30% of the initial  
16 activity by the free ANL and ANL@PD-MNPs, respectively. In contrast after exposure  
17 to the most inhibitory solvent (the ionic liquid [HMIm]BF<sub>4</sub>), the ANL@PD-MNPs  
18 retained 63.19% of its initial activity, whereas the free ANL retained only 35.79% of its  
19 initial activity. Owing to immobilization, the ANL@PD-MNPs maintained its  
20 catalytic conformation and exhibited more structural rigidity, resulting in enhanced  
21 solvent tolerance, which is similar in the previous reports[38].

1       The kinetic behavior of free ANL and ANL@PD-MNPs catalyzing *p*NPP  
2       hydrolysis were investigated and both reactions were found to follow  
3       Michaelis–Menten kinetics (Figure S4).  $K_m$  for free and immobilized lipases were 74.5  
4       and 63.2 mmol/L, respectively, which demonstrated that the immobilized lipase had  
5       moderately enhanced enzyme–substrate affinity[39]. The  $V_{max}$  for ANL@PD-MNPs  
6       and the free ANL were  $2.36 \times 10^{-2} \text{ m mol L}^{-1} \text{ min}^{-1}$  and  $3.03 \times 10^{-2} \text{ m mol L}^{-1} \text{ min}^{-1}$ ,  
7       indicating a rather lower maximal rate for the ANL@PD-MNPs compared with the  
8       free ANL. This was consistent with the fact that the specific activity of  
9       ANL@PD-MNPs was lower than that of the free ANL (1.58 vs. 2.11 U per mg).

10       The deconvolution of the amide I band from the FTIR spectrum of the free lipase  
11       (Figure S5A) has several distinct Lorentzian peaks. The band at  $1628.41 \text{ cm}^{-1}$  can  
12       tentatively be assigned to  $\beta$ -sheet structure[40]. Following this assignment and  
13       according to deconvolution results, the  $\beta$ -sheets contribution constitutes 26.15% of the  
14       secondary structures in free lipase. The band around  $1656.24 \text{ cm}^{-1}$  is characteristic of  
15       an  $\alpha$ -helical structure, and the area of this component accounts for 26.14% of the total  
16       band area in free lipase. The random coil (about 30%) and  $\beta$ -turns (about %) contribute  
17       to the bands at  $1646.74$  and  $1679.74 \text{ cm}^{-1}$ , respectively, in the free lipase[41]. In the  
18       immobilized lipase (Figure S5B), the Lorentzian bands of the deconvoluted amide I  
19       region around  $1621.04$  and  $1634.83 \text{ cm}^{-1}$  indicate 26.99% of the structure as  $\beta$ -sheets  
20       (26.99%) and the band at  $1657.80 \text{ cm}^{-1}$  suggests an  $\alpha$ -helix content of 28.88%. This  
21       suggests an increase of  $\beta$ -sheet and  $\alpha$ -helix content upon lipase immobilization of 2.74

and 0.84 percentage points, respectively (Table 1). The existence of hydrogen bonds within secondary structure elements such as  $\beta$ -sheet and  $\alpha$ -helix generally helps to maintain protein structure[42, 43], which may be one of the reasons why the immobilized lipase exhibited enhanced stability and improved tolerance to organic solvents and ionic liquid[44].

### **3.4. Application of the ANL@PD-MNPs to the regioselective acylation of DMY**

As shown in Fig.7A, when the ANL@PD-MNPs was used as the biocatalyst for acylation of DMY, the time course for the regioselective acylation reaction was similar to that catalyzed by an equal number of units of the free enzyme. The final conversion was 79.28% at 48 h with the immobilized enzyme as biocatalyst and 69.47% with the free enzyme. The greater conversion with the immobilized lipase could be explained by the better organic solvent tolerance of the immobilized enzyme.

As seen in Fig.7B, the molar ratio of substrates strongly affected the conversion rate of enzymatic DMY acylation. With the increase of the molar ratio between vinyl acetate and DMY from 2.5 to 10, the conversion rate increased sharply from 16.1% to 65.3% ( free ANL) and 20.3% to 70.6% (ANL@PD-MNPs ). However, the conversion obtain from free enzyme retain at about 70% while the molar ratio increased from 10 to 25. Thus, the molar ratio of vinyl acetate to DMY was selected at 10 for both free ANL and ANL@PD-MNPs in the following experiment.

Temperature is a key parameter in the enzymatic acylation of DMY. With temperature increased from 30 to 45°C, the conversion rate increased from 40.3% to

1 67.1% (free ANL) and 69.6% to 79.1% (ANL@PD-MNPs) respectively (Fig.7C).

2 Further increase in temperature had nearly no effect on the conversion rate. So the  
3 suitable temperature would be 45°C in the following experiment.

4 Also, enzyme concentration had a significant effect on the conversion yield. As  
5 shown in Fig.7D, when the amount of enzyme in the reaction mixture was increased  
6 from 10U to 40U, the conversion rate increased obviously for both free ANL (40.1%  
7 to 50.4%) and ANL@PD-MNPs (65.3% to 78.7%). However, further increase in  
8 ANL@PD-MNPs concentration had little effect on the conversion yield and the  
9 conversion rate retained 78%, indicating that the enzyme was saturated at 40 U in the  
10 reaction. In contrast, free ANL was saturated at 80U and the corresponding conversion  
11 rate was 65% , which manifested the ANL@PD-MNPs have better catalytic capacity  
12 than free ANL.

13 Since the ANL@PD-MNPs could easily be isolated from the reaction system in an  
14 external magnetic field, its operational stability was investigated during ten cycles of  
15 re-use (Fig. 8). The ANL@PD-MNPs retained more than 90% of its original catalytic  
16 activity in the regioselective acylation of DMY after four consecutive reaction cycles  
17 and 56% of the initial activity after ten cycles of reuse. This result strongly suggests that  
18 the ANL@PD-MNPs is applicable to repeated use as a biocatalyst.

#### 19 **4. Conclusion**

20 MNPs were successfully modified via a mussel-inspired polydopamine coating  
21 and characterized in terms of their morphology, composition, structure and magnetic

properties. The PD-MNPs proved to be suitable for ANL immobilization with high protein loading and good activity recovery. The prepared ANL@PD-MNPs manifested improved pH, thermal, solvent and storage stabilities compared with its free counterpart. Kinetic study of both immobilized and free enzymes showed that ANL@PD-MNPs had high catalytic efficiency. Significantly, the as-prepared ANL@PD-MNPs exhibited excellent reusability with over 55% of its initial activity after 10 cycles of consecutive reuse during the regioselective acylation process of DMY as well as the facility for convenient magnetic recovery of the biocatalyst.

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## Figure Captions

**Figure 1** TEM images and size distribution of MNPs (A), PD-MNPs (B) and ANL@PD-MNPs (C). The polymerization time for the PD-MNPs was 1 h.

**Figure 2** FTIR spectra for MNPs (a) and PD-MNPs (b).

**Figure 3** XRD patterns of the MNPs and PD-MNPs (2.5 mg/mL dopamine hydrochloride).

**Figure 4** Effects of immobilization conditions on the activity recovery and the protein loading. (A) Effect of pH ( 1.5 mg lipase, .3 mg PD-MNPs, 2.5mg/mL dopamine hydrochloride, polymerization time 1h; immobilization time 9 h ); (B) Effect of immobilization time (1.5 mg lipase, .3 mg PD-MNPs, 2.5mg/mL dopamine hydrochloride, polymerization time 1h; pH .0 ).

**Figure 5** Optimal pH and temperature of ANL@PD-MNPs and free lipase.

**Figure 6** Stabilities of ANL@PD-MNPs and free lipase. (A) pH stability; (B) Thermal stability; (C) Storage stability; (D) Solvent tolerance

**Figure 7** (A) The time course in enzymatic regioselective acylation of DMY catalyzed by ANL@PD-MNPs and free lipase (2 mL DMSO, 0.04 mM DMY, 0.4 mM vinyl acetate, 35 °C, 200 rpm, 60U ANL@PD-MNPs or free ANL); (B) The effect of the molar ratio of substrates on the conversion yield (2 mL DMSO, 35 °C, 200 rpm, 60U ANL@PD-MNPs or free ANL); (C) The effect of the temperature on the conversion yield (2 mL DMSO, 0.04 mM DMY, 0.4 mM vinyl acetate , 200 rpm, 60U ANL@PD-MNPs or free ANL); (D) The effect of the enzyme concentration on the conversion yield (2 mL DMSO, 0.04 mM DMY, 0.4 mM vinyl acetate , 200 rpm, 45°C);

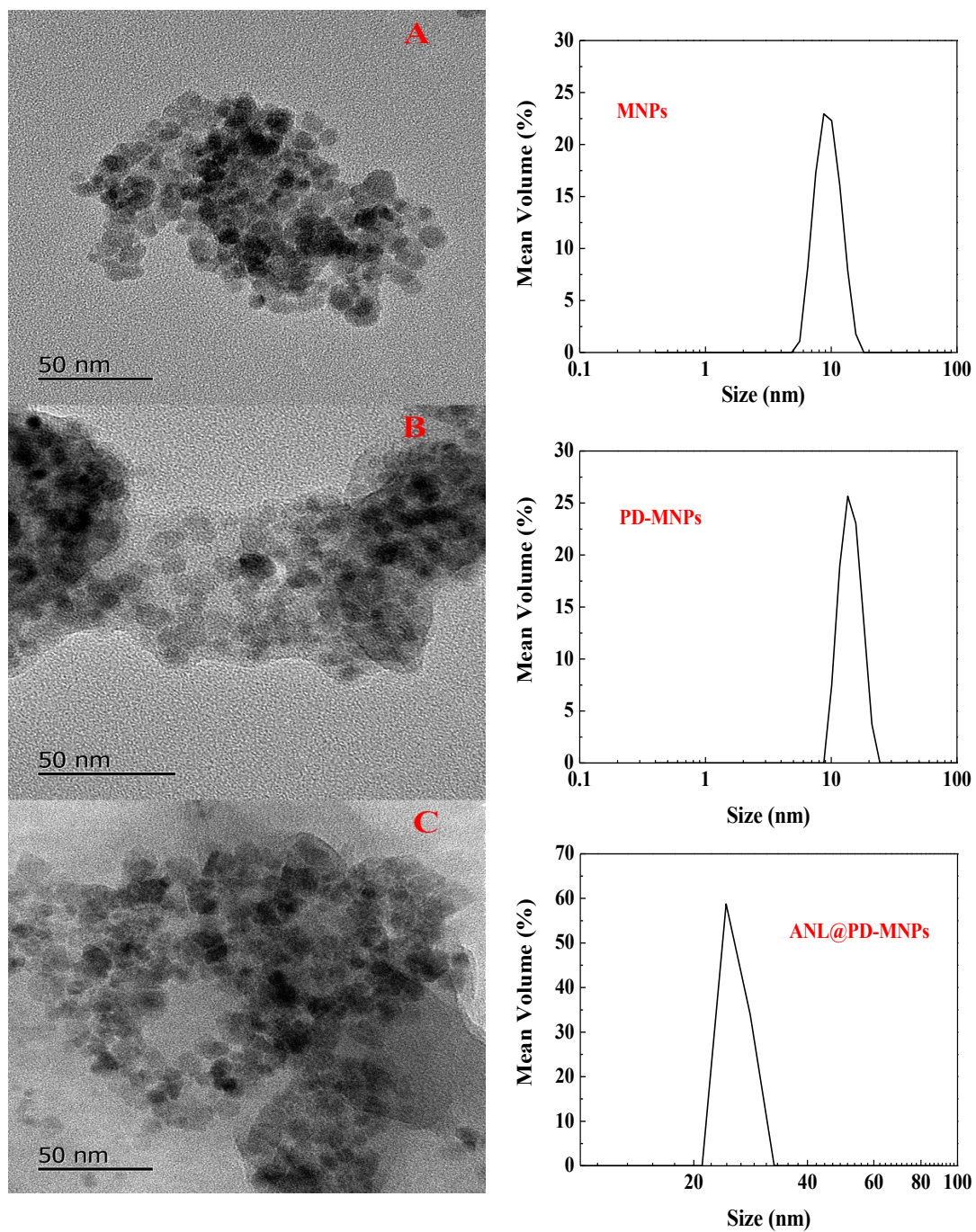
**Figure 8** The operational stability of ANL@PD-MNPs.

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**Table 1 Results of amide I band deconvolution for free lipase and ANL@PD-MNPs**

Sample	Secondary structure (%)			
	$\beta$ -sheet	$\alpha$ -helix	random coli	$\beta$ -turn
Free lipase	26.15	26.14	29.7	17.93
ANL@PD-MNPs	26.99	2.	27.46	16.67

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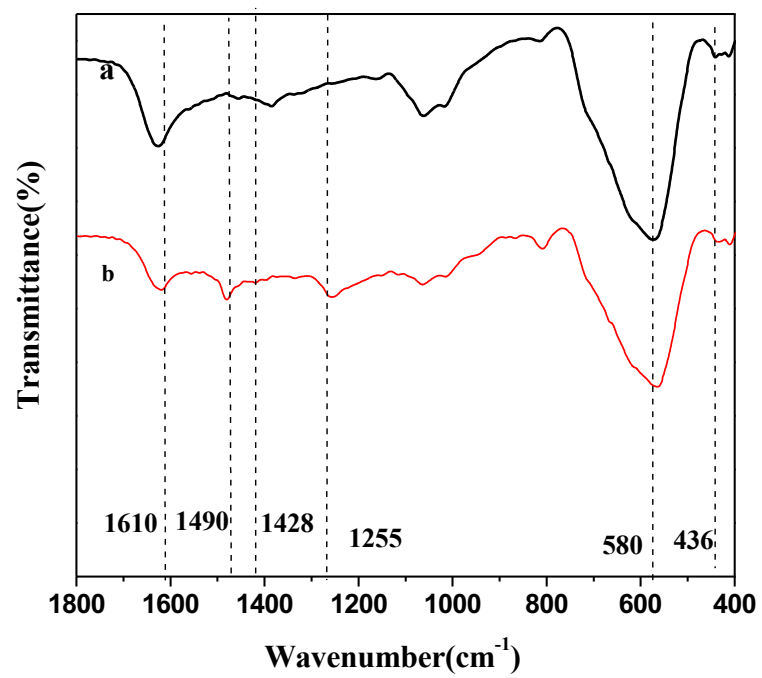
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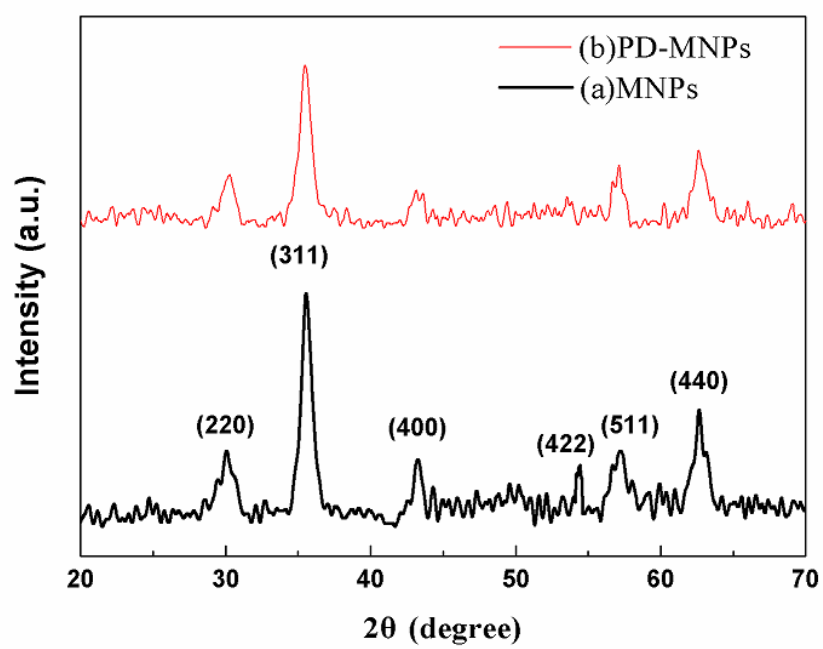
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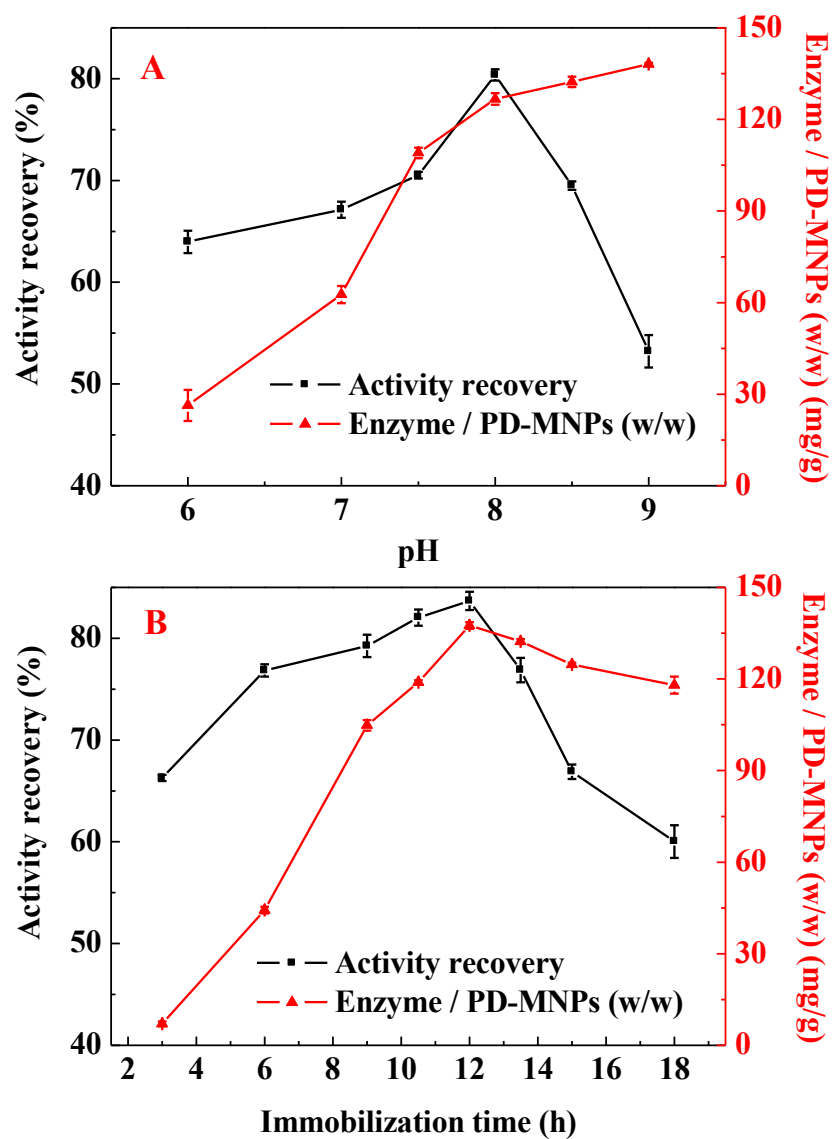
Deng X et al., Fig.1



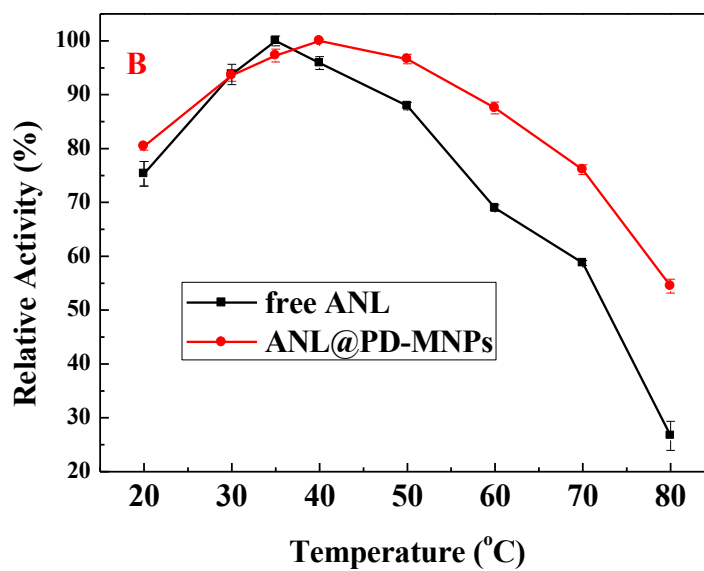
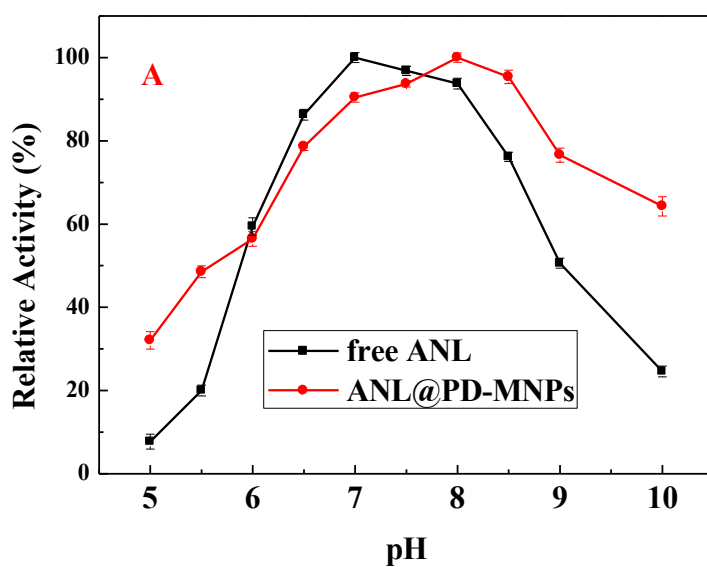
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Deng X et al., Fig.3.

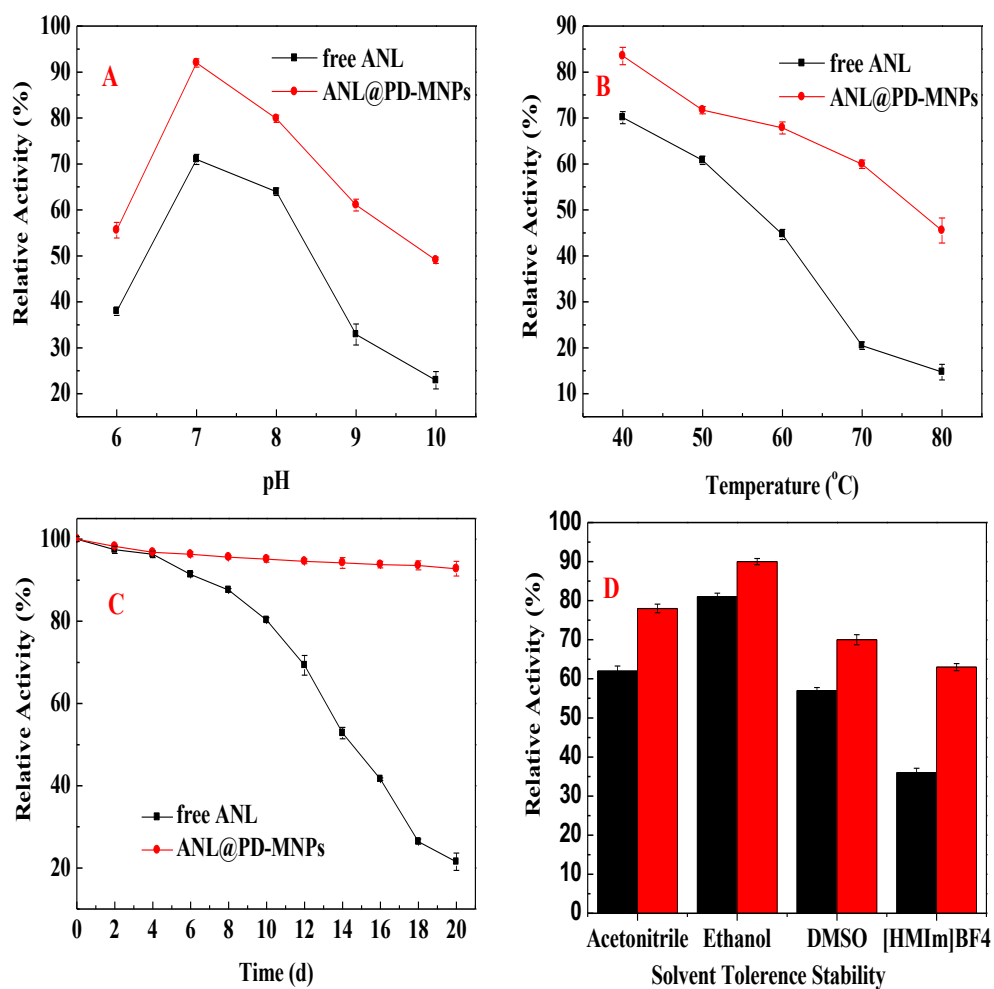


Deng X et al., Fig.4

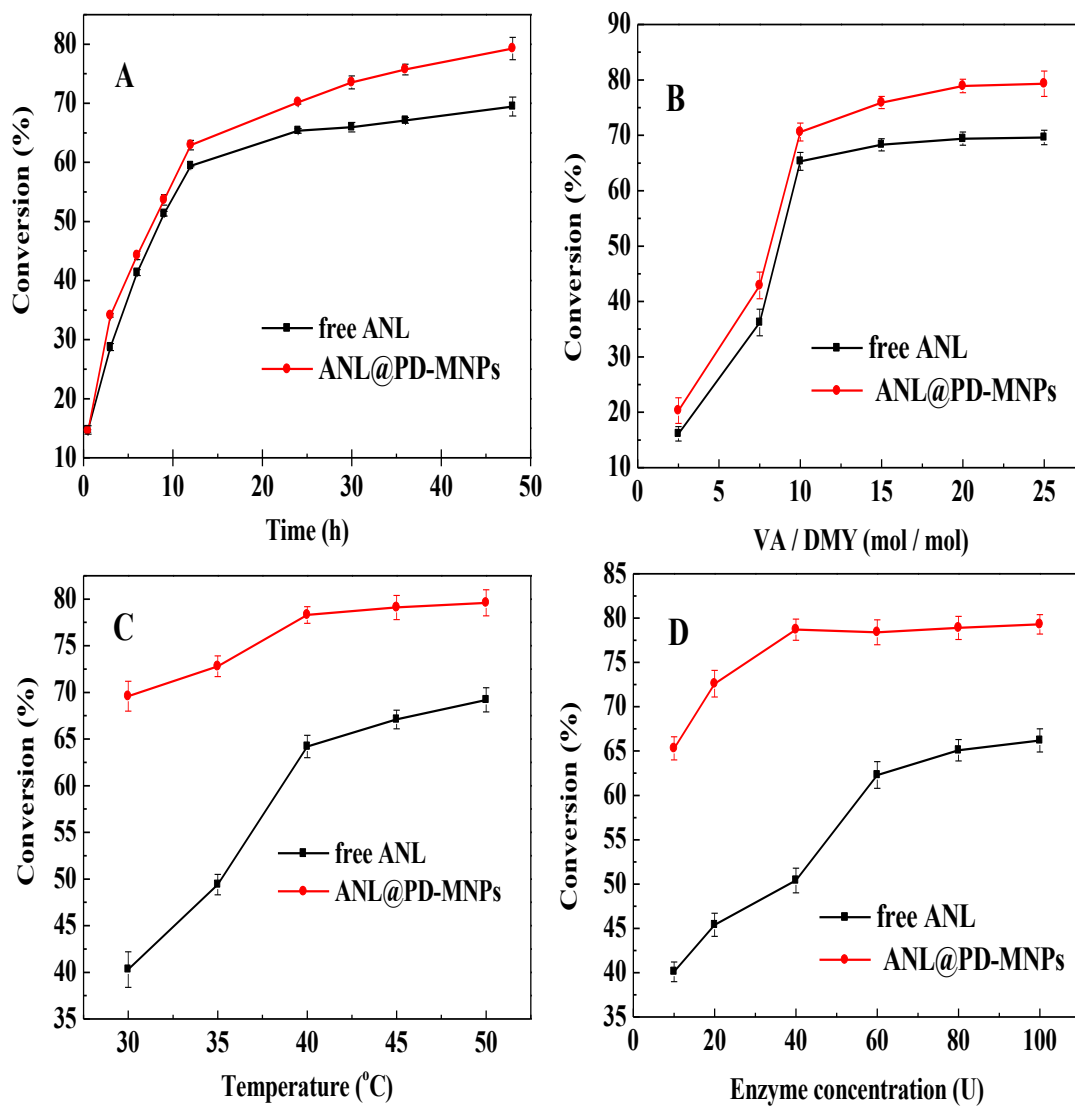


Deng X et al., Fig.5



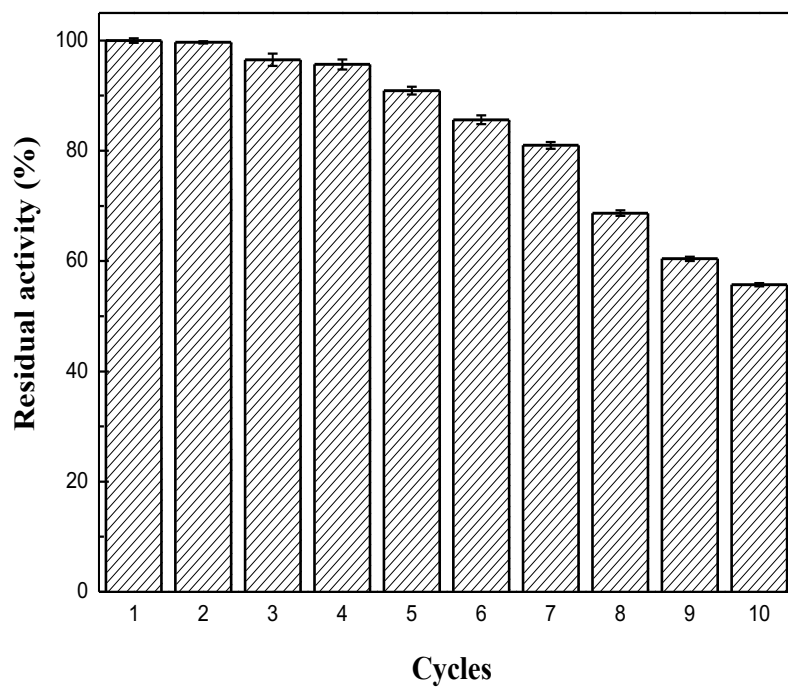


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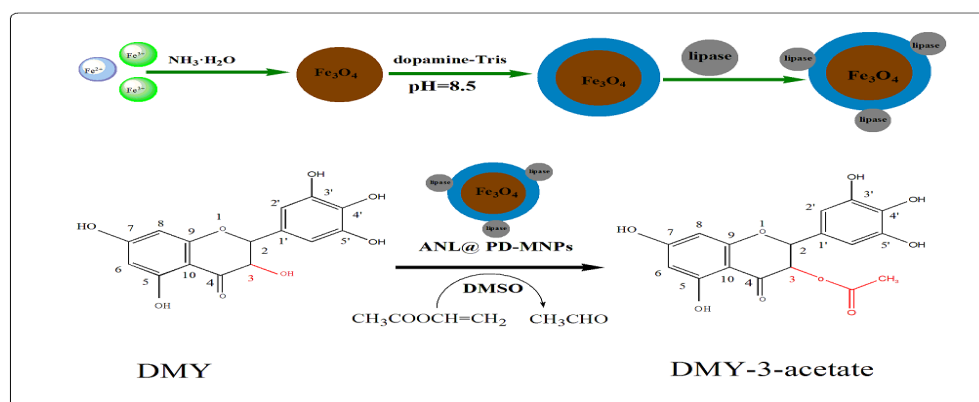


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## Graphical abstract



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