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Facile synthesis of magnetic layered double hydroxide/metal–organic framework MIL-100(Fe) for simultaneous extraction and enantiomeric determination of three chiral triazole fungicides in water and juice samples

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ABSTRACT

For the first time, magnetic layered double hydroxide/metal–organic framework (Fe₃O₄@CuZnAl-LDH@MIL-100(Fe)) was successfully fabricated and applied for enrichment of triazole fungicides from water and juice samples prior to chiral HPLC-UV analysis. Several key parameters influencing the extraction efficiency including extraction time, desorption time, sample solution pH, the ionic strength of sample solution, adsorbent amount, desorption volume, desorption solvent and sample volume were investigated by Plackett-Burman design and Box-Behnken design. Under the optimum conditions, the limit of detections (LODs) and limit of quantifications (LOQs) were in the ranges of 0.35 to 1.20 μ g L⁻¹ and from 1.00 to 3.80 μ g L⁻¹, respectively. The average spiked recoveries and enrichment factors ranged from 86.28-98.22 % and 21.6–23.8, respectively. The linearity was in the range of (5–1000 μ g L⁻¹) with satisfactory correlation coefficients (R²) values (0.9987–0.9999) and a good precision (RSDs \leq 5.74 %). Moreover, the computational simulation was first employed to analyze adsorption properties of MIL-100(Fe) against triazole fungicides. This work provides a promising method for trace chiral pesticide analysis in aqueous samples.

1. Introduction

Triazole fungicides are a group of pesticides with strong ability of agricultural pests control. The widespread usage of triazole fungicides led to their residues in water and fruits which can result in health risks to humans or other organisms [1]. Most of triazole fungicides are chiral compounds, and various chiral triazole fungicides have been produced and used as racemic mixtures [2]. Generally, the enantiomers of chiral triazole fungicides possess identical physicochemical properties, while they showed enantioselective biological behavior (e.g., biological activity, degradation and toxicity) in a chiral environment [3]. Therefore, it is essential to monitor chiral pesticides at the enantiomeric level. The key process in the enantioselective determination of chiral pesticides in the actual samples lies in the enantioseparation and sample pretreatment. Thus, developing a reliable analytical method to quantify triazole fungicides enantiomers in water and fruits is of great importance in guiding the reasonable application of chiral triazole fungicides.

Among various sample pre-treatment methods, magnetic solid-phase extraction (MSPE) has stimulated increasing research owing to its advantages such as rapid procedure and excellent extraction efficiency [4–7]. The core of MSPE is the design of magnetic adsorption materials with high extraction ability. To date, various nanomaterials have been developed as adsorbents for practical applications, such as metal--organic frameworks (MOFs), layered double hydroxides (LDHs), molecularly imprinted polymers (MIPs), covalent organic frameworks (COFs) and mesoporous carbon (MC) [8-11]. MOFs have received considerable attention due to the high stability, large surface area and good adsorption capacity towards compounds [12-14]. Besides the MOFs materials, LDHs were also exploited in adsorption applications since they have high anion substitution capacity and large specific surface area [15]. However, most of LDHs were applied in the dyes, metal ions and anions adsorption [16–19], the application in organic pollutants adsorption was limited.

The design of adsorbent that was composed of multi-type

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Fig. 1. (A) the schematic illustration of the synthesis for Fe₃O₄@CuZnAl-LDH@MIL-100(Fe); (B) the MSPE procedure for the determination of three chiral triazole fungicides in water and juice samples.

nanomaterials is an effective strategy for the adsorption and extraction of different analytes [20,21]. Considering that the adsorbents containing different types of nanomaterials not only improve the properties of adsorbents but also will be beneficial to apply in various practical fields, the design and exploration of LDHs/MOFs hybrid material would be promising for MSPE. To the best of our knowledge, the research on the LDHs/MOFs hybrid material for extraction application has been rare.

MIL-100(Fe), a kind of typical MOF, constructed by environmentally nontoxic transition metal and easily obtainable polycarboxylic acid linker, with low cost and water stability [22]. It has been widely applied in catalysis, biological probe, adsorption and separation [23–26]. However, its potential application in chiral pesticides adsorption and separation has not been investigated yet.

Hence, we focused on the synthesis of magnetic layered double hydroxide/metal-organic framework (Fe₃O₄@CuZnAl-LDH@MIL-100 (Fe)) for extracting three triazole fungicides including paclobutrazol, uniconazole and bromuconazole, and establishment of an efficacious method to simultaneously enantioseparate and analyze these three chiral triazole fungicides in water and fruit juices. The main parameters in extraction process were investigated by Plackett-Burman and Box-Behnken design. The possible adsorption mechanisms were systematically explored by adsorption kinetics, adsorption isotherms, and adsorption thermodynamics experiments. Furthermore, the molecular simulation technique was adopted to investigate the mechanism of adsorption procedure, which would provide a comprehensive vision to study the ligand-receptor interactions at atomic level. To our knowledge, this work is the first to concern the use of magnetic MIL-100(Fe) for adsorbing and extracting triazole fungicides. In addition, the molecular docking technology was applied for explaining the molecular interactions and the free binding energies between MIL-100(Fe) and triazole fungicides for the first time.

2. Experimental

2.1. Chemicals and materials

Racemic paclobutrazol (98 % purity) was obtained from Shanghai Yingxin laboratory equipment Co., Ltd (Shanghai, China). Racemic uniconazole (98.7 % purity) was purchased from the Shanghai Pesticide Research Institute (Shanghai, China). Racemic bromuconazole (98.3 % purity) was purchased from Dr. Ehrenstorfer, GmbH Company (Germany). Ultrapure water was obtained from Jilin Wahaha Foods Co., Ltd. (Jilin, China) and was used in all the experiments. Acetonitrile (ACN) of HPLC grade and all other reagents of analytical grade were obtained from Shandong Yuwang industrial Co., Ltd (Shandong, China). The stock standard solution of triazole fungicides (1.0 g L^{-1}) was prepared in HPLC-grade acetonitrile and stored at 4 °C.

2.2. Synthesis of Fe₃O₄@CuZnAl-LDH@MIL-100(Fe)

The preparation procedure for $Fe_3O_4@CuZnAl-LDH@MIL-100(Fe)$ was depicted in Fig. 1A. Fe_3O_4 nanoparticles were prepared according to the literature [27]. Then, $Fe_3O_4@CuZnAl-LDH$ were formed by coprecipitation method. Firstly, the prepared Fe_3O_4 microspheres (0.4 g) were dispersed into mixed solution of methanol (25 mL) and water (25 mL) for 10 min under ultrasound condition. A 50 mL salt solution (0.36 g $Cu(NO_3)_2 \cdot 3H_2O$, 0.45 g $Zn(NO_3)_2 \cdot 6H_2O$, 0.56 g $Al(NO_3)_3 \cdot 9H_2O$) was added dropwise to above mixture and another 50 mL alkaline solution (3 g NaOH, 2.65 g Na_2CO_3) was simultaneously added to maintain pH value of about 10. After 1 h of stirring at room temperature, the resultant was washed with deionized water and ethanol, then dried under vacuum at 70 $^\circ$ C. The final product was labelled as Fe_3O_4@CuZnAl-LDH with a yield of 97 %.

0.2 g of Fe₃O₄@CuZnAl-LDH was dispersed in 30 mL FeCl₃·6H₂O (0.24 g) ethanol solution and the mixture was heated at 120 °C for 15 min. The gotten material was washed with ethanol one time and further added to 30 mL 1,3,5-benzenetricarboxylic acid (H₃BTC, 0.25 g) ethanol solution. The mixture solution was also heated at 120 °C for 15 min, and the gotten material was separated with the help of a magnet, then washed with ethanol one time. Afterwards, the Fe₃O₄@CuZnAl-LDH@MIL-100(Fe) precursor was dispersed into 30 mL mixed ethanol solution consisting of 0.49 g FeCl₃·6H₂O and 0.50 g H₃BTC. The above mixture was heated at 120 °C for 6 h. Eventually, the products were collected by a magnet and washed several times with ethanol, and dried in a vacuum oven at 70 °C, which was denoted as Fe₃O₄@CuZnAl-LDH@MIL-100(Fe) with a yield of 94 %.

2.3. Characterization of adsorbents

The morphology, composition, porous property, thermal stability, magnetic property and crystallographic structures of the materials were investigated through scanning electron microscopy (SEM, ZEISS Gemini 300, Germany), fourier transform infrared spectrometer (FT-IR, Bruker, Saarbrucken, Germany), physical adsorption analyzer (Micromeritics 3Flex, USA), thermogravimetric analyzer (Mettler DSC3, Mettler-Toledo Corporation, Switzerland), vibrating sample magnetometer (VSM, MPMS-3, Quantum Design, USA) and X-ray diffraction (Rigaku Ultima IV, Japan).

2.4. Chiral HPLC-UV condition

The chromatographic separation was carried out in a LC-16 system (Shimadzu, Kyoto, Japan) consisting of a binary solvent delivery pump, an autosampler, a column oven and a SPD-16 UV–vis detector. Three chiral triazole fungicides including paclobutrazol, uniconazole and bromuconazole were simultaneously separated on Chiralpak IH column (250 × 4.6 mm i.d., 5 µm, Daicel, China). Chromatographic separation was carried out using acetonitrile (A) and water (B) performed in isocratic mode (40:60, v/v) at a flow rate of 1.0 mL min⁻¹. The column temperature was set at 35 °C, the UV detection was performed at 230 nm and the injection volume was 15 µL.

2.5. Sample preparation

Water samples including lake water, tap water, and drinking water were collected from Shenyang medical college (Liaoning, China). Juice samples including orange, apple, and grape juices were obtained from a market in Shenyang (Liaoning, China). All samples were filtered through 0.22 μ m nylon membranes. Besides, as for juice samples, the supernatant was diluted 1-fold (v/v) volume with ultrapure water for further experiments [6]. The water and juice matrices without target triazole fungicides were used for method validation.

2.6. MSPE procedure

The schematic MSPE procedure based on Fe₃O₄@CuZnAl-LDH@MIL-100(Fe) was shown in Fig. 1B. Firstly, 24 % (w/v) NaCl was dissolved in sample solution (5 mL) to adjust the ionic strength. Then, 10 mg Fe₃O₄@CuZnAl-LDH@MIL-100(Fe) was dispersed in 5 mL water or diluted juice sample and ultrasound for 5 min at 25 °C. Then, the adsorbent was collected by a magnet and washed with 2 mL ultrapure water. Subsequently, 2.3 mL of acetone containing 10 % (v/v) ammonium hydroxide was added and ultrasonicated for 2 min to desorb the analytes from the adsorbent. Then, the resulting elution was dried under a nitrogen stream at 30 °C and redissolved in mobile phase (200 μ L). Finally, the solution was filtered through 0.22 μ m membrane for HPLC-

UV analysis.

2.7. Adsorption experiments

The adsorption performance of Fe₃O₄@CuZnAl-LDH@MIL-100(Fe) was evaluated by several adsorption experiments. As for adsorption kinetic experiments, 1 g Fe₃O₄@CuZnAl-LDH@MIL-100(Fe) was added to 500 mL triazole fungicides solutions (80 mg L⁻¹) and the solutions were shaken in a thermostatic oscillator (25 °C, 200 rpm). Then the samples (200 μ L) were taken at specific intervals by a syringe. The adsorption capacity (*q*_e) is calculated as:

$$q_e = \frac{(C_0 - C_e)V}{m} \tag{1}$$

where $C_0 \text{ (mg L}^{-1})$ represents the initial concentrations of the analytes, $C_e \text{ (mg L}^{-1})$ represents the equilibrium concentrations of the analytes, V (mL) is the solution volume, and m (mg) is the mass of Fe₃O₄@CuZnAl-LDH@MIL-100(Fe).

Four kinetic models were adopted to investigate the adsorption kinetic performances of $Fe_3O_4@CuZnAl-LDH@MIL-100(Fe)$ which listed in ESM.

The adsorption isotherm studies were performed in 100 mL triazole fungicides aqueous solutions with different concentrations (10–300 mg L⁻¹) containing 200 mg adsorbent. The suspensions were shaken by a thermostatic oscillator (25 °C, 200 rpm) for 30 min to reach a full equilibrium. Five isotherm model equations were used to fit the experimental data which listed in ESM.

For evaluating the influence of temperature (from 288 to 308 K) on the adsorption, thermodynamic parameters were determined and the equations were listed in ESM.

2.8. Molecular modeling

The AMD Ryzen 5 4600U with Radeon Graphics CPU (2.10 GHz) with Windows 10 operating system was used to perform the molecular modeling studies of compounds. The structures of MIL-100(Fe) [28] (as receptor) was selected in the docking calculations. The structures of analytes (as ligands) were drawn by ChemBioDraw Ultra 8.0 software, transferred to 3D by ChemBio3D Ultra 8.0 and saved in PDB format, followed by the energy minimization. Then, the structures of analytes were saved in PDBQT format after merging nonpolar hydrogen and handing over Gastegier charges by AutoDock tool. The automated molecular docking was carried out by AutoDock 4.2. The grid box size of 80 \times 80 \times 80 points with the spacing of 0.75 Å was employed. Discovery Studio 4.5 software was applied for further analysis and molecular display. The 200 independent docking runs were performed for ligands and receptor to obtain the lowest free energy of binding conformation.

2.9. Method validation

The method was validated in terms of specificity, linearity, LODs, LOQs, precision, accuracy and robustness. The specificity was assessed by analyzing the chromatograms of blank samples with the spiked samples. The linearity of the method was verified by spiking a series of triazole fungicides standards at seven concentration points (5, 20, 50, 100, 200, 500, 1000 μ g L⁻¹ for each enantiomer) in each sample matrix and three replicates were made for per concentration. LODs and LOQs were investigated by baseline noise method with signal-to-noise ratios (S/N) of 3 and 10, respectively. The accuracy of the method was verified by performing spiked recovery experiments for each sample matrix at three concentration levels of 20, 250, and 500 μ g L⁻¹ in nine replicates. The intra-day precision was evaluated by testing spiked samples at the concentration of 20, 250, and 500 μ g L⁻¹ in one day (n = 9), and the inter-day precision was investigated on three consecutive days (n = 27). Robustness was assessed from the stability of mixed triazole fungicides



Fig. 2. SEM images of Fe_3O_4 (A), $Fe_3O_4@CuZnAl-LDH$ (B) and $Fe_3O_4@CuZnAl-LDH@MIL-100(Fe)$ (C); fourier-transform infrared (FT-IR) spectra of Fe_3O_4 , $Fe_3O_4@CuZnAl-LDH$ and $Fe_3O_4@CuZnAl-LDH@MIL-100(Fe)$ (D); hysteresis loops of Fe_3O_4 , $Fe_3O_4@CuZnAl-LDH$ and $Fe_3O_4@CuZnAl-LDH@MIL-100(Fe)$ (E); nitrogen adsorption–desorption isotherms (BET) of Fe_3O_4 , $Fe_3O_4@CuZnAl-LDH@MIL-100(Fe)$ (F); pore size distribution of Fe_3O_4 , $Fe_3O_4@CuZnAl-LDH@MIL-100(Fe)$ (F); pore size distribution of Fe_3O_4 , $Fe_3O_4@CuZnAl-LDH@MIL-100(Fe)$ (G); TGA analysis of Fe_3O_4 , $Fe_3O_4@CuZnAl-LDH$ and $Fe_3O_4@CuZnAl-LDH@MIL-100(Fe)$ (H).

standard solution (1000 µg L⁻¹ for each enantiomer) and spiked water sample (1000 µg L⁻¹ for each enantiomer) stored at 4 °C for 0, 12 and 24 h, and variations in the parameters of chromatographic compositions: the mobile phase condition (acetonitrile: water = 39:61/40:60/41:59, v/v), flow rate (0.9/1.0/1.1 mL min⁻¹) and column temperature (33/ 35/37 °C). The matrix effects were evaluated by comparing the response in the sample matrix and standard solution [29]. Statistical analysis was carried out using SPSS 16.0 (Chicago, USA). Microsoft Excel 2019 (Redmond, USA) was used to perform mathematical operations. For comparisons, analysis of variance (ANOVA) was used to examine the significant differences. It was considered to be statistically significant with p < 0.05.

3. Results and discussion

3.1. Preparation of Fe₃O₄@CuZnAl-LDH@MIL-100(Fe)

Firstly, the influence of Cu/Zn/Al molar ratio on the adsorption amount of three pesticides during the preparation of Fe₃O₄@CuZnAl-LDH@MIL-100(Fe) was investigated. Generally, LDHs can be represented by the formula $[M_{1^+}^{2+}M_x^{3^+}(OH)_2][A^{n-}]_{x/n}$ ·mH₂O, where x is a ratio between divalent and trivalent cations with values between 0.2 and 0.33 [30,31]. Thus, the molar ratios of Cu/Zn/Al at 1:1:1 (x = 0.33), 2:1:1 (x = 0.25), 1:2:1 (x = 0.25) and 2:2:1 (x = 0.2) were tested during the preparation of Fe₃O₄@CuZnAl-LDH@MIL-100(Fe). When selecting the molar ratio of Cu/Zn/Al at 1:1:1, the greatest adsorption amount of three pesticides were achieved (Fig. S1A). It may be explained that the Cu/Zn/Al molar ratio could influence the surface structure of

 Fe_3O_4 @CuZnAl-LDH and the further modification of MIL-100(Fe), thus affecting the adsorption performance of Fe_3O_4 @CuZnAl-LDH@MIL-100 (Fe) (Fig. S2). Therefore, the molar ratio of Cu/Zn/Al at 1:1:1 was used for further study.

The effect of reaction temperature of MIL-100(Fe) modification (70 °C, 100 °C, 120 °C and 140 °C) on the adsorption performance of Fe₃O₄@CuZnAl-LDH@MIL-100(Fe) was also investigated and presented in Fig. S1B. The adsorption of three pesticides on Fe₃O₄@CuZnAl-LDH@MIL-100(Fe) increased with the rise of reaction temperature from 70 °C to 120 °C. However, with further increase in the temperature (140 °C), the adsorption performance of Fe₃O₄@CuZnAl-LDH@MIL-100 (Fe) was not enhanced significantly. The results indicated that the reaction temperature of MIL-100(Fe) modification at 120 °C was sufficient for three pesticides adsorption. Accordingly, the reaction temperature of MIL-100(Fe) modification was chosen to be 120 °C.

3.2. Characterization of Fe₃O₄@CuZnAl-LDH@MIL-100(Fe)

3.2.1. SEM

The morphologies and structures of Fe₃O₄, Fe₃O₄@CuZnAl-LDH and Fe₃O₄@CuZnAl-LDH@MIL-100(Fe) were firstly characterized using SEM. As shown in Fig. 2A, the Fe₃O₄ nanoparticles exhibited good sphericity with average diameter of 300–500 nm. After coating with CuZnAl-LDH, the surface of Fe₃O₄ exhibited numerous nanoflakes structures (Fig. 2B). As seen in Fig. 2C, the surface of Fe₃O₄@CuZnAl-LDH@MIL-100(Fe) were rougher than that of Fe₃O₄@CuZnAl-LDH, implying successful modification of MIL-100(Fe) on surfaces of Fe₃O₄@CuZnAl-LDH. The energy-dispersive X-ray (EDX) analysis was shown in Fig. S3. The elements C, O, Al, Fe, Cu and Zn were present on the surface of Fe₃O₄@CuZnAl-LDH@MIL-100(Fe) which further supported that Fe₃O₄@CuZnAl-LDH@MIL-100(Fe) has been successfully synthesized.

3.2.2. Infrared spectra

The FT-IR spectrums of Fe₃O₄, Fe₃O₄@CuZnAl-LDH and Fe₃O₄@-CuZnAl-LDH@MIL-100(Fe) were illustrated in Fig. 2D. The strong absorbance band was observed at 592 cm⁻¹ in the spectra of Fe₃O₄ and obviously decreased in spectrum of Fe₃O₄@CuZnAl-LDH, implying the formation of core-shell structure. The broad adsorption peak around 3440 cm⁻¹ was related to the O-H stretching. The strong absorption peak appeared at 1357 cm⁻¹ was attributed to the asymmetric stretching vibration and stretching vibration of CO_3^{2-} anions [32]. Moreover, the strong band located at 3440 \mbox{cm}^{-1} region in the Fe_3O4@CuZnAl-LDH@MIL-100(Fe) because of the –OH groups on the surface of MIL-100 (Fe) [33]. The bands located at 1446 cm^{-1} , 1380 cm^{-1} , 760 cm^{-1} and 712 cm^{-1} were characteristic peaks of MIL-100(Fe), and the absorption signals at 1622 cm^{-1} and 1708 cm^{-1} were attributed to the C=O vibration and tricarboxylate groups, respectively [34]. These results indicated that Fe₃O₄@CuZnAl-LDH@MIL-100(Fe) was successfully synthesized.

3.2.3. Magnetic properties and specific surface area

Fig. 2E showed the magnetic hysteresis loops of Fe₃O₄, Fe₃O₄@-CuZnAl-LDH and Fe₃O₄@CuZnAl-LDH@MIL-100(Fe) measured by vibrating sample magnetometer (VSM) at room temperature. As seen in Fig. 2E, the Fe₃O₄@CuZnAl-LDH@MIL-100(Fe) clearly responded magnetically to an external magnetic field. The saturation magnetization values of Fe₃O₄, Fe₃O₄@CuZnAl-LDH and Fe₃O₄@CuZnAl-LDH@MIL-100(Fe) were 78.2 emu g⁻¹, 38.8 emu g⁻¹ and 29.0 emu g⁻¹, respectively. The lower magnetic value of Fe₃O₄@CuZnAl-LDH@MIL-100(Fe) was due to the addition of the external layer, but it was enough to be magnetically separated.

To further confirm the structures of synthesized materials, the N_2 adsorption–desorption experiments were conducted (Fig. 2F and 2G). The Brunauer-Emmett-Teller (BET) specific surface area of Fe₃O₄, Fe₃O₄@CuZnAl-LDH and Fe₃O₄@CuZnAl-LDH@MIL-100(Fe) were 6.9,

78.4 and 486.0 m² g⁻¹, respectively (Table S1). It is demonstrated that the attachment of the LDH and MOF layers can contribute to improving the specific surface area of Fe₃O₄. The shape and a hysteresis loop indicated the presence of both microporous and mesoporous in the Fe₃O₄@CuZnAl-LDH@MIL-100(Fe) (Fig. 2F). The Barrett-Joyner-Halenda (BJH) pore size distribution curve (Fig. 2G) showed that the Fe₃O₄@CuZnAl-LDH@MIL-100(Fe) pore size distributed mainly within 1.7–10 nm and the average pore width was 4.8 nm. These results demonstrated that the successful synthesis of Fe₃O₄@CuZnAl-LDH@MIL-100(Fe). The good structure properties of Fe₃O₄@CuZnAl-LDH@MIL-100(Fe) such as high surface area and pore volume of porous structure would provide more active sites, enhancing its adsorption capacity and extraction performance.

3.2.4. Thermogravimetric analysis

The thermal stabilities of Fe₃O₄, Fe₃O₄@CuZnAl-LDH and Fe₃O₄@-CuZnAl-LDH@MIL-100(Fe) were characterized by a thermogravimetric analyzer from 20 to 800 °C under air atmosphere with a heating rate of 10 °C min⁻¹. From Fig. 2H, the weight of Fe₃O₄ remained almost unchanged and lost about 0.8 % with the increase of temperature, which was related to the release of adsorbed water molecules [35]. For Fe₃O₄@CuZnAl-LDH, the 9.0 % of weight loss during the first step (20-150 °C) was ascribed to the evaporation of small-molecular weight solvents (e.g., H₂O) from the surface of the material. The 7.4 % of weight loss between 150 and 300 °C, which was caused by the dehydroxylation and the partial decomposition of the LDH into the oxide species. A 4.5 %weight loss in the range of 300-800 °C may be related to the decomposition of carbonate in the LDH structure [33]. The TGA curve of Fe₃O₄@CuZnAl-LDH@MIL-100(Fe) from 20 to 300 °C was similar to that of Fe₃O₄@CuZnAl-LDH. Furthermore, the weight of Fe₃O₄@CuZnAl-LDH@MIL-100(Fe) decreased sharply from 300 to 500 °C because of the MIL-100(Fe) decomposition. These results further testified that the MIL-100(Fe) was coated onto the surface of Fe₃O₄@CuZnAl-LDH.

3.2.5. X-ray diffraction (XRD) analysis

The XRD patterns of materials were obtained by Ultima IV X-ray diffractometer (Rigaku, Japan) with the scan range from 5 to 80° (20) at the rate of 5° min⁻¹ and the results were shown in Fig. S4. As for Fe₃O₄, the diffraction peaks at 20 of 18.2°, 30.1°, 35.5°, 43.1°, 53.5°, 57.0°, and 62.5° were obtained, which matched well with the literature [6]. Compared with Fe₃O₄, Fe₃O₄@CuZnAl-LDH showed similar diffraction peaks and the peak intensity was decreased. When the MIL-100(Fe) was modified onto the surface of Fe₃O₄@CuZnAl-LDH, the XRD patterns of Fe₃O₄@CuZnAl-LDH@MIL-100(Fe) was in good agreement with the MIL-100(Fe) and Fe₃O₄@CuZnAl-LDH. These results indicated that the successful preparation of Fe₃O₄@CuZnAl-LDH@MIL-100(Fe).

3.3. Optimization of enantiomeric separation

In this study, the Chiralpak IH (250 mm \times 4.6 mm, i.d. 5 μ m) column was used to simultaneously enantioseparate three triazole fungicides in reversed phase condition. Chiralpak IH column is a polysaccharide-type chiral stationary phase, which its silica gel surface is immobilized with amylose tris-[(S)- α -methylbenzylcarbamate]. To our knowledge, the Chiralpak IH column has not been reported in the simultaneous enantioseparation of three chiral triazole fungicides including paclobutrazol, uniconazole and bromuconazole.

Several chromatographic method parameters including the proportion of organic modifier (35–45 %, v/v), column temperature (25-40 °C) and flow rate (0.8–1.2 mL min⁻¹) were investigated (Table S2 and Fig. S5). When increasing the acetonitrile (ACN) content, the retention times of all analytes were reduced, however, the enantioselectivities were also decreased. Since the best separation performance was obtained at 40 % ACN, the 40 % of ACN was selected in the current study. On one hand, high column temperature can shorten the retention times; on the other hand, lower column temperatures can prolong the life of the



Fig. 3. The 3D response surface plots of average recovery of three triazole fungicides affected by adsorbent amount, desorption volume and NaCl content.

chromatographic column, thus, 35 °C was chosen as the optimum column temperature by comprehensively considering retention time, resolution and the life of column. Larger flow rate can also shorten the retention times of analytes, while the column efficiency at 1.2 mL min⁻¹ was lower than that of 1.0 mL min⁻¹ (data not shown). Therefore, the enantiomeric separation was conducted at flow rate of 1.0 mL min⁻¹. Overall, the mobile phase composed of ACN and water under isocratic mode (40:60, v/v) with the column temperature of 35 °C and a flow rate of 1.0 mL min⁻¹ (Table S3).

3.4. Optimization of MSPE parameters

In order to obtain the optimal extraction performance, several factors including adsorption time, desorption time, sample solution pH, the ionic strength of sample solution, adsorbent amount, desorption volume, the type of desorption solvent and sample volume were investigated. The univariate experiments were tested to illustrate the level ranges of these parameters and the optimized preliminary results were shown in Fig. S6. Respective text and figures were given in the ESM. During the extraction process, seven solvents including methanol, acetonitrile, acetone, acetone-5 % formic acid (v/v), acetone-5 % ammonia (v/v), acetone-10 % ammonia (v/v) and acetone-20 % ammonia (v/v) were tested as desorption solvent. As shown in Fig. S6G, when acetoneammonia was used as the desorption solvent, three triazole fungicides obtained an enhanced extraction efficiency. The results demonstrated that the analytes can be easily dissolved and desorbed in acetone. Simultaneously, ammonia could break the forces (such as hydrogen bonding and π - π interaction) between triazole fungicides and the adsorbent, further improve the desorption capacity of the desorption solvent. Moreover, the recoveries of analytes increased as the ammonia

content increased from 5 % to 10 % and remained approximately stable when the ammonia content increased from 10 % to 20 %. This indicated that the ammonia content of 10 % would be sufficient to elute the analytes from the adsorbent. Therefore, acetone-10 % ammonia (v/v) was chosen as desorption solvent. On the basis of the results from single-factor tests, other extraction parameters were ascertained through Plackett-Burman design.

In the Plackett-Burman design, seven factors were evaluated at two levels, their coded and actual values were listed in Table S4. The response (Y) was the average recoveries of three triazole fungicides and the experimental runs were carried out in triplicate (Table S5). The Plackett-Burman design was done by twelve runs and experimental data were analyzed by using DESIGNEXPERT® Software trial version 12. The analysis of variance (ANOVA) was used to assess the significance of variables and response. In Table S6, the model F-value was 22.61 with Pvalue of 0.0046, which implied that the model was significant. The Pvalues were 0.0022, 0.0409, 0.0008 for desorption volume (C), adsorbent amount (E) and NaCl content (w/v%) (F), respectively, indicating that the desorption volume, adsorbent amount and NaCl content parameters exerted an indispensable impact on extraction efficiency. The regression coefficient of determination (R²) for the model of 0.9754 predicted that 97.54 % of the variability of the response can be explained by this model. The final equation in terms of coded factor was expressed as below:

$$Y = 77.91 + 1.93A + 1.62B + 5.30C + 1.60D + 2.24E + 6.91F - 0.2117G$$
(2)

On the basis of single-factor experiments result and the Plackett-Burman design, three variables including desorption volume (1-3 mL),



Fig. 4. Combination modes between MIL-100Fe and the target analytes ((A) Paclobutrazol, (B) Uniconazole, (C) Bromuconazole). The ligands were displayed in balland-stick style by marking carbon atoms in yellow and oxygen atoms in red. The receptor was displayed in thin stick style by marking oxygen atoms in red and Fe ions in orchid. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

adsorbent amount (5–15 mg) and NaCl content (15–35 %, w/v) were further optimized by a three-level and three-factor Box-Behnken design to determine the optimum conditions. The 17 experimental schemes and obtained results were listed in Table S7, in which the response was the average recoveries. The final equation fitted by the three factors and response values was as follows:

$$Y = 92.48 + 8.43A + 3.50B + 4.92C - 0.12AB + 1.05AC - 2.71BC$$

-10.78A² - 14.98B² - 10.47C² (3)

The acceptability of the developed model was studied by analysis of variance (ANOVA) (Table S8). The F-value of 21.82 and *p*-value of 0.0003 demonstrated that the model was significant. The *p*-value of the lack of fit (0.2525) showed that it was appropriate. The coefficient of determination ($R^2 = 0.9656$), adjusted determination coefficient (Adj. $R^2 = 0.9213$) and the value of coefficient of variance (C.V.% =5.19) implied the adequacy and reliability of the established model. Hence, this all indicated the compatibility of the predicted values and the measured values. Three-dimensional (3D) response surface plots were depicted to visualize the interaction between any two variables (Fig. 3). Finally, the desorption volume of 2.3 mL, adsorbent amount of 10 mg and 24 % (w/v) NaCl for sample solution were selected as the optimal condition.

3.5. Adsorption studies

3.5.1. Adsorption kinetics

In this study, the adsorption kinetics of paclobutrazol, uniconazole and bromuconazole on Fe₃O₄@CuZnAl-LDH@MIL-100(Fe) were studied by changing contact time (Fig. S7). As can be seen from Fig. S7, the adsorption capacity of three pesticides on Fe₃O₄@CuZnAl-LDH@MIL-100(Fe) increased faster in the first 5 min due to the high concentration of analytes and the more effective adsorption sites on the surface of Fe₃O₄@CuZnAl-LDH@MIL-100(Fe). After that, the rates of adsorption process gradually decreased and the adsorption reached adsorption equilibrium over 10 min because of the decrease of analytes concentration and the reduced adsorption sites of Fe₃O₄@CuZnAl-LDH@MIL-100(Fe). For exploring the kinetic behavior of paclobutrazol, uniconazole and bromuconazole adsorptions on Fe₃O₄@CuZnAl-LDH@MIL-1DH@MIL-100(Fe), the obtained results were fitted with pseudo-firstorder model, pseudo-second-order model, Elovich model and intraparticle diffusion model.

From Table S9, we can see that the pseudo-second-order kinetic model fitted well with the adsorption data. Based on the correlation coefficients (R^2) , it was better that the adsorption of three triazole fungicides on Fe₃O₄@CuZnAl-LDH@MIL-100(Fe) was described by the pseudo-second-order kinetic model ($R^2 > 0.9994$). The experimental adsorption capacities $(Q_{e,exp})$ of the pseudo-second-order model for paclobutrazol, uniconazole and bromuconazole were close to the theoretical calculated values $(Q_{e,cal})$. The above results suggested that the adsorption process of three triazole fungicides was dominated by chemical interaction. From the results that fitted using the intra-particle diffusion model, we can see that there were three segments in the intraparticle plots of three triazole fungicides with rate constants expressed as $k_{p1} > k_{p2} > k_{p3}$, this indicated the adsorption process of three triazole fungicides was impacted by multiple processes. The first step represented the quick adsorption of analytes on the outer surface of Fe₃O₄@CuZnAl-LDH@MIL-100(Fe). The second step represented the intraparticle pore-diffusion of analytes with a slower adsorption rate. At the third step, the adsorption sites on Fe₃O₄@CuZnAl-LDH@MIL-100 (Fe) tended to be saturated, and the adsorption and desorption equilibrium states were reached. Moreover, all fitting lines did not pass through the origin of coordinates. These suggested that the adsorption was a complicated process which was controlled by other mechanisms besides the intra-particle diffusion.

3.5.2. Adsorption isotherms

The influence of initial concentrations (10–300 mg L⁻¹) on the adsorption of paclobutrazol, uniconazole and bromuconazole by Fe_3O_4 @CuZnAl-LDH@MIL-100(Fe) were investigated (Fig. S8). The adsorption amount of paclobutrazol, uniconazole and bromuconazole increased sharply at lower initial concentration because of the sufficient adsorption sites on Fe_3O_4 @CuZnAl-LDH@MIL-100(Fe), thus enhanced the mass transfer. When further increasing the initial concentration, the active sites of Fe_3O_4 @CuZnAl-LDH@MIL-100(Fe) were gradually saturated with a slower adsorption rate.

The adsorption data were fitted by five extensively used adsorption isotherm models, including Langmuir, Freundlich, Temkin, Dubinin-Radushkevich and Redlich-Peterson isotherm models. Calculated parameters were shown in Table S10. The highest values of correlation coefficients ($R^2 \geq 0.9976$) indicated that the experimental data can be best defined using Langmuir isotherm model. Paclobutrazol, uniconazole and bromuconazole adsorptions onto $Fe_3O_4@CuZnAl-LDH@MIL-100(Fe)$ were monolayer adsorptions and there was no

Table 1

Performance parameters of three chiral pesticides.

Analyte	Matrices	Linearity range	Regression	\mathbb{R}^2	LOD (µg	LOQ (µg	Repeatability	(RSD%)	Accuracy	
		(µg L ⁻¹)	equation		L ⁻¹)	L ⁻¹)	Intra-day (n = 9)	Inter-day (n $= 27$)	(Recovery, %)	
Paclobutrazol E1 ^a	Lake water	5–1000	y = 120.73x-47.08	0.9991	0.50	1.70	2.80/1.45/	3.55/4.21/	91.52/94.21/90.26	
	Tap water	5–1000	y = 128.22x + 55.34	0.9992	0.50	1.70	3.49/2.45/	4.04/3.28/	90.50/89.82/94.45	
	Drinking	5–1000	y = 130.04x-22.90	0.9990	0.50	1.70	4.51/4.45/	5.25/2.82/ 4 73	88.54/94.36/90.28	
	Orange juice	5–1000	y = 129.63x + 20.15	0.9991	0.60	2.50	2.30/3.98/	2.25/4.05/	86.28/96.24/95.05	
	Apple juice	5–1000	y = 150.52x + 25.82	0.9990	0.80	2.50	2.15/1.79/	3.54/3.28/	89.88/94.01/95.26	
	Grape juice	5–1000	y = 142.68x + 63.89	0.9991	0.50	1.60	2.34/3.98/ 1.50	4.12/3.87/ 4.54	92.06/90.88/87.73	
Paclobutrazol E2 ^b	Lake water	5–1000	y = 121.56x + 65.80	0.9994	0.50	1.70	3.49/2.45/ 1.97	2.65/3.59/ 4.21	88.04/90.28/91.64	
	Tap water	5–1000	y = 125.04x-87.89	0.9990	0.50	1.70	4.79/4.82/	4.61/2.98/	91.62/90.23/90.81	
	Drinking	5–1000	y = 130.36x-74.57	0.9992	0.50	1.70	3.31/2.89/	3.27/2.55/	92.03/88.83/94.20	
	Orange juice	5–1000	y = 130.29x + 31.06	0.9992	0.60	2.50	3.45/2.90/	3.62/2.97/	87.92/92.47/95.88	
	Apple juice	5–1000	y = 145.49x + 00.48	0.9993	0.80	2.50	0.44/2.31/	3.82/4.50/	94.03/88.52/87.91	
	Grape juice	5–1000	y = 144.37x-59.12	0.9987	0.50	1.60	3.33/3.71/ 0.95	4.64/5.11/ 4.08	98.21/93.05/94.27	
Uniconazole E1	Lake water	5–1000	<i>y</i> = 386.24 <i>x</i> -10.94	0.9997	0.35	1.00	1.91/3.37/	4.05/3.37/	95.08/90.37/89.24	
	Tap water	5–1000	y = 349.44x + 27.00	0.9996	0.35	1.00	2.26/1.37/	2.68/3.05/	93.28/95.06/97.12	
	Drinking	5–1000	y = 320.96x + 160.43	0.9991	0.35	1.00	2.56/2.84/	3.35/3.87/	91.82/90.54/89.73	
	Orange juice	5–1000	y = 319.29x + 219.11	0.9991	0.40	1.50	1.69/2.84/	5.73/4.26/	88.04/92.08/95.42	
	Apple juice	5–1000	y = 333.14x + 39.55	0.9992	0.50	1.55	2.27/1.37/	2.59/3.67/	87.97/94.97/89.52	
	Grape juice	5–1000	y = 327.42x + 51.22	0.9995	0.45	1.40	1.65/0.97/ 1.22	2.65/3.37/ 3.90	93.02/90.21/88.53	
Uniconazole E2	Lake water	5–1000	y = 376.31x-20.24	0.9997	0.35	1.00	3.22/2.55/	3.59/2.94/ 4 41	91.38/87.90/93.47	
	Tap water	5–1000	y = 345.23x + 54.40	0.9995	0.35	1.00	3.26/2.74/	2.98/3.27/	90.77/94.39/96.28	
	Drinking	5–1000	y = 310.35x + 134.34	0.9992	0.35	1.00	3.42/1.72/	3.70/2.99/	98.22/94.21/92.75	
	Orange juice	5–1000	y = 324.13x + 172.10	0.9992	0.40	1.50	3.45/2.69/	4.04/3.79/	87.43/90.18/93.80	
	Apple juice	5–1000	y = 328.20x + 26.63	0.9994	0.50	1.55	3.24/2.25/	3.01/4.17/	90.53/95.05/90.74	
	Grape juice	5–1000	y = 318.25x + 58.43	0.9993	0.45	1.40	3.38/1.33/ 2.07	4.59/2.84/ 5.08	93.27/92.18/89.39	
Bromuconazole E1	Lake water	5–1000	<i>y</i> = 93.87 <i>x</i> -94.47	0.9995	1.00	2.80	2.96/3.56/ 4.92	4.83/5.27/ 5.66	90.83/95.42/87.06	
	Tap water	5–1000	y = 90.48x + 36.92	0.9998	1.00	2.80	0.92/2.20/	2.89/3.54/	94.61/90.28/89.77	
	Drinking	5–1000	y = 86.94x-71.63	0.9991	1.00	2.80	3.91/3.55/	3.72/5.01/	87.80/92.55/96.03	
	Orange juice	5–1000	y = 90.59x + 20.16	0.9997	0.80	2.50	3.33/3.24/	2.98/4.20/	93.07/95.89/90.22	
	Apple juice	5–1000	y = 88.12x + 15.18	0.9990	1.20	3.80	2.19/3.05/	3.43/3.78/	88.30/94.18/95.27	
	Grape juice	5–1000	y = 85.99x + 48.05	0.9994	1.20	3.75	2.12 2.59/2.14/ 1.86	4.29 4.28/4.36/ 5.13	92.03/90.85/95.11	
Bromuconazole	Lake water	5–1000	<i>y</i> = 92.49 <i>x</i> -48.15	0.9989	1.00	2.80	3.30/2.22/	3.51/4.08/	88.52/89.06/93.54	
E2	Tap water	5–1000	<i>y</i> = 88.48 <i>x</i> -30.94	0.9998	1.00	2.80	2.55/2.05/ 2.49	4.27/5.15/ 5.39	93.06/88.32/87.05	

(continued on next page)

Table 1 (continued)

Analyte	Matrices	Linearity range	Regression	R ²	LOD (µg	LOQ (µg	Repeatability	Accuracy		
		(µg L ⁻¹)	equation		L ⁻¹)	L ⁻¹)	Intra-day (n = 9)	Inter-day (n = 27)	(Recovery, %)	
	Drinking water	5–1000	y = 85.82x-42.82	0.9994	1.00	2.80	3.30/2.22/ 3.79	3.70/4.28/ 5.74	89.44/92.50/90.35	
	Orange juice	5–1000	y = 89.98x-10.28	0.9998	0.80	2.50	1.92/2.63/ 1.61	2.96/3.55/ 3.78	88.39/89.54/93.18	
	Apple juice	5–1000	y = 88.04x + 35.20	0.9993	1.20	3.80	1.39/2.05/ 2.49	3.72/4.58/ 4.50	93.02/90.88/87.95	
	Grape juice	5–1000	y = 86.68x-24.94	0.9991	1.20	3.75	1.90/2.63/ 1.61	4.58/4.42/ 5.05	90.22/94.75/88.20	
Bromuconazole E3 ^c	Lake water	5–1000	y = 92.85x + 62.60	0.9991	1.00	2.80	1.82/1.49/ 3.18	3.89/5.52/ 4.30	87.75/89.21/92.87	
	Tap water	5–1000	y = 86.32x + 21.60	0.9999	1.00	2.80	2.66/1.49/ 1.26	2.85/3.72/ 3.69	89.30/92.55/95.62	
	Drinking water	5–1000	y = 84.98x-91.42	0.9994	1.00	2.80	3.36/2.93/ 2.17	4.55/4.39/ 5.28	93.36/95.20/88.65	
	Orange juice	5–1000	y = 90.15x-88.82	0.9997	0.80	2.50	2.91/2.51/ 2.06	4.25/4.84/ 5.05	87.78/89.85/92.68	
	Apple juice	5–1000	y = 85.94x + 68.53	0.9994	1.20	3.80	2.53/4.26/ 1.26	3.08/4.20/ 5.39	92.18/92.66/95.30	
	Grape juice	5–1000	y = 90.21x + 67.51	0.9993	1.20	3.75	2.89/2.53/ 2.59	2.88/3.69/ 4.85	89.26/92.77/92.04	
Bromuconazole E4 ^d	Lake water	5–1000	<i>y</i> = 93.37 <i>x</i> -85.17	0.9991	1.00	2.80	3.75/2.59/ 3.15	3.89/4.26/ 5.36	91.45/89.79/89.85	
	Tap water	5–1000	y = 85.42x + 96.87	0.9999	1.00	2.80	1.23/1.59/ 1.26	2.84/3.58/ 3.76	92.05/90.18/92.55	
	Drinking water	5–1000	y = 84.91x-55.72	0.9997	1.00	2.80	3.82/2.22/ 3.15	3.37/4.80/ 4.82	88.50/94.25/90.02	
	Orange juice	5–1000	y = 90.10x-36.76	0.9997	0.80	2.50	2.77/3.89/	3.64/4.28/ 4.59	90.55/93.82/95.03	
	Apple juice	5–1000	y = 83.29x + 22.73	0.9996	1.20	3.80	2.19/3.44/ 1.73	3.12/3.87/ 4.62	94.50/92.84/90.32	
	Grape juice	5–1000	y = 87.11x + 14.39	0.9997	1.20	3.75	2.33/3.78/	3.48/4.04/	93.78/90.20/89.76	

^a The first-eluted enantiomer.

^b The second-eluted enantiomer.

^c The third-eluted enantiomer.

^d The fourth-eluted enantiomer.

interaction or competition among three triazole fungicides.

3.5.3. Adsorption thermodynamics

For studying the effect of temperature on the adsorption of paclobutrazol, uniconazole and bromuconazole on Fe₃O₄@CuZnAl-LDH@MIL-100(Fe), the adsorption thermodynamics was investigated. The relevant thermodynamic parameters were calculated and tabulated in Table S11. The Gibbs free energy change (ΔG°) values for paclobutrazol, uniconazole and bromuconazole adsorptions on Fe₃O₄@CuZnAl-LDH@MIL-100(Fe) were negative in the range of -2.19 to -10.62 kJ mol⁻¹ at 288, 298 and 308 K, which indicated that the adsorption was spontaneous. The ΔG° values decreased with temperature increasing, illustrating that the high temperature was more favorable to the three triazole fungicides adsorptions. The positive values of enthalpy change (ΔH°) indicated that the adsorption process of three triazole fungicides was endothermic. The entropy change (ΔS°) values of all analytes were positive (93.63–110.99 J mol⁻¹ K⁻¹) indicated the randomness increased at the liquid–solid interface.

3.6. Regeneration and reusability

The reusability of Fe₃O₄@CuZnAl-LDH@MIL-100(Fe) was important in practical applications, the adsorption–desorption cycle experiment was conducted. Firstly, 10 mg Fe₃O₄@CuZnAl-LDH@MIL-100(Fe) was applied for extracting triazole fungicides in 5 mL spiked samples (1 mg L⁻¹). Then, the adsorbent was regenerated by ultrasonication (25 °C, 10 min) in acetone containing 10 % ammonium hydroxide (2.3 mL) and rinsed with acetone (2 mL) two times. After magnetic separation, the adsorbent was dried under nitrogen stream at 30 °C before its reuse. In Fig. S9, the extraction recoveries of paclobutrazol, uniconazole and bromuconazole were higher than 85 % after 8 cycles, indicating the good regeneration performance of Fe₃O₄@CuZnAl-LDH@MIL-100(Fe). The results demonstrated that the synthesized Fe₃O₄@CuZnAl-LDH@MIL-100(Fe) simultaneously possessed good adsorption and regeneration performance, which showed great potential in practical liquid sample treatment.

3.7. Molecular modeling

After being processed by AutoDock 4.2, the interaction mechanisms between three triazole fungicides and MIL-100(Fe) were shown in Fig. 4. From Fig. 4, it can be seen that the π - π interactions between benzene rings, σ - π conjugations between carbon atom and benzene ring, p- π conjugations between heteroatom and benzene ring exist between triazole fungicides and MIL-100(Fe). Additionally, van der-Waals force, hydrogen bond and hydrophobic effect also play major roles in the triazole fungicides adsorption on MIL-100(Fe).

The binding energies (BEs) between triazole fungicides and MIL-100 (Fe) were also analyzed using AutoDock 4.2 (Table S12). In Table S12, the BEs of MIL-100(Fe) towards triazole fungicides ranged from -6.41 to -5.47 kcal mol⁻¹, suggesting an exothermic adsorption of triazole fungicides over MIL-100(Fe). Generally, the greater the absolute value of BEs, the stronger the affinity of MIL-100(Fe) towards triazole fungicides. However, the order of the BEs of MIL-100(Fe) towards triazole

Table 2

Determination and recoveries of three chiral pesticides in actual samples.

Analyte	Spiked (µg L ⁻¹)	Lake water		Tap water		Drinking water		Orange juice		Apple juice		Grape juice	
		Recovery (%)	RSD (%)										
Paclobutrazol	0	_ ^e	_	_	_	_	_	_	_	_	_	_	_
E1 ^a	20	101.37	2.61	94.41	3.29	99.69	5.04	95.03	2.20	95.31	2.04	92.13	2.15
	500	95.02	1.78	88.64	2.01	89.82	4.14	96.83	2.89	91.47	1.65	96.78	1.45
Paclobutrazol	0	_	_	_	_	_	_	_	_	_	_	_	_
E2 ^b	20	99.31	3.53	99.04	4.25	92.87	2.69	92.60	2.69	94.69	0.42	90.15	3.34
	500	93.74	2.24	99.63	3.08	87.29	4.31	94.87	1.66	89.04	1.32	96.83	0.92
Uniconazole E1	0	_	_	_	_	_	_	_	_	_	_	_	_
	20	87.39	1.67	95.75	2.17	100.28	3.48	89.46	2.54	100.25	2.30	92.33	0.90
	500	98.62	3.06	96.20	1.65	90.80	2.29	90.76	1.92	95.70	2.28	89.82	1.10
Uniconazole E2	0	_	_	_	_	_	_	_	_	_	_	_	_
	20	90.10	2.90	97.13	3.16	91.65	1.55	87.54	2.35	95.79	2.29	93.49	1.24
	500	99.95	2.75	97.53	1.39	90.80	2.29	89.18	1.84	95.02	2.43	90.90	1.88
Bromuconazole	0	_	_	_	_	_	_	_	_	_	_	_	_
E1	20	88.50	2.62	99.53	0.87	92.09	3.60	91.30	2.96	96.62	2.84	95.44	2.04
	500	99.01	3.76	88.64	1.88	90.43	4.45	88.06	2.25	91.07	1.93	90.38	1.68
Bromuconazole	0	_	_	_	_	_	_	_	_	_	_	_	_
E2	20	87.74	2.85	92.62	1.90	87.84	1.94	94.45	2.37	94.59	1.32	93.60	2.46
	500	87.80	4.12	90.67	2.25	99.15	3.75	87.84	1.42	90.97	2.27	91.21	1.47
Bromuconazole	0	_	_	_	_	_	_	_	_	_	_	_	_
E3 ^c	20	89.77	1.63	91.80	2.65	97.93	4.27	92.84	2.71	92.91	2.35	90.22	2.28
	500	99.84	3.18	93.64	1.18	89.11	3.71	86.56	1.78	93.95	1.18	87.53	2.21
Bromuconazole	0	_	_	_	_	_	_	_	_	_	_	_	_
E4 ^d	20	88.26	3.31	95.50	1.18	95.32	3.64	89.33	3.65	94.44	2.07	92.23	3.48
	500	89.38	2.53	95.57	1.46	88.83	2.79	85.92	1.27	90.74	1.57	90.29	1.47

^a The first-eluted enantiomer.

^b The second-eluted enantiomer.

^c The third-eluted enantiomer.

^d The fourth-eluted enantiomer.

^e Lower than the LODs.

fungicides was not consistent with those of the adsorption capacity $(Q_{e,exp})$ obtained in experimental studies (bromuconazole > uniconazole > paclobutrazol). Additionally, the binding constants $(\ln k_0)$ of MIL-100(Fe) towards three triazole fungicides were also obtained through the equation of $\Delta G^{\circ} = -\text{RTIn}k_0$ and the order of $\ln k_0$ values were similar to BEs. This could be due to the fact that there were some other possible interactions except the best adsorption sites between MIL-100(Fe) and triazole fungicides in the experiment, and the molecular modeling was conducted under the presumptive environment. In general, molecular modeling supplied a theoretical basis for elucidating the interactions between MIL-100(Fe) and triazole fungicides in adsorption process, and showed good prospects for analyzing other pollutants.

3.8. Method validation

As shown in Figs. S10 and S11, blank water and juice samples were tested and paclobutrazol, uniconazole and bromuconazole were not detected at concentrations higher than the limits of detection. Table 1 summarized the analytical performance of established MSPE-HPLC-UV method. The calibration curves for three triazole fungicides exhibited a good linear response range (5–1000 μ g L⁻¹) with satisfactory correlation coefficients (R²) values (0.9987–0.9999). LODs and LOQs of three triazole fungicides ranged from 0.35 to 1.20 μ g L⁻¹ and from 1.00 to 3.80 μ g L⁻¹, respectively. The average spiked recoveries ranged from 86.28-98.22 % which suggested that the accuracy of method was

satisfactory. The intra-day RSDs ranged from 0.44 to 4.92 %, and the inter-day RSDs varied from 2.25 to 5.74 %. These results fulfilled the criteria of SANTE/12682/2019 (the recoveries are 70 ~ 120 % with precision RSD \leq 20 %) [36]. The robustness of developed method was evaluated by the standard and sample solution stabilities and variations in chromatographic parameters (Table S13). All enantiomers can be completely separated (Rs \geq 1.50) with RSDs of each factor less than 2.07 %. The above results showed that the developed method had good robustness. Moreover, the results of matrix effect for each enantiomer of three triazole fungicides in the range of 89.1 to 115.3 % indicated that there was no obvious matrix effect (Table S14). Therefore, the established method was suitable for applying in pesticides residues analysis.

3.9. Comparison with reported methods

A comparison regarding the type of adsorbent, adsorbent amount, extraction method, detection instrument, extraction time, the linear range, LOQs, precision and method recoveries between the established method and previous studies for analysis of triazole fungicides in water or juice samples was summarized in Table S15. Compared with most adsorbents which synthesized by previously reported methods, the preparation time of Fe₃O₄@CuZnAl-LDH@MIL-100(Fe) was shorter [6,37–40] and there was no need of various hazardous solvents (e.g. acetone, chloroform, ammonium persulfate solvent) in the preparation process [7,41–43]. Moreover, the method established in our study has a

shorter extraction time (7 min), lower adsorption amount (10 mg) and lower RSDs (0.44–5.74 %) compared to the existing methods [7,37–44]. The previous methods [6,7,40,41] exhibited lower LOQs which might be due to the requirement of sensitive and costly LC-MS/MS method. In general, the above results indicated that the proposed MSPE-chiral HPLC-UV method with suitable repeatability and sensitivity was promising for analyzing chiral triazole fungicides in water and juice samples.

3.10. Application to real samples

The application experiment of developed MSPE-chiral HPLC-UV method was performed to analyze paclobutrazol, uniconazole and bromuconazole in three kinds of water (lake water, tap water and drinking water) and fruit juice (orange juice, apple juice and grape juice). The residual concentration of paclobutrazol, uniconazole and bromuconazole in water and juice samples were below the LODs of method, consequently, 20 μ g L⁻¹ and 500 μ g L⁻¹ of triazole fungicides were spiked into actual samples to demonstrate the applicability of the established approach (Table 2). The results showed that recoveries of paclobutrazol, uniconazole and bromuconazole was between 85.92 % and 101.37 %, with RSDs of 0.42–5.04 %. These results illustrated that the proposed MSPE-chiral HPLC-UV approach was effective and reliable.

4. Conclusion

In this study, $Fe_3O_4@CuZnAl-LDH@MIL-100(Fe)$ was successfully designed and synthesized and used as a novel adsorbent for MSPE of three chiral triazole fungicides from water and juice samples, as well as a chiral HPLC-UV method for simultaneous determination of paclobutrazol, uniconazole and bromuconazole residues was developed. Compared with other methods, the established method exhibited good linearity, precision and accuracy, comparable LOQs, high efficiency and simplicity. Moreover, the molecular modeling method was applied to probe into the adsorption mechanism between the MIL-100(Fe) and triazole fungicides. The experimental results and calculated results indicated that the $Fe_3O_4@CuZnAl-LDH@MIL-100(Fe)$ was a promising adsorbent to enrich triazole fungicides in aqueous samples. The proposed MSPE-chiral HPLC-UV method can be served as an attractive tool to monitor chiral triazole fungicides from other complex environmental and food samples.

CRediT authorship contribution statement

Li Zhou: Writing – original draft, Validation, Project administration, Funding acquisition. Jing Tang: Writing – review & editing, Software, Investigation. Tong Chen: Investigation. Jiahui Peng: Investigation. Hainan Guo: Investigation. Ronghui Zhang: Software, Investigation. Xinyu Lv: Supervision, Investigation. Ronghua Fan: Writing – review & editing, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.microc.2024.110599.

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