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ORIGINAL PAPER

Dispersive solid phase extraction based on cross-linked hydroxypropyl β-cyclodextrin polymers for simultaneous enantiomeric determination of three chiral triazole fungicides in water

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Abstract

An efficient method is presented for simultaneous enantioselective determination of three chiral triazole fungicides (namely paclobutrazol, hexaconazole, and diniconazole) in water samples by DSPE-HPLC–UV. The perfect chiral separation of the enantiomers was achieved on a Chiralpak IH column within 15 min. In order to adsorb and enrich the analytes from water matrices, a cross-linked hydroxypropyl β-cyclodextrin polymer was synthesized. The prepared material exhibited good adsorption capacity, which was assessed by adsorption kinetic and adsorption thermodynamic experiments. One-variable-at-a-time and the response surface methodology were used to optimize the extraction parameters. Under the optimum sample preparation conditions, good linearity ($2.0 \sim 800$ μg L^{-1}, $R^2 \geq 0.9978$), detection limits (0.6 to 1.0 μg L^{-1}), quantitation limits (2.0 to 3.2 μg L^{-1}), recoveries ($86.7 \sim 105.8\%$), and the relative standard deviation (intra-day RSD $\leq 3.7\%$, inter-day RSD $\leq 5.1\%$) were obtained, satisfying the requirements of pesticides residues determination. These results demonstrated that the proposed method was applicable for routine determination of chiral triazole fungicide residues in water samples.

Keywords Cyclodextrin · Dispersive solid phase extraction · HPLC-UV · Enantioselective determination · Triazole fungicides · Water analysis

Introduction

Triazole fungicides are an important pesticides in the control of fungal diseases that have been widely used in agriculture due to their relatively low resistance risk and excellent biological activity [1]. However, the low biodegradability and excellent photochemical stability make them easy to remain in the environment [2]. The human health could be harmed by the long-term exposure to triazole pesticides, especially for endocrine system, the development and function of placental cell [3, 4]. Nowadays, a relatively high percentage of triazoles are chiral and produced as racemic mixtures due to economic or synthesis reasons [5]. In fact, some studies have demonstrated that the triazole pesticide enantiomers can exhibit different effects on the biological activity and environmental toxicity when exposed to a chiral environment [6–8]. From the perspectives of environmental security and food safety, developing an enantioselective analysis method is fundamental to monitoring chiral triazole fungicides at enantiomeric levels, which will help to study the environmental behavior and guide the reasonable application of chiral triazole enantiomers.

In order to test trace target analytes sensitively, developing a proper sample pretreatment method to determine triazole fungicides in actual samples is of prime importance. Among widely used pretreatment techniques, dispersive solid phase extraction (DSPE) has aroused wide spread concern due to the high efficiency, ease of operation, and no need of adsorbent conditioning [9]. In DSPE, a suitable adsorbent plays a dominant role in the improvement of adsorption efficiency.

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β-cyclodextrin (β-CD) is a product of starch hydrolysis, which has the hydrophobic internal cavity and hydrophilic outer surface [10, 11]. The β-CD adsorbent has the advantages of being inexpensive and biocompatibility [12]. Nowadays, the CD-based adsorbents can be fabricated via immobilizing CD onto water-insoluble supports (e.g., silica or nanomaterials) to abate the solubility of CD; however, the limitations of this method were the low portion of CD in the final materials and complex procedures [13, 14]. Another promising approach is the polymerization by cross-linking agents. Although many researchers constructed CD polymers by polymerizing due to their excellent adsorption ability and good regeneration performance [15–19], the reported methods still have some drawbacks like high-energy requirements and delicate operational conditions. Therefore, further developing adsorbent with high adsorption capacity towards more contaminants can expand the use of CD-based adsorbents, and this will be of great significance for practical actual sample treatment.

Recently, we synthesized CD hybrid polymer chromatographic column and applied it to capillary electrochromatography enantiomeric separation of drug racemates [20]. However, the potential of CD hybrid polymer for adsorption and extraction application is unknown, and little has been published on the preparation of hybrid CD-based adsorbents via cross-linking strategy. The literature applications of CD hybrid polymer material link only to chromatography. Nowadays, most researchers aimed to synthesize new nanomaterials to adsorb or extract pollutants, while the report of the extended application of nanostructured stationary phase material on sample pretreatment was rare. Moreover, the majority of CD-based adsorbents were mainly used in dye and metal ion removal, the application in organic pollutants adsorption was limited. To the best of our knowledge, the research on the usage of CD hybrid polymer to extract chiral pesticides has not been reported.

Herein, the cross-linked hydroxypropyl β-cyclodextrin material (CDM) was synthesized, characterized, and used to extract three triazole fungicides (paclobutrazol, hexaconazole, and diniconazole) in water samples. Response surface methodology was applied to obtain optimal experimental conditions with minimum number of tests. The adsorption behavior of material was elucidated from the adsorption parameters, adsorption kinetics, adsorption isotherms, and adsorption thermodynamics. Besides, a reversed-phase Chiralpak IH column coupled with UV detection was firstly employed to separate and quantify the three chiral triazole fungicides. Our study can extend the application of CD hybrid polymer material from chromatographic separation to sample pretreatment and offer novel possibilities for their adsorption and extraction properties. Furthermore, this method will lay the foundation for further studies on stereoselective degradation behaviors of paclobutrazol, hexaconazole, and diniconazole in actual samples.

Experimental

Chemicals and reagents

The chemicals and reagents of the work are provided in the Electronic Supporting Material (ESM).

Apparatus

HPLC analysis was performed on 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. Data were collected and processed by LabSolutions software. Enantiomeric separation was performed on a commercially immobilized Chiralpak IH chiral column (250 × 4.6 mm i.d., 5 µm), which was purchased from Daicel Chiral Technologies (Shanghai, China). Chromatographic separation was carried out using acetonitrile (A) and water (B) performed in isocratic mode (48:52, v/v) at a flow rate of 1.0 mL min^{-1}. And one injection in the chromatographic method was performed for 15 min. The column temperature was maintained at 30 °C, and the injection volume was 20 µL.

Synthesis of cross-linked HP-β-CD material (CDM)

CDM was fabricated by using our previous work [20]. The detailed preparation procedure was given in ESM.

Characterization

Scanning electron microscopy (SEM) images of CDM were recorded by a Hitachi S4800 scanning electron microscope (Hitachi, Ltd., Japan). Fourier transform infrared spectra (FT-IR) were obtained with FT-IR Spectrometer Paragon 1000. Thermal gravimetric analysis (TGA) was carried out on Mettler DSC3 (Mettler-Toledo Corporation, Switzerland).

Dispersive solid phase microextraction (DSPE) procedure

Here, 20 mg CDM was added to the water sample (10 mL). The mixed solution was sonicated for 5 min. The supernatant was decanted by centrifugation. Then, the analytes adsorbed on CDM were eluted with 2.4 mL of acetone under ultrasonication for 5.5 min. After that, the desorption solvent was collected and concentrated with a nitrogen stream at 30 °C. The residue was re-dissolved with 200 μL mobile phase and then filtered through 0.22 μm membrane for HPLC–UV analysis. The schematic diagram of DSPE procedure is shown in Fig. 1.

Adsorption experiments

The CDM adsorption performance was studied by using paclobutrazol, hexaconazole, and diniconazole as model analytes. The adsorption experiments were performed in 20-mL centrifuge tubes by a thermostatic oscillator (25 ℃, 200 rpm). The effects of initial concentration of analytes (5 ~ 300 mg L^{-1}), temperature (15 ~ 35 ℃), and adsorption time (0 ~ 60 min) on the adsorption process were studied, respectively. The residual concentrations of pesticides in water were obtained by HPLC–UV. All samples were filtrated using 0.22 μm organic membrane filters before the analysis.

Water samples

In this work, different water samples including lake water, tap water, and drinking water were selected for analysis. The lake water sample was obtained from Boxue lake (located in Shenyang Medical College in Shenyang, Liaoning). These water samples were stored at 4 °C and filtered before extraction.

Results and discussion

Characterization of the CDM

To confirm the successful fabrication of CDM, the obtained CDM was analyzed by various characterizations, such as SEM, FT-IR, TG, and DTG. The morphology of CDM by SEM was displayed in Fig. 2A and B. The CDM displayed an evident porous structure. The globular particles were aggregated on the surface of continuous skeleton to form large clusters. The existence of interconnecting mesopore and macropore structure could enhance the adsorption of analytes onto the CDM.

The FT-IR spectra of the GMA-HP-β-CD and CDM were shown in Fig. 2C. Compared to GMA-HP-β-CD, in CDM spectrum, the peak at 1380 cm^{-1} attributed to C-O absorption, the peak at 1729 cm^{-1} assigned to C = O vibration and

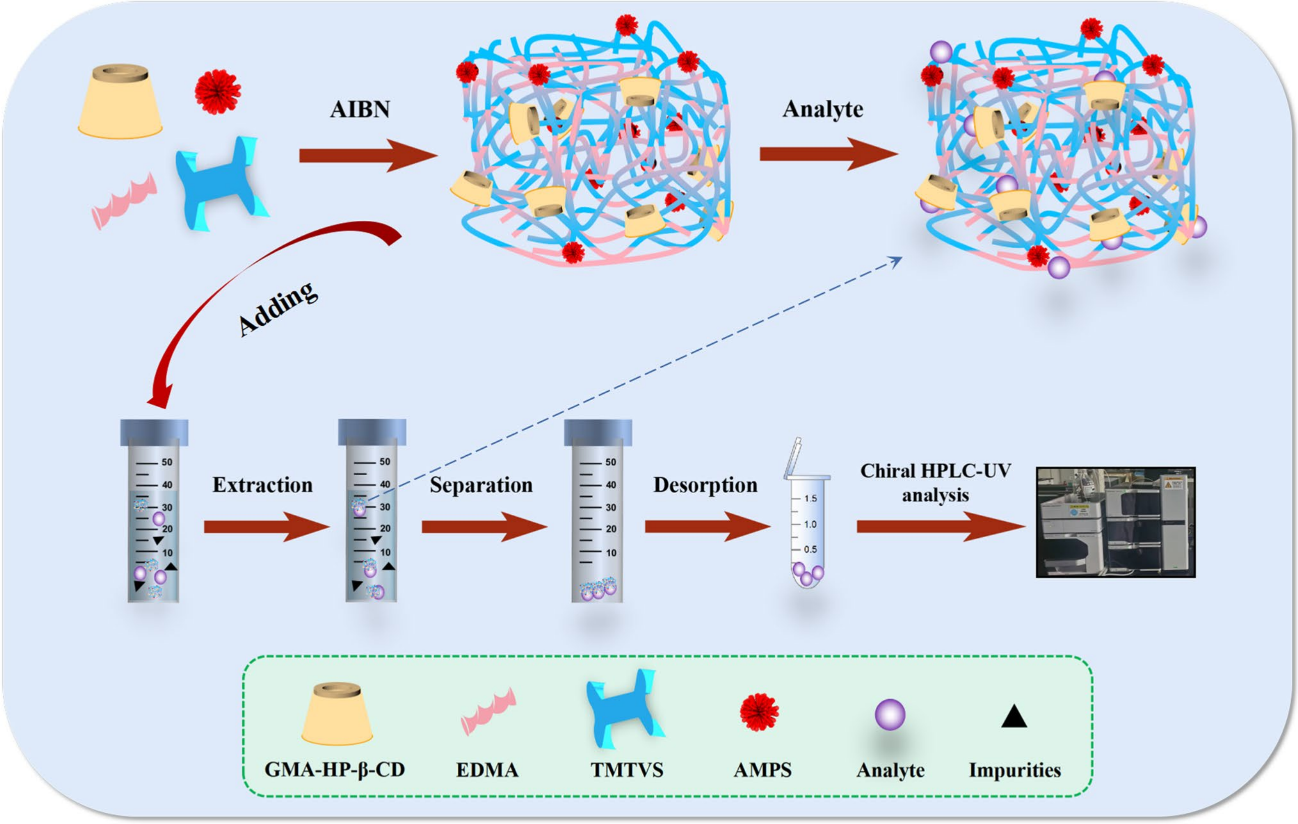

Fig. 1 Schematic diagram of DSPE procedure

the peak at 2933 cm^{-1} attributed to C-H vibration become stronger. The strong absorption bands at 3432 cm^{-1} could be attributed to the stretching vibration of -OH in GMA-HP-β-CD. The peak at 2973 cm^{-1} belonged to the $-CH_3$ group on the surface of CDM. These results suggested the presence of GMA-HP-β-CD on CDM structure.

TG-DTG was used to characterize the thermal properties of CDM (Fig. 2D). The first endothermic peak at 100 °C was related to the evacuation or removal of solvents from the pores. The weight loss of CDM was approximately 41.05% due to the decomposition of some polymer groups at 180 °C. As the temperature increased from 200 to 500 °C, an obvious weight loss of 43.17 wt% was found. This phenomenon is possibly ascribed to the basic skeleton of material destructing and decomposing.

The Brunauer–Emmett–Teller (BET) surface area and pore size distribution of CDM were also determined (Fig. 2E and F). The BET surface area of CDM was 30.74 m^2g^{-1}. Density function theory (DFT) was used to calculate the pore width distribution that gave pore width of 6.79 nm for CDM. These results exhibited the existence of mesopores in CDM structure.

Optimization of enantiomeric separation

In this work, an amylose-based chiral column—Chiralpak IH (250 mm × 4.6 mm, i.d. 5 μm)—was used for simultaneously enantioseparating the selected triazole fungicides in reversed-phase condition. As far as we know, this new polysaccharide-based chiral column has not been reported in the application of analysis of chiral triazole fungicides.

The effect of chromatographic method parameters (acetonitrile content, column temperature, and flow rate) on enantiomer separation of three chiral triazole fungicides was investigated (Table S2 and Fig. S1). When the proportion of acetonitrile decreased from 53 to 48%, three chiral triazole fungicides were completely separated. It was found that the retention time and resolution could be reduced when using high column temperature and large flow rate. Considering proper resolution with shortest analysis time, the best chromatographic conditions were as follows: the mobile phase composed of acetonitrile and water under isocratic mode (48:52, v/v) at 30 °C column temperature with a flow rate of 1.0 mL min^{-1} (Table S3).

Optimization of DSPE procedure

The selection of an appropriate desorption solvent is of high importance for DSPE process. The desorption solvent including methanol, acetonitrile, acetone, ethyl ether, acetone containing 5% (v/v) formic acid, and acetone containing 5% (v/v) ammonia was studied (Fig. S2A). Ethyl ether could not provide effective desorption of the extracted analytes from CDM. When using methanol or acetonitrile as the desorption solvent, the adsorptive analytes were also insufficiently eluted from the adsorbent. It was evident that

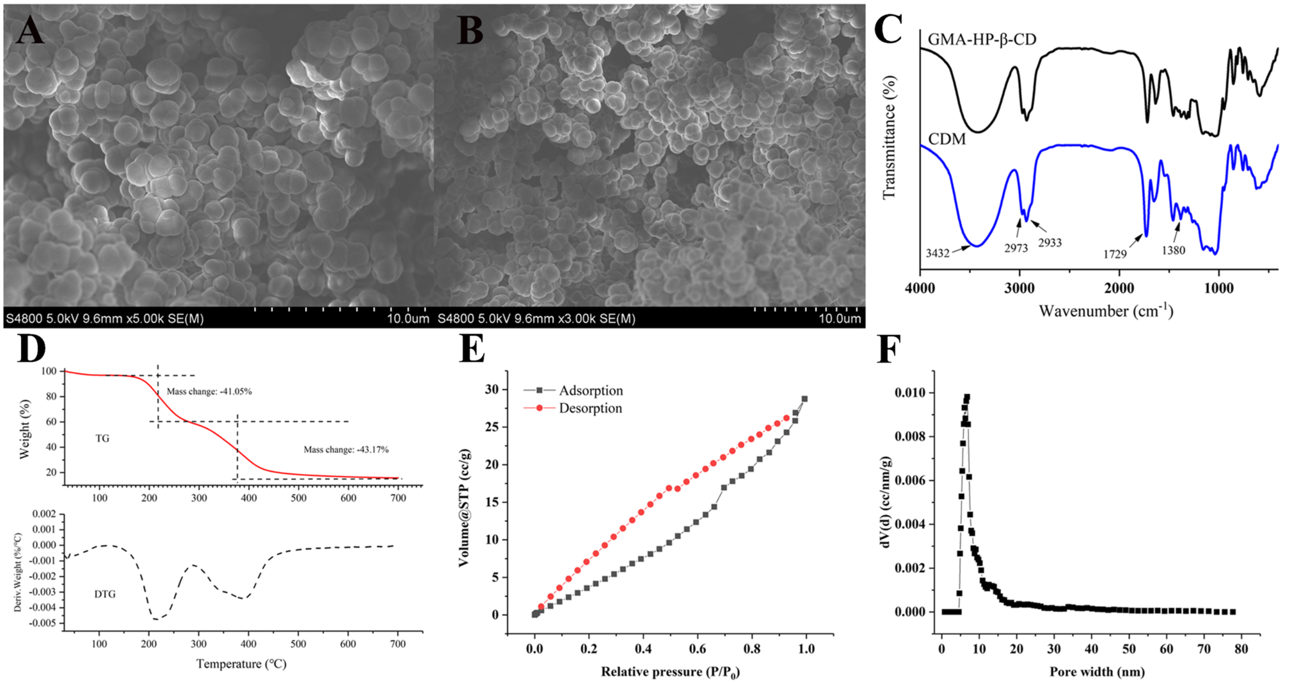

Fig. 2 SEM images of CDM (**A** and **B**); Fourier transform infrared (FT-IR) spectra of GMA-HP-β-CD and CDM (**C**); TG-DTG analysis of CDM (**D**); nitrogen adsorption–desorption isotherms (BET) of CDM (**E**); pore size distribution of CDM (**F**)

more effective in extracting three triazole fungicides from CDM than other solvents when we used acetone as the elution solvent. Considering that the extraction efficiency might be affected by hydrogen-bonding and electrostatic interactions, and acid or alkaline conditions might destroy the above-mentioned interactions between triazole fungicides and adsorbent, ammonia and formic acid were added in the desorption solvent for obtaining optimum desorption conditions. However, no significant change was observed in the extraction performance when the desorption solvent was added with acid or alkaline additive. The reason might be that the pure acetone was adequate to elute three triazole fungicides from the adsorbent. Thus, acetone was selected as the desorption solvent in the following tests.

Other extraction conditions, such as sample pH value, the amount of adsorbent, the volume of desorption solvent, adsorption time, and desorption time were optimized and shown in ESM. Based on univariate experiments, the response surface methodology (RSM) was used for subsequent experiment.

Considering that the RSM can effectively assess the effects of multiple variables separately or in combination with a small number of trials [21], five parameters (including sample solution pH, the amount of adsorbent, the volume of desorption solvent, adsorption time, and desorption time) were screened firstly using Plackett–Burman design based on the results from the univariate experiments. These parameters were studied at two levels coded as (− 1) for the low level and (+ 1) for the high level (Table S4 and S5). The data were investigated and analyzed with DESIGNEXPERT® Software trial version 12 (Stat-Ease, Inc., Minneapolis, USA). The response values (*Y*) were average recoveries of analytes, and all the trials were conducted in triplicate. The availability of the model was tested using the analysis of variances (ANOVA). As shown in Table S6, the *F*-value of model was 14.33 and the *P*-value was 0.0028, implying that the model was significant. The *P*-values were 0.0042, 0.0024, and 0.0040 for the volume of desorption solvent (*C*), adsorption time (*D*), and desorption time (*E*), respectively, implying that the three parameters had a significant impact on extraction efficiency. Moreover, the regression coefficient of determination (R^2) for the model of 0.9227 indicated that 92.27% of the variability of the response can be explained by this model. The final equation using the coding factors was expressed as below:

$$Y = 56.96 - 0.4125A + 2.34B + 4.45C - 4.99D + 4.50E \tag{1}$$

Next, three variables (including the volume of desorption solvent, adsorption time, and desorption time) were optimized by means of the RSM in this study. A three-level and three-factor Box-Behnken design was investigated and analyzed. The response values were average recoveries of analytes. So as to establish a more reliable model, the preliminary single-factor experiments were conducted to screen each variable range. Based on the results of preliminary experiments, the range of desorption solvent volume was 1 to 3 mL, adsorption time was 2 to 8 min, and desorption time was 2 to 8 min. The detailed BBD matrix was exhibited in Table S7. On the basis of multiple regression analysis of 17 experimental runs, a final equation was presented as following:

$$\begin{aligned} Y =& 92.37 + 8.17A + 2.65B + 4.83C \\ &- 7.10AB + 0.57AC + 14.02BC \\ &- 10.17A^2 - 16.92B^2 - 18.15C^2 \end{aligned} \tag{2}$$

The ANOVA test was used to analyze the significance and goodness-of-fit of the developed model (Table S8). As can be seen in Table S8, high *F*-value (133.87) and low *P*-value (< 0.0001) demonstrated that the model was remarkably significant. Moreover, an insignificant lack of fit with a *P*-value (0.4420) implied the model was proper. The coefficient of determination (R^2) and the adjusted determination coefficient (Adj. R^2) were 0.9942 and 0.9868, respectively, indicating that the established model was adequate, and the theoretical values and experimental results were compatible. In addition, the coefficient variation (C.V.%) value was 2.92, showing the regression model was reliable and reproducible. Hence, it can be concluded that the model can be used for experimental studies for the determination of paclobutrazol, hexaconazole, and diniconazole from water samples by CDM material.

Three-dimensional (3D) response surface plots were constructed by setting one variable at medium level and varying another two variables in a specific range (Fig. 3). Figure 3 indicates the existing interactions between two experimental variables and the relations between each variable and the response. Based on the obtained results, the three optimum parameters were 2.4 mL desorption solvent volume, 5 min adsorption time, and 5.5 min desorption time.

Adsorption studies

Adsorption kinetics, adsorption isotherms, and adsorption thermodynamics were studied. Respective text and figures are given in the ESM.

Regeneration and reusability

The desorption regeneration experiment is used to evaluate the recycling and reusability of CDM as an adsorbent. For recycle tests, 20 mg CDM was used to extract triazole fungicides from spiked water samples (20 mg L^{-1}, 10 mL) and then regenerated

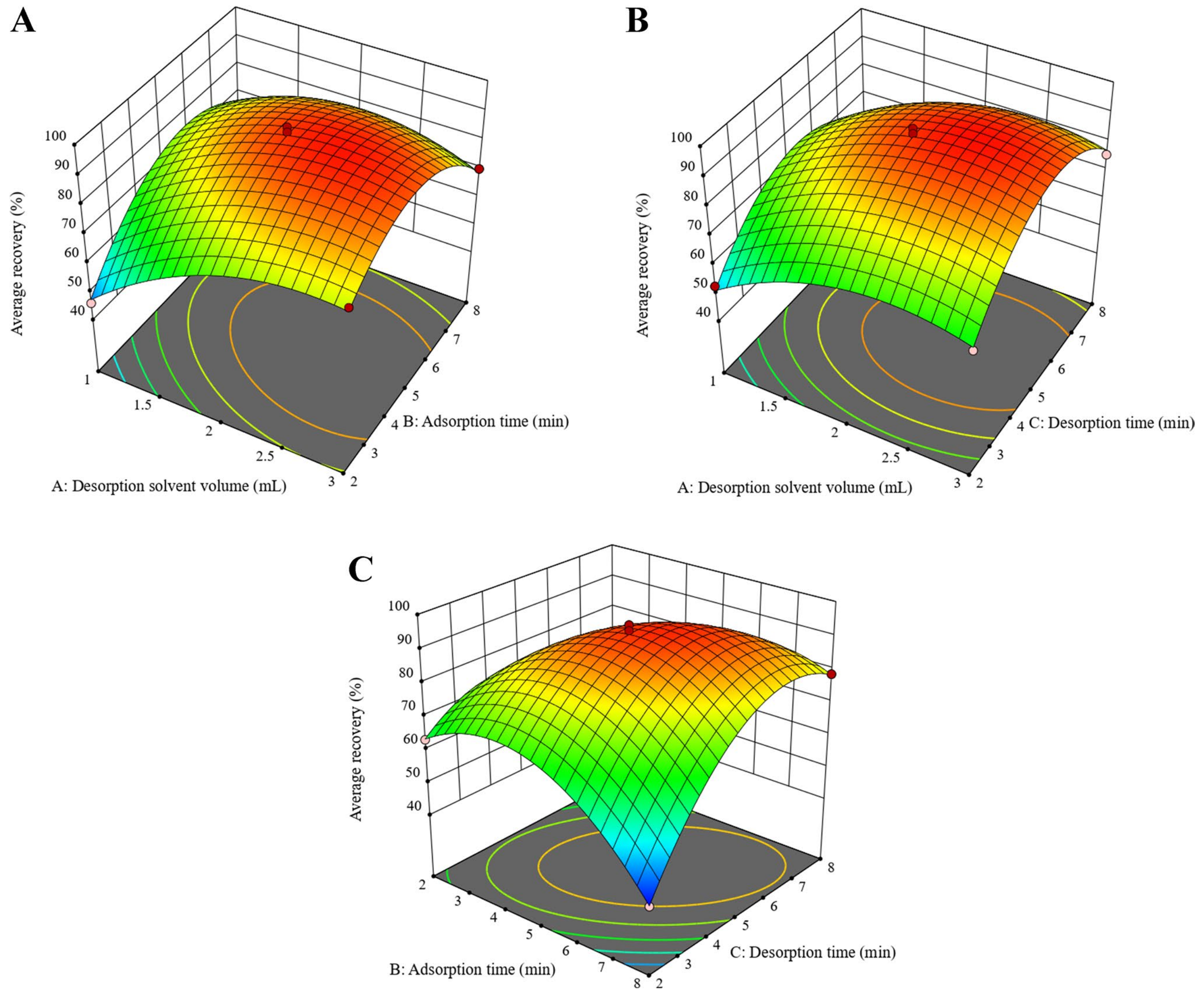

Fig. 3 3D response surface plots for the effect of three factors on the average recovery of three triazole fungicides: **A** adsorbent time vs. desorption solvent volume (desorption time, 5 min); **B** desorption time vs. desorption solvent volume (adsorption time, 5 min); **C** desorption time vs. adsorption time (desorption solvent volume, 2 mL)

by ultrasonication (10 min) with 5 mL acetone for two times. After centrifugation, the adsorbent was dried under nitrogen stream at 30 °C before its reuse. As shown in Fig. 4, for all studied triazole fungicides, the extraction recoveries were higher than 80% after 15 cycles. With increasing recycling times to 30, the analytes recoveries decreased gradually but remained over 70%, illustrating the good reusability of CDM for paclobutrazol, hexaconazole, and diniconazole adsorptions.

Method validation

As depicted in Fig. S5, blank samples were analyzed and the analytes were not found at concentrations higher than the limits of detection. For evaluating the applicability of proposed DSPE-HPLC–UV method in enantiomeric analysis of paclobutrazol, hexaconazole, and diniconazole, analytical performances including linearity, correlation coefficient (R^2), limits of detection (LODs), limits of quantitation (LOQs), repeatability, and accuracy were examined under optimum experimental conditions. The method validation results were given in Table 1. The linearity in the range of 3.2 ~ 800 μg L^{-1} for paclobutrazol, 2.5 ~ 800 μg L^{-1} for hexaconazole, 2.0 ~ 800 μg L^{-1} for diniconazole with satisfactory correlation coefficients (R^2) from 0.9996 to 0.9999 for paclobutrazol, 0.9978 to 0.9994 for hexaconazole, and 0.9997 to 0.9999 for diniconazole was obtained. The LODs range from 0.6 to 1.0 μg L^{-1} and LOQs from 2.0 to 3.2 μg

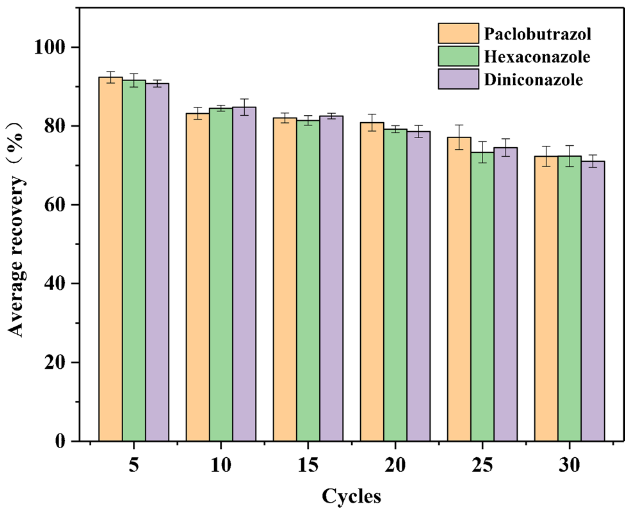

Fig. 4 Reusability of three triazole fungicides adsorption on CDM during 30 adsorption–desorption cycles. Conditions: adsorbent 20 mg, sample volume 10 mL, adsorption time 5 min, acetone as desorption solvent, desorption solvent volume 2.4 mL, desorption time 5.5 min

L^{-1}, which are based on signal-to-noise (S/N) ratios of 3 and 10, respectively. Furthermore, the precision was evaluated with intra-day repeatability (RSD ≤ 3.7%) and inter-day repeatability (RSD ≤ 5.1%). Also, the satisfactory average spiked recoveries of studied analytes were in the range of 86.7 ~ 105.8%. The above results fulfilled the criteria of SANTE/12682/2019 (the recoveries, 70 ~ 120%; precision RSD value, < 20%) [22]. Therefore, the established method can be applied for the enantioselective determination of paclobutrazol, hexaconazole, and diniconazole in water samples.

Wider scope of the adsorbent

In this study, one neonicotinoid insecticide (dinotefuran), one triazole fungicide (epoxiconazole), and two imidazole antifungals (tioconazole and fenteconazole) were used as coexisting chemically related species to study their effects on the adsorption performance of CDM. When coexisting analytes of dinotefuran, epoxiconazole, tioconazole, and fenteconazole were added to three chiral pesticides solutions (Fig. S6A), the Q_e values of paclobutrazol, hexaconazole, and diniconazole changed to approximately 8.59 ~ 8.88 mg g^{-1}, which did not significantly differ from those without addition of coexisting compounds. Therefore, the presence of chemically related species in the aqueous solution did not significantly affect the adsorption ability of CDM towards paclobutrazol, hexaconazole, and diniconazole.

To explore the wider application scope, the CDM was further used to adsorb and extract dinotefuran, epoxiconazole, tioconazole, and fenteconazole (Fig. S6 and Fig. S7). Since dinotefuran was hardly adsorbed by CDM at the studied concentration level, it was not shown in Fig. S6B, S6C, and S7. The results showed that epoxiconazole, tioconazole, and fenteconazole standards were able to elute peaks, and the method can be applied to extract and enrich analytes from their spiked samples successfully (Fig. S7).

Then, we studied the adsorption mechanisms of CDM (see ESM). The combination mechanisms (Fig. S8) including the electrostatic interaction, hydrogen-bonding interaction, and host–guest inclusion hydrophobic interaction endow CDM adsorbent the exceptional adsorption ability. The compounds with smaller sizes like dinotefuran would be replaced due to the less stability of inclusion complex with CD cavity. Other compounds including four triazole fungicides and two imidazole antifungals, which owned benzene group, triazole group, or imidazole group, suggesting that the molecular recognition selective towards these groups. These were probably the chemical groups to be interacted with the polymer, verifying the good selectivity of CDM.

The adsorption of epoxiconazole, tioconazole and fenteconazole could be well adapted to the pseudo-second-order kinetic model and Langmuir model. In Fig. S6 and Table S12, CDM adsorbent has good adsorption ability for epoxiconazole, tioconazole, and fenteconazole, with the maximum adsorption capacity being 27.933 mg g^{-1}, 41.152 mg g^{-1}, and 42.843 mg g^{-1}, respectively. Furthermore, the adsorption ability of CDM was almost completely preserved after 10 cycles of reuse (Fig. S6D). These results demonstrated that CDM was a promising adsorbent for reversible adsorption and desorption of triazole fungicides and imidazole antifungals.

Analytical performance and comparison with other methods

The method was compared with previous methods for the determination of triazole fungicides in water samples, which is summarized in Table S13. Compared to the DSPE, the commercially available SPE has the main disadvantages of longer extraction time (25 ~ 60 min), using large volumes of organic solvents (> 15 mL) and adsorption amount (500 mg) [23, 24]. Kharbouche et al. synthesized novel nanomaterial and used it as SPE adsorbent. The established method overcomes the drawbacks of large volumes of loading samples and adsorption amount, while the problem of column blockage cannot be ignored [25]. Nowadays, many researchers using MSPE method, the introduction of magnetic nanoparticle, could simplify the extraction process utilizing an external magnetic field [5, 26–29]. However, the chromatographic column may be contaminated by nano-magnetic adsorbents

Table 1 Performance parameters of three chiral pesticides

Analyte	Matrices	Linearity range (μg L^{-1})	Regression equations	$S_{y/x}$	R^2	LOD (μg L^{-1})	LOQ (μg L^{-1})	Repeatability (RSD%)		Accuracy (recovery, %)
								Intra-day ($n=9$)	Inter-day ($n=27$)	
Paclobutrazol E1[a]	Lake water	3.2–800	$y=(880.97\pm1.93)x+(1975.97\pm467.44)$	809	0.9998	1.0	3.2	3.7/2.5/3.3	4.2/3.8/3.3	99.7/99.1/98.2
	Tap water	3.2–800	$y=(882.95\pm1.56)x-(1873.60\pm378.51)$	655	0.9999	1.0	3.2	3.0/2.9/2.6	4.5/3.2/4.3	90.3/92.8/95.4
	Drinking water	3.2–800	$y=(906.92\pm8.02)x-(1174.77\pm1941.14)$	3319	0.9996	1.0	3.2	3.7/2.5/3.3	3.2/2.8/4.7	102.5/94.1/95.2
Paclobutrazol E2[b]	Lake water	3.2–800	$y=(837.91\pm3.78)x+(2611.43\pm914.38)$	1583	0.9998	1.0	3.2	2.4/2.6/3.5	2.2/3.2/2.9	105.8/103.0/101.6
	Tap water	3.2–800	$y=(883.14\pm2.25)x-(1984.93\pm544.28)$	942	0.9998	1.0	3.2	2.0/2.7/3.1	3.6/3.2/2.5	89.6/94.5/95.8
	Drinking water	3.2–800	$y=(904.84\pm7.91)x-(1087.48\pm1727.56)$	2954	0.9997	1.0	3.2	1.7/2.2/2.8	2.1/3.4/3.9	99.5/92.8/93.2
Hexaconazole E1	Lake water	2.5–800	$y=(1027.51\pm14.84)x+(6291.46\pm3590.88)$	6219	0.9992	0.8	2.5	2.1/2.0/3.3	4.5/3.9/4.3	98.1/98.3/88.3
	Tap water	2.5–800	$y=(994.11\pm21.52)x+(4761.37\pm4931.46)$	8980	0.9981	0.8	2.5	2.8/2.2/3.5	4.0/3.2/3.1	95.2/90.8/97.4
	Drinking water	2.5–800	$y=(1055.90\pm16.46)x+(3289.05\pm3771.86)$	6868	0.9990	0.8	2.5	1.6/2.2/3.0	2.5/3.4/4.2	101.5/93.5/95.7
Hexaconazole E2	Lake water	2.5–800	$y=(1022.88\pm15.20)x+(3237.22\pm3677.00)$	6368	0.9991	0.8	2.5	2.3/2.5/3.7	3.3/2.8/4.0	92.3/86.8/88.4
	Tap water	2.5–800	$y=(981.29\pm23.31)x+(5844.20\pm5341.39)$	9726	0.9978	0.8	2.5	2.1/2.4/3.5	3.0/2.2/3.2	90.5/93.6/99.4
	Drinking water	2.5–800	$y=(1033.24\pm13.10)x+(3700.74\pm3001.16)$	5465	0.9994	0.8	2.5	1.8/2.0/3.6	3.0/2.9/4.0	102.8/96.2/99.0
Diniconazole E1	Lake water	2.0–800	$y=(1868.91\pm9.09)x+(2249.39\pm2200.01)$	3810	0.9998	0.6	2.0	2.9/2.3/2.5	5.1/2.6/3.0	95.3/97.4/86.7
	Tap water	2.0–800	$y=(1742.50\pm12.13)x+(7510.43\pm2933.33)$	5080	0.9998	0.6	2.0	2.3/2.1/2.8	4.0/2.2/3.6	98.2/94.8/90.7
	Drinking water	2.0–800	$y=(1771.02\pm8.91)x+(5757.87\pm2156.42)$	3735	0.9999	0.6	2.0	2.1/1.4/1.8	2.6/4.2/3.5	101.3/102.5/96.7
Diniconazole E2	Lake water	2.0–800	$y=(1869.32\pm8.66)x+(2087.09\pm2095.21)$	3629	0.9998	0.6	2.0	2.7/2.6/1.7	3.6/2.8/3.2	96.0/91.9/91.6
	Tap water	2.0–800	$y=(1728.86\pm14.23)x+(6745.36\pm3442.76)$	5963	0.9997	0.6	2.0	2.2/1.6/2.9	3.8/2.5/3.2	99.2/92.8/96.5
	Drinking water	2.0–800	$y=(1759.12\pm9.38)x+(5654.96\pm2269.06)$	3930	0.9998	0.6	2.0	1.9/3.0/2.8	4.5/2.9/3.6	100.4/101.2/95.3

[a] The first-eluted enantiomer

[b] The second-eluted enantiomer

$S_{y/x}$, SD of residuals.

Relative standard deviation of the intra-day precision at the concentrations level of 20 μg L^{-1} ($n=3$), 250 μg L^{-1} ($n=3$), and 500 μg L^{-1} ($n=3$).

Relative standard deviation of the inter-day precision at a concentration level of 20 μg L^{-1} ($n=3$ in each day), 250 μg L^{-1} ($n=3$ in each day), and 500 μg L^{-1} ($n=3$ in each day) for 3 days.

Table 2 Determination and recoveries of three chiral pesticides in actual samples

Analyte	Spiked ($\mu g\ L^{-1}$)	Lake water		Tap water		Drinking water	
		Recovery (%)	RSD (%)	Recovery (%)	RSD (%)	Recovery (%)	RSD (%)
Paclobutrazol E1[a]	0	-[c]	-	-	-	-	-
	20	97.9	2.5	90.2	4.8	91.5	3.3
	500	93.9	3.6	94.7	2.5	93.8	2.7
Paclobutrazol E2[b]	0	-	-	-	-	-	-
	20	99.8	4.5	90.5	3.6	93.3	2.5
	500	97.2	3.8	94.5	3.8	94.1	3.0
Hexaconazole E1	0	-	-	-	-	-	-
	20	93.5	2.6	91.1	2.7	96.1	3.4
	500	93.3	4.6	93.4	2.4	94.9	2.4
Hexaconazole E2	0	-	-	-	-	-	-
	20	89.8	3.6	85.5	2.4	97.6	2.9
	500	90.8	2.8	88.5	3.8	97.2	3.2
Diniconazole E1	0	-	-	-	-	-	-
	20	90.1	3.5	93.5	4.8	90.0	3.4
	500	89.6	3.6	93.0	3.9	86.4	2.8
Diniconazole E2	0	-	-	-	-	-	-
	20	90.5	3.6	95.5	3.0	95.7	3.0
	500	93.6	3.9	98.2	3.6	93.7	3.2

[a] The first-eluted enantiomer. [b] The second-eluted enantiomer. [c] Lower than the LODs

[30]. Certainly, using LC–MS/MS method can obtain a lower LOQ of the method; it also has disadvantages of high cost and the complicated operation. Compared with most reported methods, the established DSPE-HPLC–UV technique exhibits the lower adsorbent amount (20 mg), sample amount (10 mL), and extraction time (10.5 min) [5, 23–28]. Moreover, the developed method has a lower RSDs (≤ 5.1), indicating its good precision. Meanwhile, CDM adsorbent shows good reusability which can be recycled 15 times with recoveries over 80% (Fig. 4). These results demonstrated that the procedure is simple and fast with acceptable linear range and comparable quantitation limit.

Importantly, the synthesis method of the present work overcomes the solubility problem of hydroxypropyl β-cyclodextrin, which is to form cross-linked polymer. As mentioned in the "Introduction" section, this method is promising compared with immobilization onto water-insoluble support methods. On the other hand, the preparation process of CDM does not have tedious steps (based on one-step) with much shorter preparation time compared with other hybrid CD-based adsorbents [31, 32].

In summary, the developed method is handy and suitable for the analysis of paclobutrazol, hexaconazole, and diniconazole in water samples. However, this method also has disadvantages: it needs equipment to operate, such as centrifuging and ultrasonicating.

Application to real samples

The developed DSPE-HPLC–UV method was applied in analyzing paclobutrazol, hexaconazole, and diniconazole in water samples (lake water, tap water, and drinking water). Three triazole fungicides residual concentration in samples were below the LODs of method; hence, the actual samples were spiked with the concentration levels of 20 $\mu g\ L^{-1}$ and 500 $\mu g\ L^{-1}$ to evaluate the accuracy and applicability of the analytical method. As can be observed in Table 2, the recoveries of paclobutrazol, hexaconazole, and diniconazole in all water samples ranged from 85.5 to 99.8%, with RSDs of 2.4 ~ 4.8%. These results indicated that the developed DSPE-HPLC–UV method was accurate and repeatable.

Conclusion

A reliable method based on DSPE and chiral HPLC–UV for simultaneous determination of three chiral triazole fungicides (paclobutrazol, hexaconazole, and diniconazole) was proposed and validated. The cross-linked HP-β-CD material (CDM) was prepared and firstly applied for extracting three chiral triazole fungicides in water samples. Compared with the reported methods, the established method had good linearity, satisfactory recoveries, comparable LOQs, and high precision in the determination of paclobutrazol, hexaconazole, and diniconazole in water samples. However, it has some limitations; it needed equipment to centrifuge and ultrasonicate. In summary, the presented study provides a convenient and effective method for monitoring triazole fungicides in water samples, which also contributes to reach the urgent requirement of enantiomeric determination of chiral pesticides in environmental analysis. Moreover, this work breaks the limitation of hybrid CD polymers for chromatographic application and paves a new way to extraction application. Ongoing work is aimed to improve the adsorbent synthesis procedure for better detecting the target analytes in the environmental or food samples through the combination of other technologies.

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Declarations

Competing interests The authors declare no competing interests.

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