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A multi-residue chiral liquid chromatography coupled with tandem mass spectrometry method for analysis of antifungal agents and their metabolites in aqueous environmental matrices

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The presence and fate of antifungal agents in the environment have hardly been investigated. This is despite the increased usage of antifungal agents and higher prevalence of antifungal resistance. Stereochemistry of antifungal agents has been largely overlooked due to lack of analytical methods enabling studies at the enantiomeric level. This paper introduces a new analytical method for combined separation of achiral and chiral antifungal agents and their metabolites with the utilization of chiral chromatography coupled with triple quadrupole tandem mass spectrometry to enable comprehensive profiling of wide-ranging antifungal agents and their metabolites in environmental matrices. The method showed very good linearity and range (r^2 > 0.997), method accuracy (61–143%) and precision (3–31%) as well as low (ng L^{-1}) MQLs for most analytes. The method was applied in selected environmental samples. The following analytes were quantified: fluconazole, terbinafine, *N*-desmethyl-carboxyterbinafine, tebuconazole, epoxiconazole, propiconazole and *N*-deacetyl ketoconazole. They were predominantly present in the aqueous environment (as opposed to wastewater) with sources linked with animal and plant protection rather than usage in humans. Interestingly, chiral fungicides quantified in river water were enriched with one enantiomer. This might have consequences in terms of their ecological effects which warrants further study.

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1. Introduction

Antifungal agents are widely used as pharmaceuticals, in household products and in agriculture, which has an impact on the environment. The global reporting of fungal diseases has increased significantly in recent years because of an increasing population leading to a rise in the use of antifungal drugs.[1] Generally, there are 3 classes of antifungal agents used in medicines. These are azoles, polyenes, and allylamines.[2] Azole antifungal agents can also be used in an anti-dandruff shampoo[3] and for material preservation in paints, plastics, sealants, wall adhesives, binders, papers, or polymerised materials, such as leather, rubber, and paper.[4] As a result, antifungal agents, especially azoles, have emerged as a new group of pollutants in the environment and a risk to human health due to unintentional (non-clinical) exposure.[5,6] Furthermore, fungicides are commonly used on fruits and vegetables because fungal diseases are a major threat to crop production. The use of fungicides improves crop yield, quality and shelf-life. In the European Union (EU), fungicide sales constitute more than 40% of the total pesticide sales. In wine-growing regions, fungicides may account for more than 90% of all pesticide applications. Moreover, the trend of fungicide use is predicted to rise because of climate change, development of antifungal resistance, and invasive fungal species.[7]

Antifungal agents are found in surface waters and wastewater at up to μg L^{-1} levels.[8] Although antifungal drugs and fungicides are determined at relatively low levels in the environment, there are effects of antifungal agents on the aquatic environment, humans, and animals, especially antifungal resistance, that require immediate attention. The impact of antifungal agents on the aquatic environment has been widely reported. These include effects on the survival, growth, molting, and reproduction of invertebrates. The growth rates of plants and mortality of fish were also the result of contamination with antifungal agents.[8,9] Moreover, azole agents were linked with the decrease in the formation of estradiol and testosterone in humans.[10]

Worldwide emergence of resistance to antifungal drugs has been reported. The use of antifungal agents for the treatment of fungal diseases in animals, humans and plants can lead to the development of antifungal resistance.[1] Resistance in *Candida* spp. to triazole antifungal pharmaceuticals has increased in patients, including patients with AIDS, because triazole agents were used widely for prophylaxis and treatment.[11] In addition,

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azole-resistance in *Aspergillus fumigatus* has been found in Western European countries as well as in the Asia–Pacific due to the use of fungicides in agriculture to treat cereal crops and wheat. Thus, the risk of endocrine effects was considered in farmers and greenhouse workers from preparing azole spray mixtures.[4]

An important overlooked phenomenon characteristic of many antifungal agents is their chirality. Enantiomers of the same drug have different biological properties[12] leading to enantiomer-dependent effects on human metabolism, as well as occurrence in and biological effects on the environment.[13–15] However, despite several papers published on the enantiomer-dependent fate and effects of several pharmaceuticals, the role of stereochemistry of most antifungal agents in the context of their fate and effect remains unknown. One of the reasons for this is the lack of available sensitive and selective analytical methods that can differentiate between enantiomers of the same pharmaceutical. Though several chiral methods have been developed to analyse chiral pharmaceuticals in the environment, high-performance liquid chromatography (HPLC) is the most commonly used technique. Chiral drugs are present in the environment at trace levels and in very complex matrices. Therefore, HPLC tandem mass spectrometry with triple quadrupole (QqQ) needs to be used for sensitive targeted identification and quantification. High resolution mass spectrometry such as QTOF can also be used for retrospective analysis and suspect screening, albeit with usually lower sensitivity. There are many factors which influence chiral recognition. These include the type of chiral selector, as well as mobile phase composition. HPLC-MS/MS has been applied in the analysis of enantiomers of antifungal agents in human serum using albumin (HSA), α1-acid glycoprotein (AGP), cellulose, and amylose columns. The occurrence of antifungal agents and their enantiomers was reported in raw wastewater, sludge, soil, and fruit samples.[16–24]

Although the presence of antifungal agents in the environment has become a major clinical and public health problem,[1] only a few reports have been published on the investigations of antifungal agents in China,[16] Germany,[25] Switzerland,[8] Ireland,[26] Belgium,[27] Spain[28] and UK.[29] Additionally, there is a lack of research in metabolism and transformation of chiral and achiral antifungal agents in the environment. Thus, this paper's objective is to introduce a new analytical method for combined separation of achiral and chiral antifungal agents and their metabolites with the utilization of chiral chromatography coupled with triple quadrupole tandem mass spectrometry to enable comprehensive profiling of wide-ranging antifungal agents and their metabolites in environmental matrices.

2. Materials and methods

2.1 Materials

HPLC-grade methanol (MeOH), acetonitrile (ACN), isopropanol (IPA), ammonium formate (NH_4HCO_2), ammonium acetate (NH_4OAc), formic acid (≥96%) and dimethyl sulfoxide (DMSO) were purchased from Sigma Aldrich (UK). Ultrapure water was obtained from a Milli-Q system (UK). Achiral antifungal agents clotrimazole, fluconazole, hydroxy-tebuconazole, naftifine, prochloraz and terbinafine were purchased from Sigma Aldrich (UK). *N*-Desmethyl-carboxyterbinafine was purchased from Toronto Research Chemicals (Canada). Chiral antifungal agents used as racemates, (±)-econazole, (±)-ketoconazole, (±)-miconazole, (±)-propiconazole, (±)-prothioconazole-desthio, (±)-tebuconazole and hydroxy-tebuconazole, were purchased from Sigma Aldrich. (±)-Epoxiconazole, (±)-*N*-deacetyl ketoconazole and (±)-prothioconazole were purchased from Toronto Research Chemicals (UK). Stereoisomerically pure 2*R*,3*S*-voriconazole was purchased from Sigma Aldrich (UK). The deuterated standards terbinafine-d7, naftifine-d3, (±)-miconazole-d5, and (±)-econazole-d6 were purchased from Toronto Research Chemicals (Canada). (±)-Ketoconazole and (±)-voriconazole-d3 were purchased from Sigma Aldrich (UK). All chemicals used were of high purity (≥97%). The target antifungal agents in this work were selected based on UK prescription data, usage of fungicides in the UK and occurrence in the environment. Table 1 shows the analytes with their CAS number, structure, molecular formula, molecular weight, pK_a, and log *P* along with their application.

2.2 Sample collection and preparation

River water, wastewater effluent and influent samples were collected in South West England in PTFE bottles as 24 h flow proportional composite samples (influent and effluent wastewater) or grab samples (river water) and placed in a cool box with ice during the transport from the site of sampling to the laboratory. Once in the laboratory, and after adjustment to pH 7 and addition of internal standards (to give the following concentrations: 1 ng mL^{-1} in wastewater and 0.5 ng mL^{-1} in river water or 100 ng mL^{-1} in SPE extracts), samples were subject to filtration and solid-phase extraction (SPE) as described below.

2.3 Solid phase extraction

SPE was carried out using Oasis HLB cartridges (60 mg, Waters, UK). The SPE protocol is discussed in detail elsewhere.[32] Briefly after filtration through a GF/F filter (0.7 μm), 100 mL of river water or 50 mL wastewater was loaded into Oasis HLB cartridges (at 3 mL min^{-1}) and pre-conditioned with 2 mL of MeOH and 2 mL of H_2O (at 1 mL min^{-1}). The cartridges, after drying under vacuum for 30 min, were then eluted with 4 mL MeOH at 1 mL min^{-1}. The obtained eluate was subject to evaporation under nitrogen using a TurboVap evaporator (40 °C, N_2, <5 psi) and reconstituted with 500 μL mobile phase (NH_4OAC/MeOH 1 : 99).

2.4 Chiral liquid chromatography-mass spectrometry (cLC-MS/MS)

Chromatographic separation was carried out using a chiral CHIRALCEL® OZ-RH column (5 μm particle size, *L* × I. D.: 15 cm × 2.1 mm, Chiral Technologies, France) with a 2.0 mm × 2.0 mm guard filter (Chiral Technologies, France). The MS system was a triple quadrupole mass spectrometer (Xevo TQD, Waters, Manchester, UK) equipped with an electrospray

Table 1 List of compounds and their chemical properties[30,31]

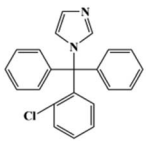
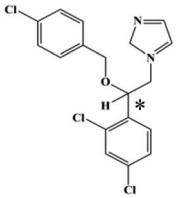
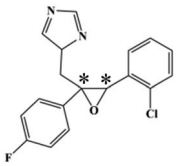
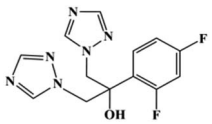
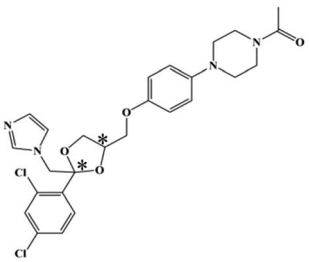
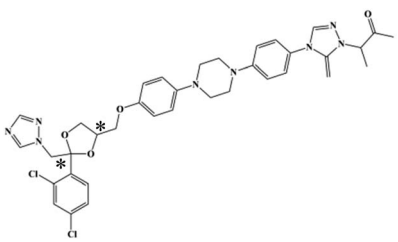
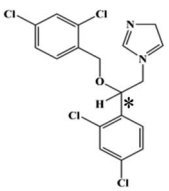
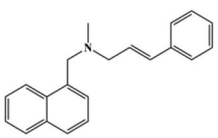
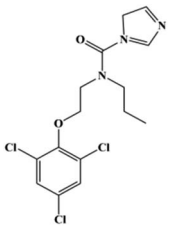
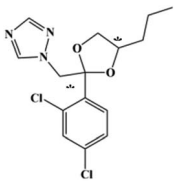
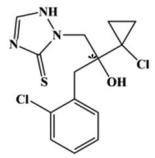
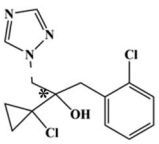
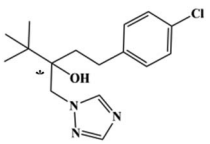
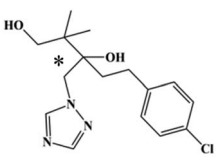
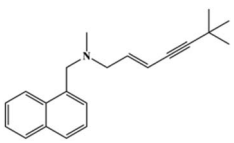
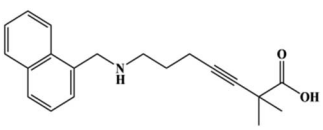
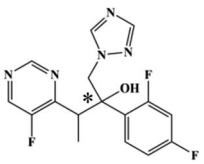
Compounds	Structure	CAS	Formula	M_W (g mol^{-1})	pK_a	Log P	Application
Clotrimazole		23593-75-1	$C_{22}H_{17}ClN_2$	344.8	4.1	0.5	Human or animal
Econazole		27220-47-9	$C_{18}H_{15}Cl_3N_2O$	381.7	6.77	5.35	Human or animal
Epoxiconazole		133855-98-8	$C_{17}H_{13}ClFN_3O$	329.8	—	—	Crops
Fluconazole		86386-73-4	$C_{13}H_{12}F_2N_6O$	306.27	1.76	0.4	Human or animal
Ketoconazole		65277-42-1	$C_{26}H_{28}Cl_2N_4O_4$	531.4	3.96	4.35	Human or animal
N-Deacetyl ketoconazole		67914-61-8	$C_{24}H_{26}Cl_2N_4O_3$	489.39	—	—	Metabolite of ketoconazole
Miconazole		22916-47-8	$C_{18}H_{14}Cl_4N_2O$	416.1	6.77	6.1	Human or animal
Naftifine		65472-88-0	$C_{21}H_{21}N$	287.4	9.08	5.4	Human or animal

Table 1 (*Contd.*)

Compounds	Structure	CAS	Formula	M_W (g mol^{-1})	pK_a	Log *P*	Application
Prochloraz		67747-09-5	$C_{15}H_{16}Cl_3N_3O_2$	376.7	3.8	3.5	Crops
Propiconazole		60207-90-1	$C_{15}H_{17}Cl2N3O_2$	342.2	1.09	3.72	Crops
Prothioconazole		178928-70-6	$C_{14}H_{15}Cl_2N_3OS$	344.3	6.9	2.0	Crops
Prothioconazole-desthio		120983-64-4	$C_{14}H_{15}Cl_2N_3O$	312.19	13.25	—	Metabolite of prothioconazole
Tebuconazole		80443-41-0	$C_{16}H_{22}ClN_3O$	307.82	5.0	3.7	Crops
Hydroxy-tebuconazole		212267-64-6	$C_{16}H_{22}ClN_3O_2$	323.82	—	—	Metabolite of tebuconazole
Terbinafine		78628-80-5	$C_{21}H_{26}ClN$	327.9	8.86	5.51	Human or animal
N-Desmethylcarboxy terbinafine		99473-15-1	$C_{20}H_{21}NO_2$	307.39	—	—	Metabolite of terbinafine
Voriconazole		137234-62-9	$C_{16}H_{14}F_3N_5O$	349.31	12.71	1	Human or animal

ionisation source (ESI) in positive mode with an optimised capillary voltage of 3 kV, source temperature of 350 °C, desolvation temperature of 350 °C and desolvation gas flow of 650 L h^{-1}. Nitrogen, supplied by a high purity nitrogen generator (Peak Scientific, UK), was used as a nebulising and desolvation gas. Argon (99.999%) was used as a collision gas. The system was controlled using MassLynx 4.1 software (Waters, UK). The data processing software was TargetLynx (Waters, Manchester, UK).

2.5 SPE-cLC-MS/MS performance

2.5.1. cLC-MS/MS performance. The instrument linearity and concentration range were assessed using a 21-point calibration curve with a concentration range of 0 to 1000 ng mL^{-1}. Internal standards were used at 100 ng mL^{-1}. All calibration standard solutions were run in triplicate. Standard stock solutions were prepared in methanol, acetonitrile and DMSO at 1 mg mL^{-1}. Mixed working solutions containing all analytes were prepared from stock solutions at different concentration levels by dilution with the mobile phase.

The instrumental limit of detection (IDL) and the instrumental limit of quantification (IQL) were measured from the calibration curve as the lowest measured concentration with an average peak signal to noise ratio (S/N) greater than or equal to 3 (S/N $\geq$ 3) across three repeat injections. The IQL was determined as the lowest measured concentration with an average S/N $\geq$ 10 across three repeat injections.

The enantiomeric fraction (EF) was calculated from the concentration of the first- (E_1) and the second-eluted enantiomer (E_2) of chiral compounds from eqn (1). The EF provided the relative concentration of enantiomers of chiral compounds as follows: EF equals 1 or 0 in the case of an enantiomerically pure compound, and 0.5 in the case of a racemate.[33]

$$\mathrm{EF} = \frac{[E_1]}{[E_1 + E_2]} \quad (1)$$

The resolution of enantiomeric pairs (R_s) was calculated from the retention times of the first- (t_1) and the second-eluted enantiomer (t_2) and the widths of the responses at the baseline (w_1, w_2) on the basis of the following equation:[33]

$$R_s = \frac{t_2 - t_1}{0.5(w_1 + w_2)} \quad (2)$$

Instrument accuracy and precision were calculated from eqn (3) and (4). Standard solutions were spiked in the mobile phase at 10, 100 and 500 ng mL^{-1}. The accuracy and precision were determined by replicate measurements of the same concentrations (three times) within one day (intra-day) ($n = 3$) and over different three day periods (inter-day) ($n = 9$) where x is the theoretical concentration and x_{1-3} is the concentration measured in each sample.[33]

$$\text{Intra-day accuracy } (\%) = \left(\frac{x}{\text{average}(x_1, x_2, x_3)}\right) \times 100 \quad (3)$$

$$\text{Intra-day precision } (\%\ \text{RSD}) = \left(\frac{\sigma_{x_{1-3}}}{\text{average}(x_1, x_2, x_3)}\right) \times 100 \quad (4)$$

2.5.2. SPE-cLC-MS/MS performance. Relative recovery was calculated by comparison of analyte concentrations in river

Table 2 MRM transitions and associated optimised cone voltages (CVs) and collision energy (CE) for standards to be analysed

Compounds	CV/CE	MRM1	CV/CE	MRM2
Clotrimazole	49/26	277.1 > 165.0	49/31	277.1 > 241.0
Econazole	35/29	381.7 > 125.0	35/18	381.7 > 193.0
Econazole d6	45/50	387 > 130.0		
Epoxiconazole	44/25	330.1 > 121.0	44/18	330.1 > 141.0
Fluconazole	30/16	307.1 > 238.0	30/18	307.1 > 220.0
Ketoconazole	32/35	531.2 > 219.0	32/35	531.2 > 489.3
Ketoconazole d4	48/50	535.2 > 181.2		
N-Deacetyl ketoconazole (DAK)	32/35	489.2 > 178.2	32/35	489.2 > 136.1
Miconazole	30/25	415.0 > 69.0	30/32	415.0 > 159.0
Miconazole d5	40/50	421.0 > 161.0		
Naftifine	30/15	288.0 > 117.0	30/18	288.0 > 141.0
Naftifine d3	30/15	291.43 > 118.0		
Prochloraz	18/13	376.1 > 308.0	18/17	376.1 > 266.0
Propiconazole	44/30	342.0 > 158.9	44/24	342.0/69.0
Prothioconazole	42/27	341.9 > 306.0	42/15	341.9/99.8
Prothioconazole-desthio	42/27	312.1 > 124.9		
Tebuconazole	25/33	308.2 > 125.0	25/22	308.2 > 151
Hydroxy-tebuconazole	25/33	324.2 > 125.0	25/33	324.2 > 70.0
Terbinafine	30/18	292.2 > 105.0	30/19	292.2 > 141.2
Terbinafine d7	40/20	299.2 > 121.0		
N-Desmethyl-carboxyterbinafine	30/18	308.2 > 141.1	30/18	308.2 > 123.1
Voriconazole	25/15	350.1 > 127	25/15	350.1 > 224
Voriconazole d3	36/45	353.3 > 127		

water or wastewater (analyte conc.$_x$) to analyte concentrations in the mobile phase (analyte conc.$_{QC_x}$). The concentration of analyte in the blank river water and wastewater samples (analyte conc.$_0$) was subtracted from the measured concentration, to account for analyte already present in the matrix (eqn (5)). Recoveries were determined in triplicate at three different

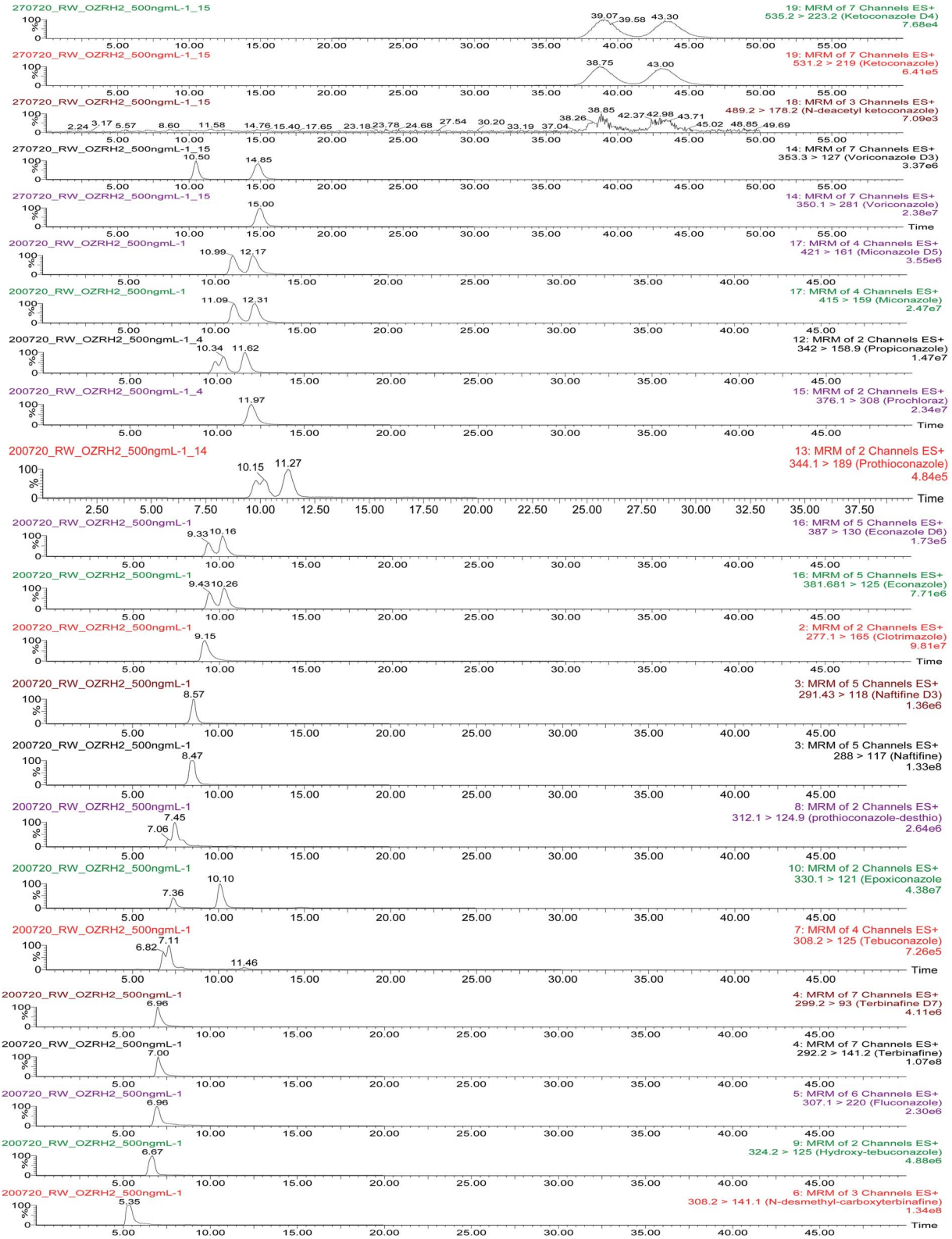


Fig. 1 Separation of antifungal agents by cLC-MS/MS.

Table 3 Instrumental performance data for selected antifungals and metabolites in the mobile phase

Compounds	Retention time	Linear range (ng mL^{-1})	R^2	EF	R_s	IDL (ng mL^{-1})	IQL (ng mL^{-1})	Intra-day		Inter-day	
								Accuracy [%]	Precision [%]	Accuracy [%]	Precision [%]
Clotrimazole	9.3	0.02–500	0.997			0.007	0.02	107	7	111	11
		600–1000	0.997								
Econazole E_1	9.52	0.08–500	0.997	0.52	0.56	0.02	0.08	103	2	104	5
		600–1000	0.997								
Econazole E_2	10.4	0.04–500	0.997			0.002	0.04	95	1	96	5
		600–1000	0.997								
Epoxiconazole E_1	7.41	0.03–500	0.997	0.55	1.87	0.01	0.03	98	11	92	9
		600–1000	0.998								
Epoxiconazole E_2	10.24	0.02–500	0.995			0.006	0.02	97	9	98	9
		600–1000	0.997								
Fluconazole	6.96	0.1–500	0.997			0.04	0.1	95	2	105	2
		600–1000	0.997								
Ketoconazole E_1	33.69	1.2–400	0.998	0.52	0.65	0.4	1.2	96	2	96	5
		500–1000	0.997								
Ketoconazole E_2	37.46	0.9–400	0.991			0.2	0.9	115	1	111	7
		500–1000	0.997								
N-Deacetyl ketoconazole (DAK) E_1	33.54	21.3–400	0.997								
		500–100	0.998	0.49	0.61	6.4	21.3	101	6	102	5
N-Deacetyl ketoconazole (DAK) E_2	39.22	38.6–400	0.997								
		500–100	0.997			11.6	38.6	90	2	94	8
Miconazole E_1	11.24	0.03–500	0.997	0.52	0.54	0.01	0.03	111	4	101	9
Miconazole E_2	12.46	0.03–500	0.993			0.01	0.03	108	1	108	2
Naftifine	8.17	0.004–1000	0.997			0.001	0.004	93	2	88	4
Prochloraz	10.89	0.02–900	0.997			0.005	0.02	105	1	105	6
Propiconazole E_1	10.54	0.06–1000	0.998	0.51	0.82	0.02	0.06	94	4	98	12
Propiconazole E_2	11.47	0.04–1000	0.998			0.01	0.04	97	1	91	11
Prothioconazole E_1	10.3	2.9–1000	0.997	0.52	0.80	0.9	2.9	90	4	99	14
Prothioconazole E_2	11.67	2.8–1000	0.999			0.8	2.8	96	2	99	6
Prothioconazole-desthio	7.45	0.4–700	0.98			0.1	0.4	98	3	96	5
Tebuconazole	7.11	0.1–1000	0.993			0.04	0.1	93	1	96	6
Hydroxy-tebuconazole	6.67	0.07–1000	0.997			0.02	0.07	108	4	99	10
Terbinafine	7.05	0.01–1000	0.998			0.002	0.01	98	3	95	6
N-Desmethyl-carboxyterbinafine	5.84	0.07–300	0.996			0.01	0.07	109	5	106	7
		500–1000	0.992								
Voriconazole	16.17	0.02–1000	0.998			0.006	0.02	100	2	98	3

concentrations, and then averaged. The analyte was spiked into the sample matrix with the internal standard, before filtration and SPE as described above.[33]

$$\text{Overall relative recovery (\%)} = \frac{\text{Analyte conc.}_x - \text{analyte conc.}_0}{\text{Analyte conc.}_{QC_x}} \times 100 \quad (5)$$

The matrix effect (ME) was calculated by comparing the concentrations of the post-spiked sample (analyte $\text{conc.}_{ME,x}$) minus analyte concentrations in the blank (analyte conc._0) to analyte concentrations in the mobile phase (analyte conc._{QC_x}) at the following concentration levels (eqn (6)).[33]

$$\text{Matrix effect (\%)} = \left(\frac{\text{Analyte conc.}_{ME,x} - \text{analyte conc.}_{ME,0}}{\text{Analyte conc.}_{QC_x}}\right) - 1 \times 100 \quad (6)$$

In environmental samples, the method detection limit (MDL) was calculated using the following equation:[34]

$$\text{MDL} = \frac{(\text{IDL}_{ng/L} \times 100)}{\text{Rec} \times \text{CF}} \quad (7)$$

In the same way, the method quantification limit (MQL) in the environmental samples was calculated as follows:[34]

$$\text{MQL} = \frac{(\text{IQL}_{ng/L} \times 100)}{\text{Rec} \times \text{CF}} \quad (8)$$

Rec is the relative recovery of the analyte in the matrix, that is the average of the recoveries obtained at three different concentrations considering the internal standard, and CF is the concentration factor.

Method accuracy (MD) was calculated (eqn (9)) to determine how close the measured concentration (analyte $\text{conc.}_{x_1-x_3}$) was to spiked concentrations (x) and method precision (MP) was used to measure how similar the measured concentration values were to each other (eqn (10)). The concentration of the analyte in the blank river water and wastewater samples (analyte $\text{conc.}_0)_{x_1-x_3}$ was subtracted from the measured concentration. The standard deviation of analyte concentration is denoted by σ.

$$\text{Method accuracy (\%)} = \frac{x}{(\text{average analyte conc.}_x - \text{analyte conc.}_0)_{x_1-x_3}} \quad (9)$$

$$\text{Method precision (\% RSD)} = \frac{\sigma(\text{average analyte conc.}_x - \text{analyte conc.}_0)_{x_1-x_3}}{(\text{average analyte conc.}_x - \text{analyte conc.}_0)_{x_1-x_3}} \quad (10)$$

3. Results and discussion

3.1 Liquid chromatography-tandem mass spectrometry

Antifungal compounds and their metabolites were analysed using cLC-MS/MS in ESI+ mode. Optimised multiple reaction monitoring (MRM) transitions are presented in Table 2. Seventeen compounds were separated using a chiral CHIRALCEL® OZ-RH column (5 μm particle size, $L \times$ I. D.: 15 cm × 2.1 mm, Chiral Technologies, France) with a 2.0 mm × 2.0 mm guard filter (Chiral Technologies, France). The following parameters were considered when selecting method conditions: analytical characteristics such as peak area, enantiomeric resolution and signal-to-noise ratio. The selected mobile phase was 10 mM NH_4OAc/MeOH 1 : 99 at a flow rate of 0.075 mL min^{-1} and temperature of 25 °C.

Mass chromatograms showing analyte and enantiomeric separations are presented in Fig. 1. Prothioconazole, econazole, miconazole, ketoconazole and ketoconazole metabolite, epoxiconazole and propiconzole were separated with R_s denoting 0.80, 0.56, 0.54, 0.65, 0.61, 1.87 and 0.82, respectively. The

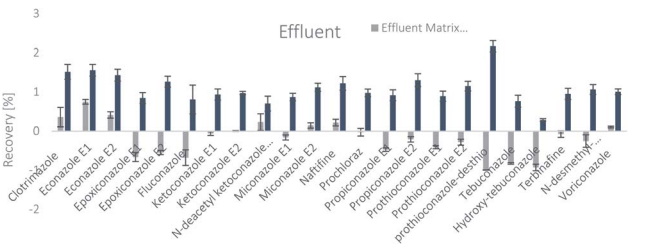


Fig. 3 SPE recovery and matrix effect of antifungal agents in effluent samples (a negative value indicates ionization suppression and a positive value indicates ionization enhancement).

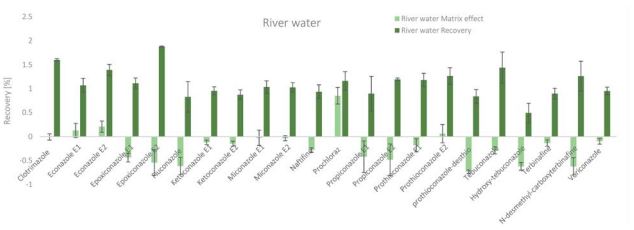


Fig. 2 SPE recovery and matrix effect of antifungal agents in river water samples (a negative value indicates ionization suppression and a positive value indicates ionization enhancement).

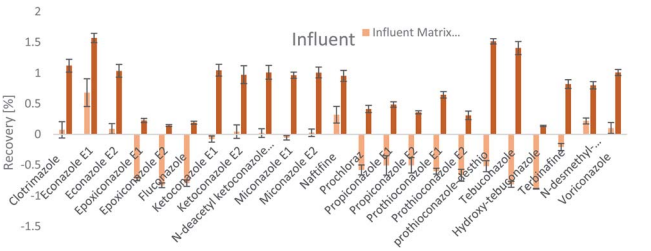


Fig. 4 SPE recovery and matrix effect of antifungal agents in influent samples (a negative value indicates ionization suppression and a positive value indicates ionization enhancement).

Table 4 Method performance data for antifungal agents and metabolites

	River water						Effluent						Influent					
Compounds	EF	R_s	MDL (ng L^{-1})	MQL (ng L^{-1})	MA (%)	MP (%)	EF	R_s	MDL (ng L^{-1})	MQL (ng L^{-1})	MA (%)	MP (%)	EF	R_s	MDL (ng L^{-1})	MQL (ng L^{-1})	MA (%)	MP (%)
Clotrimazole	—	—	2.4	7.1	85	23	—	—	4.5	15.1	69	15	—	—	6.1	20.4	86	18
Econazole E_1	0.46	0.59	10.9	36.2	105	13	0.50	0.51	14.9	49.8	96	10	0.49	0.73	14.8	49.3	104	15
Econazole E_2	—	—	0.6	14.4	93	8	—	—	1.3	27.9	98	12	—		1.7	38.6	113	7
Epoxiconazole E_1	0.49	2.04	3.7	12.2	100	13	0.52	1.81	9.7	32.3	81	19	0.49	1.93	36.0	120.01	112	7
Epoxiconazole E_2	—	—	1.5	5.04	94	15	—	—	4.5	15.0	72	11	—	—	39.8	132.5	109	7
Fluconazole	—	—	26.06	86.9	88	17	—	—	53.4	177.9	87	18	—	—	225.6	751.9	89	16
Ketoconazole E_1	0.50	0.82	192.6	641.9	96	9	0.61	0.84	393.4	1311.3	61	10	0.64	0.89	351.2	1170.7	94	6
Ketoconazole E_2	—	—	98.3	536.5	101	9	—	—	176.8	964.8	97	3	—		176.5	963.3	125	5
N-Deacetyl ketoconazole (DAK) E_1	—	—	—	—	—	—	—	—	1045.1	30362.5	135	18	—	—	6315.3	21051.1	98	12
N-Deacetyl ketoconazole (DAK) E_2	—	—	—	—	—	—	—	—	—	—	—	—	—		—	—	—	—
Miconazole E_1	0.58	0.68	4.5	14.9	86	19	0.55	0.69	10.6	35.4	95	23	0.59	1.26	9.5	31.8	95	3
Miconazole E_2	—	—	4.9	16.4	123	24	—	—	9.05	30.2	104	22	—	—	10.0	33.4	143	31
Naftifine	—	—	0.6	1.9	87	11	—	—	0.9	2.8	89	16	—	—	1.1	3.6	97	27
Prochloraz	—	—	2.2	7.5	78	16	—	—	5.3	17.9	84	15	—	—	12.6	42.0	94	13
Propiconazole E_1	0.48	0.81	9.4	31.5	92	17	0.50	1.01	18.5	61.9	94	9	0.52	1.09	34.8	116.1	95	9
Propiconazole E_2	—	—	4.9	16.4	102	22	—	—	9.03	30.1	89	19	—	—	32.6	108.7	104	18
Prothioconazole E_1	0.50	0.94	373.4	1244.6	88	5	0.48	1.21	989.9	3299.8	96	14	0.52	1.02	1363.5	4545.0	78	8
Prothioconazole E_2	—	—	334.2	1114.2	99	19	—	—	735.3	2450.9	89	8	—	—	2720.8	9069.5	92	17
Prothioconazole-desthio	—	—	62.7	208.9	74	23	—	—	48.4	161.4	75	13	—	—	69.3	231.1	63	3
Tebuconazole	—	—	14.9	49.8	90	16	—	—	56.5	188.5	96	6	—	—	30.6	102.05	61	25
Hydroxy-tebuconazole	—	—	22.3	74.2	126	10	—	—	77.7	259.0	87	9	—	—	159.6	532.05	105	19
Terbinafine	—	—	1.02	3.4	106	17	—	—	1.9	6.4	96	6	—	—	2.2	7.4	107	9
N-Desmethyl-carboxyterbinafine	—	—	3.8	12.8	82	19	—	—	9.1	30.5	78	23	—	—	12.1	40.4	127	7
Voriconazole	—	—	3.4	11.2	103	9	—	—	6.4	21.3	100	7	—	—	6.3	21.1	107	8

results of 2 chiral center compounds (ketoconazole, ketoconazole metabolite, epoxiconazole and propiconazole) provided 2 peaks because chemical compounds in this research study are a racemic mixture of 2 enantiomers. Other racemic compounds (tebuconazole, hydroxy-tebuconazole and prothioconazole-desthio) could not be separated and are reported as the sum of two enantiomers. The method provided very good separation and peak shapes for achiral compounds.

3.2 cLC-MS/MS performance

The following parameters were measured to test instrument performance: linearity, the instrumental limit of detection (IDL), the instrumental limit of quantification (IQL), the enantiomeric fraction (EF) of chiral compounds and instrument accuracy and precision.

All analytes showed average linearities of $r^2 > 0.997$ within the tested linearity range. Table 3 shows the r^2 and range of all selected analytes including 7 enantiomeric pairs (econazole, epoxiconazole, ketoconazole, miconazole, *N*-deacetyl ketoconazole (DAK), propiconazole and prothioconazole). However, some compounds (clotrimazole, econazole, epoxiconazole, fluconazole, ketoconazole, *n*-deacetyl ketoconazole (DAK), prochloraz, propiconazole, terbinafine and voriconazole) required two calibration curves to maintain $r^2 \geq 0.99$.

Inter-day and intra-day instrument precision were studied at three different concentrations, 10, 100 and 1000 ng mL^{-1}. As can be seen in Table 3, intra-day and inter-day instrumental precision was <15% for all compounds. Moreover, the method is characterized by high accuracy between 88 and 115% for most compounds.

The EF provided the relative ratio of enantiomers of chiral compounds. As can be seen from Table 3, EFs of econazole, epoxiconazole, miconazole, ketoconazole and its metabolite, propiconazole and prothioconazole are within 0.49–0.55 at low, medium and high concentration levels. The resolutions of enantiomers are between 0.54 and 1.87. Very good method sensitivity was achieved with IDLs ranging from 0.001 to 11.6 ng mL^{-1} and IQLs ranging from 0.004 to 38.6 ng mL^{-1}.

3.3 SPE-cLC-MS/MS performance

The SPE methodology utilized a hydrophilic lipophilic balanced (HLB) copolymer as the extraction phase. SPE recoveries and matrix effects were calculated using eqn (3) and (4), respectively. As can be seen from Fig. 2–4, the SPE recoveries and matrix effects of antifungal agents are on average 98%. The recoveries of ketoconazole, miconazole, terbinafine, *N*-desmethyl-carboxyterbinafine and voriconazole of river water, influent and effluent samples were between 80 and 119% with deviation from 100% linked with matrix effects. Lower apparent recoveries of epoxiconazole, fluconazole, hydroxyte-buconazole, propiconazole, pothioconazole, and prothioconazole-desthio in the influent are due to ion suppression as shown by the high negative percentage of matrix effects in Fig. 2–4.

Table 4 shows method performance parameters. MDLs and MQLs were calculated from eqn (5) and (6), respectively. MQLs for liquid matrices ranged from 1.9 ng L^{-1} for naftifine in surface water, to 30362.5 ng L^{-1} for the metabolite of ketoconazole in the effluent. The MDLs and MQLs of most analytes are low enough to measure in the environment.[8,16,26,27,29,35–41] EFs are within 0.46–0.64. The resolutions of enantiomeric pairs are between 0.51 and 2.04 in river water, effluent and influent. Most

Table 5 Average concentrations of antifungal agents and metabolites found in several matrices

Compounds	River water (ng L^{-1})	Effluent (ng L^{-1})	Influent (ng L^{-1})
Clotrimazole	ND	ND	ND
Econazole E_1	ND	ND	ND
Econazole E_2	ND	ND	ND
Epoxiconazole E_1	67.3 ± 26.5	ND	ND
Epoxiconazole E_2	13.2 ± 4.4	ND	ND
Fluconazole	<MQL	101.0 ± 35.6	ND
Ketoconazole E_1	ND	ND	ND
Ketoconazole E_2	ND	ND	ND
N-Deacetyl ketoconazole (DAK) E_1	ND	218.2 ± 38.6	ND
N-Deacetyl ketoconazole (DAK) E_2	ND	ND	ND
Miconazole E_1	ND	ND	ND
Miconazole E_2	ND	ND	ND
Naftifine	ND	ND	ND
Prochloraz	ND	ND	ND
Propiconazole E_1	32.2 ± 2.0	ND	ND
Propiconazole E_2	41.3 ± 0.9	ND	ND
Prothioconazole E_1	ND	ND	ND
Prothioconazole E_2	ND	ND	ND
Prothioconazole-desthio	ND	ND	ND
Tebuconazole	252.4 ± 70.2	927.5 ± 2.4	115.1 ± 37.6
Hydroxy-tebuconazole	228.9 ± 54.8	ND	ND
Terbinafine	50.2 ± 6.5	ND	30.5 ± 2.4
N-Desmethyl-carboxyterbinafine	<MDL	ND	ND
Voriconazole	ND	ND	ND

of the compounds provided good method accuracy (61–143%) and precision (3–31%).

3.4 Application to environmental matrices

The new multi-residue analytical method was applied to determine the concentration of antifungal drugs and plant fungicides in river water, influent and effluent samples collected in South West England (Table 5). The fungicide tebuconazole was found at the following concentrations: 252.4 ± 70.2, 927.5 ± 2.4 and 115.1 ± 37.6 ng L^{-1} in river water, effluent and influent, respectively. It is worth noting that its concentrations were higher in river water than wastewater influent indicating other than communal sources of this fungicide in the aqueous environment. Interestingly, effluent concentrations are the highest, which warrants further study regarding transformation of tebuconazole during wastewater treatment. Indeed, tebuconazole is primarily used on crops. Its metabolite, hydroxy-tebuconazole, was quantified only in the river water at 228.9 ± 54.8 ng L^{-1} confirming its usage and environmental transformation. Terbinafine (used in both human and animal treatment) was also determined in river water (50.2 ± 6.5 ng L^{-1}) at higher concentrations than in wastewater influent (30.5 ± 2.4 ng L^{-1}). Its metabolite, *N*-desmethyl-carboxyterbinafine, was identified only in river water at <MDL indicating other than communal sources of this contaminant. Fluconazole was present at <MQL and 101.0 ± 35.6 ng L^{-1} in river water and effluent, respectively. Epoxiconazole enantiomers (with primary usage on crops) were quantified only in river water with significant predominance of the E_1 enantiomer: 67.3 ± 26.5 ng L^{-1} and 13.2 ± 4.4 ng L^{-1} for E_1 and E_2, respectively. Propiconazole enantiomers (with primary usage on crops) were also quantified only in river water at concentrations of 32.2 ± 2.0 ng L^{-1} and 41.3 ± 0.9 ng L^{-1} for E_1 and E_2 enantiomers, respectively. However, only one enantiomer of deacetyl-ketoconazole was determined in effluent wastewater at a concentration of 218.21 ± 38.62 ng L^{-1}. In summary, the results of this study indicate predominance of antifungal agents in the aqueous environment with sources linked with animal and plant protection rather than usage in humans. Interestingly, chiral fungicides quantified in the river water were enriched with one enantiomer. This might have consequences in terms of their ecological effects which warrants further study.

4. Conclusions

A new multiresidue method utilizing chiral chromatography (with a chiral CHIRALCEL® OZ-RH column) and triple quadrupole tandem mass spectrometry was developed for sensitive and selective enantiomer-dependent analysis of fungicides and their metabolites in aqueous matrices such as river water and wastewater. The method showed very good linearity and range ($r^2 > 0.997$), method accuracy (61–143%) and precision (3–31%) as well as low MQLs (1.9–30362.5 ng L^{-1}). The method was applied in selected environmental samples. The following analytes were quantified: fluconazole, terbinafine, *N*-desmethyl-carboxyterbinafine, tebuconazole, hydroxy-tebuconazole, epoxiconazole, propiconazole and *N*-deacetyl ketoconazole. They were predominantly present in the aqueous environment (as opposed to wastewater) with sources linked with animal and plant protection rather than usage in humans. Interestingly, chiral fungicides quantified in the river water were enriched with one enantiomer. This might have consequences in terms of their ecological effects which warrants further study, also focussed on identification of individual enantiomers.

Conflicts of interest

The authors declare no conflicts of interest.

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