Chapter 11

The Development and Application of Cellulose-Based Stationary Phases in Stereoselective Separation of Chiral Pesticides

Jing Qiu, Shouhui Dai, Tingting Chai, Wenwen Yang, Shuming Yang and Hualin Zhao

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/56575

1. Introduction

In the 1980s, polysaccharide-based chiral stationary phases (CSPs) were identified as versatile and useful chiral sorbents for separation of enantiomers/stereoisomers in high performance liquid chromatography (HPLC). Chiral discrimination abilities of these CSPs can be derived from the highly organized structure of the left-handed 3/2 helical chain conformations [1]. Some chiral cavities with specific configuration can be formed on the CSPs, which provide the suitable site for a particular enantiomer and make it easier to interact with CSPs by hydrogen bonding and π-π interactions. This leads to enantioseparation of chiral compounds by different retention and elution on CSPs between their enantiomers [2]. Okamoto et al. reported that the introduction of various kinds of substituents on the hydroxyl group of polysaccharides can improve their stereoslectivity [3].

Cellulose is an important polysaccharide, it is also a highly crystalline polymer which occurs with various crystal structures. In the 1970s, Hesse and Hagel first synthesized microcrystalline cellulose triacetate (MCTA), and thought its chiral recognition ability might originate from secondary structures creating chiral cavities upon swelling, which can clamp stereoselectively compounds with aromatic residues [4]. In recent years, different cellulose derivatives have been synthesized, coated or covalently bonded on decorative silica gel, and broadly used as CSPs in enantiomeric separation of chiral compounds especially on pesticides and pharmaceuticals. These derivatives exhibit powerful chiral recognition ability towards a wide number of different racemic compounds. More and more commercial cellulose-based CSPs including cellulose acetate, benzoate and phenylcarbamates are being developed and applied in enantioseparation [2,3].

Chiral compounds account for 25% of all agrochemical compounds used commercially and for 26% of the total value of the world agrochemical market [5]. The enantiomers of chiral pesticides possess similar physicochemical properties in a non-chiral environment while they show different activities in biological systems due to enantioselective interactions with enzymes, receptors, and other enantiomeric biological entities. For example, triadimenol is a systemic fungicide and has four stereisomers due to the presence of two chiral centers in its molecule. Of the four, the (1S, 2R)-isomer shows the highest fungicidal activity (up to 1000-fold more active than the other three) [6]. However, most chiral pesticides are produced and formulated as racemic mixture even though the desired biological activity may be derived from only one enantiomer. It is therefore very important to be able to separate enantiomers of chiral pesticides in order to prepare single enantiomers, develop enantiomeric analysis methods and evaluate their bioactivity and environmental fates.

This work focuses mainly on a review of the development of cellulose derivatives for CSPs which are prepared as cellulose-based chiral columns by coating and bonding on supports, and their applications in stereoselective separations of chiral pesticides.

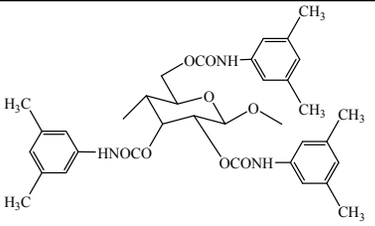
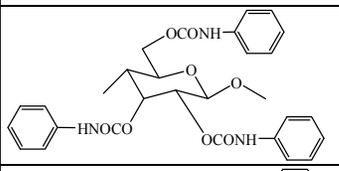
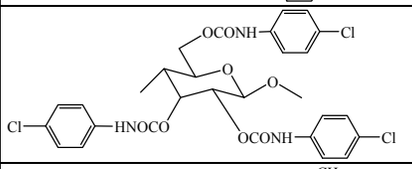
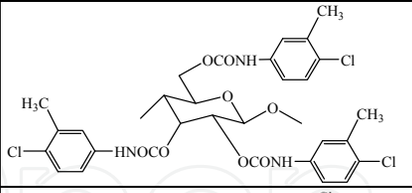
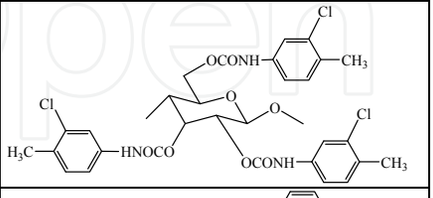
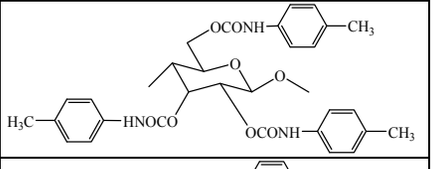
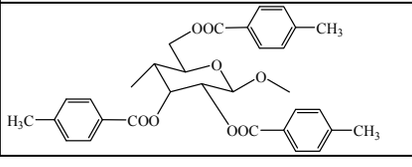
2. The development of cellulose-based CSPs

The cellulose-based CSPs generally are of two types: the coated and the bonded. The coated cellulose-based CSPs consisting of the low-molecular-weight cellulose benzoate or phenyl carbamate showed higher chiral recognition than the covalently bonded CSPs for most racemates. The major reason was considered to be an optimal secondary and supermolecular structure for the chiral recognition mechanism of polysaccharide derivatives under coated conditions [1,3]. However, the coated CSPs can only be used with a limited range of solvents as mobile phases such as alkanes, alcohols, acetonitrile, or aqueous solvents including alcohols or acetonitrile because CSPs may dissolve in 'strong' solvents such as tetrahydrofuran (THF) and chloroform ($CHCl_3$). Such a dissolution would damage or destroy the CSPs. This limited the application range of the coated CSPs on separation and preparation of chiral compounds, because the solubility of the sample in the mobile phase is very important to increase the amount of racemates loaded on CSPs, especially on a preparative large-scale separation [7].

The bonded CSPs were prepared by covalently bonding cellulose derivates to silica gel. They can be applied to a wider range of resolving conditions than the coated type. The fixation can affect the conformation of cellulose derivates and make it difficult to obtain optimal supermolecular structure. This results in lower chiral recognition ability of the bonded-type CSPs. However, the fixation improves versatility in the solvent selection, and allows the use of some solvents that cannot usually be applied on the coated CSPs as mobile phases or sample dissolving reagents [8].

The commercial cellulose-based CSPs including the coated and the bonded CSPs currently in use are summarized in Table 1. As can be seen, there are only two columns (Chiralpak IB and Chiralpak IC) prepared from cellulose derivatives by bonding out of 13 commercial chiral columns. This means that the coated CSPs include more cellulose derivatives and are

more frequently used for the resolution of chiral compounds than the bonded CSPs. Some of these chiral columns can be selectively used in normal-phase HPLC (NP-HPLC), like Chiralcel OD, Chiralcel OA, Chiralcel OB, Chiralcel OC, Chiralcel OF, Chiralcel OG and Chiralcel OJ etc.; some can be used in reversed-phase HPLC (RP-HPLC), like Chiralcel OD-R, Chiralcel OZ-R and Chiralcel OJ-R; and some can be used in both NP-HPLC and RP-HPLC, like Lux Cellulose-1, Lux Cellulose-2 , Lux Cellulose-3, Lux Cellulose-4, Chiralpak IB and Chiralpak IC [9,10]. Some studies have been done to evaluate comparatively the enantioselective and chromatographic properties of Chiralcel OD and Chiralpak IB using a set of 48 compounds that differ in their physical and chemical properties [11]. The uses of these CSPs in different mobile phases mainly depend on their different preparation methods.

No.	Chemical name	Shortened name	Commercial product [9,10]	Type	Chemical structure of cellulose derivative
1	cellulose-*tris*-(3,5-dimethylphenylcarbamate)	CDMPC	Chiralcel OD-H; Chiralcel OD; Chiralcel OD-RH; Chiralcel OD-R; Lux Cellulose-1; Kromasil CelluCoatTM	Coating	
2	cellulose-*tris*-phenylcarbamate	CTPC	Chiralcel OC	Coating	
3	cellulose-*tris*-(4-fluoro-phenylcarbamate)	CFPC	Chiralcel OF	Coating	
4	cellulose-tris(4-chloro-3-methylphenylcarbamate)		Chiralcel OX-H; Lux Cellulose-4	Coating	
5	Cellulose-tris(3-chloro-4-methylphenylcarbamate		Chiralcel OZ-H; Chiralcel OZ-RH; Lux Cellulose-2	Coating	
6	cellulose-*tris*-(4-methylphenylcarbamate)	CMPC	Chiralcel OG	Coating	
7	cellulose-*tris*-(4-methylbenzoate)	CTMB	Chiralcel OJ-H; Chiralcel OJ; Chiralcel OJ-RH; Lux Cellulose-3	Coating	

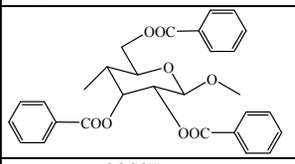
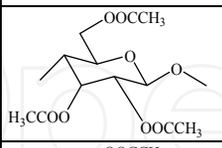
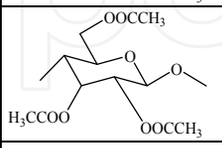
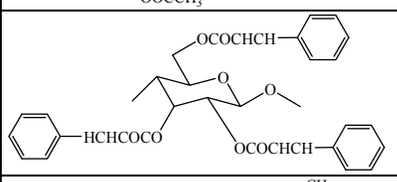
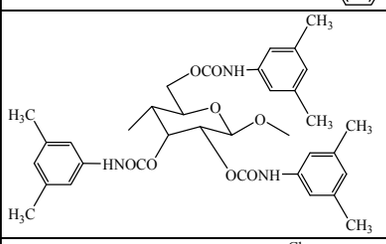
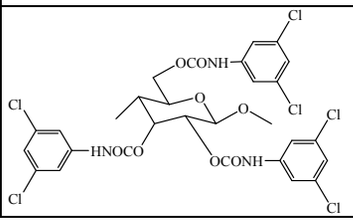
No.	Chemical name	Shortened name	Commercial product [9,10]	Type	Chemical structure of cellulose derivative
8	cellulose-*tris*-benzoate	CTB	Chiralcel OB-H Chiralcel OB	Coating	
9	cellulose-*tris*-acetate	CTA	Chiralcel OA	Coating	
10	Mricocrystalline cellulose-*tris*-acetate	MCTA	Chiralcel CA-1	Coating	
11	cellulose-*tris*-cinnamate	CTC	Chiralcel OK	Coating	
12	cellulose-*tris*-(3,5-dimethylphenylcarbamate)	Bonded CDMPC	Chiralpak IB	Bonding	
13	cellulose-*tris*-(3,5-dichloro-phenylcarbamate)	Bonded CDCPC	Chiralpak IC	Bonding	

Table 1. The list of commercial cellulose-based CSPs in the present.

2.1. The development of coated cellulose-based CSPs

Various cellulose derivatives were reported as CSPs in recent years, especially on cellulose benzoates and phenylcarbamates because of their higher enantiomeric discrimination ability and wide applications. Okamoto et al, synthesized some cellulose triphenylcarbamate derivatives and absorbed them on silica gel as CSPs, and then compared optical resolution abilities with the characteristics of the substituents on the phenyl rings. The results showed that dimethylphenyl- and dichlorophenylcarbamates substituted at 3,4- or 3,5-positions exhibited better chiral recognition for most reacemates than monosubstituted derivaties. Of the these, cellulose tris-(3,5-dimethylpheyl-carbamate) (CDMPC) offered the highest enantiomeric separability [12]. In another investigation on chiral recognition ability of cellulose phenylcarbamate derivatives, cellulose-tris-(3-fluoro-5-methylphenylcarbamate) was reported to be better than 3,5-difluoro- and 3,5-dimethylphenylcarbamates of cellulose for enantioseparation of ten racemates [13].

The investigations of four regioselectively substituted cellulose derivatives having two different substituents at 2-, 3-, and 6-positions showed better enantioseparations were sometimes obtained on these CSPs, compared to the corresponding homogeneously tris-substituted cellulose derivatives-based CSPs. Cellulose 2,3-(3-chloro-4-methylphenylcarbamate)-6-(3,5- dimethylphenylcarbamate), and 2,3- (3,5-dimethylphenyl-carbamate)-6-(3-chloro-4-methylphenylcarbamate) exhibited the most efficient enantioseparations for tested racemates in four CSPs [14]. The cellulose derivative of benzoylcarbamate also showed a higher chiral discrimination ability compared to those of phenylcarbonate, *p*-toluenesulfonylcarbamate, and benzoylformate when they used as CSPs on HPLC. This discrimination could be achieved by hydrogen bonding of the racemates' hydrogen atoms with the carbonyl group of the benzoylcarbamates [15].

Chiral recognition abilities of cellulose-methoxyphenylcarbamates were significantly influenced by the position, bulkiness, and number of alkoxy groups introduced on the phenyl group. The 3-position was found to be the best for introducing an alkoxy group, and cellulose-tris-(3-methoxyphenylcarbamates) exhibited much higher recognitions. Additionally, the recognition abilities also increased with the increases of the bulkiness of the 3-alkoxy group [16]. Cellulose-tris- (3-trifluoromethylphenylcarbamate) also exhibited characteristic enantioseparation and were better to resolve some chiral compounds than Chiralcel OD [17].

During the preparation of polymer cellulose-based CSPs by coating on silica gel, chiral additives such as (+)-L-Mandelic acid, (+)-1-phenyl-1,2-ethanediol and (-)-2-phenyl-1-propanol for CSPs of cellulose tribenzoate, and (-)-2-phenyl-1- propanol and (+)-phenylsuccinic for CSPs of cellulose trisphenylcarbamate have a substantial effect on the resolution and efficiency of the CSPs, and can improve chiral recognition ability compared to the original CSPs [18].

Some new supports other than decorative silica gel were also used to prepare the coated CSPs. For example, a new CSP of CDMPC was prepared by coating CDMPC on TiO_2/SiO_2 particles. Its good chiral separation ability and a comparably low column pressure proved that TiO_2/SiO_2 could be used as an alternative to silica gel, and could enlarge the range of base materials when preparing CSP [19].

2.2. The development of bonded cellulose-based CSPs

CDMPC and CDCPC were covalently bonded to decorative silica gel to obtain the bonded chiral columns of Chiralpak IB and Chiralpak IC respectively [9]. CTPC regioselectively bonded at the 6-position to silica gel exhibited a higher chiral recognition than either CTPC regioselectively bonded at the 2- or 3-position or non-regioselectively bonded at the 2-, 3-, and 6-positions [20]. When cellulose derivatives bearing pyridyl and bipyridyl residues were compared in chiral recognition abilities, the results showed that the regioselectively substituted derivatives exhibited higher recognition compared with cellulose derivatives bearing these residues at the 2-, 3- and 6-positions of a glucose ring. This ability was significantly influenced by the coordination of Cu(II) ion to the bipyridyl groups that resulted in the difference of the higher-order structures of cellulose derivatives [21].

CSP with poly[styrene-*b*-cellulose 2,3-bis-(3,5-diphenylcarbamate)] was prepared by the surface-initiated atom transfer radical polymerization (SI-ATRP) of cellulose 2,3-bis-(3,5-dimethylphenylcarbamate)-6-acrylate after the SI-ATRP of styrene on the surface of silicon dioxide supports in pyridine. This CSP showed considerably high column efficiency for the resolution of tested racemates [22].

Laureano Oliveros et al, prepared five mixed 10-undecenoate/benzoates of cellulose and linked them to allyl silica gel by means of a radical reaction. The investigation of chiral recognition ability showed that CSP5 (10-undecenoate/3,5-dichlorobenzoate) has the highest enantioselectivity for most of tested racemates, followed by CSP3 (10-undecenoate/4-methylbenzoate) and CSP4 (10-undecenoate/benzoate). These CSPs showed lower resolution than the coated CSPs although they have higher column efficiency. The reason may be the lack of polar amino groups on the surface of the CSPs. However, when being compared with the coated CSPs, these CSPs can tolerate the use of more polar solvents such as chloroform in the mobile phase [23].

Three cellulose-based CSPs were prepared by reticulation of the same cellulose derivative on three end-capped silica gels with different pore sizes (50Å, 100Å and 4000Å). The comparison of chiral recognition ability among them showed that CSPs with higher pore size exhibited higher selectivity factors, because it can accommodate a larger amount of accessible cellulose derivative on its surface [7].

Four mixed 10-undecenoyl-3,5-dimethylphenylaminocarbonyl derivatives of cellulose with increased proportion of alkenoyl groups were bonded on allylsilica gel. Their comparison showed that CSPB presents the best chiral recognition and can separate the widest range of the tested racemates. The reason may be the higher number of substitution of glucose units. The important decrease in the recognition ability of these CSPs could be attributed to their higher degree of reticulation. More heterogeneous reaction sites of allysilica gel with cellulose derivatives can result in lower degree of reticulation in CSPs and therefore improve their recognition ability [24].

Azido cellulose phenylcarbamate (AzCPC) was synthesized regioselectively and chemically immobilized onto amino-functionalized silica gel to obtain urea-bonded CSPs. Enantioseparation using $CHCl_3$ on these CSPs showed better separation than traditional hexane/2-propanol in mobile phases for some tested racemates. The pre-coating of AzCPC onto silica gel prior to chemical immobilization could significantly improve immobilization efficiency, and obtained better enantioselectivity [25].

3. The preparation method of cellulose-based CSPs

3.1. The preparation method of coated CSPs

Generally, benzoate and phenylcarbamate derivatives of cellulose were prepared by reaction between cellulose and excess benzoyl chloride or phenyl isocyanate derivatives in dry pyridine (Figure 1). These derivatives are then coated onto macro-porous 3-aminopropylsilica (APS) from a solution by evaporation of the solvent to obtain coated

CSPs. The APS was prepared beforehand by silanizing silica gel with a solution of 3-aminopropyltriethoxysilane. Finally, the CSPs were packed into HPLC columns by the slurry method, to obtain coated chiral columns [18, 26]. For example, CDMPC was synthesized by reaction of microcrystalline cellulose with 3,5-dimethylphenylcarbimide in pyridine; the product was filtered off, washed with methanol and dried at 60° C for 24h. CDMPC was then dissolved in THF and coated on the APS under vacuum to dryness. Finally, the coated CDMPC were packed into a stainless-steel column at 3.7×10^7Pa by the high-pressure slurry method to obtain the corresponding CSP [26].

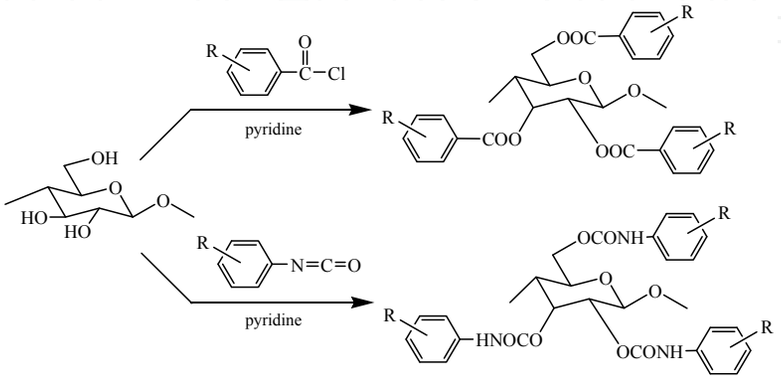


Figure 1. The synthesized routes of cellulose benzoates or phenylcarbamates.

Investigations on the influence of the pore size of silica gel, the coating amount , the coating solvent, and the column temperature on chiral discrimination of CDMPC showed that CSPs prepared with a large-pore silica gel having a small surface area exhibited higher recognition abilities. An increase in the amount of coating of CDMPC on the silica gel can improve the loading capacity of racemates, and a CSP coated with 45% CDMPC by weight can be used for both analytical scale and semi-preparative scale separations. CSPs coated with acetone showed higher enantioselectivity than those coated with THF or a mixture of CH_2Cl_2 and phenol [27].

3.2. The preparation method of covalently bonded CSPs

Generally, cellulose-derived CSPs covalently bonded on silica gel are prepared by using a benzoyl chloride or a phenyl isocyanate to react with cellulose in homogeneous conditions, to obtain the corresponding benzoates or carbamates. However, other methods to prepare this type of CSP have been reported. Ikai et al. summarized various immobilization methods of the polysaccharide derivatives mainly onto silica gel: immobilization using diisocyanate, vinyl groups by polymerization and copolymerization with a vinyl monomer etc. [28,29]. Several methods of synthesis are shown in Figures 2 to 4.

CDMPC can be efficiently immobilized on silica gel as CSPs by copolymerizing with vinyl monomers. The introduction of vinyl groups or the employment of vinyl monomers can readily tune the immobilization efficiency and the chiral recognition of cellulose derivatives [30]. The new method was applied to immobilize CDMPC onto bare silica gel via the intermolecular polycondensation of triethoxysilyl groups, which were introduced onto the

glucose unit by the epoxide ring-opening reaction under acidic conditions. The CSPs thus obtained also exhibited high chiral recognition ability for 10 tested racemates and could be used with various eluents that are not compatible with the conventionally coated CSPs [31]. One-pot method was applied to synthesize CDCPC bearing a small amount of 3-(triethoxysilyl) propyl residues, and then immobilized onto silica gel through intermolecular polycondensation. The immobilized CSPs exhibited chiral recognition abilities similar to the corresponding coated CSP and slightly different from the commercial Chiralpak IC [32].

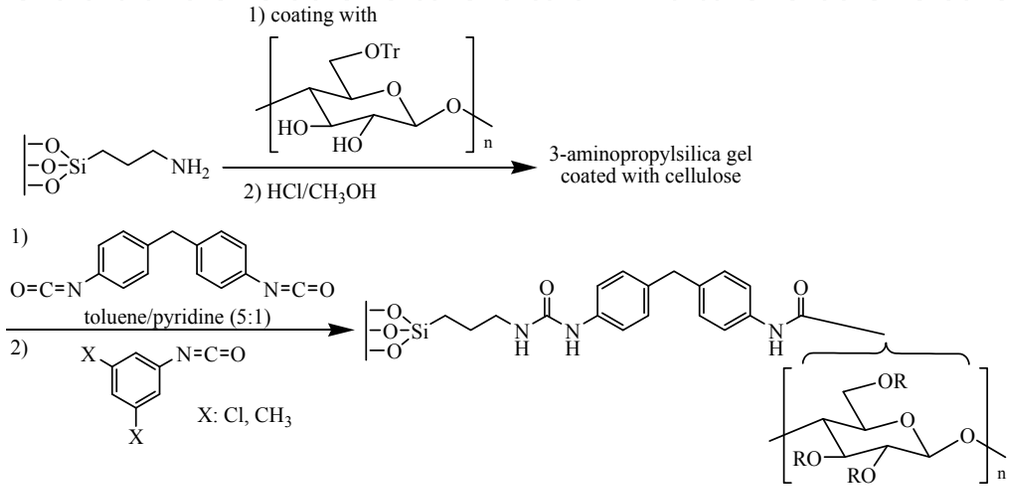


Figure 2. The covalent bonding of 3,5-dichloro- and 3,5-dimethylphenylcarbamate of cellulose onto APS [33].

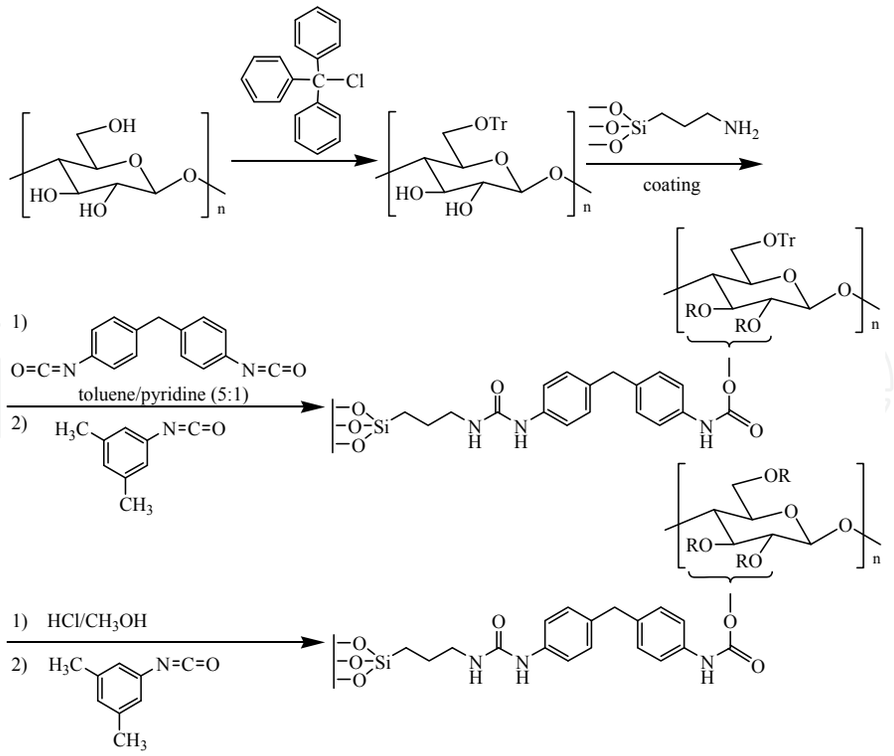


Figure 3. Regioselective covalent bonding of CDMPC to positions 2 and 3 of the glucosidic rings.

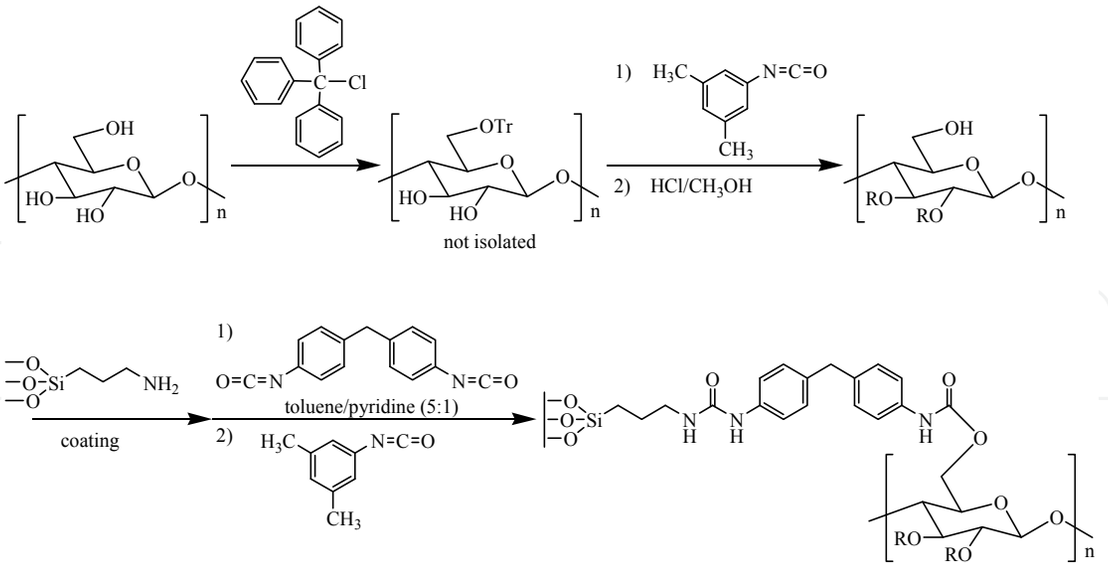


Figure 4. Regioselective covalent bonding of CDMPC to position 6 of the glucosidic rings [34].

Cellulose-(diphenymethyldicarbamate/phenylcarbamate) covalently bonded to APS showed some chiral recognition ability [35]. Cellulose-tris-phenylcarbamate was covalently bonded to silica gel with different spacers. The results showed CSPs prepared with spacer 1(4-(1-(3-(triethoxysilyl)-propyl)urea)-benzyl-4-isocyanatobenzene) exhibited higher resolution ability than spacer TEPI (3-(triethoxysilyl) propyl isocyanate) with the same preparation procedure. The amount of spacer in the synthesis influences the optical resolution ability of CSPs, and a lower amount can produce higher resolution ability [36].

Polar monodisperse amine terminated polymer (2-aminoethyl methacrylate-co-ethylenedimethacrylate) beads can be used as the replacement of silica gel, and are suitable as supports for the preparation of cellulose-based CSPs coated by simple adsorption and immobilized with a diisocyanate linker. However, the chiral recognition abilities of these CSPs shows no enhancement because the uses of cellulose-based selectors and preparation methods may completely cover the surface of polymer supports. Thus, the analytes have no access to the native surface of the support and non-specific interactions with the surface functionalities are not observed. [37].

4. The application of cellulose-based CSPs in enantioseparation of chiral pesticides

Chiral HPLC is a good method to separate enantiomers/stereoisomers of chiral pesticides because it facilitates the preparation of single enantiomers for study of enantiomeric bioactivity, toxicology and environmental fate. In recent years, cellulose-based CSPs prepared with different cellulose derivatives and methods resulted in their very broad application for chiral separation of pesticides such as organophosphates [38], organochlorine, triazole, synthetic pyrethroids, acylanilides, imidazolinones, phenoxypropanoic-acid herbicides and related compounds [39].Table 2 summarizes the resolution results of 79 chiral pesticides in current references.

As shown in Table 2, the stereoselective separations of most of chiral pesticides can be achieved on NP-HPLC and some on RP-HPLC using cellulose-based CSPs. The most efficient CSP with the highest chiral recognition ability is CDMPC, available under the commercial names of Chiralcel OD, Chiralcel OD-H, Chiralcel OD-R, Chiralcel OD-RH, Lux Cellulose-1 and Kromasil CelluCoatTM. The coated CDMPC on APS exhibited higher chiral discrimination for most of pesticides than the bonded type available under the commercial names of Chiralpak IB and Chiralpak IC. For example, the resolution factor (Rs) of systemic fungicide-metalaxyl on the coated CDMPC is 4.54 with hexane/IPA (80:20) as the mobile phase, which is significantly higher than that on the bonded CDMPC with an Rs of 0.632 using hexane/IPA (97/3) as the mobile phase.

The second most efficient CSP in terms of resolution is CTMB available under the commercial names of Chiralcel OJ, Chiralcel OJ-H, Chiralcel OJ-RH, Lux Cellulose-3. It exhibited higher chiral discrimination for some chiral pesticides than CDMPC. For example, the Rs of triazole fungicide-imazalil on Chiralcel OJ-H is 5.21, which is significantly higher than 1.51 obtained on Chiralcel OD-H using the same mobile phase of hexane/IPA (100/3) and the same flow rate of 0.8 mL/min on NP-HPLC. The combination of CDMPC and CTMB on NP-HPLC and RP-HPLC can separate most chiral pesticides listed in Table 2.

The separations on NP-HPLC were better than those on RP-HPLC for most chiral pesticides. The cellulose-based CSPs on NP-HPLC can generally give better resolution and yield a larger amount of a single enantiomer in one injection. However, its application is limited because some racemates are polar and difficult to dissolve in the weak polar solvents used as mobile phase on NP-HPLC. For this reason, the amount of racemates loaded on CSPs cannot be increased. The separation on RP-HPLC is sometimes less effective than on NP-HPLC, but it can use more methanol, acetonitrile or water in the mobile phase and can thus significantly improve the solubility of some racemates that will not readily dissolve in the hexane, heptane and isopropanol used in NP-HPLC. This is very helpful to prepare optically pure enantiomer of polar chiral compounds and obtain more enantiomer in a shorter time. Additionally, the use of HPLC in the reversed phase can easily be connected in tandem with mass spectrometry, which makes it possible to establish more sensitive and more efficient analytical methods for enantioselective studies of chiral pesticides [40-42].

No.	Pesticide	CSP or Chiral colum	Chromatographic condition*1	Separation effect*2	Elution order*3	Reference
1	amiprophos	Chiralcel OJ-H	hexane/IPA(100/5); 0.8mL/min; UV 254nm	Rs: 1.65		[43]
		Chiralcel OD-H	hexane/IPA(100/5); 0.8mL/min; UV 254nm	-		[43]
2	benalaxyl	CDMPC	hexane/IPA(97/3); 1.0 mL/min; UV 22nm	Rs>1.5	R-(-) /S-(+)	[44]
		ChiralpakIB; Chiralcel OJ-H	hexane(IPA or ethanol); 0.5 mL/min; UV 220 nm;			[45]
3	benzex	Chiralce1 OJ	hexane/IPA(91/9); 0.5 mL/min			[46]

No.	Pesticide	CSP or Chiral colum	Chromatographic condition*1	Separation effect*2	Elution order*3	Reference
4	bifenthrin	Chiralcel OJ-H	hexane/ethanol(98/2); 1.0 mL/min; CD 230nm			[47]
5	bioallethrin	CDMPC	hexane/ethanol(99/1); 1.0 mL/min;	α: 1.27		[48]
		CMPC	hexane/ethanol(99/1); 1.0 mL/min;	α: 1.39		[49]
6	bitertanol	Chiralcel OD-H	hexane/IPA(100/3); 0.8mL/min; UV 254nm	Rs: 1.52		[50]
		Chiralcel OJ-H	hexane/IPA(100/10); 0.8mL/min; UV 254nm	Rs: 3.70		[50]
7	carfentrazone-ethyl	CDMPC	hexane/IPA(99.9/0.1); 1.0 mL/min; UV 230nm	Rs: 0.52		[51]
8	chlordane	Chiralcel OD	hexane; 1.0 mL/min		OR: TC(trans)+/- CC(cis)+/-	[52,53]
9	crotoxyphos	Chiralcel OJ	hexane/ethanol(90/ 10); 0.8mL/min; UV 230nm	Rs: 1.81	OR: -/+	[54,55]
10	crufomate	Chiralcel OD	heptane/ethanol(90/10); 1.0 mL/min;	Rs: 1.1	OR: +/-	[55]
		Chiralcel OJ	heptane/ethanol(99.4/ 0.6); 0.3mL/min; UV 203nm	Rs: 0.90	OR: -/+	[55]
11	cycloprothrin	Chiralcel OJ-H	hexane /IPA(70/30), 35°C, 1.0 mL/min, UV 254 nm			[56]
		Chiralcel OD-H	Hexane/IPA(90/10), 35°C, 1.0 mL/min, UV 254 nm			[56]
12	cypermethrin	CDMPC	hexane/IPA (90/10); 0.5mL/min; UV 230nm	seven peaks		[57]
13	alpha-cypermethrin	CDMPC	hexane/IPA (90/10); 0.5mL/min; UV 230nm	Rs: 1.53		[57]
14	theta-cypermethrin	CDMPC	hexane/IPA(99/1); 0.8mL/min; UV 230nm	Rs: >1.5	OR: -/+	[58,57]
15	beta-cypermethrin	CDMPC	hexane/IPA (99/1); 0.5mL/min; UV 230nm	four peaks		[57]
16	dialifos	Chiralcel OJ	heptane/ethanol(90/ 10); 0.9mL/min; UV 220nm	Rs: 3.12	OR: +/-	[55]
17	dichlorprop	Chiralcel OJ-H	hexane/IPA (90/10); 0.5mL/min; UV 228nm	Rs: 1.34	S/R	[59]
18	diclofop-methyl	CDMPC	hexane/IPA (95/5); 0.5mL/min; UV 270 nm	Rs: 11.8	S/R	[60-62]
		CDMPC	hexane/n-butyl alcohol (84/16); 0.5mL/min; UV 280 nm			[63]

No.	Pesticide	CSP or Chiral colum	Chromatographic condition*1	Separation effect*2	Elution order*3	Reference
		CDMPC	hexane/isobutanol (98/2); 1.0 mL/min; UV 230nm	Rs: 6.15	OR: -/+	[64,39,65]
		CDMPC coated on TiO2/SiO2	hexane/IPA(65/35), 1.0 mL/min	Rs: 1.50		[19]
		CDMPC	ACN/water (50/50); 0.8 mL/min; UV 230 nm	Rs: 1.53	OR: -/+	[66]
		CTMB	hexane/IPA (50/50); 0.5mL/min; UV 254 nm	Rs: 1.68	R/S	[67,68,63]
		CTB	hexane/n-butyl alcohol (84/16); 0.5mL/min; UV 280 nm			[63]
		CTPC	hexane/n-butyl alcohol (84/16); 0.5mL/min; UV 280 nm			[63]
		Chiralcel OJ-H	hexane/IPA/acetic acid (90/10/0.2); 0.5mL/min; CD 282nm	Rs: 5.49	R/S	[69,70]
19	diclofop acid	Chiralcel OJ-H	hexane/IPA/acetic acid (90/10/0.2); 0.5 mL/min; UV 230 nm			[70]
20	difenoconazole	Chiralcel OJ	hexance/ethanol(90/10); 0.6 mL/min; UV 230nm.	Rs: 3.79	OR: +/-/+/-	[71]
21	diniconazole	CDMPC; Chiralcel OD	hexane/n-butyl alcohol(98/2); 1.0 mL/min; UV 220nm	Rs: 1.53	OR: +/-	[72,61]
		Chiralcel OD	hexane/IPA(90/10); 0.6mL/min; UV 253nm	Rs: 1.17	OR: +/-	71
		Chiralcel OD-H	hexane/IPA(100/5); 1.0 mL/min; UV 225nm	α: 1.20	R(-)/S(+)	[73,50]
		Chiralcel OJ; Chiralcel OJ-H	hexane/IPA(100/3); 1.0 mL/min; UV 225nm	α: 1.14	R(-)/S(+)	[73,74]
		Lux Cellulose-1	ACN/water(70/30), MET/water(80/20); 1.0 mL/min; UV 220nm	Rs: 2.31, 2.62	OR: -/+	[75,66]
22	dioxabenzofos	Chiralcel OJ	hexane/IPA(95/5); 1.0 mL/min; UV 220nm	Rs: 1.56	OR: -/+	[76]
		Chiralcel OD	hexane/IPA(99.5/0.5); 1.0 mL/min; UV 220nm	Rs: 1.42	OR: -/+	[76]
23	epoxiconazole	Lux Cellulose-1; CDMPC	ACN/water(50/50), MET/water(80/20); 1.0 mL/min; UV 220nm	Rs: 2.04, 1.62	OR: −/+	[75,66]
24	ethofumesate	CDMPC	hexane/IPA (98/2); 1.0 mL/min; UV 230nm	Rs: 6.34		[77]
			hexane/IPA (93/7); 1.0 mL/min; UV 230nm	α: 1.58	OR; +/-	[78,79]

No.	Pesticide	CSP or Chiral colum	Chromatographic condition*1	Separation effect*2	Elution order*3	Reference
			hexane/isobutanol (95/5); 1.0 mL/min; UV 230nm	Rs: 7.05	OR: +/-	[64,80]
25	fenamiphos	Chiralcel OJ	heptane/ethanol(99.1/ 0.9); 0.5mL/min; UV 203nm	Rs: 1.08	OR: +/-	[55]
		CDMPC	ACN/water(70/30); 0.8mL/min; UV 230nm	α: 1.00		[81]
26	fenbuconazole	Lux Cellulose-1	ACN/water(90/10), MET/water(70/30); 1.0 mL/min; UV 220nm	Rs: 4.79, 3.96	OR: +/-	[75]
27	fenoxaprop-ethyl	CDMPC	hexane/ethanol (93/7); 0.5mL/min; UV 290nm	Rs: 1.83		[61]
			MET/water (80/20); 0.8mL/min; UV 265nm	Rs: 1.01	OR: +/-	[66]
			ACN/water (50/50); 0.8mL/min; UV 230nm	Rs: 1.53	OR: -/+	[66]
28	fensulfothion	Chiralcel OJ	heptane/ethanol(96/4); 0.8mL/min; UV 201nm	Rs: 1.21	OR: -/+	[55]
29	fenthiaprop	CDMP	ACN/water (50/50); 0.8mL/min; UV 230nm	Rs: 1.53	OR: -/+	[66]
30	fipronil	Chiralcel OD	isooctane/IPA(96/6); 6.0 mL/min;			[82]
		CDMPC	hexane/IPA(95/5); 1.0 mL/min; UV 230nm			[83]
31	flamprop-methyl	CDMPC	hexane/ IPA(97/3); 1.2mL/min; UV 230nm	Rs: 1.59	R/S	[84]
32	fluazifop-butyl	CDMPC	hexane/n-butyl alcohol (89/11); 0.5mL/min; UV 270nm	Rs: 2.55	S/R	[61]
33	fluazifop-p-butyl	CDMPC	hexane/ IPA (95/5); 0.5mL/min; UV 251nm	Rs: 3.80	S/R	[60]
		CHIRALPAK IC	hexane/IPA(90/10); 1.0 mL/min; UV 254nm			[85]
34	fluroxypyr-meptyl	CDMPC	hexane/ IPA(99/1); 0.5 mL/min; UV 230nm	Rs: 1.31		[86]
		CDMPC	MET/water(80/20); 0.5mL/min; UV 230nm	Rs: 1.07	OR: +/-	[66]
35	flutriafol	Chiralcel OD; Chiralcel OD-H; CDMPC	hexance/IPA(95/5); 0.6mL/min; UV 230nm	Rs: 1.37	OR: -/+	[71,50, 64]
		Lux Cellulose-1	ACN/water(70/30), MET/water(70/30); 1.0 mL/min; UV 220nm	Rs: 1.99, 1.39	OR: -/+	[75]
36	tau-fluvalinate	Chiralcel OJ	hexane/ethanol(90/10); 0.3mL/min; UV 210 nm	Rs: 1.59		[87]

No.	Pesticide	CSP or Chiral colum	Chromatographic condition*1	Separation effect*2	Elution order*3	Reference
		Chiralcel OG	hexane/IPA	Rs: <0.91		
		Chiralcel OD-R	MET/water; UV 210 nm	Rs: <0.91		
37	fonofos	Chiralcel OJ	heptane/ethanol(99.5/0.5);1.0 mL/min; UV 202nm	Rs: 2.1	OR: +/-	[55,54]
		Chiralcel OJ-H	hexane/IPA(100/10); 0.8mL/min; UV 254nm	Rs: 9.58		[43]
		Chiralcel OD-H	hexane/IPA(100/0.5); 0.8mL/min; UV 254nm	-		[43]
38	heptachlor epoxide	Chiralcel OD	hexane; 1.0 mL/min; UV 215nm			[53]
39	hexaconazole	CDMPC; Chiralcel OD	hexance/IPA(91/9); 0.5mL/min; UV 270.9nm	Rs: 4.79	OR: +/-	[61,66, 71,72]
		CDMPC	hexance/ tertiary butanol (95/5); 0.5mL/min; UV 270nm	Rs: 2.30		[88]
		Chiralcel OD-H	ACN/MET(98/2); 0.5mL/min; UV 254nm	Rs: 1.51		[89]
		Lux Cellulose-1	ACN/water(90/10), MET/water(80/20); 1.0 mL/min; UV 220nm	Rs: 2.25, 2.12	OR: +/-	[75]
40	imazalil	Chiralcel OD-H	hexane/IPA(100/3); 0.8mL/min; UV 220nm	Rs: 1.51		[50]
		Chiralcel OJ-H	hexane/IPA(100/3); 0.8mL/min; UV 220nm	Rs: 5.21		[50]
		Chiralcel OD	ACN/water(50/50); 0.8mL/min; UV 240nm	Rs: 0.91	OR: −/+	[66]
41	imazamox	Chiralcel OD-R	ACN/ PBS buffer(50mM)(20/80); 1.0 mL/min			[39]
		Chiralcel OJ	hexane(0.1%TFA)/IPA(60/40	Rs: 0.89		[90]
42	imazapic	Chiralcel OJ	hexane/ alcohol/TFA (75/25/0.1); 1.0 mL/min; UV 254nm		OR: +/-	[90]
43	imazapyr	Chiralcel OJ	hexane/ IPA/acetic acid (84.6/15.4/0.1); 0.8mL/min; UV 275nm		OR: +/-	[91]
44	imazaquin	Chiralcel OJ-H	Hexane/IPA/Acetic acid(84.6/15.4/0.1); 0.8 mL/min; UV 275 nm		CD: +/-	[91,39]
		Chiralcel OD-R	ACN/ PBS buffer(50mM)(20/80); 1.0 mL/min	Rs: 2.44		[90]
45	imazethapyr	Chiralcel OJ	hexane/ethanol/ acetic acid (75/25/0.5); 1.0 mL/min; UV 250nm		OR: +/-	[92]

No.	Pesticide	CSP or Chiral colum	Chromatographic condition*1	Separation effect*2	Elution order*3	Reference
		Chiralcel OJ	hexane/ IPA/acetic acid (84.6/15.4/0.1); 0.8mL/min; UV 275nm			[90]
46	indoxacarb	Lux cellulose-1; Chiralcel OD	hexane/IPA(85/15) 0.8mL/min; UV 310 nm		OR: -/+	[93,94]
47	isocarbophos	CDMPC	hexane/IPA(98/2); UV 225nm	Rs: 2.42	OR: -/+	[64,51,95]
48	isofenphos	Chiralcel OG	heptane/IPA(98/2); 1.0 mL/min;	Rs: 1.1	OR: +/-	[55]
		Chiralcel OJ	heptane/ethanol(99.4/ 0.6); 0.3mL/min; UV 201nm	Rs: 1.11	OR: +/-	[55]
49	isofenphos-methyl	Chiralcel OJ-H	hexane/IPA(100/1); 0.8mL/min; UV 280nm	Rs: 1.59		[81]
		Chiralcel OD-H	hexane/IPA(100/1); 0.8mL/min; UV 280nm	Rs: 1.73		[43]
		CDMPC	ACN/water(70/30); 0.8mL/min; UV 230nm	α: 1		[81]
50	iso-malathion	Chiralcel OJ	hexane/IPA(97/3); 1.0 mL/min; UV 220nm			[66]
51	lactofen	CDMPC	hexane/IPA(99/1); 1.0 mL/min; UV 230nm	Rs: 1.87	OR: +/-	[64, 39]
		CDMPC	MET/water(75/25); 0.8mL/min; UV 265nm	Rs: 1.07	OR: -/+	[66]
		Chiralpak IC	hexane/ CH_2Cl_2/TFA (65/35/0.1)	Rs: 8.11		[96]
52	lambda-cyhalothrin	Chiralecl OD	Hexane/IPA(95/5), 0.5 mL/min; UV 236 nm		CD: -/+	[97]
		Chiralecl OJ	hexane; ethanol (95/5); 0.6 mL/min, UV 236 nm		CD: -/+	[97]
		Chiralecl OJ	Hexane/IPA(90/10); 0.4 mL/min, UV 236 nm		CD: -/+/+/-	[97]
53	malaoxon	Chiralcel OJ	hexane/IPA(96/4); 1.0 mL/min; UV 220nm	Rs: 4.06	R/S OR: +/-	[98]
54	malathion	Chiralcel OJ	heptane/ethanol(90/ 10); 0.9mL/min; UV 220nm	Rs: 4.11	OR: +/-	[55]
		Chiralcel OJ	hexane/IPA(97/3); 1.0 mL/min; UV 220nm	Rs: 3.35	OR: +/-	[98]
		CDMPC	hexane/IPA(99/1); 1.0 mL/min; UV 210nm	Rs: 1.44	OR: +/-	[65]
		CDMPC	ACN/water(70/30); 0.8mL/min; UV 230nm	α: 1.0		[81]
55	metalaxyl	CDMPC	hexane/IPA(80:20); 1.0 mL/min; UV 230nm	Rs: 4.54		[26,99]
		CDMPC coated on TiO_2/SiO_2	hexane/IPA(65/35); 1.0 mL/min	Rs: 2.97		[19]

No.	Pesticide	CSP or Chiral colum	Chromatographic condition*1	Separation effect*2	Elution order*3	Reference
		ChiracelOJ-H	hexane/IPA(90:10); 0.5 mL/min; CD 236 nm		S/R	[100]
		Bonded CDMPC	MET/water(50/50)	Rs: 0.506		[101]
		Bonded CDMPC	ACN/water(80/20)	Rs: 0.766		[101]
		Bonded CDMPC	hexane/IPA(97/3)	Rs: 0.632		[101]
		Bonded CDMPC	hexane/tertbutyl alcohol (95/5)	Rs: 0.918		[101]
56	metalaxyl acid	CDMPC	hexane/IPA/TFA(70/30/0 .1%); 1.0 mL/min	Rs: 1.96	CD(-)/(+)	[102]
57	metalaxyl intermediate	CDMPC	hexane/IPA(99/1); 1.0 mL/min;	Rs: 1.85	CD (-)/(+) at 228 nm; CD(+)/(-) at 280nm	[102,26]
58	methami-dophos	CDMPC	hexane/IPA(90/10); 1.0 mL/min; UV 230nm	Rs: 1.54	OR: +/-	[65,103]
		Chiralcel OD	heptane/ethanol(90/ 10); 1.0 mL/min;	Rs: 1.7	OR: +/-	[55]
		Chiralcel OJ	heptane/ethanol(93.5/6.5); 0.8mL/min; UV 200nm	Rs: 1.56	OR: +/-	[55]
		CDMPC	ACN/water(70/30); 0.8mL/min; UV 230nm	α: 1.0		[81]
59	metolachlor	Chiralcel OD-H	hexane/diethyl ether (91/9); 0.8 mL/min; UV 230 nm			[104]
60	myclobutanil	CDMPC	hexane/IPA(73/26); 0.5mL/min; UV 221.5nm	Rs: 13.3		[61]
		CTPC	hexane/IPA(73/26); 0.5mL/min; UV 221.5nm	Rs: 1.54		[50]
		Lux Cellulose-1; CDMPC; Chiralcel OD	ACN/water(90/10), MET/water(90/10); 1.0 mL/min; UV 220nm	Rs: 5.10, 4.91	OR: +/-	[75, 66]
61	naproanilide	CDMPC	hexane/IPA(80/20); 1.0 or 0.5mL/min	Rs: 1.91		[105]
		Chiralcel OD-H; Chiralcel OJ-H	hexane; 1.0 mL/min; UV 254 nm		OR: +/−	[106]
		Bonded-CTB	hexane; 1.0 mL/min; UV 254 nm		OR: −/+	[106]
62	napropamide	Chiralpak OJ-H	hexane/IPA(80/20); 0.5mL/min; 40°C; UV 220nm			[107]
63	paclobutrazol	CDMPC	ACN/water(40/60); 0.8 mL/min; UV 230nm.	Rs: 1.93	OR: +/−	[108]
		Chiralcel OD; CDMPC	hexance/IPA(100/2); 0.8 mL/min; UV 225nm.	Rs: 1.83		[50, 61]
		OJ	hexance/IPA(100/10); 0.8 mL/min; UV 225nm.	Rs: 4.05		[50]

No.	Pesticide	CSP or Chiral colum	Chromatographic condition*1	Separation effect*2	Elution order*3	Reference
64	penconazole	Lux Cellulose-1 Chiralcel OD-H	ACN/water(50/50), MET/water(90/10); 1.0 mL/min; UV 220nm	Rs: 7.58, 2.29	OR: -/+	[75,89]
65	permethrin	Chiralcel OJ	hexane/ethanol(95/15); 0.3mL/min; UV 210 nm	Rs: 1.47		[87]
		Chiralcel OD-R	MET/water; UV 210 nm	Rs: <0.91		
66	phenthoate	Chiralcel OJ	hexane/IPA(90/10); .6mL/min; UV 230nm		OR: -/+	[109]
		CDMPC	ACN/water(70/30); 0.8mL/min; UV 230nm	α: 1.0		[81]
67	profenofos	CDMPC	hexane/IPA(99.5/0.5); UV 210nm	Rs: 1.35	OR: +/-	[64]
		Chiralcel OJ	heptane/ethanol(99.5/0.5); 1.0 mL/min; UV 202nm	Rs: 3.52	OR: +/-	[55]
		Chiralcel OJ	hexane; 0.8mL/min; UV 230nm	Rs: 1.12	OR: +/-	[54]
		CDMPC	ACN/water(70/30); 0.8mL/min; UV 230nm	α: 1.0		[81]
68	propiconazole	Chiralcel OD	hexance/IPA(90/10); 0.6 mL/min; UV 230nm.	Rs: 2.95/ 2.72/ 1.04	OR: +/-/+/-	[71]
69	prothiophos	Chiralcel OJ	heptane/ethanol(98/2); 15°C; 1.0 mL/min; UV 202nm	Rs: 1.6	OR: +/-	[55]
70	quizalofop-P-ethyl	CDMPC	hexane/NPA (91/9); 0.5mL/min; UV 332nm	Rs: 1.7	R/S	[61]
		Chiralcel OJ-H	hexane/MET/methylene dichloride(450/2/8); 1.0 mL/min; UV 290 nm		S/R	[110]
71	pyraclofos	Chiralcel OD	hexane/IPA(90/10); 1.0 mL/min; UV 254nm		OR: -/+	109
72	tebuconazole	CDMPC; Chiralcel OD	hexane/IPA(98/2); 1.0 mL/min; UV 220nm	Rs: 1.63	OR: -/+	[50,61, 64, 71]
		Chiralcel OJ-H; CTMB	hexane/IPA(100/10); 0.8mL/min; UV 225nm	Rs: 5.64		[50, 61]
		CTPC	hexane/IPA(91/9); 0.6mL/min; UV 269.8nm	Rs: 1.16		[61]
		Chiralcel OD-H	ACN/IPA(70/30); 0.5mL/min; UV 254nm	Rs: 0.67		[89]
73	tetraconazole	Lux Cellulose-1	ACN/water(90/10); 1.0 mL/min; UV 220nm	Rs: 1.39	OR: +/-	[75]
74	triadimefon	CDMPC; Chiralcel OD	hexane/IPA(99/1); 1.0 mL/min; UV 230nm	Rs: 1.47	OR: -/+	[64, 71]
		Chiralcel OD	hexane/IPA(100/5); 1.0 mL/min; UV 225nm	α: 1.20	R(-)/S(+)	[73]

No.	Pesticide	CSP or Chiral colum	Chromatographic condition*1	Separation effect*2	Elution order*3	Reference
		Chiralcel OJ	hexane/IPA(100/5); 1.0 mL/min; UV 225nm	α: 1.17	R(-)/S(+)	[73]
		Lux Cellulose-1 Chiralcel OD-H	ACN/water(70/30), MET/water(90/10); 1.0 mL/min; UV 220nm	Rs: 2.43, 2.73	OR: -/+	[75, 66, 89]
75	triadimenol	Chiralcel OD-H	hexane/IPA(100/3); 1.0 mL/min; UV 225nm	α: 1.81	1R,2S(+)/1S, 2R(-)	[73]
		Chiralcel OD-H	hexane/IPA(100/2); 1.0 mL/min; UV 225nm	α: 1.03	1S,2S(-)/1R,2R(+)	[73]
		CDMPC	hexane/ethanol(99.2/0.8); 0.8mL/min; UV 278nm	Rs: 0.64/2.87/0.37		[61]
		Chiralcel OJ-H	hexane/IPA(100/3); 1.0 mL/min; UV 225nm	α: 1.16	1R,2R(+)/1S,2S(-)	[73]
		CTMB	hexane/n-butyl alcohol (89/11); 0.5mL/min; UV 278nm	Rs: 0.18/ 0.69/ 0.52		[61]
		CTPC	hexane/IPA(91/9); 0.5mL/min; UV 278nm	Rs: 1.53/ 0.88		[61]
		Lux Cellulose-1	MET/water(60/40); 0.5 mL/min; UV 220nm	Rs: 1.45/2.73/2.16	OR: (-)-A,/(+)-A/(-)-B/ (+)-B	[40]
76	trichlorfon	CDMPC	ACN/water(70/30); 0.8mL/min; UV 210nm	α: 1.0		[81]
77	trichloronate	Chiralcel OD	heptane; 1.0 mL/min	Rs: 1.1		[55]
		Chiralcel OJ	heptane; 1.0 mL/min; UV 205nm	Rs: 1.40		[55]
		Chiralcel OJ	hexane/heptane/ethanol (90/5/5); 1.0 mL/min	Rs: 4.03	OR: +/-	[111]
78	uniconazole	CDMPC	hexane/ n-butyl alcohol(89/11); 0.5mL/min; UV 268.6nm	Rs: 1.45		[61]
		CTPC	hexane/ ethanol (93/7); 0.5mL/min; UV 269.8nm	Rs: 2.16		[61]
79	vinclozolin	CDMPC	hexane/IPA(99/1); 1.0 mL/min; 2.0 UV 210nm	Rs: 1.46	OR: +/-	[65]

*1 ACN, MET and IPA means acetronitrile, methanol and isopropanol respectively.

*2 α and Rs means the separation factor and the resolution facotr respectively.

*3 CD and OR means signals obtained from circular dichrism detector and optical rotation detector respectively.

Table 2. Summary of resolution results of chiral pesticides on cellulose-based CSPs

5. Conclusion

Cellulose derivatives have high chiral recognition abilities for racemates and have already become a very popular and useful source material for CSPs. Cellulose-based CSPs can be prepared by coating or bonding cellulose derivatives on decorative silica gel or other supports with various preparation methods. The coated CSPs exhibite higher discrimination abilities for chiral pesticides and are more popular than the bonded CSPs. However, the bonded CSPs can tolerate broader solvent ranges, including THF and $CHCl_3$, which cannot be used on coated CSPs as mobile phases because they have strong dissolution abilities that can dammage or destroy them. Coated CDMPC and CTMB had the broadest application in the stereoselective separations of chiral pesticides. For most pesticides, better separations were obtained on NP-HPLC than on RP-HPLC. However, RP-HPLC can improve the amount of racemates loaded on CSPs as it allows the use of more polar solvents to enhance the solubility of racemates in mobile phases. Additionally, it can be easily connected in tandem with MS, allowing for the development of more sensitive methods for analysis of enantiomers/stereoisomers. The cellulose-based CSPs on NP-HPLC and RP-HPLC provide very powerful tools to prepare individual enantiomers and study the activity, toxicity and environmental fates of chiral pesticides.

Author details

Jing Qiu, Shouhui Dai, Tingting Chai, Wenwen Yang, Shuming Yang and Hualin Zhao
Institute of Quality Standards & Testing Technology for Agro-Products, Chinese Academy of Agricultural Sciences, Beijing, China
Key Laboratory of Agri-Food Quality and Safety, Ministry of Agriculture, Beijing, China

Acknowledgement

The financial support from National Natural Science Foundation of China (Project number 21177156 and 20907073) for this work is hereby gratefully acknowledged.

6. References

[1] Okamoto Y, Ikai T. Chiral HPLC for efficient resolution of enantiomers. Chem Soc Rev 2008;37:2593-2608.
[2] Wang T, Chen YW. Application and comparison of derivatized cellulose and amylase chiral stationary phases for the separation of enantiomers of pharmaceutical compounds by high-performance liquid chromatography. J Chromatogr A 1999;855:411-421.
[3] Okamoto Y, Kaida Y. Resolution by high-performance liquid chromatography using polysaccharide carbamates and benzoates as chiral stationary phases. J Chromatogr A 1994;666: 403-419.

[4] Hesse G, Hagel R. Eine vollständige Recemattennung durch eluitons-chromagographie an cellulose-tri-acetat. Chromatographia 1973;6(6):277-280.
[5] Williams A. Opportunities for chiral agrochemicals. Pestic Sci 1996;46:3-9.
[6] Racke KD, Skidmore M, Hamilton DJ, Unsworth JB, Miyamoto J, Cohen SZ. Pesticide fate in tropical soils. Pestic Sci 1999;55(2):219-220.
[7] Franco P, Minguillón C, Oliveros L.Bonded cellulose-derived high- performance liquid chromatography chiral stationary phases III. Effect of the reticulation of the cellulose derivative on performance. J Chromatogr A 1997; 791:37-44.
[8] Kasuya N, Kusaka Y, Habu N, Ohnishi A. Development of chiral stationary phases consisting of low-molecular-weight cellulose derivatives covalently bonded to silica gel. Cellulose 2002;9:263-269.
[9] Daicel Chiral Technologies (China) Co., Ltd. The list of Chiral columns: http://www.daicelchiraltech.cn/hand/hand.asp (accessed 21 April 2012).
[10] Guangzhou FLM Scientific Instrument Co., Ltd. Chiral columns on HPLC: http://www.gzflm.com/product/ category _4_6_10.aspx (accessed 21 April 2012).
[11] Thunberg L, Hashemi J, Andersson S. Comparative study of coated and immobilized polysaccharide-based chiral stationary phases and their applicability in the resolution of enantiomers. J Chromatogr B 2008;875:72-80.
[12] Okamoto Y, Kawashima M, Hatada K. Chromatographic resolution : XI. Controlled chiral recognition of cellulose triphenylcarbamate derivatives supported on silica gel. J Chromatogr 1986;363:173-186.
[13] Chankvetadze B, Chankvetadze L, Sidamonidze S, Kasashima E, Yashima E, Okamoto Y. 3-fluoro, 3-chloro and 3-bromo-5-methylphenylcarbamates of cellulose and amylase as chiral stationary phases for high-performance liquid chromatographic enantioseparation. J Chromatogr A 1997;787:67-77.
[14] Tang SW, Liang XF, Wang F, Liu GH, Li YL, Pan FU. Synthesis and HPLC chiral recognition of regioselectively carbamoylated cellulose derivatives. Chirality 2012;24:167-173.
[15] Ikai T, Yamamoto C, Kamigaito M, Okamoto Y. Enantioseparation by HPLC using phenylcarbonate, benzoylformate, p-toluenesulfonylcarbamate, and benzoylcarbamates of cellulose and amylose as chiral stationary phases. Chirality 2005;17:299-304.
[16] Yamamoto C, Inagaki S, Okamoto Y. Enantioseparation using alkoxyphenylcarbamates of cellulose and amylose as chiral stationary phase for high-performance liquid chromatography. J Sep Sci 2006;29:915-923.
[17] Jin ZL, Hu FF, Wang Y, Liu GH, Wang F, Pan FY, Tang SW. Preparation and evaluation of amylose and cellulose tris(3-trifluoromethylphenyl- carbamates)-based chiral stationary phases. Chinese J Chromatogr 2011;29:1087-1092.
[18] Chang YX, Yuan LM, Zhao F. Effect of chiral additives in the preparation of cellulose-based chiral stationary phases in HPLC, and effect on enantiomer resolution. Chromatographia 2006;64:313-316.
[19] Ge J, Zhao L, Shi YP. Preparation and evaluation of a novel cellulose tris(n-3,5-dimethylphenylcarbamate) chiral stationary phase. Chinese J Chem 2008;26:139-142.

[20] Chen X, Yang L, Zou HF, Zhang Q, Ni JY. Preparation of the chemically bonded cellulose phenylcarbamates chiral stationary phases for the separation of enantiomers. Chinese J Anal Chem 2000;28:1074-1078.

[21] Katoh Y, Tsujimoto Y, Yamamoto C, Ikai T, Kamigaito M, Okamoto Y. Chiral recognition ability of cellulose derivatives bearing pyridyl and bipyridyl residues as chiral stationary phases for high-performance liquid chromatography. Polymer Journal 2011;43:84-90.

[22] Yang JH, Choi SH. Synthesis of a chiral stationary phase with poly[styrene-bcellulose 2,3-bis(3,5-dimethylphenylcarbamate)] by surface-initiated atom transfer radical polymerization and its chiral resolution efficiency. J Appl Polym Sci 2011,122:3016-3022.

[23] Oliveros L, Senso A, Minguillón C. Benzoates of cellulose bonded on silica gel: chiral discrimination ability as high-performance liquid chromatographic chiral stationary phases. Chirality 1997;9:145-149.

[24] Minguillón C, Franco P, Oliveros L, López P. Bonded cellulose-derived high-performance liquid chromatographic chiral stationary phases I. Influence of the degree of fixation on selectivity. J Chromatogr 1996;728:407-414.

[25] Zhang S, Ong TT, Ng SC, Chan HS. Chemical immobilization of azido cellulose phenylcarbamate onto silica gel via Staudinger reaction and its application as a chiral stationary phase for HPLC. Tetrahedron Letters 2007;48:5487-5490.

[26] Zhou ZQ, Qiu J, Jiang SR. HPLC separation of metalaxyl and metalaxyl intermediate enantiomers on cellulose-based sorbent. Anal Lett 2004; 37(1): 167-172.

[27] Yashima E, Sahahvattanapong P, Okamoto Y. Enantioseparation on cellulose tris(3,5-dimethylphenylcarbamate) as a chiral stationary phase: influences of pore size of silica gel, coating amount, coating solvent, and column temperature on chiral discrimination. Chirality 1996;8:446-451.

[28] Ikai T, Yamamoto C, Kamigaito M, Okamoto Y. Immobilized polysaccharide-based chiral stationary phases for HPLC. Polymer Journal 2006;38:91-108.

[29] Ikai T, Yamamoto C, Kamigaito M, Okamoto Y. Immobilized-type chiral packing materials for HPLC based on polysaccharide derivatives. J Chromatogr B 2008;875:2-11.

[30] Chen XM, Okamoto Y. Efficient immobilization of polysaccharide derivatives as chiral stationary phases via copolymerization with vinyl monomers. Macromol Res 2007;15:134-141.

[31] Tang SW, Okamoto Y. Immobilization of cellulose phenylcarbamate onto silica gel via intermolecular polycondensation of triethoxysilyl groups introduced with (3-glycidoxypropyl)triethoxysilane. J Sep Sci 2008;31:3133-3138.

[32] Qu HT, Li JQ, Wu GS, Shen J, Shen XD, Okamoto Y, Preparation and chiral recognition in HPLC of cellulose 3,5-dichlorophenylcarbamates mmobilized onto silica gel. J Sep Sci 2011;34:536-541.

[33] Okamoto Y, Aburatani R, Miura S, Hatada K. Chiral stationary phases for HPLC: cellulose tris(3,5-dimethylphenylcarbamate) and tris(3,5dichlorophenylcarbamate) chemically bonded to silica gel. J Liq Chromatogr 1987;10:1613-1628.

[34] Yashima E, Fukaya H, Okamoto Y. 3,5-Dimethylphenylcarbamates of cellulose and amylose regioselectively bonded to silica gel as chiral stationary phases for high-performance liquid chr. J Chromatogr A 1994; 677:11-19.
[35] Qiu W, Han XQ, Wei Y, Liu YH, Chang J, Liu WL. Preparation of covalenfly bonded cellulose-derived chiral stationary phase and enantioseparation. Chemical Engineer 2009;161:5-7.
[36] Qin F, Chen Xm, Liu YQ, Zou HF, Wang JD. Improved procedure for preparation of covalently bonded cellulose tris-phenylcarbamate chiral stationary phases. Chinese J Chem 2005;23:885-890.
[37] Ling F, Brahmachary E, Xu MC, Svec F, Jean MJ. Polymer-bound cellulose phenylcarbamate derivatives as chiral stationary phases for enantioselective HPLC. J Sep Sci 2003;26:1337-1346.
[38] Nillos MG, Gan J, Schlenk D. Chirality of organophosphorus pesticides: Analysis and toxicity. J Chromatogr B 2010;878:1277-1284.
[39] Ye J, Wu J, Liu WP. Enantioselective separation and analysis of chiral pesticides by high-performance liquid chromatography. Trends in Anal Chem 2009; 28(10):1148-1163.
[40] Liang HW, Qiu J, Li L, Li W, Zhou ZQ, Liu FM, Qiu LH. Stereoselective separation and determination of triadimefon and triadimenol in wheat, straw and soil by liquid chromatography-tandem mass spectrometry. J Sep Sci 2011; 34: 1-8.
[41] Qian MR, Wu LQ, Zhang JW, Li R, Wang XY, Chen ZM. Stereoselective determination of famoxadone enantiomers with HPLC-MS/MS and evaluation of their dissipation process in spinach. J Sep Sci 2011;34:1236-1243.
[42] Qiu J, Yang SM, Yu HX. A method to simultaneously detect enantiomers of chiral triazole pesticides. China: CN 102353740A; 2012.
[43] Wu T, Li CY, Li QL, Zhang BZ, Li JY. Study of enantiomeric separation of chiral pesticides by High-performance Liquid Chromatography. Journal of hebei normal university 2009;33:218-223.
[44] Qiu J, Wang QX, Zhu WT, Jia GF, Wang XW, Zhou ZW. Stereoselective determination of benalaxyl in plasma by Chiral High-Performance Liquid Chromatography with diode array detector and application to pharmacokinetic study in rabbits. Chirality 2007;19:51-55.
[45] Feng SL, Lin CM. Study on enantiomer separation of triazole chiral fungicides with supercritical fluid chromatography. Zhejiang University of Technology,2010:63-70.
[46] Liu WP, Zhang AP, Yuan HJ. Residues and enantiomeric fractions of organochlorine pesticides in agricultural soils from Zhejiang. Zhejiang University of Technology 2009:44-45.
[47] Liu HG, Zhao MR. Enantioselective eytotoxicity of the insecticide bifenthrin on a human amnion epithelial(FL) cell line. Toxicology 2008;253:89-96.
[48] Zhou ZQ, Liu J, Wang M, Jiang SR. Determination of optical purity of sr-bioallethrin enantiomers by chiral high performance liquid chromatography. Chinese J Chromatogr 2001;19(6):526-528.
[49] Zhou ZQ, Liu J, Wang M, Jiang SR. The Separation of Bioallethrin on Chiral Column. Chinese J Anal Chem 2002;30(4): 504.

[50] Wu T. Study on the separation and conversion of chiral pesticide enantiomers. University of science and technology of Hebei; 2009.
[51] Wang P, Jiang SR, Liu DH, Jia G, Wang Q, Wang P, Zhou ZQ. Effect of alcohols and temperature on the directchiral resolutions of fipronil, isocarbophos and carfentrazone-ethyl. Biomed Chromatogr 2005;19:454-458.
[52] Yuan HJ, Zhang AP. The analysis and detection of EF value of chiral chlorine pesticids in soil. The forth national conference on persistent organic pollutants 2009:39-40.
[53] William L, Champion JR, Lee J, Garrison AW. Liquid chromatographic separation of the enantiomers of *trans*-chlordane, *cis*-chlordane, heptachlor, heptachlor epoxide and α-hexachlorocyclohexane with application to small-scale preparative separation. J Chromatogr A 2004;1024:55-62.
[54] Nillos MG, Fuentes GR. Enantioselective acetylcholinesterase inhibition of the organophosphorous insecticides profenofos, fonofos and crotoxyphos. Environ Toxicol Chem 2007;26:1949-1954.
[55] Ellington JJ, Evans JJ, Rickett KB, Champion WL. High-performance liquid chromatographic separation of the enantiomers of organophosphorus pesticides on polysaccharide chiral stationary phases. J Chromatogr A 2001;928:145-154.
[56] Jiang B, Wang H, Fu QM, Li ZY. The chiral pyrethroid cycloprothrin: Stereoisomer synthesis and separation and stereoselective insecticidal activity. Chirality 2008; 20:96.
[57] Wang P, Zhou ZQ, Jiang SR, Yang L. Chiral resolution of cypermethrin on cellulosetris(3,5-dimethylphenylcarbamate) chiral stationary phase. Chromatographia 2004;59: 625-629.
[58] Wang QX, Qiu J, Zhu WT, Jia GF, Li JL, Bi CL, Zhou ZQ, Stereoselective degradation kinetics of theta-cypermethrin in rats. Environ Sci Technol 2006;40(3): 721-726.
[59] Ma Y. Study on the analysis of chiral pesticide enantiomers dichlorprop and enantioselective behavior in environment.Zhejiang University; 2005.
[60] Shen BC, Yuan JY, Wang HC. Enantioseparation of three aryloxyphenoxypropionic acids herbicides on CDMPC and vancomycin CSP Column. Journal of Instrumental Analysis 2008;27(12):1379-1382.
[61] Pan CX, Wu QZ, Shen BC, Zhang DT, Xu XZ. Enantioseparation of four aryloxyphenoxypropionic acid herbicides by high performance liquid chromatography on cellulose tris-(3.5-dimethylphenylcarbamate and(S,S)-Whelk-O 1. Chinese J Anal Chem 2006;34(2): 159-164.
[62] Li XJ, Di ZD, Ming YF, Zhao YF, Li YM, Chen LR. Enantiomeric resolution of diclofopmethyl by HPLC on Chiralcel OD column. Chemical Researches 2005;16(3):71-74.
[63] Pan CX. The separation of drug enantiomers on HPLC. Zhejiang University; 2005.
[64] Wang P. Study on the analysis of chiral pesticide enantiomers and enantioselective degradation behaviors in soil. China Agricultural University; 2006.
[65] Wang P, Jiang SR, Liu DH, Zhang HJ, Zhou ZQ. Enantiomeric resolution of chiral pesticides by high-performance liquid chromatography. J Agric Food Chem 2006;54:1577-1583.

[66] Tian Q. Study on the analysis and separation of chiral pesticide enantiomers on polysaccharide-type chiral stationary phases under reversed phase conditions. China Agricultural University; 2007.
[67] Chen P, Na PJ, Han XQ, Pan CP, Hou JG, Du XZ, Gao JZ. Enantiomeric resolution of diclofop-methyl by HPLC with chiral stationary phase. Journal of Instrumental Analysis 2003;22(3):39-41.
[68] Liu WL, Han XQ. Enantioseparation of dichlofop-methyl on chemically bonded chiral stationary phase. Chemical reagents 2009;31(10): 825-827.
[69] Cai XY. Effects of MCD and humic acid on aquatic toxicity and bioavailability of the chiral herbicide diclofop methyl. Zhejiang University; 2006.
[70] Lin KD, Cai XY, Chen SW, Liu WP. Simultaneous determination of enantiomers of rac-diclofop methyl and rac-diclofop acid in water by high performance liquid chromatography coupled with fluorescence detection. Chinese J Anal Chem 2006;34(5):613-616.
[71] Zhou Y, Li L, Lin K, Zhu XP, Liu WP. Enantiomer separation of triazole fungicides by high-performance liquid chromatography. Chirality 2009;21:421-427.
[72] Wang P, Jiang SR, Liu DH, Wang P, Zhou ZQ. Direct enantiomeric resolutions of chiral triazole pesticides by high-performance liquid chromatography. J Biochem Biophys Methods 2005;62:219-230.
[73] Li CY, Zhang YC, Li QL. Chiral separation and enantiomerrization of triazole pesticides. Chinese J Anal Chem2010;38: 237-240.
[74] Wu YS, Lee HK, Li SFY. High-performance chiral separation of fourteen triazole fungicides by sulfated b-cyclodextrin-mediated capillary electrophoresis. J Chromatogr A 2001;912 :171-179.
[75] Qiu J, Dai SH, Zheng CM, YangSM, Chai TT, Bie M. Enantiomeric separation of triazole fungicides with 3-μm and 5-μm particle chiral columns by Reverse-Phase High-Performance Liquid Chromatography. Chirality, 2011;23: 479-486.
[76] Zhou SS. Stability and stereoselective biological activities of chiral organophosphorus pesticides.China, Zhejiang: Zhejiang University; 2009.
[77] Wang P, Jiang SR, Zhou ZQ. Study on the chiral separation of the enantiomers ethofumestate. Chemical World 2004;11:581-582.
[78] Wang P. Studies on enantiomeric activity and stereoselective behavior of chiral pesticide ethofumesate in organism and environment. China Agricultural University; 2005.
[79] Wang P, Jiang SR, Qiu J, Wang QX, Wang P, Zhou ZQ. Stereoselective degradation of ethofumesate in turfgrass and soil. Pesticide Biochemistry and Physiology 2005;82:197-204.
[80] Zhang XJ, Shen BC, Chen JJ, Xu BJ, Xu XZ. The sthdy of separation and thermodynamics of adsorpation of the enantiomers of ethofumasate on a modified cellulose. Anal Lett 2006;39:1451-1461.
[81] Tian Q, Lv CG, Wang P, Ren LP, Qiu J, Li L, Zhou ZQ. Enantiomeric separation of chiral pesticides by high performance liquid chromatography on cellulose tris-3,5-dimethyl carbamate stationary phase under reversed phase conditions. J Sep Sci 2007;30:310-321.

[82] Bo ZB. The separation of efficacy fipronil enantiomers. World Pesticides 2004;26:14-15.
[83] Lu DH, Liu DH, Gu X, Diao JL, Zhou ZQ. Stereoselective metabolism of fipronil in water hyacinth (Eichhornia crassipes). Pestic Biochem Phys 2010;97:289-293.
[84] Hou SC. The preparation of Liquid chromatography chiral stationary phase and its performance study. China Agricultural University; 2003.
[85] Qu LF, Hu JL, Zhan B. A study on analytical methods of the chiral isomers of fluazifop-p-butyl. Hangzhou Chemical Industry 2010;40(1):40-42.
[86] Qiu J, Li L, Zhou ZQ, Jiang SR, Zhao HX. Separation of fluroxypyr-meptyl enantiomers by High Performance Liquid Chromatography. Chinese J Pestic Sci 2004; 6(2):84-86
[87] Yang GS, Vázquez PP, Frenich AG, Martínez JL and Aboul-Enein HY. Separation and simultaneous determination of enantiomers of tau-fluvalinate and permethrin in drinking water. Chromatographia 2004;60:523-526.
[88] Han XQ, Wen XG, Guan YH. Influences of mobile phase composition and temperature on chiral separation of some triazole pesticides. Chinese Journal of Applied Chemistry 2004;21:140-143.
[89] Han XQ, Wei Y. The enantioseparation of some triazole pesticides on chiralcel OD-H column. Chemical Reagents 2010;32:74-76.
[90] Lao WJ, Gan JY. High-performance liquid chromatographic separation of imidazolinone herbicide enantiomers and their methyl derivatives on polysaccharide-coated chiral stationary phases J Chromatogr A 2006;1117:184.
[91] Lin KD, Xu C, Zhou SS, Liu WP, Gan J. Enantiomeric separation of imidazolinone herbicides using chiral high-performance liquid chromatography. Chirality 2007;19:171-178.
[92] Zhou QY. Study on the enantioselective inhibition of Phytotoxicity of Imazethapyr to corn roots and its mechanism. Zhejiang University; 2010.
[93] Sun DL, Qiu J, Wu YJ, Liang HW, Liu CL, Li L. Enantioselective degradation of indoxacarb in cabbage and soil under field conditions. Chirality 2012, DOI: 10.1002/chir.22047.
[94] Xu Q, Liu KT, Tang FR, Wang JB. Determination of indoxacard 15% SC by HPLC. Modern Agrochemicals 2010,9:31-35.
[95] Lin K, Liu WP, Li L, Gan J. Single and joint acute toxicity of isocarbophos enantiomers to daphnia magna. J Agric Food Chem 2008;56:4273-4277.
[96] Zhang T, Nguyen D, Franco P, Isobe Y, Michishita T, et al. Cellulose tris-(3,5-dichlorophenylcarbamate) immobilised on silica: a novel chiral stationary phase for resolution of enantiomers. J Pharmaceut Biomed 2008;46:882-891.
[97] Xu C, Wang JJ, Liu WP, Sheng GD, Tu YJ, Ma Y. Separation and aquatic toxicity of enantiomers of the pyrethroid insecticide lambda-cyhalothrin. Environ Toxicol Chem 2008;27:174.
[98] Zhang AP. Effect of cyclodextrins on environmental behavior of selected chiral pesticides. Zhejiang University; 2006.
[99] Ming YF, Zhang HL, Li YM. The separation of the enantiomers of metalaxyl. The first academic exchange conference on chromatography of the Midwest China 2006;8:145-148.

[100] Chen SW, Lin KD, Liu WP. Determination of metalaxyl enantiomeric purity by nonchiral high performance liquid chromatography with circular dichroism detector. Chinese J Anal Chem 2006;4(34):525P-528.

[101] Han XQ, Li J, Yun CL, Sun YY, Wang HS. Chiral Separation of Compounds on Covalently Bonded Cellulose Chiral Stationary Phase by NO1Tflal and Reversed Phase HPLC. Journal of Instrumental Analysis 2007;26:55-58.

[102] Qiu J, Wang QX, Zhou ZQ, Yang SM. Enantiomeric separation and circular dichroism detection of metalaxyl acid metabolite by Chiral High Performance Liquid Chromatography. Asian J Chem 2009;21(8): 6095-6101.

[103] Lin K, Zhou SS, Xu C, Liu WP. Enantiomeric resolution and biotoxicity of methamidophos. J Agric Food Chem 2006;54:8134−8138.

[104] Polcaro CM, Berti A, Mannina L, Marra C, Sinibaldi M, Viel S. Chiral HPLC resolution of neutral pesticides. J Liq Chromatogr Relat Technol 2004;27:49-61.

[105] Cai XJ, Li Z, Xu XZ. Study on Enantioseparation of several herbicides on chiral stationary phases with HPLC. Journal of Instrumental Analysis 2007;26(6):891-894.

[106] Lin CM, Liu JY, Zhang DT. Enantioseparation of naproanilide on cellulose derivatives chiral stationary phases. Agrochemicals 2007;46(8):526-528.

[107] Chen SW, Cai XY, Liu WP. Characterization of napropamide enantiomers by CD and determination of the enantiomeric ratios in water. Spectrosc Spect Anal 2009;26(9):1649-1652.

[108] Burden RS, Carter GA, Clark T, Cooke DT, Croker SJ, Deas AHB, Hedden P, James CS, Lenton JR. Comparative activity of the enantiomers of triadimenol and paclobutrazol as inhibitors of fungal growth and plant sterol and gibberellin biosynthesis. Pestic Sci 1987;21:253-267.

[109] Yang HY. Study on environmental behavior of insecticide pyraclofos. Zhejiang University; 2008.

[110] Pan H, Duan R, Liao Y, Xu BM. Chromatographic separation of chiral pesticides and their intermediates. Chemistry & Bioengineering 2007;24(8):76-78.

[111] Liu WP, Lin K, Gan JY. Separation and aquatic toxicity of enantiomers of the organophosphorus insecticide trichloronate. Chirality 2006;18:713-716.