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Abiotic Enantiomerization of Permethrin and Cypermethrin: Effects of Organic Solvents

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All synthetic pyrethroids are chiral compounds, and isomerization has been frequently observed from exposure to certain solvents. However, so far, pyrethroid isomerization caused by solvents has not been characterized at the enantiomer level. In this study, we evaluated the occurrence of enantiomerization of two commonly used pyrethroids, permethrin and cypermethrin, in various organic solvents and solvent−water systems. The four stereoisomers of permethrin were stable under all test conditions. Rapid enantiomerization of cypermethrin was observed in isopropanol and methanol but not in *n*-hexane, acetone, or methylene chloride. After 4 days at room temperature, 18−39% conversions occurred for the different cypermethrin stereoisomers in isopropanol and methanol, and the enantiomerization invariably took place at the α-carbon position. The extent of enantiomerization was affected by temperature dependence and was also influenced by water as a cosolvent. In solvent−water mixtures, cypermethrin underwent gradual enantiomerization in acetone−water and rapid enantiomerization in isopropanol−water or methanol−water. The extent of enantiomerization varied among the solvents and as a function of the solvent-to-water ratio. Results from this study suggest that exposure to certain solvents and water may cause artifacts in chiral analysis and that for isomer-enriched pyrethroid products, such abiotic enantiomerization may render the products less effective because the conversion leads to the formation of inactive stereoisomers.

KEYWORDS: Isomerization; enantiomerization; enantiomers; pyrethroids; chiral analysis

INTRODUCTION

A large number of modern pesticides are chiral compounds (*1*). Recent studies have increasingly shown that enantiomeric specificity, that is, enantioselectivity, commonly occurs for chiral pesticides in their biologically mediated processes, including pesticidal activity (*2*, *3*), bioaccumulation (*4*−*6*), and biodegradation (*7*−*9*). Enantioselectivity in these processes has two important implications. First, enantioselective biodegradation or bioaccumulation results in preferential enrichment (or depletion) of one enantiomer over the other. To better predict environmental risks, fate and transport of chiral pesticides must be characterized at the enantiomer level by using chiral selective analytical methods (*10*). On the other hand, to take advantage of enantioselectivity in pesticidal activity, enantiomer-pure or enantiomer-enriched products are viewed as "green chemistry" options over the conventional use of racemic products, because the environmental load of the inactive enantiomer(s) is essentially eliminated or greatly reduced (*3*). This is evident, for example, in the recent switch from the racemic mecoprop formulations to *R*-mecoprop in Europe (*7*).

A unique example of chiral pesticides is the class of pyrethroid insecticides. All pyrethroid compounds are chiral compounds consisting of two or four pairs of enantiomers, with each enantiomer pair constituting a diastereomer that is named as *cis* or *trans* (*11*). Chirality in a pyrethroid can arise from the acid moiety (i.e., the cyclopropyl ring), the alcohol moiety (i.e., the α-cyano carbon), or both (*12*). Enantioselectivity of pyrethroids has been observed not only in insecticidal activity (*13*, *14*) but also increasingly in environmental fate (*10*, *15*) and aquatic toxicities (*10*, *16*). The enantioselectivity in insecticidal activity has led to the marketing of several enantiomer-pure (e.g., esfenvalerate, deltamethrin) and enantiomer-enriched (e.g., α-, *β*-, and *θ*-cypermethrin (CP), *λ*-cyhalothrin, and *β*-cyfluthrin) pyrethroid products.

Several earlier studies showed that isomerization may occur for pyrethroids when in contact with polar solvents (*17*−*19*). However, in those studies, isomerization was evaluated only at the diastereomer level, not at the enantiomer level, apparently due to the lack of chiral separation methods at that time. Enantiomerization due to solvents can cause analytical biases in chiral selective analysis, because such solvents may be used in sample extraction, storage, and analysis. In addition, solvents are commonly used in pesticide formulations, and enantiomerization may render an enantiomer-enriched product less effective due to the conversion of an insecticidally active stereoisomer to a nonactive stereoisomer. In this study, we evaluated the isomerization of permethrin (PM) and CP (**Figure 1**) in various solvents and solvent−water systems at the enantiomer level using recently developed chiral selective analytical methods. Knowledge about enantiomerization of pyrethroids in solvents

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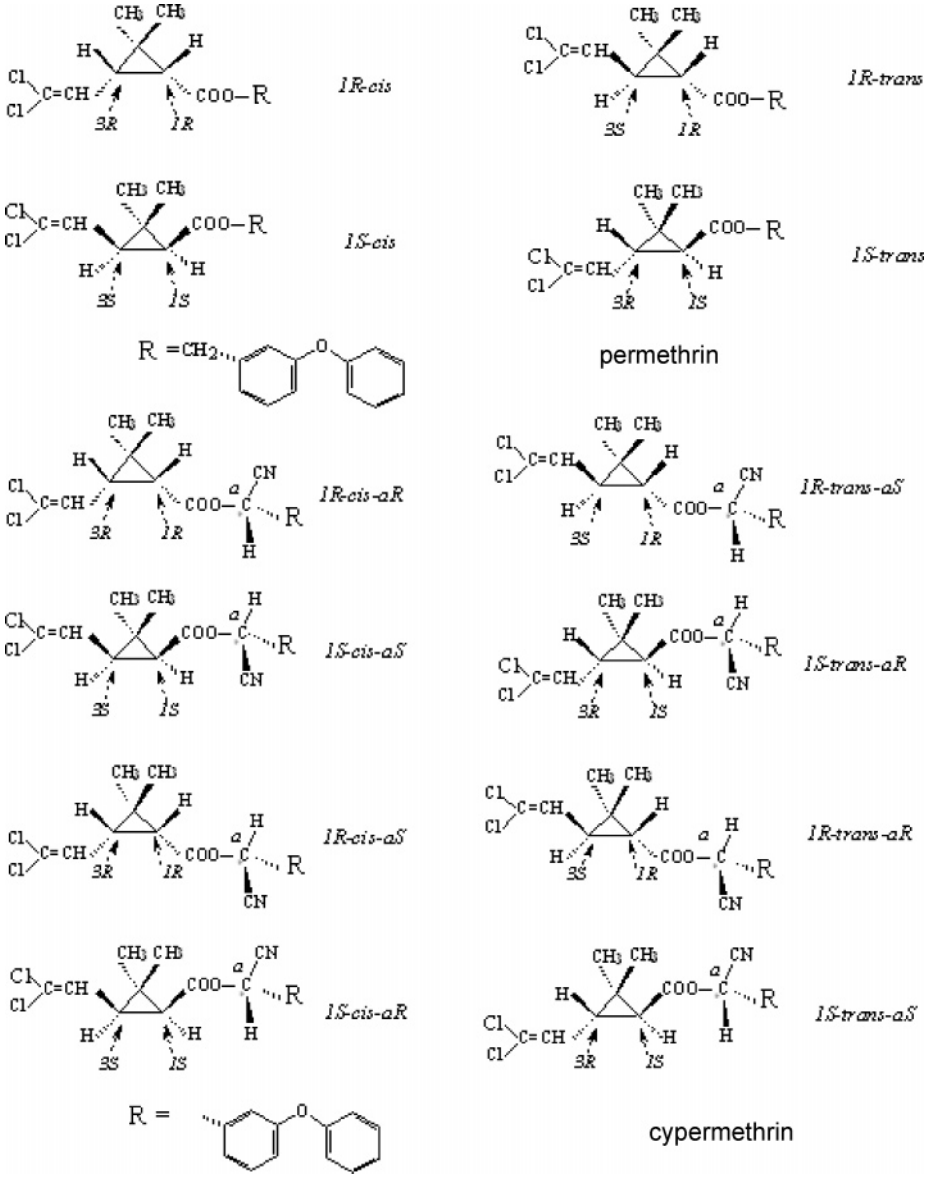

Figure 1. Chemical structure of PM and CP enantiomers showing chiral positions (labeled with 1, 3, or α) in the structure.

and solvent−water mixtures will be of great value for developing rigorous analytical methods and for proper formulating or handling of enantiomer-enriched products.

MATERIALS AND METHODS

Chemicals. Analytical standards of PM (99%) and CP (98%) were purchased from Chem Service (West Chester, PA). The stereoconfigurations of PM and CP are shown in **Figure 1**. By using previously established chiral selective high-performance liquid chromatography (HPLC) methods (*20*), individual enantiomers were isolated and prepared. Four enantiomers from PM, *R-cis*-PM, *S-cis*-PM, *R-trans*-PM, and *S*-trans-PM, and four enantiomers from two of the four diastereomers of CP, 1*R-cis*-α*R*-CP, 1*S-cis*-α*S*-CP, 1*R-trans*-α*R*-CP, and 1*S-trans*-α*S*-CP, were obtained. The purity of the isolated enantiomers was determined to be >99% by HPLC and gas chromatography (GC) analysis prior to their use. Other solvents or chemicals used in this study were of analytical or HPLC grade.

Experiments in Pure Solvents. Individual pyrethroid enantiomers were added to 1.0 mL of a solvent in brown glass GC vials at 10 μg mL^{-1}. Five different solvents, *n*-hexane, methylene chloride, isopropanol, acetone, and methanol, were included. The sample vials were capped with crimp seals, covered with aluminum foil, and kept in the dark at room temperature (20 ± 1 °C). After 1, 2, and 4 days of incubation, duplicate samples in separate vials were removed, blown to dryness under nitrogen, and redissolved in 0.5 mL of *n*-hexane. The samples were immediately analyzed on GC using a previously developed method to determine the enantiomer composition (*21*, *22*). One set of samples was kept at 4 °C in a refrigerator and subjected to the same analysis to understand the temperature effect.

Experiments in Solvent−Water Mixtures. A 5.0 mL solution of an individual PM or CP enantiomer was prepared in a 20 mL glass vial at 1.0 μg mL^{-1}. The solution was a mixture of water and a water-miscible solvent at different ratios. Three ratios (90:10, 50:50, and 10:90, v/v) were used for methanol, and one ratio (50:50, v/v) was used for isopropanol and acetone. The samples were capped, covered with aluminum foil, and kept in the dark at room temperature (20 ± 1 °C). After 1, 2, and 4 days of incubation, duplicate samples were removed and 10 g of anhydrous sodium sulfate was added to each sample vial to absorb the water. Five milliliters of methylene chloride was then added, and the sample was mixed on a vortex for 1 min. After the collection of the methylene chloride phase, the same extraction step was repeated. The solvent extracts were combined, filtered through 10 g of anhydrous sodium sulfate in a funnel, and transferred to a concentration tube. Another 2 mL of methylene chloride was used to rinse the sodium sulfate layer, and the combined extract was then blown

to dryness under nitrogen and redissolved in 0.5 mL of hexane. Samples were immediately analyzed on GC to determine the enantiomer composition.

GC Analysis. Chiral selective analysis was carried out on an Agilent 6890 GC equipped with electron capture detector (Agilent Technologies, Palo Alto, CA) using a BGB-172 capillary column (30 m × 0.25 mm × 0.25 μm, *tert*-butyldimethylsilyl-β-cyclodextrin dissolved in 15% diphenyl- and 85% dimethyl-polysiloxane, BGB Analytik, Adliwil, Switzerland). The detector temperature was 310 °C, and the makeup gas was nitrogen flowing at 60 mL min^{-1}. The inlet temperature was 160 °C. The column was initially held at 160 °C for 1 min and then ramped to 230 °C at 1 °C min^{-1}, followed by holding at 230 °C until complete elution of all enantiomers. Under the conditions used, all enantiomers from the cis diastereomers were well-separated, while those from the trans diastereomer of PM and CP were not resolved (*15*, *21*). Preliminary experiments showed that the method detection limits for the selected enantiomers were 1−2 ng mL^{-1}. Peak areas were directly used to calculate enantiomer composition, assuming the same instrument response for enantiomers from the same compound.

RESULTS

Enantiomerization in Pure Solvents. The enantioselective separation and identification of selected pyrethroids on GC were described in a previous study (*22*). To minimize the heat-induced enantiomerization during GC analysis (*22*), the inlet temperature was lowered to 160 °C. Injecting individual enantiomers under these conditions, the conversion of CP enantiomers induced by the GC inlet was found to be relatively small (~3%), and no isomerization was detectable for PM. During each sequence of analysis, pure enantiomers in *n*-hexane were analyzed to quantify the enantiomer conversion caused by GC analysis and this fraction of conversion was subtracted when calculating the enantiomerization rate due to exposure to a solvent. In addition, as all samples were incubated in the dark, the potential contribution from ambient light to the observed isomerization was considered to be insignificant.

The GC column used in the analysis was chiral selective and, hence, capable of resolving enantiomers from the cis diastereomers of PM and CP. After the individual enantiomers of *cis*-PM (*R-cis*-PM and *S-cis*-PM) were stored in the different solvents at room temperature, no second peak was found for any of the solvents. However, for *cis*-CP enantiomers (1*R-cis*-α*R*-CP and 1*S-cis*-α*S*-CP), in addition to the starting enantiomer, a new peak appeared in some solvents (**Figure 2**). While enantiomerization of CP was insignificant (<2%) in acetone and nondetectable in *n*-hexane or methylene chloride, significant enantiomerization occurred in isopropanol and methanol. For 1*R-cis*-α*R*-CP, the conversion resulted in the formation of 1*R-cis*-α*S*-CP, whereas for 1*S-cis*-α*S*-CP, the conversion led to the production of 1*S-cis*-α*R*-CP. Therefore, in the selected aliphatic alcohols, enantiomerization invariably took place on the α-carbon, and bond rotation did not occur at the C1 or C3 position on the cyclopropyl ring. For enantiomers from the trans diastereomers of PM or CP, a similar pattern was observed. No enantiomerization was detected for *R-trans*-PM and *S-trans*-PM in any of the solvents. However, for *trans*-CP enantiomers (1*R-trans*-α*R*-CP and 1*S-trans*-α*S*-CP), a second peak was also observed after exposure in isopropanol or methanol. Under the used analytical conditions, the enantiomer pair from the *trans*-CP diastereomer was not completely resolved and appeared as one peak. Therefore, when 1*R-trans*-α*R*-CP was exposed to isopropanol or methanol, the resulting enantiomer could be either 1*R-trans*-α*S*-CP, 1*S-trans*-α*R*-CP, or both. A similar assessment may also be made for 1*S-trans*-α*S*-CP. However, as found with the *cis*-CP enantiomers, if enantiomerization only occurred at the α-carbon position, it may be extrapolated that 1*R-trans*-α*R*-CP was converted to 1*R-trans*-α*S*-CP, while 1*S-trans*-α*S*-CP was converted to 1*S-trans*-α*R*-CP.

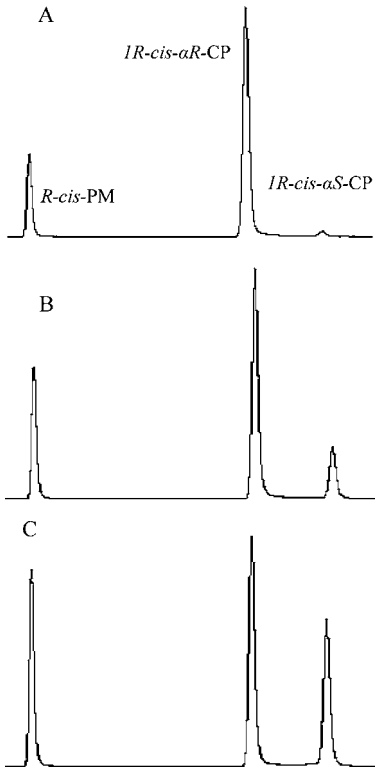

Figure 2. Gas chromatograms of *R-cis*-PM and 1*R-cis*-α*R*-CP after exposure to methanol for different time intervals. (**A**) 0, (**B**) 1, and (**C**) 4 days.

Enantiomerization as a function of time in the selected solvents is plotted in **Figure 3** for 1*R-cis*-α*R*-CP (**Figure 3a**) and 1*R-trans*-α*R*-CP (**Figure 3b**). The patterns for 1*S-cis*-α*S*-CP were almost identical to those for 1*R-cis*-α*R*-CP (data not shown), and the patterns for 1*S-trans*-α*S*-CP were similar to those for 1*R-trans*-α*R*-CP (data not shown). In isopropanol and methanol, enantiomerization was rapid for all four enantiomers of CP examined in this study. After 4 days, 18−39% conversion occurred for the different enantiomers in these alcohols. Assuming that the conversion between a pair of enantiomers was a process of equilibrium, then when 1*R-cis*-α*R*-CP (the starting enantiomer) was converted to 1*R-cis*-α*S*-CP (the resulting enantiomer), 1*R-cis*-α*S*-CP was also converted back to 1*R-cis*-α*R*-CP. If the conversion in both directions obeyed first-order kinetics, which was verified in a previous study (*19*), the following equation can describe the dissipation of the starting enantiomer (*22*):

$$[S] = 0.5[S]_0(1 + e^{-k_1 t}) \quad (1)$$

where [*S*] is the concentration of the starting enantiomer at time *t*, $[S]_0$ is the initial concentration of the starting enantiomer, and k_1 is the rate constant for the conversion. The estimated k_1 values (day^{-1}) for enantiomerization of the selected CP enantiomers in isopropanol and methanol are given in **Table 1**. The results show that conversion of CP enantiomers was faster in methanol than in isopropanol and that the rate of enantiomerization was similar between enantiomers from the same diastereomer,

Temperature influence was further evaluated by measuring enantiomer stability in the selected solvents at 4 °C. Enantiomers

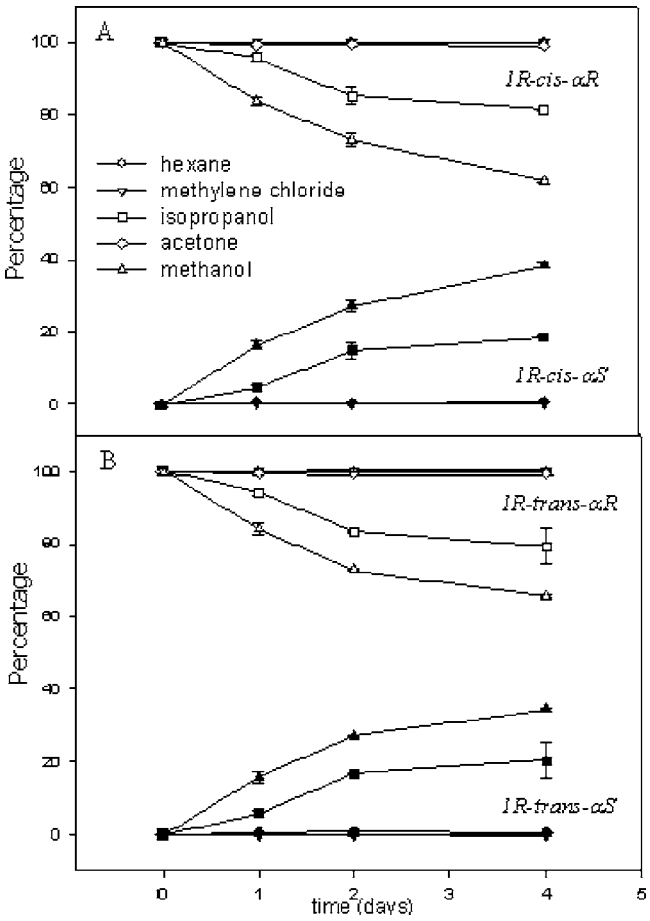

Figure 3. Disappearance of the starting enantiomer and appearance of the converted enantiomer of CP as a function of time in selected organic solvents. (**A**) Enantiomerization of 1*R-cis*-α*R* to 1*R-cis*-α*S* and (**B**) enantiomerization of 1*R-trans*-α*R* to 1*R-trans*-α*S*. Open dots refer to starting enantiomer, and solid dots refer to converting enantiomer.

Table 1. Kinetic Constant k_1 (day^{-1}) (Mean ± Standard Error) for Interconversion of CP Enantiomers in Selected Organic Solvents at Room Temperature

enantiomer	isopropanol	methanol
1*R-cis*-α*R*	0.120 ± 0.007	0.217 ± 0.017
1*S-cis*-α*S*	0.096 ± 0.034	0.258 ± 0.066
1*R-trans*-α*R*	0.185 ± 0.010	0.279 ± 0.023
1*S-trans*-α*S*	0.145 ± 0.022	0.340 ± 0.008

of PM were found to be stable in all solvents at 4 °C. For CP enantiomers, the same enantiomerization patterns were consistently observed at 4 °C in isopropanol and methanol, but the extent of conversion was smaller, ranging from 3.8 to 6.4% in isopropanol and from 9.8 to 11.8% in methanol (**Table 2**).

Enantiomerization in Solvent−Water Systems. On the basis of water miscibility and popularity in usage, acetone, methanol, and isopropanol were chosen to prepare the solvent−water systems. All enantiomers of PM were stable in any of the solvent−water mixtures. In addition, preliminary experiments showed that both PM and CP were stable when incubated in water at room temperature. However, CP enantiomers underwent conversion after incubation in all of the selected solvent−water mixtures. **Figure 4** shows the enantiomerization of 1*R-cis*-α*R*-CP (**Figure 4a**) and that of 1*R-trans*-α*R*-CP (**Figure 4b**) in the different solvent−water systems at a 1:1 (v/v) ratio. The patterns of enantiomerization for 1*S-cis*-α*S*-CP (data not shown) were similar to those in **Figure 4a**, and the patterns for 1*S-trans*-α*S*-CP (data not shown) were similar to those in **Figure 4b**. Enantiomerization was very rapid for all enantiomers in all solvent−water (1:1) mixtures, reaching equilibrium in 1 day, (except for) 1*R-cis*-α*R*-CP and 1*S-cis*-α*S*-CP in the acetone−water mixture (1:1, v/v) (**Figure 4**). In acetone−water (1:1, v/v), enantiomerization of 1*R-cis*-α*R*-CP and 1*S-cis*-α*S*-CP was slower but still reached an apparent equilibrium in 4 days. At equilibrium, about 45% of the starting enantiomer was converted to the corresponding epimer. Because of the lack of measurements at time intervals less than 1 day, rate constants for these treatments were not calculated. It is evident, however, that the presence of water as a cosolvent substantially enhanced the conversion of CP enantiomers for all selected solvents when compared to that in pure solvents (**Figure 3**). While enantiomerization of CP was negligible in pure acetone, it became significant in the acetone−water (1:1, v/v) mixture. Complete enantiomerization of CP in methanol−water (1:1, v/v) and isopropanol−water (1:1, v/v) occurred in 1 day (**Figure 4**).

The effect of solvent−water ratio was further studied by evaluating enantiomerization of CP in methanol−water mixtures of different ratios (**Table 3**). As compared to the rate of enantiomerization of CP in pure methanol, enantiomerization was significantly faster in methanol−water mixtures at the 9:1 or 1:1 ratio but slower at the 1:9 ratio. In the 9:1 or 1:1 methanol−water mixture, an apparent equilibrium was reached in 1 day for the trans enantiomers, while a steady state was reached for the cis enantiomers in 2 days. From **Table 3**, it may be concluded that enantiomerization in methanol−water mixtures depended on the methanol-to-water ratio and that enantiomerization was faster for the *trans*-CP enantiomers than for the *cis*-CP enantiomers.

DISCUSSION

Isomerization of pyrethroids in different solvents has been investigated previously but only at the diastereomer (i.e., cis−trans) level, apparently due to the unavailability of chiral separation methods. Under UV light, deltamethrin in methanol, *n*-hexane, or acetonitrile−water (3:2) underwent cis−trans conversion. Exposure of diluted solutions in methanol to sunlight caused racemization at the α-carbon position (*17*). Conversion between cis and trans diastereomers on the cyclopropyl ring was also observed for PM in water and water−acetone mixture after exposure to artificial light (λ > 290 nm) (*23*). The cis−trans isomerization reached equilibrium in less than 4 h under the test conditions. In those studies, even though the isomerization was attributed to photochemistry, results from the current study suggest that the solvents used in the measurement could have partly contributed to the observed isomerization of deltamethrin. However, our results confirm that isomerization observed for PM in earlier studies was likely caused only by photochemical processes.

In another study (*16*), stability of the four diastereomers of cyfluthrin, which is structurally similar to CP, was investigated in different solvents. In aprotic solvents such as *n*-hexane, acetonitrile, and dichloromethane and in the absence of light, cyfluthrin diastereomers were found to be stable. However, when cyfluthrin diastereomers were incubated in methanol or methanol−water mixtures, rapid isomerization was observed. At 22 °C, a 1:1 mixture of two diastereomers was formed after 20 h in methanol (*16*). Enantiomerization on the α-carbon was implied, and isomerization reduced the toxicity of the active cyfluthrin diastereomers to selected invertebrate species. These results were in agreement with our observation that pyrethroid compounds

Table 2. Enantiomerization of CP after Incubation in Different Solvents at 4 and 20 °C for 4 Days (% Converted, with 50% as Complete Conversion)

starting enantiomer	hexane		methylene chloride		acetone		isopropanol		methanol	
	4 °C	20 °C	4 °C	20 °C	4 °C	20 °C	4 °C	20 °C	4 °C	20 °C
1*R-cis*-α*R*	ND	ND	ND	ND	0.2 ± 0.1	0.8 ± 0.1	3.8 ± 0.1	18.5 ± 0.2	9.8 ± 1.0	38.3 ± 0.5
1*S-cis*-α*S*	ND	ND	ND	ND	0.3 ± 0.0	0.7 ± 0.0	6.4 ± 0.5	24.5 ± 1.2	11.8 ± 0.8	32.6 ± 0.8
1*R-trans*-α*R*	ND	ND	ND	ND	0.6 ± 0.1	0.6 ± 0.1	4.2 ± 0.3	20.5 ± 4.7	11.3 ± 0.4	34.5 ± 0.6
1*S-trans*-α*S*	ND	ND	ND	ND	0.4 ± 0.1	0.4 ± 0.2	6.0 ± 0.2	23.8 ± 3.3	11.5 ± 0.7	34.9 ± 0.6

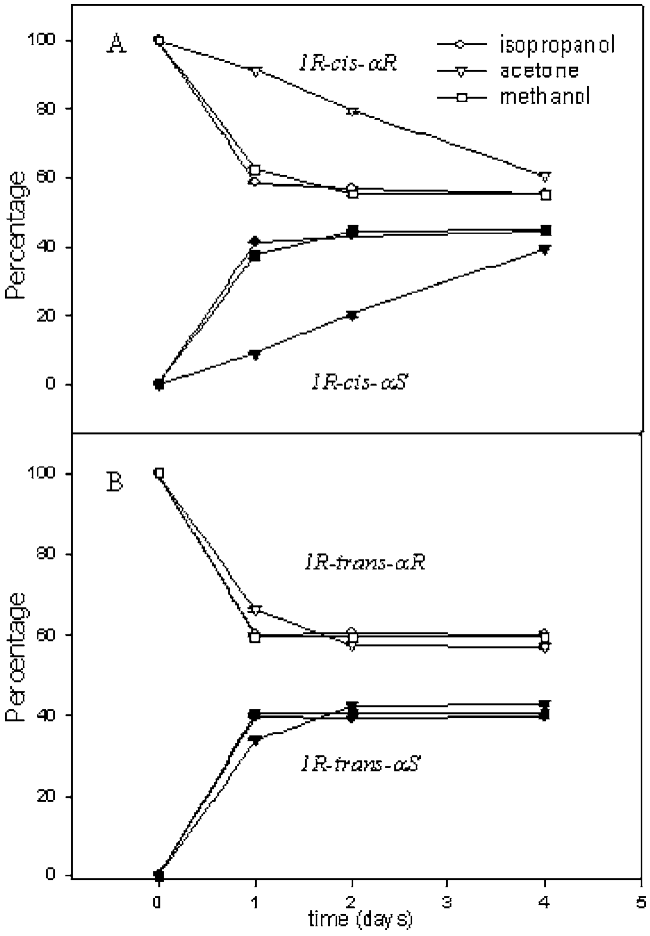

Figure 4. Disappearance of the starting enantiomer and appearance of the converted enantiomer of CP as a function of time in solvent–water mixtures (1:1, v/v). (**A**) Enantiomerization of 1*R-cis*-α*R* to 1*R-cis*-α*S* and (**B**) enantiomerization of 1*R-trans*-α*R* to 1*R-trans*-α*S*. Open dots refer to starting enantiomer, and solid dots refer to converting enantiomer.

with α-cyano group were unstable in protic solvents such as aliphatic alcohols.

Enantiomerization induced by heat was previously reported for CP during GC analysis (*22*). When the GC inlet temperature was raised from 160 to 260 °C, conversion of CP enantiomers increased from about 3 to 9%. When exposed to both high temperature and a catalyst, isomerization was further observed for PM enantiomers (*24*). When PM samples were heated at 210 °C in an oven, no isomerization was observed. However, when PM was subjected to both heat and potassium chlorate (a salt present in smoke-generating formulations of some pyrethroids), conversion occurred between *cis*-PM and *trans*-PM. Other salts of the type KXO_3 or $NaXO_3$, where X is a halogen or nitrogen, also led to significant isomerization. Similar results were also obtained for deltamethrin and β-cyfluthrin when they were heated to 210 °C in the presence of potassium chlorate (*24*).

Table 3. Enantiomerization of CP after Incubation in Methanol–Water Mixtures at Different Ratios (Solvent-to-Water, v/v) (% Converted, with 50% as Complete Conversion)

starting enantiomer	days	10:0	9:1	1:1	1:9
1*R-cis*-α*R*	1	16.3 ± 1.0	39.9 ± 0.1	37.6 ± 0.7	8.4 ± 0.1
	2	27.1 ± 1.8	42.6 ± 0.4	44.6 ± 0.3	9.6 ± 0.8
	4	38.3 ± 0.5	43.1 ± 0.1	44.8 ± 0.0	20.0 ± 0.3
1*S-cis*-α*S*	1	12.5 ± 0.1	38.1 ± 0.6	37.7 ± 0.0	6.7 ± 0.9
	2	28.0 ± 2.1	39.7 ± 0.1	41.1 ± 0.1	9.1 ± 0.6
	4	32.6 ± 0.8	40.7 ± 0.6	41.8 ± 0.3	16.1 ± 1.0
1*R-trans*-α*R*	1	15.9 ± 1.4	38.9 ± 0.0	40.4 ± 0.1	8.8 ± 0.5
	2	27.1 ± 0.3	39.7 ± 0.7	40.5 ± 0.1	17.7 ± 0.3
	4	34.5 ± 0.6	40.5 ± 0.8	40.4 ± 0.1	23.2 ± 1.0
1*S-trans*-α*S*	1	21.4 ± 0.3	39.4 ± 0.2	40.5 ± 1.0	9.7 ± 0.1
	2	28.6 ± 1.7	38.6 ± 0.6	40.7 ± 0.1	14.7 ± 0.6
	4	34.9 ± 0.6	40.3 ± 0.3	42.0 ± 0.0	24.0 ± 0.2

In previous studies, attempts were made to correlate the rate of pyrethroid isomerization in organic solvents with solvent properties. For example, in Ruzo et al. (*17*), a relationship between isomerization and solvent polarity or viscosity was established. A similar relationship, however, was not identifiable in the current study. In spite of comparable polarities of acetone and methanol, the measured rates of enantiomerization were quite different. The viscosity of the test solvents followed an order isopropanol (2.04) > methanol (0.55) > methylene chloride (0.40) > acetone (0.30) > *n*-hexane (0.29) (*25*), while the enantiomerization of CP occurred in an order methanol > isopropanol > acetone > *n*-hexane ≈ methylene chloride. Therefore, enantiomerization at the α-carbon position appeared to occur in protic solvents having the capacity to form hydrogen bonds, such as alcohols. When exposed to various solvents, deltamethrin isomerization was found to be more rapid in short- and straight-chain alcohols than in long- and branched-chain alcohols (*17*), while no isomerization was detected in the other solvents. These observations are consistent with our finding that faster enantiomerization of CP occurred in methanol than in isopropanol. The more rapid enantiomerization in methanol may be due to its less steric hindrance, which, according to Ruzo et al. (*17*), may affect the rate of the ground-state reaction through α-proton exchange with the solvent.

As a polar protic solvent, water has been found to cause isomerization of some pyrethroids under certain conditions. Isomerization was observed for deltamethrin (1*R-cis*-α*S*) in natural water when it was kept in dark or irradiated by sunlight (*18*) and 1*S-cis*-α*S*, 1*R-trans*-α*S*, 1*S-trans*-α*S*, or 1*S-cis*-α*S* deltamethrin were produced. The fact that isomerization occurred in both sterile and nonsterile water for deltamethrin suggests that water alone may lead to isomerization of some pyrethroids. Rapid isomerization occurred for cyfluthrin diastereomers in methanol−water mixture (90:10, v/v) at room temperature in the dark (*16*). Slow isomerization in water was also observed for CP and cyfluthrin in another study (*22*). These results together suggest that as a polar protic solvent, water may

induce enantiomerization, especially when it is mixed with an alcohol or exposed to sunlight.

This study is the first instance where the isomerization of pyrethroids in organic solvents and solvent−water systems was evaluated at the enantiomer level. This was made possible by using a combination of chiral selective HPLC and GC analytical procedures. Results from this study showed that pyrethroids with chiral centers only on the cyclopropyl ring were relatively stable in various solvents and solvent−water mixtures at ambient temperature. However, for CP with an asymmetric α-carbon, enantiomerization on the α-carbon readily occurred in aliphatic alcohols and in mixtures of a protic solvent and water. Although only CP was used in this study, given the structural similarity, it is reasonable to speculate that similar enantiomerization may also occur for cyfluthrin and cyhalothrin.

Enantiomerization on the α-carbon due to exposure to solvents may have significant consequences. For instance, enantiomerization caused by solvents during sample extraction and analysis may result in analytical artifacts and erroneous information on the composition of stereoisomers. When environmental samples are analyzed, caution should be used to avoid the use of inappropriate solvents. Enantiomerization caused by solvents may also produce unexpected toxicity in bioassays and to nontarget species in the environment. In addition, products with a single enantiomer (e.g., esfenvalerate and deltamethrin) or selected stereoisomers (e.g., α-, β-, and θ-CP, λ-cyhalothrin, and β-cyfluthrin) are increasingly being used nowadays, because such products have improved efficacy and are also considered more environmentally friendly due to the lower application rate (*10*). However, enantiomerization caused by solvents in formulation or during application may easily decrease the intended efficacy and also lead to inaccurate expectations of environmental benefits from such uses.

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