

Sorption–Desorption of Imidacloprid and Its Metabolites in Soils

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Sorption–desorption of imidacloprid [1-[(6-chloro-3-pyridinyl)methyl]-*N*-nitro-2-imidazolidinimine] and metabolites 1-[(6-chloro-3-pyridinyl)methyl]-2-imidazolidinone (imidacloprid–urea), 1-[(6-chloro-3-pyridinyl)methyl]-4,5-dihydro-1*H*-imidazol-2-amine (imidacloprid–guanidine), and 1-[(6-chloro-3-pyridinyl)methyl]-1*H*-imidazol-2-amine (imidacloprid–guanidine–olefin) in three soils was determined using the batch equilibration technique with initial concentrations for the four chemicals ranging from 0.05 to 1.5 $\mu\text{g mL}^{-1}$, which corresponds to a field application rate of 0.2–1.0 kg ha^{-1} . Calculated slopes of the Freundlich sorption isotherms were significantly less than 1. The order of sorption (K_f) was imidacloprid–guanidine > imidacloprid–guanidine–olefin > imidacloprid > imidacloprid–urea in the three soils. Average K_{f-oc} values were 203, 412, 2740, and 3200 for imidacloprid–urea, imidacloprid, imidacloprid–guanidine–olefin, and imidacloprid–guanidine, respectively. Desorption was hysteretic for all chemicals in all soils. Greatest hysteresis was observed with imidacloprid–guanidine and imidacloprid–guanidine–olefin. Sorption–desorption of imidacloprid determined at half the solubility (250 $\mu\text{g mL}^{-1}$) ($K_{oc} = 77$) greatly overpredicts potential leaching compared to K_{oc} determined at field application rates ($K_{f-oc} = 411$).

Keywords: *Imidacloprid; metabolites; sorption; desorption; hysteresis*

INTRODUCTION

Imidacloprid [1-[(6-chloro-3-pyridinyl)methyl]-*N*-nitro-2-imidazolidinimine] is a new systemic insecticide of the chemical group chloronicotinyl. It has a novel mode of action; it acts as an agonist of nicotinic acetylcholine receptor (Bai et al., 1991; Mullins, 1993). This insecticide is effective for controlling sucking insects, soil insects, termites, and some species of chewing insects and is used as seed dressing, soil treatment, and foliar treatment in different crops (Tomlin, 1994). It is effective at low doses such as 0.3 ppm (Moriya et al., 1992).

Very little information is published concerning the fate of imidacloprid and its metabolites in soil. It does not appear to leach below the surface soil (Rouchaud et al., 1994, 1996). Degradation half-lives of 40 days in field experiments (Rouchaud et al., 1994) and 48 days in standardized laboratory tests (Scholz and Spiteller, 1992) have been reported. The main imidacloprid metabolites identified in soil include 1-[(6-chloro-3-pyridinyl)methyl]-2-imidazolidinone (imidacloprid–urea), 6-chloronicotinic acid, and 6-hydroxynicotinic acid (Rouchaud et al., 1996), which will ultimately lead to formation of CO_2 (Scholz and Spiteller, 1992).

The lack of leaching observed in soil for imidacloprid and its metabolites and the decreased degradation in soil with the addition of organic amendment (Rouchaud et al., 1996) are presumably due to sorption–desorption

characteristics of the chemicals. Sorption–desorption processes are important in determining the fate and distribution of agrochemicals in the soil/water environment, since they determine the amount of pesticide that can reach the target organism and the amounts that can be volatilized, degraded, and leached. However, there is no information available on sorption–desorption of imidacloprid or any of its metabolites.

The objective of the present study was to characterize the sorption–desorption of imidacloprid and three of its metabolites, imidacloprid–urea, imidacloprid–guanidine [1-[(6-chloro-3-pyridinyl)methyl]-4,5-dihydro-1*H*-imidazol-2-amine], and imidacloprid–guanidine–olefin [1-[(6-chloro-3-pyridinyl)methyl]-1*H*-imidazol-2-amine] in soils. The data can then be used to assess the bioavailability and leaching potential of this new chemical.

MATERIALS AND METHODS

Chemicals. Pure analytical standards (chemical purity > 99%) and radiochemical materials (radiochemical purity > 97%) were supplied by Bayer Corp. Figure 1 shows the structures of imidacloprid and the imidacloprid–urea, –guanidine, and –guanidine–olefin metabolites.

Soils. Three soils from Minnesota were selected for this study. Fresh soils from the 0–15 cm depth of a Webster clay loam (Typic Haploquoll), Waukegan silt loam (fine-silty over sandy or sandy-skeletal, mixed mesic Typic Hapludoll), and Verndale sandy loam (coarse loamy over sandy, mixed frigid Udic Argiboroll) were collected, air-dried, and passed through a 2-mm-diameter sieve. Selected physicochemical properties of the soils are given in Table 1. Soil texture was determined by the hydrometer method (Gee and Bauder, 1986). Soil pH

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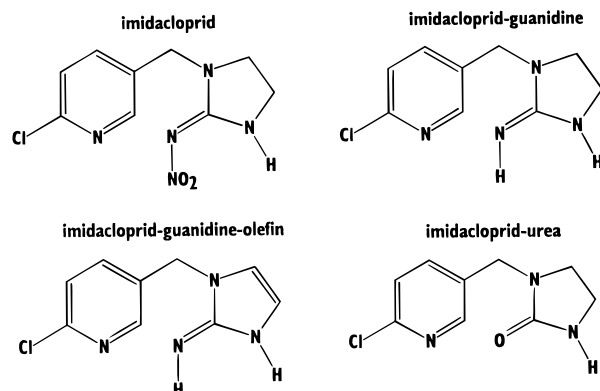


Figure 1. Chemical structures of imidacloprid and three metabolites.

Table 1. Soil Characteristics of Three Minnesota Soils

soil	texture	organic carbon content (%)	clay content (%)	pH ^a
Webster	clay loam	4.1	35	6.7
Waukegan	silt loam	1.8	22	5.5
Verndale	sandy loam	1.4	28	6.1

^a Measured in 1:2 (w/w) soil/water.

was measured in a 1:2 (w/w) soil/deionized water mixture. The organic carbon content of the soil samples was determined by dichromate oxidation (Nelson and Sommers, 1982).

Sorption. Sorption experiments were carried out using the batch equilibration technique. Duplicate 2-g soil samples were equilibrated with 10 mL of 0.01 N CaCl₂ solutions of imidacloprid, imidacloprid-urea, imidacloprid-guanidine, and imidacloprid-guanidine-olefin in the range of 0.05–1.5 μg mL⁻¹. In the case of imidacloprid, sorption experiments were also carried out at higher concentrations (25–250 μg mL⁻¹). The 250 μg mL⁻¹ concentration is half the imidacloprid solubility. Radiolabeled chemicals were added to nonradioactive solutions to give a final solution concentrations of ~4000 dpm mL⁻¹. To maintain constant ionic strength of sorption and desorption equilibration solutions and to facilitate flocculation of the soil, 0.01 N CaCl₂ was used as the background electrolyte.

Soil suspensions were shaken mechanically at 21 ± 2 °C in 25-mL glass centrifuge tubes closed with Teflon-lined caps for 24 h. Batch kinetic studies (data not shown) performed with the Webster soil indicated that equilibrium is reached within 1 h and that no changes in concentration occurred after 48 h of shaking and no degradation occurred within this period. Soils were then centrifuged at 4000 rpm for 30 min, and 5 mL of supernatant was removed for analysis. Solutions shaken in tubes without soil served as controls and showed no loss of ¹⁴C from the solution during the equilibration periods.

Desorption. Desorption experiments were conducted immediately after the sorption experiment of imidacloprid and its metabolites using the soils from the initial concentration of 0.05 and 1.5 μg mL⁻¹. In the case of imidacloprid, desorption experiments were also conducted using soils from the 25 and 250 μg mL⁻¹ solutions. After centrifugation in the sorption experiment and 5 mL removed for analysis, 5 mL of 0.01 N CaCl₂ without chemical was added to the soil. Soils were then resuspended in a vortex action shaker and shaken for another 24 h. Soil suspensions were centrifuged, and 5 mL of supernatant was removed for analysis. This desorption cycle was repeated four times for each sample.

Chemical Analyses. One milliliter aliquots of the clear supernatants were mixed with 6 mL of EcoLite scintillation cocktail, and the amount of radioactivity was determined by liquid scintillation counting for 5 min in a 1500 TRI-CARB Packard liquid scintillation analyzer. The amount of imidacloprid or metabolite in solution was calculated by considering the specific activity of each chemical.

Data Analyses. The amount of chemical sorbed to the soil after equilibration was calculated from the difference between the initial and equilibrium solution concentrations. Sorption

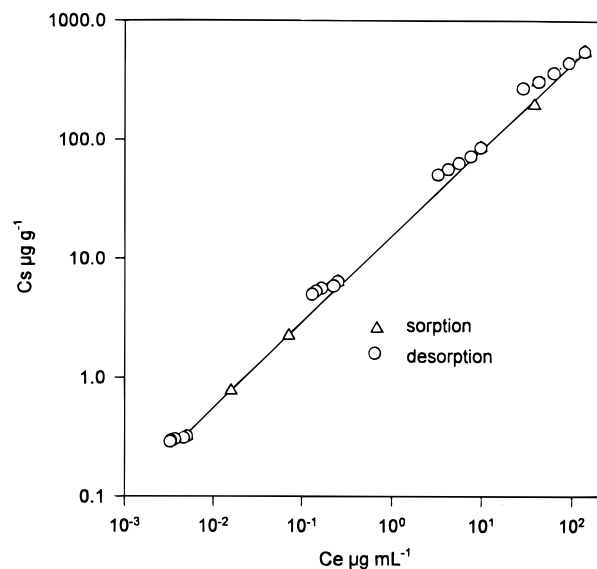


Figure 2. Sorption–desorption isotherms of imidacloprid in Webster clay loam soil.

Table 2. Imidacloprid Sorption Coefficients Determined over Different Ranges of Initial Solution Concentrations: $C_i = 0.05–1.5$, $25–250$, and $0.05–250$ μg mL⁻¹

C_i (μg mL ⁻¹)	soil	K_f (μg ^{1-1/n} g ⁻¹ mL ^{1/n})	K_{f-oc}	$1/n_f$	r^2
0.05–1.5	Webster	18 (17–19) ^a	432	0.76 ± 0.02 ^b	0.999
	Waukegan	6.7 (6.4–7.0)	369	0.82 ± 0.02	0.999
	Verndale	6.1 (5.9–6.4)	436	0.81 ± 0.02	0.999
25–250	Webster	16.7 (16.6–20.4)	407	0.70 ± 0.05	0.994
	Waukegan	7.39 (6.90–7.93)	411	0.69 ± 0.02	0.999
	Verndale	6.70 (5.13–8.74)	479	0.66 ± 0.06	0.997
0.05–250	Webster	15.5 (15.1–16.0)	378	0.72 ± 0.01	0.999
	Waukegan	5.81 (5.62–6.01)	323	0.75 ± 0.01	0.999
	Verndale	5.00 (4.80–5.30)	357	0.73 ± 0.01	0.998

^a Numbers in parentheses are standard errors about the mean K_f . ^b Numbers are mean $1/n_f$ ± standard deviation.

and desorption isotherms were calculated using the linearized form of the Freundlich equation $\log C_s = \log K_f + 1/n_f \log C_e$, where C_s is the amount of chemical sorbed (μg g⁻¹ of soil), C_e is the equilibrium concentration (μg mL⁻¹ of solution), and K_f and $1/n_f$ are the sorption–desorption coefficients expressing sorption capacity and intensity, respectively. Sorption–desorption coefficients were calculated by the least-squares technique on the mean of the replicates of the log-transformed equilibrium data. K_f and $1/n_f$ standard deviations were calculated, and, in the case of imidacloprid, distribution coefficients K_d ($K_d = C_s/C_e$) and K_{oc} values ($K_{oc} = K_d/\%$ organic carbon × 100) were calculated for some initial solution concentrations (C_i). A desorption hysteresis coefficient was calculated as the percentage of the ratio between the desorption and sorption isotherm slopes ($H = (1/n_{f-des})/(1/n_f) \times 100$).

RESULTS AND DISCUSSION

All sorption data fit the Freundlich equation, $r^2 > 0.994$. Figure 2 shows a representative Freundlich sorption isotherm of imidacloprid in the Webster soil. Sorption coefficients of imidacloprid in the three soils and different ranges of initial solution concentrations studied are given in Table 2. Imidacloprid sorption coefficients were not significantly different for the 0.05–1.5 and 25–250 μg mL⁻¹ concentration ranges. K_f increased with organic carbon content (Table 1) for each soil. Linear regression analysis between K_f and soil organic carbon content gave a correlation coefficient $r^2 = 0.995$. Thus, expressing sorption as a function of soil

Table 3. K_d and K_{oc} for Imidacloprid Determined at Initial Solution Concentrations $C_i = 0.05, 1.5,$ and $250 \mu\text{g mL}^{-1}$

soil	$C_i = 0.05 \mu\text{g mL}^{-1}$		$C_i = 1.5 \mu\text{g mL}^{-1}$		$C_i = 250 \mu\text{g mL}^{-1}$	
	K_d (mL g^{-1})	K_{oc}	K_d (mL g^{-1})	K_{oc}	K_d (mL g^{-1})	K_{oc}
Webster	64.0	1560	25.5	531	3.9	81
Waukegan	14.4	802	7.47	415	1.4	78
Verndale	12.5	893	6.45	461	1.0	71

organic carbon content (K_{f-oc}) reduces variability between soils (Green and Karickhoff, 1990) over the entire concentration range: $K_{f-oc} = 353 \pm 28$.

Sorption isotherms showed marked curvature with slopes ($1/n_f$), significantly less than 1 in every case. The slope of the isotherm was dependent on the range of concentration used; $1/n_f$ values calculated at the lower concentration range ($0.05\text{--}1.5 \mu\text{g mL}^{-1}$) are significantly higher than those calculated at the higher concentration range ($25\text{--}250 \mu\text{g mL}^{-1}$), especially in the case of the Waukegan and Verndale soils. The $1/n_f$ values calculated from the isotherm over the whole $0.05\text{--}250 \mu\text{g mL}^{-1}$ range are between the two. Slopes of sorption isotherms ($1/n_f$) < 1 indicate sorption is dependent on initial solution concentration, i.e. the amount of chemical in the system, with greater concentration dependence at the higher initial solution concentrations.

The impact that $1/n_f < 1$ has on sorption determined at a single solution concentration is shown in Table 3. Table 3 shows K_d and K_{oc} for imidacloprid calculated at $0.05, 1.5,$ and $250 \mu\text{g mL}^{-1}$ C_i in the three soils studied. For the three soils, increasing the initial concentration from 0.05 to $250 \mu\text{g mL}^{-1}$ decreased K_d by a factor of 13. The same feature is observed expressing sorption as K_{oc} ; average K_{oc} for the three soils at $0.05 \mu\text{g mL}^{-1} = 1085$ compared to 77 at $250 \mu\text{g mL}^{-1}$ (Table 3).

In the case of imidacloprid, which has a very high water solubility and low application rate, these results indicate that sorption coefficients calculated at half the solubility underpredict sorption under field conditions. This in turn would overpredict the leaching potential of the chemical. The leachability index model Groundwater Ubiquity Score (GUS) (Gustafson, 1989) has been used to show this effect. This model classifies a chemical's potential to leach to groundwater according to the combined effect of degradation and sorption processes:

$$\text{GUS} = \log_{10}(t_{1/2}\text{-soil}) \times [4 - \log_{10}(K_{oc})]$$

$t_{1/2}\text{-soil}$ is the soil degradation half-life assuming first-order kinetics. According to this model, a chemical would be classified as "leacher" if $\text{GUS} > 2.8$, "non-leacher" if $\text{GUS} < 1.8$, and transitional if $1.8 < \text{GUS} < 2.8$. In the Webster soil, considering a K_{oc} of 1560 ($C_i = 0.05 \mu\text{g mL}^{-1}$), imidacloprid would only be considered a leacher when $t_{1/2} > 2863$ days and a nonleacher when $t_{1/2} < 170$ days, whereas considering a K_{oc} of 81 ($C_i = 250 \mu\text{g mL}^{-1}$), it would be considered a leacher when $t_{1/2} > 22$ days and a nonleacher when $t_{1/2} < 7$ days. Even in the worst case scenario for leaching, the Verndale sandy soil, imidacloprid would only be considered a leacher when $t_{1/2} > 466$ days using $K_{oc} = 893$ ($C_i = 0.05 \mu\text{g mL}^{-1}$), whereas using a $K_{oc} = 71$ ($C_i = 250 \mu\text{g mL}^{-1}$) imidacloprid would be considered a leacher when $t_{1/2} > 20$ days.

Another interesting feature observed in Table 3 is that, although K_{oc} reduces variability between soils

Table 4. Imidacloprid Desorption Coefficients for $C_i = 0.05, 1.5, 25,$ and $250 \mu\text{g mL}^{-1}$ and Hysteresis Coefficients ($H = (1/n_f)/(1/n_{f-\text{des}}) \times 100$)

concn ($\mu\text{g mL}^{-1}$)	soil	$1/n_{f-\text{des}}$	r^2	H
0.05	Webster	0.19 ± 0.04^a	0.909	26
	Waukegan	0.25 ± 0.01	0.992	33
	Verndale	0.29 ± 0.05	0.915	40
1.5	Webster	0.32 ± 0.05	0.941	44
	Waukegan	0.36 ± 0.00	1.000	48
	Verndale	0.30 ± 0.03	0.980	41
25	Webster	0.47 ± 0.02	0.989	65
	Waukegan	0.25 ± 0.03	0.948	33
	Verndale	0.23 ± 0.02	0.970	32
250	Webster	0.46 ± 0.02	0.992	64
	Waukegan	0.29 ± 0.04	0.945	39
	Verndale	0.23 ± 0.01	0.998	32

^a Number is the standard error about the mean $1/n_f$.

when compared with K_d , this reduction is more significant at higher concentrations. This can be attributed to a higher contribution of other soil components (i.e. clay) to sorption when solution concentrations are low (Cox et al., 1995).

Imidacloprid Freundlich desorption coefficients are given in Table 4. Figure 2 shows imidacloprid desorption isotherms in the Webster soil at different C_i values. As it can be seen in Tables 2 and 4, $1/n_f \gg 1/n_{f-\text{des}}$, indicating that a significant amount of the sorbed imidacloprid is very difficult to desorb and that desorption cannot be predicted from sorption isotherms. Hysteresis coefficients have been calculated and are given in Table 4. The higher hysteresis coefficients correspond to the Webster soil and higher imidacloprid solution concentrations, indicating that although this soil has a much higher sorption capacity than the Waukegan and Verndale soil, greater amounts can be desorbed. Another interesting feature observed in Table 4 is that, in the Webster soil, the slopes of the desorption isotherms, which indicate desorption intensity, are much lower at lower concentrations of imidacloprid and, accordingly, hysteresis coefficients decrease with solution concentration. This indicates that the lower the concentration of imidacloprid, the more difficult to desorb. This effect is not shown in the cases of the less sorptive soils.

Desorption hysteresis has been reported for a large number of soil-organic compound systems, and several explanations, such as chemical or biological transformation, nonequilibrium conditions, and high-energy bonding, have been proposed (Clay and Koskinen, 1990; Pavlostathis and Mathavan, 1992). In our case, the extended kinetic study did not indicate that degradation was taking place during desorption experiments, although further studies would be needed to understand this hysteresis phenomenon.

Sorption-desorption coefficients of imidacloprid metabolites imidacloprid-urea, imidacloprid-guanidine, and imidacloprid-guanidine-olefin are given in Tables 5, 6 and 7, respectively. Figures 3 and 4 show representative sorption-desorption isotherms for imidacloprid-urea in the Waukegan soil and imidacloprid-guanidine in the Verndale soil, respectively. Sorption of imidacloprid metabolites is also affected by soil properties. Sorption K_f values for each metabolite increase with increasing soil organic carbon content (Table 1).

The order of sorption, including parent compound in the same range of solution concentration ($0.05\text{--}1.5 \mu\text{g}$

Table 5. Sorption–Desorption Coefficients and Hysteresis Coefficients of Imidacloprid–Urea Metabolite

soil	sorption				desorption, $C_i = 1.5 \mu\text{g mL}^{-1}$			desorption, $C_i = 0.05 \mu\text{g mL}^{-1}$		
	$K_f (\mu\text{g}^{1-1/n} \text{g}^{-1} \text{mL}^{1/n})$	$1/n_f$	K_{f-oc}	r^2	$1/n_{f-des}$	r^2	H	$1/n_{f-des}$	r^2	H
Webster	8.67 (8.42–8.93) ^a	0.84 ± 0.01 ^b	211	1.000	0.42 ± 0.05	0.958	50	0.32 ± 0.05	0.932	38
Waukegan	3.41 (3.35–3.48)	0.85 ± 0.01	189	0.995	0.33 ± 0.04	0.951	39	0.31 ± 0.03	0.971	37
Verndale	2.93 (2.83–3.04)	0.82 ± 0.02	209	0.999	0.27 ± 0.03	0.968	33	0.18 ± 0.02	0.979	22

^a Numbers in parentheses are standard error about the mean K_f . ^b Numbers are mean $1/n_f \pm$ standard deviation.

Table 6. Sorption–Desorption Coefficients and Hysteresis Coefficients of Guanidine Metabolite

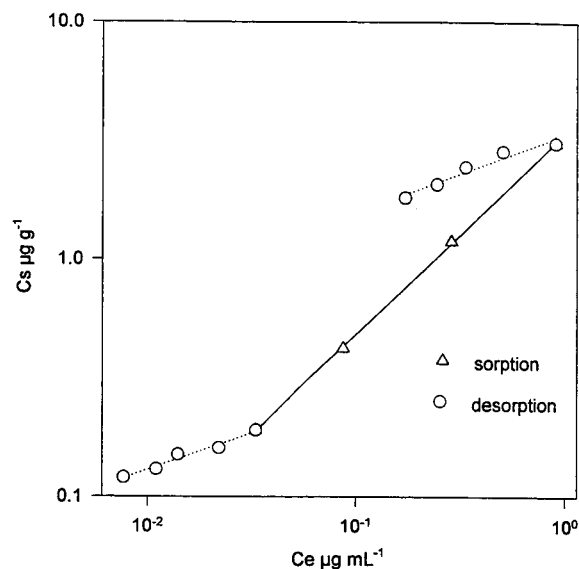
soil	sorption				desorption, $C_i = 1.5 \mu\text{g mL}^{-1}$			desorption, $C_i = 0.05 \mu\text{g mL}^{-1}$		
	$K_f (\mu\text{g}^{1-1/n} \text{g}^{-1} \text{mL}^{1/n})$	$1/n_f$	K_{f-oc}	r^2	$1/n_{f-des}$	r^2	H	$1/n_{f-des}$	r^2	H
Webster	156 (137–176) ^a	0.88 ± 0.02 ^b	3805	0.999	0.16 ± 0.05	0.775	18	0.03 ± 0.08	0.814	3
Waukegan	66.0 (59.9–72.4)	0.87 ± 0.02	3667	0.999	0.47 ± 0.15	0.822	54	0.08 ± 0.03	0.760	9
Verndale	29.8 (27.6–32.1)	0.85 ± 0.02	2129	0.999	0.31 ± 0.03	0.973	37	0.17 ± 0.02	0.972	20

^a Numbers in parentheses are standard error about the mean K_f . ^b Numbers are mean $1/n_f \pm$ standard deviation.

Table 7. Sorption–Desorption Coefficients and Hysteresis Coefficients of Guanidine–Olefin Metabolite

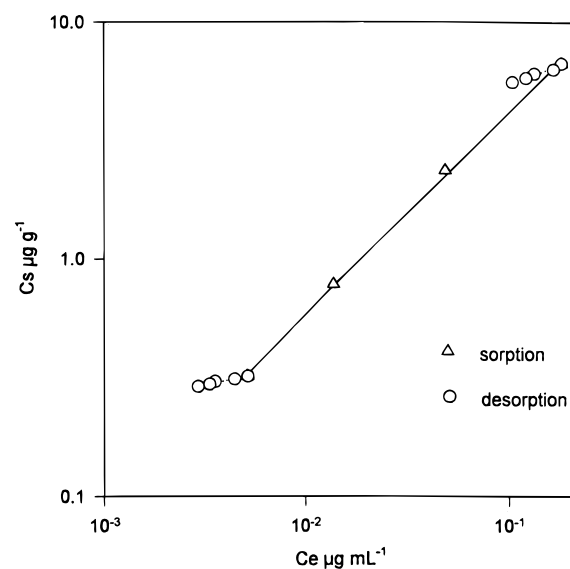
soil	sorption				desorption, $C_i = 1.5 \mu\text{g mL}^{-1}$			desorption, $C_i = 0.05 \mu\text{g mL}^{-1}$		
	$K_f (\mu\text{g}^{1-1/n} \text{g}^{-1} \text{mL}^{1/n})$	$1/n_f$	K_{f-oc}	r^2	$1/n_{f-des}$	r^2	H	$1/n_{f-des}$	r^2	H
Webster	116 (89–152) ^a	0.87 ± 0.05 ^b	2829	0.993	0.07 ± 0.01	0.957	8	0.13 ± 0.03	0.709	15
Waukegan	55.5 (49.1–62.9)	0.85 ± 0.03	3083	0.998	0.12 ± 0.02	0.910	14	0.14 ± 0.02	0.931	17
Verndale	32.4 (29.7–35.4)	0.82 ± 0.02	2314	0.999	0.27 ± 0.05	0.895	33	0.10 ± 0.03	0.824	12

^a Numbers in parentheses are standard error about the mean K_f . ^b Numbers are mean $1/n_f \pm$ standard deviation.

**Figure 3.** Sorption–desorption isotherms of imidacloprid–urea metabolite in Waukegan silt loam soil.

mL^{-1}), was imidacloprid–guanidine \geq imidacloprid–guanidine–olefin $>$ imidacloprid $>$ imidacloprid–urea in the three soils. These results illustrate the effect changes in functional groups of the parent molecule can have on sorption of these chemicals to soils. A much higher sorption is observed in the case of the imidacloprid–guanidine and imidacloprid–guanidine–olefin metabolites ($>\text{C}=\text{NH}$) when compared with the imidacloprid–urea metabolite ($>\text{C}=\text{O}$). The $>\text{C}=\text{NH}$ group of the imidacloprid–guanidine metabolite molecules could interact with acidic and phenolic groups of soil organic matter directly through hydrogen bonding or through water bridges (Senesi and Chen, 1989). In the case of imidacloprid, an NO_2 replaces the reactive H ($>\text{C}=\text{N}-\text{NO}_2$), decreasing the reactivity and subsequent sorption, whereas the urea functional group ($>\text{C}=\text{O}$) is less reactive.

Freundlich desorption coefficients and hysteresis coefficients for imidacloprid metabolites are given in Tables 5–7. Representative desorption isotherms are given in

**Figure 4.** Sorption–desorption isotherms of imidacloprid–guanidine metabolite in Verndale sandy loam soil.

Figures 3 and 4. As in the case of the parent compound, $1/n_f < 1/n_{f-des}$. Hysteresis coefficients of the less sorbable imidacloprid–urea are similar to the corresponding to imidacloprid. In the case of the more sorbable imidacloprid–guanidine imidacloprid–guanidine–olefin metabolites, hysteresis coefficients were generally lower, especially for the Webster soil of higher sorption capacity. These very low hysteresis coefficients observed in the most sorptive system seem to indicate that irreversibility of strongly bound chemical to soil colloidal components, especially soil organic matter surfaces, can be the reason for the hysteresis phenomenon, although, as in the case of desorption studies with the parent compound, further investigation is required.

CONCLUSIONS

Sorption of imidacloprid and its metabolites is affected by soil properties, increasing with soil organic carbon

content. The marked curvature of the sorption isotherms indicates the importance of the range of concentration in experimentally determining sorption coefficients. This laboratory information is essential to the development and verification of a computer simulation model of pesticide fate and to aid in the interpretation of results from ground water monitoring studies and thus should be calculated at realistic soil solution concentrations. Higher sorption than the parent compound was observed for the guanidine metabolites and lower sorption for the urea derivative, indicating a contribution of the functional groups of imidazol ring of the molecule in binding mechanisms. Desorption was hysteretic in every case. Lower desorption in the more sorptive system might indicate that hysteresis can be attributed to irreversible binding of the molecules to soil surfaces.

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LITERATURE CITED

- Bai, D.; Lummis, S. C. R.; Leicht, W.; Breer, H.; Sattelle, B. D. Actions of Imidacloprid and a Related Nitromethylene on Cholinergic Receptors of an Identified Insect Motor Neurone. *Pestic. Sci.* **1991**, *33*, 197–204.
- Clay, S. A.; Koskinen, W. C. Characterization of Atrazine Desorption from Soils. *Weed Sci.* **1990**, *38*, 74–80.
- Cox, L.; Hermosin, M. C.; Cornejo, J. Adsorption and desorption of thiazafuron as a function of soil properties. *Int. J. Environ. Anal. Chem.* **1995**, *58*, 305–314.
- Gee, G. W.; Bauder, J. W. Particle-size Analysis. In *Methods of Soil Analysis. Part 1. Physical and Mineralogical Methods*, 2nd ed.; Klute, A., Ed.; ASA: Madison, WI, 1986; pp 383–409.
- Green, R. E.; Karickhoff, S. W. Sorption estimates for modeling. In *Pesticides in the Soil Environment: Processes,*

- Impacts and Modeling*, Cheng, H. H., Ed.; SSSA: Madison, WI, 1990; pp 79–101.
- Gustafson, D. I. Groundwater-Ubiquity Score, a simple method for assessing pesticide leachability. *Environ. Toxicol. Chem.* **1989**, *8*, 339–357.
- Moriya, K.; Shibuya, K.; Hattori, Y.; Tsuboi, S.; Shiokawa, K.; Kagabu, S. 1-(6-Chloronicotiny)-2-nitroimino-imidazolidines and Related Compounds as Potential New Insecticides. *Biosci., Biotechnol., Biochem.* **1992**, *56*, 364–365.
- Mullins, J. W. Imidacloprid: A new nitroguanidine insecticide. In *Pest Control with Enhanced Environmental Safety*; ACS Symposium Series 524; American Chemical Society: Washington, DC, 1993; pp 183–198.
- Nelson, D. W.; Sommers, L. E. Total Carbon, Organic Carbon and Organic Matter. In *Methods of Soil Analysis. Part 2. Chemical and Microbiological Properties*, 2 ed.; Page, A. L., Ed.; ASA: Madison, WI, 1982; pp 539–579.
- Pavlostathis, S. G.; Mathavan, G. N. Desorption Kinetics of Selected Volatile Organic Compounds from Field Contaminated Soils. *Environ. Sci. Technol.* **1992**, *26*, 532–538.
- Rouchaud, J.; Gustin, F.; Wauters, A. Soil Biodegradation and Leaf Transfer of Insecticide Imidacloprid Applied in Seed Dressing in Sugar Beet Crops. *Bull. Environ. Contam. Toxicol.* **1994**, *53*, 344–350.
- Rouchaud, J.; Gustin, F.; Wauters, A. Imidacloprid Insecticide Soil Metabolism in Sugar Beet Field Crops. *Bull. Environ. Contam. Toxicol.* **1996**, *56*, 29–36.
- Scholz, K.; Spiteller, M. Influence of Groundcover on the Degradation of ¹⁴C-Imidacloprid in Soil. *Brighton Crop Prot. Conf.—Pests Dis.* **1992**, *2*, 883–888.
- Senesi, N.; Chen, Y. Interactions of Toxic Organic Chemicals with humic substances. In *Toxic Organic Chemicals in Porous Media*; Gerstl, Z., Chen, Y., Mingelgrin, U., Yaron, B., Eds.; Springer-Verlag: Berlin, 1989; pp 37–90.
- Tomlin, C. *The Pesticide Manual*; British Crop Protection Council: Surrey, U.K.; The Royal Society of Chemistry: Cambridge, U.K., 1994.

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