

Sorption of Carbofuran and Diuron Pesticides in 43 Tropical Soils of Sri Lanka

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To better understand the environmental fate of pesticides in Sri Lankan soils, we studied the sorption behavior of two commonly used pesticides (carbofuran and diuron) in 43 surface soils representing a range of soil physicochemical properties from dry and wet zones of Sri Lanka. For carbofuran, the K_d (L/kg) values varied from 0.11 to 4.1 (mean, 0.83; median, 0.62) and K_{oc} ranged from 7.3 to 120.6 (mean, 41.65; median, 36.1), whereas for diuron K_d values varied from 0.5 to 75 (mean, 9.6; median, 5.15) and K_{oc} ranged from 55.3 to 962 (mean, 407; median, 328). A comparison of sorption data on these tropical soils with published studies (mostly European and north American soils) showed that the ranges of sorption coefficients from Sri Lankan soils were within the wide range of K_{oc} values reported in the literature. However, these values for both pesticides in soils from dry zones of Sri Lanka were consistently higher (up to two times) than those from the wet zone. The wide range of K_{oc} values in Sri Lankan soils may be due to the possible difference in the nature of soil organic carbon, which needs to be further investigated.

KEYWORDS: Sorption coefficients; tropical soils; nature of organic carbon; Sri Lankan soils

INTRODUCTION

Like many other developing countries, Sri Lankan society is primarily based on agriculture. Pesticide use in agricultural crops in many parts of the country has increased tremendously in recent years (1). Lack of knowledge on the fate and behavior of pesticides in the Sri Lankan environment has contributed to public perceptions fueled by local media about increasing adverse health effects due to exposure to pesticides. Consequently, there is an urgent need to enhance our understanding of the environmental fate of pesticides in Sri Lanka.

The sorption of pesticides to soil and sediments is one of the important processes determining their fate and effectiveness in the environment and potential contamination of soils and water. In fact, various other processes, such as efficacy, persistence, chemical and biological degradation, mobility, translocation, and toxicity, are affected by the nature of pesticide sorption in soils. The sorption behavior of a range of pesticides in soils has been extensively studied in many countries from the temperate regions especially in developed countries (e.g., the United States, Canada, Australia, and European countries), and databases on the environmental fate of pesticides in those regions are available (2, 3). In contrast, however, pesticide sorption data from tropical countries are relatively meager. The numbers of published studies on tropical soils are, however, rapidly growing (4–11).

The behavior of pesticides in Sri Lankan soils remains poorly understood, and only few studies have been carried out (12, 13). Unfortunately, sorption coefficients were not reported in these two studies. The environmental fate data from the soils of the temperate regions may not always be directly transferable to tropics due to the differences in soil types, climatic conditions, and cropping systems (7). Our previous studies on comparisons of sorption in soils from Australia, the United Kingdom, and Pakistan (7) showed that the sorption per unit mass of organic carbon in soils from the three countries was markedly different and established that the chemical nature of organic carbon plays a vital role in pesticide sorption in soils (14). Considering that the nature of organic carbon in soils from various agroclimatic regions is often very different, it is hypothesized that sorption data from literature may not be directly applicable to tropical soils (such as in Sri Lanka), on which currently little local data is available. In any case, to gain the confidence on the applicability of published sorption data from overseas soil to local conditions, it is imperative to make a comparative assessment with a larger data set. Therefore, the specific objectives of this study were (i) to determine the sorption behavior of two commonly used pesticides (carbofuran and diuron) in a wide range of Sri Lankan soils and (ii) to compare the sorption behavior of these pesticides in these soils with data available from the literature.

MATERIALS AND METHODS

Soils. To cover a wide range of soil types, 43 Sri Lankan surface soils (0–15 cm) were collected from 28 different soil series (15) in the wet zone and 15 selected sites of the dry zone of Sri Lanka

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Table 1. Some Physical and Chemical Properties of the Surface Soils Used in the Study

soil series	classification		pH	EC (mS/cm)	organic C (%)	clay (%)	sand (%)	silt (%)
	local (15)	U.S. Department of Agriculture						
wet zone soils								
Agalawatta	Red Yellow Podzolic	Typic Hapludults	5.0	0.03	2.1	27	60	13
Akurana	Immature Brown Loam	Typic Troporthents	6.6	0.05	1.8	38	61	1
Boralu	Laterite with Red Yellow Podzolic	Typic Paleudults	5.4	0.06	1.7	14	58	28
Dodangoda	Red Yellow Podzolic	Typic Plinthudults	5.6	0.03	2.3	26	57	17
Galigamuwa	Red Yellow Podzolic	Haplustults	4.9	0.06	1.5	34	45	21
Gampaha	Low Humic Gley	Typic Endoaquents	5.2	0.06	2.0	21	47	32
Gampola	Alluvials	Typic Troporthents	5.8	0.03	1.8	40	43	17
Homagama	Red Yellow Podzolic	Typic Tropopsamments	5.4	0.02	1.4	15	58	27
Horton	Red Yellow Podzolic	Typic Humitropepts	4.8	0.03	7.8	20	48	32
Kandy	Red Brown Latozolic	Typic Troporthents	5.7	0.01	0.67	34	57	9
Katunayake	Regosols	Typic Troporthents	6.4	0.04	0.49	5	74	21
Kiribathkumbura	Low Humic Gley Soils	Aeric Fulvaquents	5.9	0.05	1.3	45	34	20
Madabokka	Half Bog Soil	Typic Sulphhemists	4.8	0.33	8.3	13	57	30
Malaboda	Red Yellow Podzolic	Humic Haplohumults	5.5	0.02	2.1	23	66	11
Maskeliya	Red Yellow Podzolic	Typic Dystropepts	5.0	0.06	2.4	11	72	17
Matale	Red Brown Latozolic	Typic Rhodusalfs	6.1	0.12	1.8	38	52	11
Mattakale	Red Yellow Podzolic	Typic Hapludults	4.7	0.06	2.2	44	41	16
Mawanella	Immature Brown Loam	Udic Ustorthents	5.3	0.01	0.94	25	65	10
Minuwangoda	Hard Latrite with Red Yellow Podzolic	Typic Rhodudults	5.0	0.02	1.8	22	64	14
Negombo	Regosols	Ustic Quartzipsamments	6.9	0.04	0.15	0	78	22
Nuwara Eliya	Red Yellow Podzolic	Typic Paleudults	4.5	0.06	7.6	40	28	32
Palatuwa	Half Bog Soil	Typic Sufaquents	5.0	0.2	3.2	29	45	27
Pallegoda	Red Yellow Podzolic	Typic Paleudults	5.1	0.05	1.3	32	68	0
Pugoda	Alluvial	Typic Ustifluents	5.5	0.02	2.3	37	43	20
Ratupasa	Red Latazols	Psammentic Paleudalfs	5.8	0.03	0.82	8	70	22
Ukuwalla	Red Brown Latozolic	Typic Rhodudults	5.0	0.04	1.5	51	33	16
Wagura	Bog Soil	Typic Sulphhemists	3.0	19.86	8.5	55	0	45
Weddagala	Red Yellow Podzolic	Typic Haplohumults	5.5	0.03	2.2	12	63	24
dry zone soils								
Binkama	Alluvial	not classified yet	7.1	0.05	1.2	29	71	0
Ethbatuwa	Reddish Brown Earth	not classified yet	7.3	0.1	1.2	22	76	1
Kachchigalera	Alluvial	not classified yet	8.1	0.13	3.4	29	34	36
Ketagalara	Low Humic Gley Soils	not classified yet	7.3	0.6	1.8	19	76	5
Kirimatiya	Low Humic Gley Soils	not classified yet	7.9	1.26	1.6	5	83	12
Kuttigala	Reddish Brown Earth	not classified yet	7.3	0.08	2.1	21	64	14
Mahagalera	Reddish Brown Earth	not classified yet	7.4	0.04	1.1	23	75	2
Moraketiya	Alluvial	not classified yet	6.9	0.03	1.7	30	64	6
Nonagama	Reddish Brown Earth	not classified yet	6.8	0.03	0.89	34	66	0
Pallegama	Alluvial	not classified yet	7.9	0.05	1.6	40	52	8
Ranna	Reddish Brown Earth	not classified yet	7.5	0.08	1.5	30	66	4
Siyambala	Solonized Solonets	not classified yet	6.9	0.05	0.98	28	72	0
Thimboldetiya	Alluvial	not classified yet	7.2	0.03	1.6	24	63	13
Walawa	Reddish Brown Earth	not classified yet	6.1	0.02	0.7	29	66	6
Kalpitiya	not classified yet	not classified yet	6.7	0.29	1.8	11	73	16
Urrbrae	Red Brown Earth	Rhodoxeralf	5.9	0.06	1.4	13	59	28

(Embilipitiya and Kalpitiya). All of the soil series from the wet zone are characterized (15). These soils were collected and immediately brought to a quarantine laboratory in Australia for sorption studies, which commenced within a month; thus, the soils were not stored for a long time. An Australian surface soil (0–15 cm), previously well-studied for sorption of pesticides in CSIRO laboratory and representing a very common soil type (Red Brown Earth—Alfisol from Urrbrae, Adelaide in South Australia) was also included. This provided a reference point for us to cross-check the current experimental results. All soil samples were air-dried in the laboratory, ground, and passed through a 2 mm sieve prior to use. The soil pH and the electrical conductivity (1:5, soil:water) were measured using an ORION-960 pH meter and ORION-160 conductivity meter, respectively. The percentages of clay, sand, and silt were measured by Perkin-Elmer spectrum one FT-IR spectrometer using the MIR method (16). The total organic carbon was determined on a microprocessor-controlled induction furnace LECO CR 12 carbon analyzer manufactured by the LECO Corp. (United States) and corrected for carbonate C determined by the MIR method where appropriate. Soil series and some chemical and physical characteristics are given in **Table 1**.

Pesticides. The two nonionic pesticides, carbofuran (2,3-dihydro-2,2-dimethylbenzofuran-7-yl methylcarbamate, C₁₂H₁₅NO₃) and diuron [3-(3,4-dichlorophenyl)-1,1-dimethylurea, C₅H₁₀Cl₂N₂O], were selected

to study the soil pesticide sorption behavior in Sri Lankan soils. The pesticides were chosen for three reasons: (i) because of their common use in agricultural areas in Sri Lanka, (ii) the availability of literature data on these pesticides, and (iii) the variation in their hydrophobicity and residue analysis considerations. The technical grade samples of the two pesticides (>98% purity) were obtained from Sigma-Aldrich.

Carbofuran belongs to the carbamate family and is a systemic as well as contact insecticide–nematicide. It is widely used for the control of soil dwelling and foliar feeding insects including earthworms, white grubs, weevils, stem borers, aphids, and nematodes in vegetables, potatoes, rice, sugar cane, and other crops. It is either applied as a foliar spray or granular formulation. Carbofuran has an aqueous solubility at 320 mg/L at 20 °C, a log *K_{ow}* of 1.52, and a vapor pressure of 0.031 mPa at 20 °C (17). Diuron is a substituted phenylurea herbicide used to control emergent grass weeds and broad-leaf weeds in many crops. It is a moderately soluble and nonvolatile herbicide with the aqueous solubility of 36.4 mg/L at 25 °C, a log *K_{ow}* of 2.85, and a vapor pressure of 1.1 × 10⁻³ mPa at 25 °C (17).

Pesticide Analysis. The two pesticides were analyzed using an Agilent 1100 series high-performance liquid chromatograph (HPLC), which was equipped with a variable wavelength diode array detector (model G 1315 B), a vacuum degasser (model G 1322 A), a quaternary pump (model G 1311 A), and an autosampler (model G 1313 A). Data

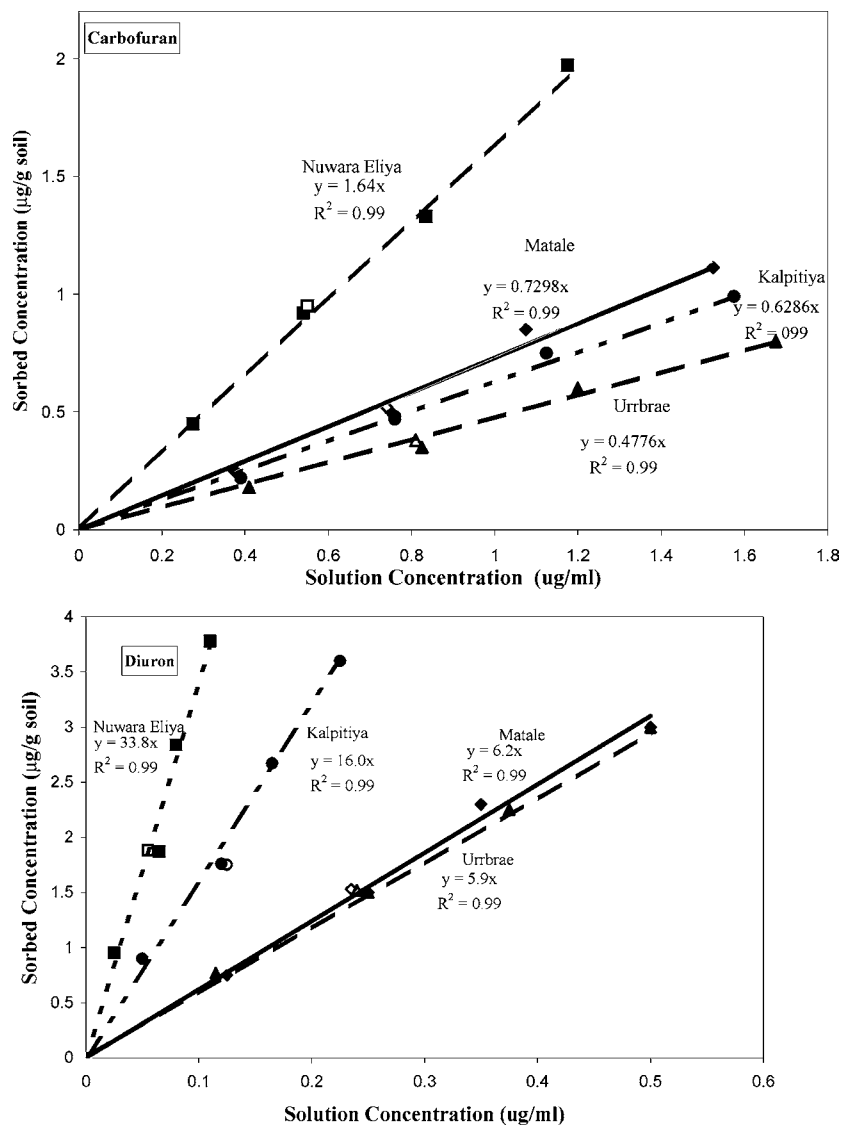


Figure 1. Sorption isotherms of carbofuran and diuron in selected soils. Open symbols represent data from the single concentration sorption measurement for comparison. Each value is an average of duplicate samples.

were processed using the Agilent Chem-station software. For both pesticides, all measurements were done in duplicate.

The operating conditions for carbofuran were as follows: a Prevail select C18 cartridge (150 mm \times 2.1 mm i.d., 5 μ m particle size) fitted with an Alltima C18 guard column (7.5 mm \times 4.6 mm); gradient elution at a flow rate of 0.6 mL/min; injection volume of 20 μ L; acetonitrile (HPLC grade) and water (Milli-Q) used as the mobile phase; UV wavelength of 280 nm. The gradient elution started with 1% acetonitrile, increased to 60% acetonitrile at 8.5 min, further increased to 90% acetonitrile for 2 min, and then remained constant for the 15 min run. The retention time for carbofuran under these conditions was noted to be 8.7 min with a minimum detection limit of 0.05 mg/L.

The operating conditions for diuron were as follows: Apollo C18 cartridge (250 mm \times 4.6 mm i.d., 5 μ m particle size); isocratic flow at a rate of 1.0 mL/min; injection volume of 20 μ L; mobile phase of acetonitrile:water ratio 60:40; UV wavelength of 220 nm. The retention time for diuron was noted to be 6.2 min with a minimum detection limit of 0.04 mg/L.

Pesticide Sorption Equilibria. Three different types of sorption studies were conducted on the two pesticides, namely, sorption kinetics, multiple-point sorption isotherms, and single-point sorption coefficients. However, the methodology was essentially similar and is described below.

In each case, a 5 g aliquot of soil was shaken with 10 mL of pesticide solution at a given concentration in a 20 mL polypropylene tube. All

pesticide sorption measurements were carried out with 0.01 M CaCl₂ electrolyte solutions containing 2% NaN₃ as the medium. CaCl₂ was used as a background electrolyte to mimic realistic soil ionic strength and to help flocculation of clay particles (18, 19). NaN₃ was used as a microbial growth inhibitor to prevent microbial actions on pesticides (20). After they were shaken for 16 h (based on sorption kinetics experiment, see below) at the ambient laboratory temperature (25 \pm 3 $^{\circ}$ C), the tubes were centrifuged for 20 min at 1600g and allowed to settle. The supernatant was filtered through 0.45 μ m Sartorius syringe filters and analyzed on HPLC for pesticide concentrations. The difference between pesticide concentrations at the initial and at the equilibrium stage was assumed to be caused by the sorption. Controls were run parallel, in one case with 0.01 M CaCl₂ and 2% NaN₃ but with no pesticide and in another with the pesticide in 0.01 M CaCl₂ and 2% NaN₃ with no soil. These allowed a check on analytical interferences due to soil extracts and for interaction between pesticides and tubes. Appropriate corrections were applied as necessary. The solution was filtered through 0.45 μ m Sartorius syringe filters and analyzed on HPLC. No significant sorption of pesticide on the walls and cap of polypropylene tube, syringes, and membrane filters was observed for the two pesticides.

Sorption Kinetics. Three Sri Lankan soils with different soil characteristics, namely, Palatuwa, Matale, and Walawa, and the Australian soil (Urrbrae) were chosen to establish the time needed for sorption to reach apparent equilibrium in the chosen soil system.

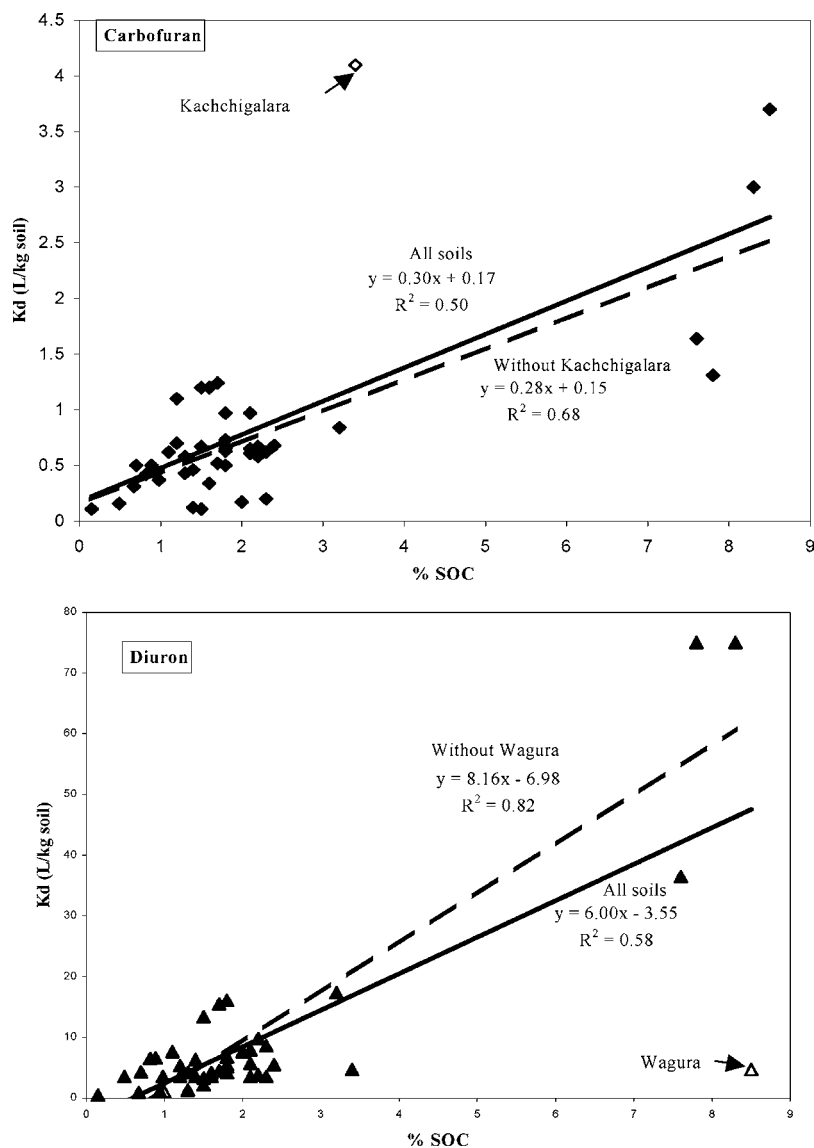


Figure 2. Relationship between soil organic carbon (%) and K_d values (L/kg) for carbofuran and diuron. The solid line represents data for all soils, and the dotted line is for data excluding the solitary outlier.

Duplicate samples and blanks were shaken for 0.5, 1, 2, 4, 8, 16, 24, and 48 h at the ambient laboratory temperatures (25 ± 3 °C). A 16 h shaking was employed in the subsequent sorption experiments, as over that period there were no appreciable degradation losses of the pesticides. The time selected was also consistent with some other experiments done on pesticide sorption studies (12, 18, 19).

Pesticide Sorption Measurements. The study was designed to include a large number of soils with a main objective to explore if the soils collected from the topical climate of Sri Lanka were likely to show different sorption behaviors for pesticides than that on soils from other agroclimatic conditions. Therefore, only single-point sorption measurements were carried out. However, sorption isotherms using a range of initial solution concentrations were measured only for a selected number of soils, namely, Nuwara Eliya, Matale, Kalpitiya, and Urrbrae soils, to determine the nature of the isotherms, since an assumption on linearity of isotherm was made for the calculation of K_{oc} . Pesticide solution concentrations of 0.5, 1, 1.5, and 2 $\mu\text{g/mL}$ were employed for equilibration with 5 g of soil and 10 mL of solution. The solution contained 0.01 M CaCl_2 , and 2% NaN_3 was shaken for 16 h using a previously described procedure.

Subsequently, sorption was measured for all 44 soils using a single concentration. An aliquot of (5 g) each of the 44 soils was equilibrated for 16 h at a pesticide concentration of 1 $\mu\text{g/mL}$. The samples were run in duplicate together with the controls and were shaken at the

ambient laboratory temperature (25 ± 3 °C) for 16 h, using the procedure described above.

The sorption coefficient, K_d (L/kg), was determined either from the slope of the linear plots of sorbed vs aqueous pesticide concentrations or from the single solution concentration of the pesticide. The sorption coefficient normalized on the basis of soil organic carbon, K_{oc} , was derived as (K_d/f_{oc}) , where K_d is the sorption coefficient (L/kg) and f_{oc} is the mass fraction of organic carbon present in the soil sample.

Infrared Spectroscopy. For two soils that showed unusual behavior in terms of pesticide sorption, subtraction DRIFT (diffuse reflectance infrared Fourier transform) spectra (16) were obtained from finely ground (<0.1 mm) neat soil samples. First, the samples were scanned as oven-dried material, and then, the samples were heated in an oven overnight at 350 °C to leave only the mineral components in the soils. These samples were then scanned, and the resultant spectra were subtracted from the original whole soil spectra, thus effectively removing much of the spectral mineral components and increasing the spectral sensitivity to the organic components in the soils.

RESULTS AND DISCUSSION

Sorption Isotherms of Carbofuran and Diuron. Sorption isotherms of carbofuran and diuron in selected soils, namely, Nuwara Eliya, Matale, Kalpitiya, and Urrbrae, are shown in

Table 2. Soil Sorption Coefficients (K_d) and Organic Carbon Normalized Sorption Coefficients (K_{oc}) for Carbofuran and Diuron

soil series	soil organic carbon (%)	L/kg soil			
		carbofuran		diuron	
		K_d	K_{oc}	K_d	K_{oc}
Agalawatta	2.1	0.7	30.9	5.7	271
Akurana	1.8	0.7	36.1	5.2	289
Boralu	1.7	0.5	30.5	4.5	265
Dodangoda	2.3	0.6	26.9	8.6	374
Galigamuwa	1.5	0.1	7.3	3.3	220
Gampaha	2.0	0.2	8.5	7.6	380
Gampola	1.8	0.7	40.6	6.8	378
Homagama	1.4	0.1	8.6	3.5	250
Horton	7.8	1.3	16.8	75.0	962
Kandy	0.7	0.3	46.2	0.9	134
Katunayake	0.5	0.2	32.6	3.5	714
Kiribathkumbura	1.3	0.6	44.6	4.2	323
Madabokka	8.3	3.0	36.1	75.0	904
Malaboda	2.1	0.6	29.0	7.9	376
Maskeliya	2.4	0.7	28.3	5.5	229
Matale	1.8	0.7	40.6	6.5	283
Mattakale	2.2	0.6	26.4	3.8	173
Mawanella	0.9	0.4	45.7	1.1	117
Minuwangoda	1.8	0.5	27.8	4.2	233
Negombo	0.2	0.1	73.3	0.5	333
Nuwara Eliya	7.6	1.6	21.6	36.5	480
Palatuwa	3.2	0.8	26.0	17.3	541
Pallegoda	1.3	0.4	33.1	1.3	100
Pugoda	2.3	0.2	8.7	3.5	152
Ratupasa	0.8	0.4	51.2	6.5	793
Ukuwalla	1.5	0.7	44.7	2.2	147
Wagura	8.5	3.7	43.5	4.7	55.3
Weddagala	2.2	0.7	30.5	9.8	445
Binkama	1.2	0.4	35.0	7.1	592
Ethbatuwa	1.2	0.7	58.3	3.6	300
Kachchigalara	3.4	4.1	120.6	4.7	138
Ketagalara	1.8	1.0	53.9	5.5	306
Kirimatiya	1.6	1.2	75	3.6	225
Kuttigala	2.1	1.0	46.2	3.5	167
Mahagalera	1.1	0.6	56.3	7.6	691
Moraketiya	1.7	1.2	72.9	15.5	912
Nonagama	0.9	0.5	56.2	6.6	742
Pallegama	1.2	1.1	91.7	5.3	442
Ranna	1.5	1.2	80.0	13.4	893
Siyambala	0.9	0.4	37.8	3.5	357
Thimboldketiya	1.6	0.3	21.3	4.2	263
Walawa	0.7	0.5	71.4	4.3	614
Kalpitiya	1.8	0.6	35.0	16.1	894
Urrbrae	1.4	0.5	32.9	6.3	450

Figure 1. Sorption data for both pesticides followed essentially linear isotherms in the four soils studied with a coefficient of determination (R^2) of 0.99, indicating a good fit. Sorption coefficients (K_d as indicated by slope of linear isotherm) for both pesticides were highest in the Nuwara Eliya soil, which has the highest organic carbon content (7.6%) among the selected four soils. In contrast, the sorption was lowest in the Urrbrae soil that had the lowest organic carbon content (1.4%). Sorption coefficients for the two pesticides in a wider range of soils (44 soils) were obtained by equilibration with a single solution concentration of the pesticide. A comparison of the sorption measurement was made by both methods: Multipoint and single-point determinations (**Figure 1**). Note that the open symbols show the sorption values when soil was equilibrated with only a single concentration of pesticide in a separate experiment. The coefficient of variation between multiple-point and single-point K_d values was 10% for carbofuran and 6% for diuron.

The sorption coefficients, K_d and K_{oc} values, of carbofuran and diuron in all 44 soils are given in **Table 2**. In all soils, sorption was higher for diuron than carbofuran, consistent with

previous studies. Only in some soils, the sorption coefficients followed the trend of organic carbon contents. For example, the lowest K_d values for diuron and carbofuran were obtained for the Negombo soil, which contains the lowest organic carbon content in the selected soils. Similarly, a high K_d value for diuron was observed in soils from Madabokka, which is consistent with their high SOC content. However, for carbofuran, the Kachchigalara soil showed the highest K_d , which contained much lower carbon contents than other soils (e.g., Madabokka). For carbofuran, the K_d values (L/kg) varied from 0.11 to 4.1 (mean, 0.83; median, 0.62) and K_{oc} values ranged from 7.3 to 120.6 (mean, 41.65; median, 36.1). However, for diuron, the range of K_d was higher varying from 0.5 to 75 (mean, 9.6; median, 5.15) and K_{oc} ranged from 55.3 to 962 (mean, 407; median, 328). The large variation in K_{oc} values indicates the possible difference in the nature of SOC in different soil series in Sri Lanka. The relationships between K_d , SOC, and other soil properties are further explored in the following section.

Relationship of Sorption Coefficients with the Soil Organic Carbon. The sorption coefficients were plotted against the organic carbon content of soils and are shown in **Figure 2**. Substantial scatter in the data was observed for both pesticides, and correlation coefficients (R^2) showed that only about 50% of variation in carbofuran and 58% in diuron data were explained by the soil organic carbon content variation. There were clear outliers in the plots, which had significant leverage on the data, e.g., Wagura and Kachchigalara. When these data points were removed, the correlation coefficient for both pesticides increased significantly. This effect was more prominent for diuron, where removal of only a single data point (Wagura) increased the R^2 value from 0.52 to 0.75. For carbofuran, the soil from Kachchigalara, which has a medium value of SOC, showed the highest sorption. Similarly, diuron sorption was not consistent with SOC for Wagura soil. The regression lines generated without these two points in two plots gave a better fit with $R^2 > 0.68$. Very poor ($R^2 = 0.16$) correlation was noted between the K_d values for carbofuran and for diuron (shown in **Figure 3**). However, removal of the two outliers (Wagura and Kachchigalara—the same two soils showing unusual sorption behavior) improved the correlation substantially ($R^2 = 0.59$).

In terms of role of other soil properties, such as soil clay content and pH (21), given that both compounds were nonionic in nature, the pH is not expected to affect the sorption directly but may have indirect effects such as by its influence on the nature of organic carbon. Clay and organic matter are often intimately associated. The multiple regression of the K_d for diuron (**Table 3**) against % SOC, % clay, and pH was significant, with the coefficients for % SOC being significant at the $P < 0.001$ level. The value for % clay was small, negative, and marginally ($P < 0.05$) significant, and for pH, the coefficient was positive but not significant. For carbofuran, the coefficients were significant for % SOC at the $P < 0.001$ level and for pH at the $P < 0.01$ level.

Clearly, soil OC content alone is not able to adequately account for the observed variation in pesticide sorption. It is now increasingly recognized that organic carbon chemistry has a major role to play in determining their affinity for pesticides. For example, Ahmad et al. (14), on the basis of their sorption studies on a range of soils from Australia and Pakistan, showed that rather than the content of SOC, the aromaticity of SOC was a strong determinant of pesticide sorption in soils. The important role that the chemistry of carbon can play in sorption of organic compounds in soils and sediments is now well-

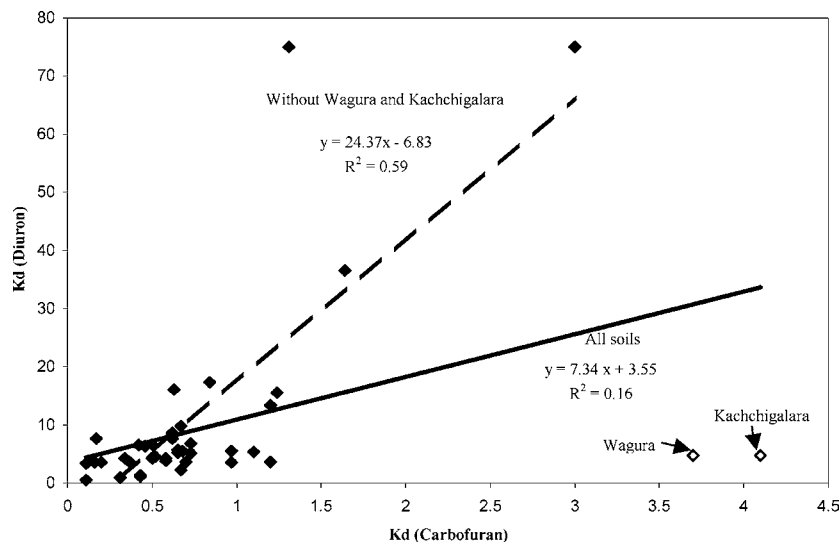


Figure 3. Relationship of carbofuran K_d values and diuron K_d values. The solid line represents data for all soils, and the dotted line is for data excluding the two outliers.

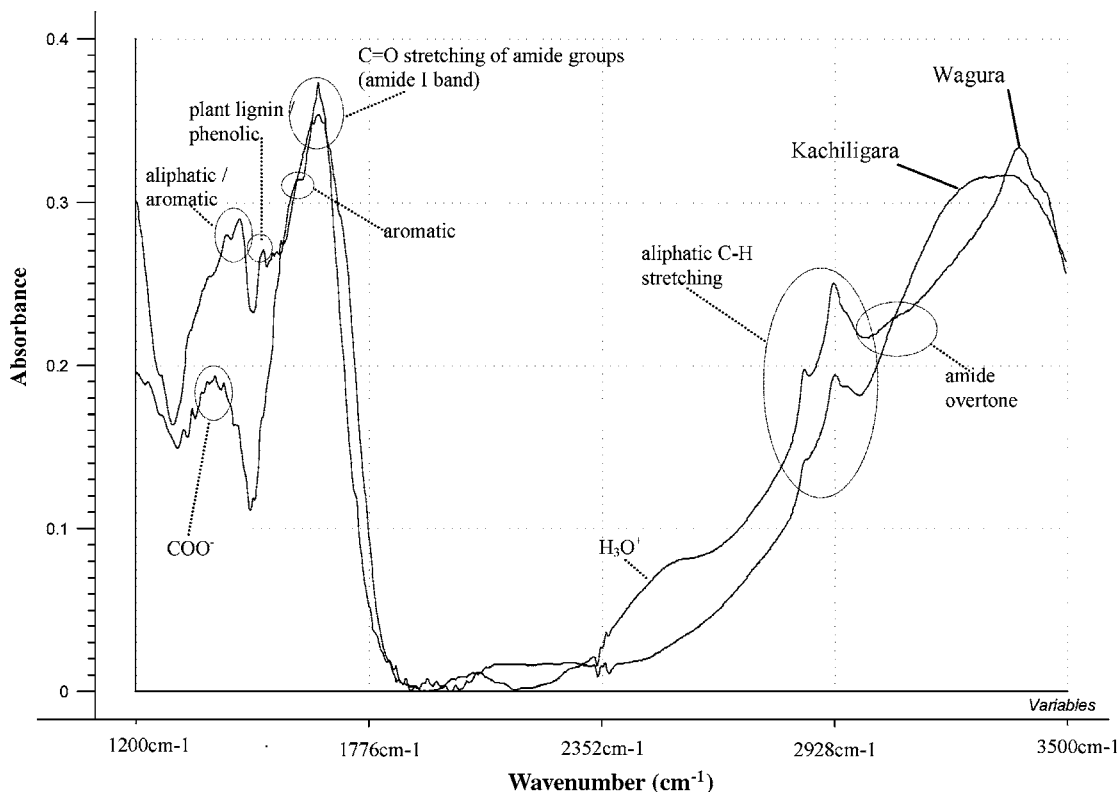


Figure 4. Subtraction DRIFT (diffuse reflectance infrared Fourier transform) spectra obtained from finely ground (<0.1 mm) neat samples for Wagura (wet zone) and Kachchigalara (dry zone) soils. Note that the spectra from soils heated at 350 °C (to leave only the mineral components) were subtracted from the original spectra on whole soil.

recognized (e.g., 14, 28). The differences in the chemistry of SOC in the soils from the present study are not clear. However, as a quick check, we applied the infrared spectroscopy to the two soils that show unusual sorption behavior (Wagura and Kachchigalara from the wet and dry zones of Sri Lanka, respectively) to examine the chemistry of soil organic carbon (29). The DRIFT spectra presented in **Figure 4** revealed that the two soils indeed differed markedly with regard to the quantity and nature of aliphatic and aromatic carbon. The Wagura soil is higher in these components, more acidic in nature (H_3O^+ peak centered around 2500 cm^{-1}), and exhibited peaks that indicated the presence of amides and the presence of

phenolic aromatics, possibly lignin. The Kachchigalara subtraction spectrum also showed the possible presence of COO^- at around 1390 cm^{-1} , and although showing a sharp peak at the amide I band (1650 cm^{-1}), the absence of the amide overtone centered at 3060 cm^{-1} makes assignment of this peak difficult. How these variations in the chemistry of soil organic carbon are related to the contrasting sorption behavior in these soils is not obvious from the data. Clearly, the role of chemistry of soil organic carbon in determining the sorption behavior of pesticides in the soils of wet and dry zones of Sri Lanka needs a thorough investigation, with potential application of solid state C^{13} nuclear magnetic resonance and other techniques (14).

Table 3. Regression Analysis for Single Point Sorption Data

	coefficients	standard error	t stat	P value
carbofuran (multiple)				
intercept	-2.014	0.683	-2.949	0.005
% SOC	0.384	0.051	7.548	3.84E-09
% Clay	0.007	0.007	1.012	0.318
pH	0.301	0.092	3.258	0.002
diuron (multiple)				
intercept	-15.843	12.729	-1.245	0.221
% SOC	7.153	0.949	7.536	3.98E-09
% Clay	-0.296	0.133	-2.230	0.032
pH	3.042	1.720	1.769	0.084
diuron (simple linear)				
intercept	-2.60	0.68	-1.00	0.32
% SOC	5.88	0.87	6.73	0.00

Table 4. Median of the K_d (L/kg) Values of Some Other Reports

country	median of K_d	no. of soils	% SOC (or % OM) range	median of K_{oc}
carbofuran				
United States (Illinois)	1.39	7	0.4–16.8	52 ^a (22)
United States (Washington)	0.84	4	0.2–1.22	288 ^a (20)
Taiwan	0.35	2	1.28–1.68	19 (23)
United States	NR	NR	NR	22 (4)
this study				
Sri Lanka (wet zone)	0.595	28	0.15–8.5	31
Sri Lanka (dry zone)	0.7	15	0.7–3.4	56
diuron				
Spain	6.89	3	0.18–4.61	413 (18)
United Kingdom	15	11	1.5–36.5	667 ^a (24)
Canada	13.4	5	(1.77–10.49) ^c	675 ^b (25)
Australia (tropical)	3.82	4	0.69–1.77	403 (11)
Australia (temperate)	13.63	12	2.10–4.91	478 (11)
Philippines	9.91	6	1.27–4.07	500 (11)
United States (Iowa)	27.3	6	0.95–6.6	671 (26)
United States (Florida)	2.11	7	0.5–1.67	188 (27)
United States	NR	NR	NR	480 (4)
this study				
Sri Lanka (wet zone)	5.15	28	0.15–8.5	286
Sri Lanka (dry zone)	5.3	15	0.7–3.4	442

^a Calculated. ^b K_{oc} calculated using 1.73 as the conversion factor for organic carbon to organic matter. ^c The values are the organic matter and not carbon content. NR, not reported. The values in parentheses are reference numbers for the source of data.

Comparison of Sorption in Tropical Soils with Published Data. To see if these data are strikingly different than those published in the literature on these two pesticides, the medians of some reported K_d and K_{oc} values for these two pesticides in soils from other countries are shown in **Table 4**. The median data of K_{oc} in **Table 4** show a very wide range for both pesticides. The median values of K_{oc} (L/kg) for carbofuran in soils from various published studies ranged from 19 to 288, where the corresponding values for the Sri Lankan soils were 31 for wet zone and 56 for the dry zone soils. It is worth noting that the median K_{oc} value in the dry zone soils was nearly double of that in the soils from the wet zone of Sri Lanka. The same trend was noticed for diuron, where the median K_{oc} value once again was much higher (1.5 times greater) for soils from the dry zone than those from the wet zone of Sri Lanka. The reasons for this difference are not clear. In the case of diuron, the median K_{oc} values in other published studies varied from 188 to 675 and these for Sri Lankan soils ranged from 286 to 442. While there is little data to make a valid comparison between tropical and temperate soils, no striking difference between the sorption data in soils from tropical or temperate regions was apparent.

This is consistent with our previous studies (11), where we found no significant differences in sorption behavior of diuron between the tropical soils from the Philippines and the temperate soils from Australia. These studies indicate that the origin of the soils (i.e., temperate vs tropical) appears to have no significant effect on sorption behavior of pesticides. However, we have noted that in some cases land use can significantly affect the sorption behavior of pesticides in soils from the same region (30–32). The difference in dry and wet zones soils of Sri Lanka may also be related to land use or some other local differences. To answer the question if the published data from European and North American soils (source of most current data in the literature) is relevant to tropical soils or the extrapolation of data from one region to the other in a country is appropriate, a larger database on environmental fate of pesticides in tropical soils and in soils from a range of land uses is needed.

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