

Evaluation of Herbicide Pollution in the Kerian Ricefields of Perak, Malaysia

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Abstract: Pesticide use in agriculture can cause undesirable effects to the natural environment as well as to humans. A field trial to determine residues of 2,4-D and paraquat in the ricefield soil and surface water of the drainage canals in the Kerian district of Perak, Malaysia, was conducted during 2006/2007. Analyses of 2,4-D and paraquat in the soil and water samples were carried out using a high performance liquid chromatograph (HPLC) fitted with a UV detector. The water sampling activities were conducted from 12 April to 03 September 2006 and 18 February to 15 April 2007. The parameters of water drainage were measured during the study. Residues of paraquat were detected in only a few of the water samples at levels ranging from 0.6-6.9 µg/l but in many samples from the drainage canals 2,4-D was detected frequently at levels ranging from 0.04-1.49 µg/l. The fate of 2,4-D and paraquat in clay loam soil under tropical conditions showed that both herbicides leached downward to the depth of 5 cm on the first day after treatment (DAT). Throughout the sampling period, 2,4-D and paraquat were detected in the soil profile at levels ranging from 0.046-0.128 and 0.212-0.362 mg/kg, respectively. The maximum concentrations at one DAT at the (0-5) cm soil depth were 0.128 and 0.362 mg/kg for 2,4-D and paraquat respectively.

Key words: Water analysis • Leaching • 2,4-D • Paraquat • HPLC • Southeast Asia

INTRODUCTION

Nowhere, at the present time, are pesticides more valued than in developing countries, particularly tropical regions seeking to enter the global economy by providing off-season agricultural crops to countries with temperate climates. Malaysia is a country where large areas are being used for agriculture. Rubber and oil palm are the two major plantation crops which occupy 3.8 million hectares, covering 70% of the total agricultural land area. In addition to this, rice is also an important agricultural crop contributing to nearly 60% of the country's annual rice consumption. The use of pesticides in the agricultural sector in Malaysia has been increasing over the years. It was reported that pesticide pollution of ground and surface water causes problems in tropical countries such as Malaysia, which have heavy rainfall, high humidity and high temperature [1, 2]. Ismail *et al.* [3] identified the degree of dissipation of some herbicides in two different Malaysian soils. Several studies have been reported on

the fate of herbicides in rice fields and plantations [4-6], as well as in vegetable-growing areas in the Cameron Highlands, Pahang and in Kluang, Johor and also in cultivated tobacco areas [4]. It was reported that pesticide pollution of surface and ground water has become a growing concern in tropical countries [7, 8]. A study of the water resources in the rice fields of the Muda area [9] identified endosulfan as the dominant organochlorine pesticide (OCP) contaminant in the water with concentrations ranging from <0.005 to 25.5 ng/ml. The above study has shown the need for the monitoring of pesticide contamination in Malaysian soils since soil is a potential pathway in the contamination of remote areas and aquatic ecosystems.

Currently, direct seeding of rice is the dominant crop establishment method in the rice field areas of Malaysia since its initiation in 1970 [10]. This technique requires higher levels of pesticide applications for effective weed management [11]. The use of pesticides, particularly insecticides and herbicides, is required for successful

cultivation of rice. Pesticides such as BPMC, carbofuran, endosulfan and lindane are commonly used insecticides while 2,4-D, paraquat and molinate are some of the commonly used herbicides [12].

Heavy rainfall causes significant movement of the herbicides in irrigation, drainage and runoff water sequentially from the rice field to irrigation/drainage canals, whereby they are dispersed widely through the water system [13]. On the other hand, in irrigated rice farming where high-yielding varieties are used, chemical pesticide usage is a common practice; but rice farmers in developing countries frequently ignore recommended pesticide application regimes. During the period, when the rice field areas are flooded by irrigation water or rainfall, a high percentage of chemical residues may flow through the surface water runoff into the drainage canals.

Scheduled monitoring has been the most widely used method of assessing surface water contamination with pesticides. The impact of pesticide contamination on aquatic ecosystems has been well studied in North America, Japan and many parts of Europe [14]. In contrast, there is very little data on the levels of pesticide residues in the aquatic ecosystems of developing countries. Therefore, data from developing countries is an important source of information portraying the state of environmental pollution in these countries as well as reflecting the effectiveness of environmental policies. In the current study environmental contamination by the herbicides 2,4-D and paraquat under tropical conditions was investigated by testing samples of the ricefield soil, surface water and drainage water collected from the Kerian district ricefields. The fate of 2,4-D and paraquat was studied because these herbicides are used widely by the farmers in the Kerian area for control of weeds in the ricefields.

MATERIALS AND METHODS

Area Description: The Kerian district is noteworthy because it is the most prosperous agricultural district in the northern portion of the state of Perak and also because it is home to the largest mangrove swamp in the state, which spans from north of the Kurau river, stretching to the coastal mangrove swamps in the west to Kerian in the east. The area downstream of the Bukit Merah Lake consists of one huge network of paddy fields. In the rice-growing areas, the year is divided into a distinct monsoon season (October to March) and a

non-rainy season (April to September). During the rainy season, rice is grown with supplemental irrigation whereas during the non-rainy season rice cultivation is fully irrigated. The major agricultural areas include paddy fields - 24,010 hectares, oil palm - 8,211 hectares and others 5,000 ha (vegetables etc.). The most commonly used herbicides in the ricefields of Kerian during 2003 and 2005 were 2,4-D, Paraquat, Propanil, Cyhalofop butyl, Ecomax, Glyphosate, Cinosulfuron and Pretilachlor. The ricefield irrigation water is supplied from the Bukit Merah Lake and flows via a network of main, secondary and tertiary canals.

Chemicals and Reagents: All reagents and solvents used in the present study were of analytical grade. Methanol and hydrochloric acid were obtained from Merck. Orthophosphoric acid (85%), Ammonium Hydroxide, Sodium Hydroxide, Cetyl Trimethyl Ammonium Bromide (95%), 1-Hexanesulfonic Acid (98%), Diethylamine (Fluka), Amberlite IR-120 resin (Cation exchange) were also obtained from Merck, - all of reagent grade. Individual standard herbicide of 2,4-D (99.7%) was purchased from the Laboratories of Dr. Ehrenstorfer, Germany, while paraquat (98.8%) was obtained from Sigma. Deionized water was obtained from the Millipore-ultra pure water system. The solid phase extraction ENV⁺ cartridges containing 200 mg of sorbent were obtained from International Sorbent Technology (IST), MidGlamorgan UK.

HPLC Conditions: An Agilent HPLC, 1100 Series fitted with a UV detector was used for quantification of paraquat and 2,4-D. The HPLC column and wavelength used for detection of paraquat and 2,4-D in water and soil samples were C18 at 273 nm and C₈-NH₄ at 214 nm, respectively. The collected data was processed using a LC workstation with CHEMSTATION software. The paraquat mobile phase was prepared by adding the following: 500 ml of deionized water with 13.5 ml of orthophosphoric acid; 10.3 ml of diethylamine; 1.0 g of 1-hexanesulfonic acid and sodium salt followed by dilution with deionized water to a final volume of 1 litre. The mobile phase for 2,4-D was MeOH and buffer (H₂O with + Potassium sodium 3.4 g/l + Hydrochloric acid in pH 2.3), in the ratio of 30:70. All of the solvents and solutions used in the mobile phase were previously filtered and degassed by ultrasound. The flow rate of the mobile phase and injection volume for both herbicides were 1 ml/min and 20 µl respectively.

Herbicide Extraction Procedure: To extract the 2,4-D herbicide residues from the soil, extraction on triplicate soil samples (5 ± 0.002 g) was done with 40 ml of methanol, acidified to approximately pH 2 with acetic acid (85%) and sonicated for one hour. Ten ml of the extract were pipetted out and transferred into a 10 ml vial. The extract was then filtered (Whatman No.41) and dried under vacuum and redissolved in 1 ml of methanol, prior to analysis using the HPLC [15]. The detection limit for this method was $0.04 \mu\text{g/g}$.

Paraquat herbicide residues from the triplicate soil samples underwent the following procedure: To 25 ± 0.002 g of the soil sample in a round bottomed flask was added 65 ml of deionized water and 35 ml sulphuric acid (97%). The round bottomed flask containing the sample was placed on a heating mantle. A water-cooled reflux condenser was attached and the contents heated to boiling. The solution was refluxed for five hours and allowed to cool. The contents of the flask were filtered by suction through two layers of Whatman No.5 filter paper. The filtrate was transferred to a large beaker and the pH was adjusted to around 8-9 by adding 10 N sodium hydroxide slowly with constant stirring to dissipate the generated heat. The pH was further adjusted to 6 or 7 with 5 M hydrochloric acid. The solution was re-filtered through two layers of Whatman No.5 filter paper and the filtrate was washed with deionized water (100 ml) before the volume was made up to 1 litre. The diluted extracts were percolated through resin columns in prepared burettes at a flow rate of 5 ml/min. The column was washed with 25 ml deionised water, 2 M hydrochloric acid (50 ml), deionised water (25 ml), 2.5% ammonium chloride (100 ml) and finally 25 ml deionized water at a flow rate of 3-5 ml/min. The paraquat was eluted from the resin with saturated ammonium chloride at a maximum flow rate of 1 ml/min [16]. The detection limit for this method was $0.02 \mu\text{g/g}$.

Extraction of Paraquat and 2,4-D from Water Samples:

To determine the 2,4-D residue, the water samples (in triplicate) were first acidified to pH 2.0 with hydrochloric acid and sonicated for 30 min. The SPE C18 cartridge was pre-washed with 3 ml methanol and 3 ml distilled water. With the aspirator on, the water sample was passed (by suction) through the cartridge of either the ISOLUTE EN⁺ (polyvinylidene), or C18. The herbicide adsorbed in the cartridge, was then eluted with 3 ml methanol. The elute was dried completely in vacuum. The residue was then redissolved with 1 ml methanol before being

injected into the HPLC-UV [17]. The detection limit for this method was $0.04 \mu\text{g/l}$.

A similar procedure was applied for determining the paraquat residue in the water samples, except that the triplicate water samples were initially alkalized to pH 9.0 with sodium hydroxide and sonicated for 30 min. In determining the paraquat residue in the water samples, a SPE C18 cartridge was attached to the manifold which was pre-washed with 3 ml methanol, solution A, methanol, deionized water and finally solution B at a flow rate of 3-5 ml/min. With the aspirator on, the water sample was passed (by suction) through the cartridge of either the ISOLUTE EN⁺ (polyvinylidene), or C18. The herbicide adsorbed in the cartridge, was then eluted with 2×2.5 ml of elution solution. The elute was injected into the HPLC-UV [18]. The detection limit for this method was $0.6 \mu\text{g/l}$. For both herbicides a similar procedure was applied to the blank water sample before injection into the HPLC.

Elution Solution: Orthophosphoric acid (13.5 ml) and diethylamine (10.3 ml) were dissolved in 500 ml of deionized water and diluted to 1 litre in a volumetric flask.

Solution A: Cetyl trimethyl ammonium bromide (0.1 g) and 5 ml of concentrated ammonium hydroxide were dissolved in 500 ml of deionized water and diluted to 1 litre in a volumetric flask.

Solution B: 1- hexanesulfonic acid (1 g), sodium salt (1 g) and 10 ml of concentrated ammonium hydroxide were dissolved in 250 ml of deionized water and diluted to 500 ml in a volumetric flask.

Surface Water Sampling: Fourteen sampling points were set up for determining the environmental contamination by 2,4-D and paraquat in the drainage water of the Kerian district ricefields from 12 April - 03 September 2006 and 18 February to 15 April 2007. Water sampling was carried out regularly at each sampling station using a 1 L amber glass bottle. The physico-chemical parameters of the water samples were then measured for water temperature, pH and conductivity using the portable multi parameter YSI 500D. Before collecting samples of the water from the drainage canals, the amber bottles used to collect the samples were rinsed twice with the water, then only was the collection made. The samples were adjusted to pH 2 using hydrochloric acid solution. A space of one to two inches from the top of the bottle was left to allow for thermal expansion. Blank samples of distilled water were filled into similar bottles and treated in the same manner as the other samples.

The herbicide concentration (in µg/l) in the water samples was calculated using the following formula;

$$\text{Conce.std} \times V_1 / V_2 \times A_1 / A_2 \times FV / W$$

Where;

Conc.std = Concentration of standard injection (µg/ml)

V_1 = Volume of sample injection (µl)

V_2 = Volume of standard injection (µl)

A_1 = Peak area of sample response

A_2 = Peak area of standard response

FV = Final volume of elute (ml)

W = Volume (l) of the water sample

Mobility of 2,4-D and Paraquat in Paddy Soil:

Field experiments on the fate of paraquat and 2,4-D were conducted during the wet season of 2007 in the Kerian ricefield, located in the state of Perak in North West Malaysia. The study plot covered 1 ha and consisted of 4 sub-plots of 0.25 ha each and the subplots were separated by a 0.5 m buffer zone. The soil contained clay (39.07%), sand (34.17%), silt (26.76%) and organic matter content of 5.94% and was classified as clay loam soil. All soil data are expressed on dry weight basis. Three subplots received the recommended dosage of the herbicide and the fourth plot remained untreated, serving as the control plot.

Under zero tillage, weeds were treated with the only commercial formulation of paraquat as an aqueous spray (1.0 l/ha) 3 weeks before sowing, when the weed coverage in the plot reached 80%. After treatment, soil samples were collected according to the sampling schedule. The soil samples were collected at four depths (5, 10, 15 and 20 cm).

One month after sowing, the commercial formulation of 2,4-D (2 l/ha) was applied to control broadleaved weeds. For the application of 2,4-D, the water level of the plot was reduced to about 1 cm to expose the broadleaved weeds to the 2,4-D herbicide. Both herbicides were applied to the plots with a backpack sprayer fitted with a TEEJET 8006 E nozzle.

To measure the vertical translocation of both herbicides in the soil profile, composite samples were collected before application of both herbicides and subsequently at 1, 3, 7 and 14 days after treatment (DAT). Soil samples were taken to a depth of 20 cm using a zero contamination soil probe. On each sampling day, 20 cm cores (x 3 replications) were taken from each of the three treated plots and 20 cm cores (x 3 replications) were

sampled from the control plot. Soil cores were further segmented in the laboratory into 0-5, 5-10, 10-15 and 15-20 cm depending on their respective position. Cores were combined by plot number, sampling date and sampling depth (i.e., replicates from within the same plot were combined according to depth) and were homogenized using a food processor. After homogenization, aliquots were frozen at -10°C and later thawed, passed through a 2 mm sieve and stored frozen until chemical analysis.

RESULTS AND DISCUSSION

Surface Water: A field trial to test the presence of residues of 2,4-D and paraquat in the drainage canals of the Kerian ricefields was conducted from 12 April - 03 September 2006 and 18 February to 15 April 2007. The parameters of water drainage were measured during this study. In general, the analytical results of the water parameters in the drainage canals were still within the acceptable values according to the standard water quality criteria for natural inland water of Malaysia [19]. The pH values of all water samples measured during the study were within the water quality range of pH (6.0-9.0). As for other parameters such as temperature and conductivity the levels recorded were 28-31°C and 100-900 µS/cm, respectively, these levels did not exceed the maximum acceptable level as stipulated in the standard quality criteria [19].

Residue levels of 2,4-D and paraquat were monitored from water collected at 14 selected points in the drainage canals of the paddy fields. The individual concentrations of paraquat and 2,4-D residues in drainage canals are summarized in Table 1. Overall, the water samples collected were found to be highly polluted with 2,4-D as compared to paraquat. Residues of paraquat were detected in only a few water samples at levels ranging from- ≤ 0.6 to 6.9 µg/l but in many samples, 2,4-D was detected frequently and at the levels ranging from ≤ 0.04 to 1.49 µg/l.

The occurrence of 2,4-D and paraquat residues were seasonal, being more widespread during the period when the herbicides were applied. The amount of 2,4-D residues was not surprising considering that its mobility is considered to be moderate [20]. 2,4-D was detected in 49 out of the 168 samples taken from the drainage canals. The residues however were not expected to persist in the environment in view of the short half-life of 2,4-D, which is reported to be in the range of 3.4 days in aerobic muck to 9.3 days under anaerobic conditions [21].

Table 1: Summary of the concentration of 2,4-D and paraquat detected in water taken from 14 sampling points in the drainage canals of the Kerian paddy fields

Time of Sampling	Pesticides Detected	No. Detection	Concentration ($\mu\text{g/l}$)
12-Apr-06	2,4-D	2	< 0.05 - 0.2
	Paraquat	ND	ND
18-Apr-06	2,4-D	6	< 0.04 - 0.5
	Paraquat	ND	ND
15-May-06	2,4-D	3	< 0.07 - 3.1
	Paraquat	ND	ND
20-Jul-06	2,4-D	1	< 0.05
	Paraquat	2	<0.6-1.05
3-Aug-06	2,4-D	8	< 0.1 - 1.06
	Paraquat	ND	ND
5-Aug-06	2,4-D	5	< 0.07 - 0.93
	Paraquat	ND	ND
3-Sep-06	2,4-D	1	< 0.23
	Paraquat	ND	ND
18-Feb-07	2,4-D	2	< 0.1 - 1.09
	Paraquat	3	<0.6- 6.92
20-Mar-07	2,4-D	8	< 0.05 - 0.75
	Paraquat	ND	ND
23-Mar-07	2,4-D	10	< 0.071 - 1.49
	Paraquat	ND	ND
12-Apr-07	2,4-D	3	< 0.12 - 1.03
	Paraquat	ND	ND
15-Apr-07	2,4-D	ND	ND
	Paraquat	ND	ND

ND= Not detected

The occurrence of paraquat residues in the drainage canals of the Kerian ricefields was rather unexpected considering its property of strong adsorption to soil colloidal particles and the fact that the soils in rice growing areas tested were mainly clayey. Residue levels detected however were extremely low and did not pose any toxicological concern. Cheah *et al.* [21] reported that the herbicide, paraquat, accidentally applied to surface water, was rapidly sorped into the sediments. Paraquat was detected in 5 of the 168 samples taken from the drainage canals. The source of paraquat contamination was difficult to establish but most of the farmers are aware of the potential of contamination when they apply more than the recommended dosage or release pesticides into the canals when washing the spray tanks.

On the other hand, the irrigation canals of the Kerian ricefields are built higher than the drainage canals and they are normally constructed on the opposite side of the drainage canals in the paddy field. As such, the pesticides that are carried with the effluents of the paddy fields as surface runoffs or adsorbed on suspended solids would end up first in the drainage canals. It is at this point when the pesticides begin to move out of their target area and

travel towards larger tributaries. Small drainage canals would flow into larger canals that eventually drain into rivers or the sea.

It was observed that Paraquat exhibited low incidence of occurrence in the water samples compared to 2,4-D. In terms of concentration, 2,4-D was found in relatively higher concentrations in the water samples than paraquat. The higher concentration of 2,4-D (compared to paraquat) probably reflected the different chemical properties of the two herbicides. Thorstensen *et al.* [22] reported that due to the low k_d of phenoxy acid herbicides in water, 2,4-D easily enters surface water through natural drainage. On the other hand, vertical movement of paraquat in the soil is limited due to adsorption and therefore it remained concentrated at the top surface of the soil (0-5 cm). The horizontal transportation of paraquat to surface water was also limited because most of the paraquat in the study was absorbed to soil particles and suspended solids present in the irrigation water at the initial day of application. On the other hand, Carr *et al.* [23] reported that if paraquat was not subject to sorption, it would rapidly be degraded by microorganisms and thus no longer be effective. Therefore, there is low risk of the presence of paraquat in surface water.

Loss of herbicides from the soil surface in runoff occurred when the plots were irrigated heavily a few days after the herbicide application. Water management especially in the earlier period after application, where there was higher herbicide concentration in the paddy water, was important for controlling herbicide losses from the paddy fields. In California, rice growers are required to hold paddy water following pesticide application for various periods, depending on the active ingredients of the herbicides [(up to 30 days in the case of granular thiobencarb)] [24]. However, for rice production in the Kerian area during the spraying of post-emergence herbicides, some farmers practiced continuous irrigation, (leading to overflowing into the drainage canals), to save working time. This type of practice may have been responsible for appreciable herbicide losses (e.g. 2,4-D) to the aquatic environment, especially during periods of significant rainfall.

Several workers have indicated that point sources (i.e. the spills and washings from the farmyard) can contribute to between 18 and 84% of the pesticide load measured in individual catchments [25]. Better training of sprayer operators and good machinery maintenance can reduce the amount of spills, furthermore, the release of herbicides to the farmyard caused by spray tank washings should be minimized [26]. The application of treatment systems at the farm level could enhance the protection of the aquatic ecosystem and reduce water treatment costs.

Pesticide Concentrations in Paddy Soil: The fate of 2,4-D and paraquat in clay loam soil under tropical conditions was studied in a rice plot in Kerian, Malaysia. The plot was treated with paraquat and 2,4-D according to the normal agricultural practices of farmers in Kerian. Soil samples were taken following a sampling schedule.

The soil samples were analysed in the laboratory to determine the amount of herbicide residue present. Fig. 1 and 2 show the concentration of 2,4-D and paraquat in the soil samples (0-20 cm) collected during the wet season at intervals of 1, 3, 7 and 14 days after treatment, respectively.

Throughout the sampling period, 2,4-D and paraquat were detected in the soil profile in the range of <0.046-0.128 and <0.031-0.181 mg/kg, respectively. The maximum concentration at 1 DAT in the top 5 cm of the soil layer was 0.128 and 0.181 mg/kg, respectively for 2,4-D and paraquat. The 2,4-D and paraquat concentration was reduced proportionally with time (of sampling). It was found that 2,4-D degraded rapidly and was not detected at seven days after treatment.

Fig. 1 shows that no residue of 2,4-D was detected at the depth of 15-20 cm at the time of treatment, while on day 14, no residue of 2,4-D was detected irrespective of the depth of the soil profile studied. The concentration of 2,4-D in the top layer decreased faster compared to that in the lower layer, most probably due to the movement of the compound downward through the soil to the lower layers or because of the effect of direct sunlight. The faster degradation of the two studied pesticides in comparison to that in temperate climates was probably due to increased microbial and chemical degradation, because of higher soil temperatures [27, 28]. A similar rapid dissipation of pesticides in sub-tropical/tropical soils and climate was also reported for atrazine [29] and endosulfan [30]. Rudel [31] reported trifluraline volatilisation losses of 64% of the applied amount from the soil surface within 24 h at 20°C air temperature. Therefore the extremely rapid dissipation of 2,4-D in part to volatilisation losses may also be due to the high vapour pressure under tropical weather conditions, where daily temperatures range from 35-45°C.

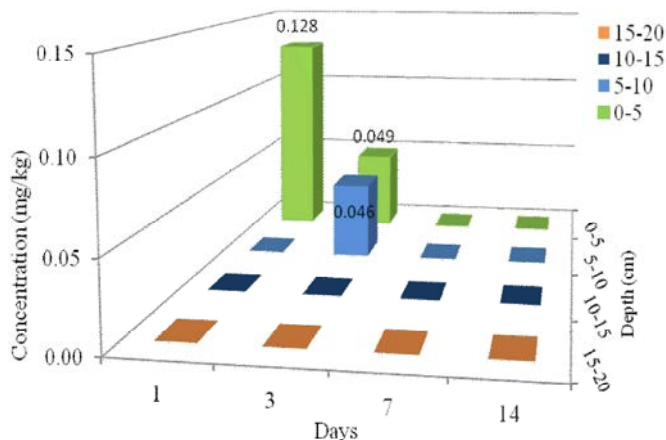


Fig. 1: 2,4-D concentration in the soil profile

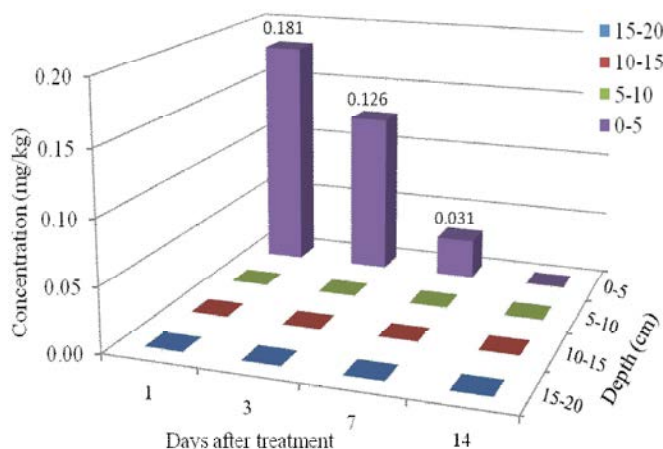


Fig. 2: Paraquat concentration in the soil profile

Fig. 2 shows that no paraquat was detected below 0-5 cm of the soil profile on any sampling date and that the maximum amount of paraquat was detected at 1 DAT in the top 5 cm of the soil. The presence of paraquat in the upper 0-5 cm soil level only indicates that this pesticide could not leach deeper into the soil under the conditions of the Kerian rice fields.

Previous studies by Kidd and James [32] have demonstrated that the main factors that influenced leaching of pesticides in the soil are adsorption of the pesticide to the soil particles, water solubility of the pesticide, volume of water flow, pH and soil texture. However in general, adsorption is the most important factor affecting the leaching of pesticides in the soil.

In a field study of ricefield soils, dissipation of paraquat into clay loam soil was faster compared that obtained from a laboratory study of paraquat as reported by Cheah *et al.* [21]. The cause of the fast initial disappearance of paraquat was chemical and microbial degradation, volatilisation and/or physical losses due to high vapour pressure and high daily temperature of between 35 to 45°C. Field studies on organophosphorus pesticides in humid tropical soils have been reported [33-35]. These studies were conducted using acidic soils with organic matter content of 0.8-5.9% and clay content of 5.2-54%. The results of the studies showed that field dissipation rates of organophosphorus pesticides in humid tropical top soils were rapid with half-lives of less than 20 days for bare soil and soil with vegetation. For soil with no vegetation, the half-life of organophosphorus pesticides was longer ranging from 0.4 to 20 days [34].

CONCLUSION

It is important to monitor the presence of pesticides in freshwater bodies because hazardous effluents from

paddy fields directly drain into them [36] and they are the most important sources of pesticide contamination in coastal environments [37]. Pesticides detected in coastal areas are mostly brought by river tributaries that receive effluents as a result of farming activities located upstream. Of the two herbicides tested, paraquat had the lower incidence of occurrence in all the water samples tested compared to 2,4-D. In terms of concentration, 2,4-D occurred in relatively higher concentrations than paraquat. Paraquat residues were found in the surface water (drainage) and its presence was not unpredicted. Paraquat was found in the water following direct usage or because of overflow from ricefield areas. The K_d value seemed to have a major influence on the fate of a herbicide. A strongly sorbed pesticide is expected to stay close to the soil surface and remain available for possible runoff loss via water or sediment. Paraquat is bound strongly to the soil because of its high K_d value. This makes paraquat less available to the water medium as shown by the low incidence and its relatively low concentration in the water samples. The presence of paraquat in the upper 0-5 cm soil level only indicates that this pesticide could not leach deeper into the soil under the conditions of the Kerian ricefields.

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