

Controlled Release of Phenylurea Herbicides from a Lignin Matrix: Release Kinetics and Modification with Urea

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The release kinetics of five phenylurea herbicides from granules based on a lignin matrix system were evaluated in water using a static immersion test. The T_{50} values, the time taken for 50% of the active ingredient to be released, were used to investigate a possible correlation of the release with the water solubility, octanol–water partition coefficient (K_{OW}), and the solubility parameter of the herbicide. A linear correlation of the T_{50} value and the K_{OW} of the herbicides was observed. Urea was added to a diuron–lignin matrix as a processing aid and a release modifier. This resulted in an increased rate of release of diuron, and an unexpected chemical reaction between diuron and urea resulted in the formation of dichlorophenylurea (DCPU). As the amount of DCPU formed was very small and it is a metabolite of diuron, its formation is expected to have minimal impact.

Keywords: *Controlled release; lignin; herbicides; release kinetics*

INTRODUCTION

Controlled release (CR) pesticide formulations have the potential to reduce the environmental problems associated with the application of pesticides. There are many advantages of CR formulations including an increased safety to the user and nontarget organisms, a reduction in the amount of pesticides applied, reduced leaching of pesticides, and increased persistence of the active ingredient (AI) (Bahadir and Pfister, 1990; Schreiber et al., 1993).

The use of biodegradable polymers in CR formulations is one area which is expected to grow in the future (Wilkins, 1995). Lignin is a naturally occurring biodegradable polymer, which is readily available, is cheap, and has shown promise in the area of pesticide formulations (Wilkins, 1990). Certain pesticides have the ability to dissolve kraft lignins when heated under melt conditions. On cooling a glassy matrix forms, from which the pesticide is released by diffusion (Chanse and Wilkins, 1987). Reforest Aid is a commercially available formulation of the herbicide 2,4-D with lignin which is used in forestry. Field trials on carbofuran–lignin matrix formulations showed increased grain yields and reduced virus infection in flooded rice in the Philippines and Indonesia compared to conventional formulations (Wilkins et al., 1984, 1988).

Pesticides are predicted as being compatible with lignin in a matrix formulation if they have a solubility parameter close to that of lignin, ca. 20–25 MPa^{1/2} (Dellicolli, 1980). The widely used phenylurea herbicide diuron, which has a solubility parameter of 24.7 MPa^{1/2}, was found to be compatible with various isolated lignins for matrix formulations (Cotterill, 1994; Wilkins and Cotterill, 1993). The use of additives to this type of lignin matrix, for example, small amounts of high polymers (Chanse and Wilkins, 1987), or urea and rosin (Baker, 1983) as processing aids has been reported. The additives not only improve the physical properties of the formulations but also affect the release kinetics. The use of urea has the benefit of allowing a lower minimum

percentage of herbicide in the formulation for solvation of lignin (as urea itself solvates lignin). Urea is also a good fertilizer of soil, cheap, and environmentally safe.

In this paper five phenylurea herbicides of varying physicochemical properties were formulated with a kraft lignin. The release kinetics of the herbicides were compared to see the effect of various properties of the herbicides on the release. The main objective of the work was to gain a deeper understanding of the release mechanism of the herbicides and to predict the release kinetics and suitability of lignin matrix formulations for a wide range of pesticides of varying properties. The effect on the release rates of diuron with the addition of urea was also investigated.

EXPERIMENTAL PROCEDURES

Chemicals. The lignin, L₁, was a commercially available pine kraft lignin, Indulin AT (Westvaco Corp., Charleston, SC). Technical grade herbicides were kindly supplied by the following companies: diuron (Stavely Chemicals Ltd., Derbyshire, U.K.) and chloroxuron, chlortoluron, fluometuron, and metoxuron (Ciba Geigy, Whittlesford, Cambridge, U.K.). Urea was lab reagent grade (Fisons Scientific Equipment, Loughborough, U.K.).

Formulations. The lignin and the herbicides were mixed together in the ratio 1:1 (w/w) and heated under melt conditions for 8–10 min (Wilkins and Cotterill, 1993). The temperatures used to formulate were 160–170, 165–175, 175–185, 170–180, and 140–150 °C for chloroxuron, chlortoluron, diuron, fluometuron, and metoxuron, respectively. Formulations containing diuron, lignin, and urea were also made, heating at 175–185 °C for 8–10 min. The ratios of diuron:urea:lignin were 8:1:8, 4:1:4, and 1:1:1 (coded DULa, DULb, and DULc, respectively). On cooling the glassy matrices were crushed in a hammer mill and then sieved to obtain granules of size between 0.71 and 1.0 mm. A code for the formulations was used, XL₁Y, where X represents the AI, L₁ is the pine kraft lignin, and Y is the percentage of AI in the formulation (w/w). The AIs are represented by the following: Cx, chloroxuron; Ct, chlortoluron; D, diuron; F, fluometuron; M, metoxuron, U, urea.

Analysis of AI in the Granules. *Herbicides.* Granules (20 mg) were treated with methanol (25 mL) in an ultrasonic bath for 10 min. This led to the complete disintegration of the granules. After standing for 24 h at room temperature, the mixture was sonicated for a further 10 min and then

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filtered quantitatively through a syringe filter (0.2 μm). The volume was then made up to 50 mL with methanol, and the resulting solution was then diluted 1:4 with methanol and analyzed for the herbicide using HPLC. Three replicates were carried out for each formulation.

Urea. Granules (20 mg) were treated with double-distilled water (25 mL) in an ultrasonic bath for 20 min, which led to the disintegration of the granules. The flasks were then left to stand at room temperature for 24 h and then sonicated for a further 10 min. The mixture was filtered quantitatively (0.2 μm), and the volume was made up to 50 mL with water. The solution was then analyzed for urea using an enzymic analyzer (COBAS MIRA). The analysis was based on the reaction of urease and glutamate dehydrogenase in the presence of NADH, measuring the decrease in NADH absorption using an ultraviolet detector. Three replicates were carried out for each formulation.

Static Immersion Tests. Granules (40 mg) were immersed in double-distilled water (300 mL, pH 5.5–6.5) at 30 $^{\circ}\text{C}$, with three replicates for each formulation. Samples were taken for analysis by HPLC every day for the first week, after 10 and 14 days, and then every week thereafter. After each sampling time the water was replaced with fresh water to maintain sink conditions (Cotterill, 1994). Due to the very low water solubility of chloroxuron (3.7 mg L^{-1}), a lower mass of granules and a larger volume of water were used in order to maintain sink conditions. In this case the granules (10 mg) were immersed in 500 mL of water and the tests carried out as above.

HPLC Analysis. The aqueous samples from the static immersion tests and the methanol extracts of the herbicide matrices were analyzed using a reverse phase column (ODS, 150 \times 4.6 mm, 5 μm packing) and detection on a variable wavelength UV detector at 254 nm. A flow rate of 1 mL min^{-1} was used, with an isocratic mobile phase composition of methanol and water. The percentage of methanol was 84%, 75%, 80%, 85%, and 70% for chloroxuron, chlortoluron, diuron, fluometuron, and metoxuron, respectively.

Treatment of Data from Release Studies. The release data were analyzed by using the generalized model $M_t/M_\infty = kt^n + c$, where M_t/M_∞ is the proportion of AI released at time t and k , n , and c are constants. The exponent n indicates the mechanism of release (Ritger and Peppas, 1987). The data was fitted up to 80% release of the AI (excluding the first data point to allow for the removal of the AI from the surface of the granules and for water to penetrate the granules). The various constants and the correlation coefficient r^2 were determined using the curve-fitting utility of Fig. P software (version 6.0 c, Biosoft, 1992).

Investigation into the Chemical Reaction between Diuron and Urea. Following the extraction of the diuron-urea-lignin (DUL) formulations, it was observed that the losses of both diuron and urea were higher than expected (see Table 4). A new peak of slightly lower retention time than that of diuron also appeared on the HPLC chromatogram. It was shown that there was a chemical reaction occurring between diuron and urea, lignin not being directly involved. An unknown compound was isolated using column chromatography and analyzed by infrared and mass spectroscopy.

RESULTS AND DISCUSSION

Matrix Formulations. All five of the phenylurea herbicides were found to be compatible with lignin for the matrix formulations. The solubility parameter of the herbicides ranged from 22.2 to 27.1 $\text{MPa}^{1/2}$, so compatibility was expected (see Table 3). It can be seen from Table 1 that the losses of the herbicides on formulating with lignin were relatively low, between 3.9% and 4.6%. Losses of herbicides are ascribed to the evaporation, degradation, or hydrolysis of the AI on heating with lignin at temperatures above their melting points. The actual percentage of herbicide in the matrix was used when calculating the percentage of AI released in the static immersion tests.

Table 1. Extraction of Herbicide from Granules^a

formulation	AI (%)		
	initially	extracted	loss
CxL ₁ 50	49.59	47.67 (0.57)	3.9
CtL ₁ 50	49.91	47.66 (0.20)	4.5
DL ₁ 50	49.77	47.48 (0.84)	4.6
FL ₁ 50	50.25	48.32 (0.34)	3.8
ML ₁ 50	50.13	48.15 (0.48)	3.9

^a Standard deviation of three replicates shown in parentheses.

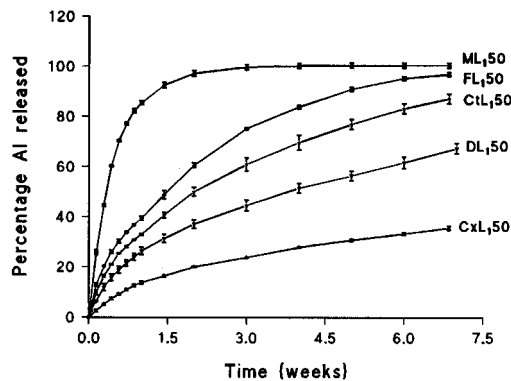


Figure 1. Cumulative release of phenylurea herbicides from lignin granules into static water (error bars represent the standard deviation of three replicates).

Table 2. Constants from Fitting the Generalized Model $M_t/M_\infty = kt^n + c$ to the Release Data of Phenylurea Herbicides from Lignin Granules^a

matrix	k	n	c	r^2	T_{50} (weeks)
CxL ₁ 50	24.01 (1.48)	0.34 (0.02)	-10.57 (1.44)	0.9996	15.20
CtL ₁ 50	42.74 (3.34)	0.44 (0.03)	-8.71 (3.19)	0.9992	2.06
DL ₁ 50	36.45 (1.51)	0.38 (0.01)	-10.57 (1.43)	0.9996	3.81
FL ₁ 50	36.84 (2.90)	0.61 (0.04)	3.51 (2.69)	0.9988	1.46
ML ₁ 50	196.5 (101.3)	0.21 (0.14)	-105.1 (103.7)	0.9978	0.32

^a Standard errors shown in parentheses.

Table 3. Water Solubility (S), Octanol-Water Partition Coefficient (K_{OW}), and Solubility Parameter (δ) of Phenylurea Herbicides

herbicide	S (mg L^{-1})	K_{OW}	δ ($\text{MPa}^{1/2}$)
chloroxuron	3.7	1585	22.2
chlortoluron	70	257	22.4
diuron	42	479	24.7
fluometuron	105	263	27.1
metoxuron	678	44	23.8

Release Studies. The release of the phenylurea herbicides from granules into static water is shown in Figure 1. The release rates of the five herbicides were very different, with the release of the most water soluble herbicide, metoxuron, being by far the fastest. The release data for the herbicide release were fitted to the generalized model, with the constants shown in Table 2.

The release from all of the herbicide formulations fitted the generalized model well, with a correlation coefficient r^2 of at least 0.9978. Values of n close to 0.5 indicate that diffusion of the herbicides through the lignin matrix is rate-controlling (Ritger and Peppas, 1987). The T_{50} values for the five herbicides were calculated and found to range from 0.3 to 15.2 weeks. The T_{50} values were used to compare the formulations, and a possible correlation of the T_{50} value with the water solubility (S), the octanol-water partition coefficient (K_{OW}), and the solubility parameter (δ) was investigated. These values are shown in Table 3 for the five herbi-

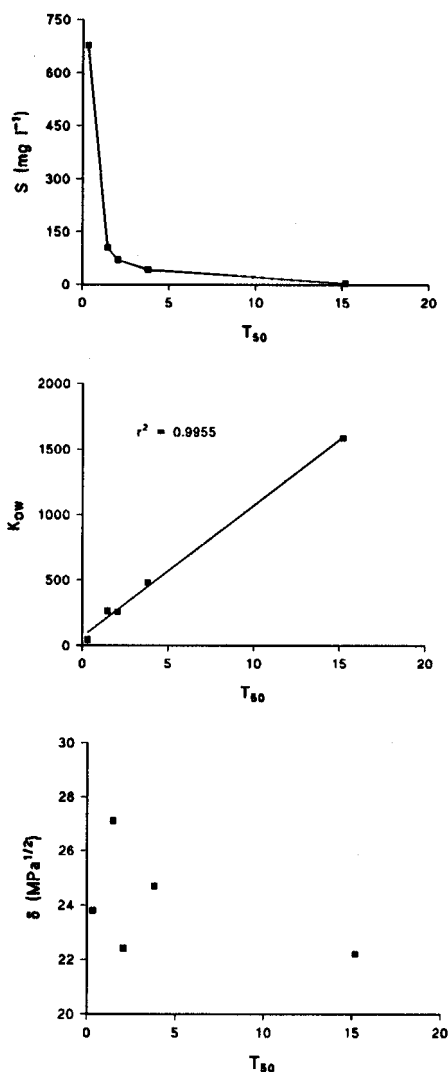


Figure 2. Plot of the T_{50} values versus the water solubility, octanol–water partition coefficient, and solubility parameter of the phenylurea herbicides.

Table 4. Percentage of Diuron, Urea, and DCPU Extracted from DUL Granules^a

matrix	diuron (%)		urea (%)		DCPU %
	initially	extracted	initially	extracted	
DULa	47.0	39.0 (0.5)	5.9	4.6 (0.3)	2.4 (0.2)
DULb	44.3	36.2 (0.7)	11.3	9.7 (0.4)	2.6 (0.2)
DULc	33.3	25.3 (0.6)	33.4	30.1 (0.6)	3.0 (0.3)

^a Standard deviation of three replicates shown in parentheses.

cides. The water solubilities of all of the herbicides were taken from Worthing and Hance (1991). The solubility parameters were calculated using the group contribution method of Meusberger (1988), and the K_{OW} values were taken from Briggs (1981) and Worthing and Hance (1991). Figure 2 shows the plots of the T_{50} values versus the S , K_{OW} , and δ values of the herbicides.

Clearly there is a relationship between the T_{50} value and both the water solubility and K_{OW} of the herbicides. No correlation was found with the T_{50} value and the solubility parameter of the herbicide. It can be seen that there is a trend of increasing water solubility leading to a faster release. A linear correlation of the K_{OW} value of the herbicide with the T_{50} value is shown ($r^2 = 0.9955$). The octanol–water partition coefficient, K_{OW} , is a measure of the partitioning of a chemical between the organic and aqueous phases. The lower

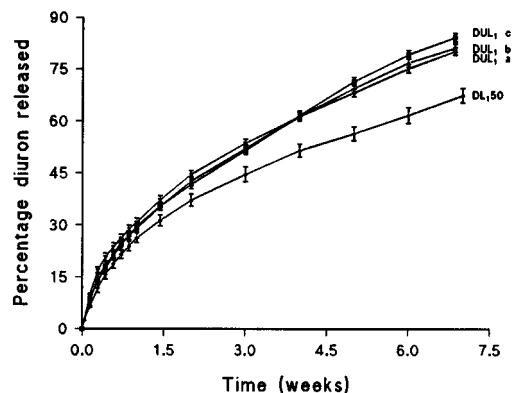


Figure 3. Cumulative release of diuron from DL₁₅₀ and DUL granules in static water (error bars represent the standard deviation of three replicates).

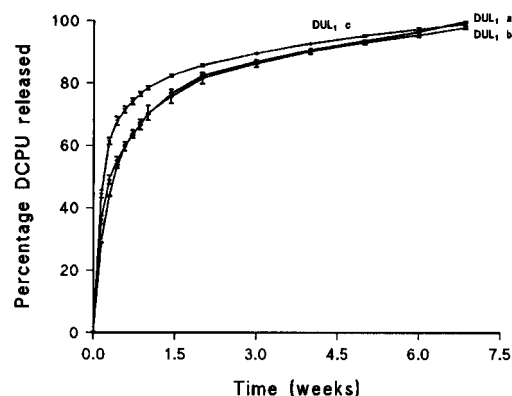


Figure 4. Cumulative release of DCPU from DUL granules in static water (error bars represent the standard deviation of three replicates).

the K_{OW} value, the more hydrophilic the compound. The higher the K_{OW} of the herbicide, the higher the partitioning in the organic phase, lignin, which results in a slower release of the herbicide, i.e., a higher T_{50} value. From the linear correlation the release of related AIs not previously evaluated could be readily predicted from the K_{OW} value if the release kinetics of pesticides of similar structure are known.

The five phenylurea herbicides have a very broad range of applications in the field; hence the desired rate and duration of release will depend very much on the particular situation. For example, diuron is used for general weed control on noncrop areas where a long period of release would be required. It is also used selectively pre-emergence where shorter release periods may be preferred to prevent carry over into the next season. Formulations with the desired release profile can be readily made by variation in the granule size, percentage of herbicide, and inclusion of additives (Cotterill, 1994).

Addition of Urea to Diuron–Lignin Matrix. From the extractions of DUL granules (Table 4), it can be seen that the losses of diuron and urea were higher than expected with average losses of between 15% and 20%. These values can be compared to the 4.6% loss of diuron during the preparation of the DL₁₅₀ formulation. The high losses are due to a chemical reaction between diuron and urea in the melt which led to the formation of dichlorophenylurea (DCPU). DCPU was found to be present at ca. 3% in the DUL formulations. The remaining losses of diuron and urea were attributed to the formation of dimethylurea (DMU) (the other reaction product) and evaporation/degradation products.

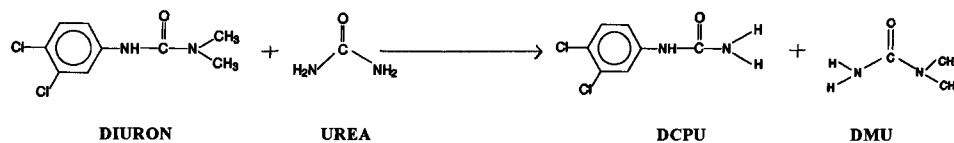


Figure 5. Proposed chemical reaction between diuron and urea.

Table 5. Constants from Fitting the Generalized Model $M_t/M_\infty = kt^n + c$ to the Release of Diuron from DUL and DL₁₅₀ Granules in Static Water^a

matrix	<i>k</i>	<i>n</i>	<i>c</i>	<i>r</i> ²	<i>T</i> ₅₀ (weeks)
DUL a	31.71 (1.27)	0.48 (0.01)	-0.40 (1.20)	0.9998	2.63
DUL b	28.12 (1.04)	0.55 (0.01)	1.10 (0.98)	0.9998	2.73
DUL c	26.89 (2.25)	0.59 (0.03)	1.73 (1.23)	0.9987	2.70
DL ₁₅₀	36.45 (1.51)	0.38 (0.01)	-10.57 (1.43)	0.9996	3.81

^a Standard errors shown in parentheses.

Figure 3 shows the cumulative release of diuron from static water from the three DUL formulations and DL₁₅₀ granules. It can be seen that the release of diuron is faster from the granules containing urea than from the DL₁₅₀ formulation. From the analysis of urea in the samples, it was found that almost 100% of the urea in the granules was released within the first sampling period. This increased rate of release of diuron from the DUL formulations may have occurred due to the fast release of urea. This would result in an enhanced porous structure forming within the granule, which is expected to aid the diffusion of diuron through the granules.

The data from static immersion tests were fitted to the generalized model, with the constants shown in Table 5. Values of *n* close to 0.5 were observed, which again indicates that the diffusion of diuron through the matrix is the rate-controlling step. It can be seen that the addition of urea, even at the lowest ratio of urea to diuron of 1:8 (DULa), results in a *T*₅₀ value approximately three-fourths the value for the DL₁₅₀ formulation. It should be noted that although the ratio of urea in the formulations varied, the release of diuron was found to be very similar in all three cases. It seems that even at the lowest ratio of urea in the granules, the formation of the porous structure due to the fast release of urea results in an increased release of diuron, possibly due to an increased penetration of water into the granules.

Due to a chemical reaction, DCPU was found to be present at <3% by weight in the DUL matrices. The percentage of DCPU released with time is shown in Figure 4. The release of DCPU is much faster than that of diuron, with over 70% of the DCPU being released within the first week. This can be explained by DCPU being more hydrophilic than diuron, with a *K*_{OW} of 437 (Briggs, 1981). However, due to the low percentage of DCPU (<3%) in the formulation, the actual mass of DCPU released/week is very low compared to the mass of diuron.

Investigation into Reaction between Diuron and Urea. The compound isolated from the reaction of diuron and urea was analyzed by IR and mass spectroscopy. The main peaks of interest in the IR spectra were an intense peak at 1667 cm⁻¹ (C=O str) and peaks at 3486 and 3304 cm⁻¹ (N-H str). The mass spectra showed a molecular ion at 204, with fragments at 161 and 126 clearly visible. On this basis, it was deduced that the unknown compound was DCPU (see Figure 5). DCPU has a molecular weight of 204, corresponding to the molecular ion found at 204, and

the fragments at 161 were assigned to the Cl₂Ar-NH₂ group and at 126 to the ClAr-NH₂ group.

DCPU is a metabolite of diuron and is, itself, a slight Hill reaction inhibitor, although it is much less phytotoxic than diuron (Suzuki and Casida, 1981). Due to the very low amounts formed, and the fact that DCPU is a metabolite of diuron of lower phytotoxicity, then its formation in the diuron-urea-lignin matrix is expected to have a minimal impact on the use of such formulations in the field.

Conclusions. It has been shown that there is a strong correlation between the *T*₅₀ value and the *K*_{OW} of the phenylurea herbicides. This indicates that within a structural class of pesticides, the release rate of a pesticide may be estimated from the *K*_{OW} value, if the release kinetics of a few pesticides within the same structural class are known. The use of urea as a processing aid resulted in increased rates of release of diuron. The formation of DCPU in the matrix (<3% by weight) is expected to have minimal impact on the performance of such formulations.

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