

Controlled Release of a Herbicide from Matrix Granules Based on Solvent-Fractionated Organosolv Lignins

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An organosolv (Alcell) lignin was fractionated with both sequential solvent-extraction and solvent-mixture precipitation using various organic solvent systems. The resulting fractionated lignins were used to prepare matrix granules with bromacil as a model compound using a melt process. The release rates of bromacil in vitro from the granular matrix system were influenced by both the lignin used as carrier and the solution fractionation. The variations in release rates were related to the high proportion of low-molecular-weight fraction and its associated water-soluble lignin in the fractionated lignins. Fickian diffusion was a predominant factor in controlling the release of bromacil from the matrix granules based on the low-molecular-weight fraction (L_{fr1}). For the matrix granules based on the other fractionated lignins, the release of bromacil was of super-case II transport. The fine structure of the matrix granules before and after release was also studied. An unique release pattern of bromacil was observed for the matrix granules based on the low-molecular-weight fraction (L_{fr1}), showing a fast release followed by zero-order release, which was a result of remarkable changes in the structure of the matrix granules during the course of release.

Keywords: *Controlled release; organosolv lignin; fractionation; solvent system; water-soluble lignin; bromacil; release kinetics; Fickian diffusion; super-case II transport; matrix; granule; formulation; herbicide; pesticide*

INTRODUCTION

Lignin, a polyphenylpropane macromolecule, is the second-most abundant naturally occurring polymer in the world. Lignin is a waste or byproduct from many pulping processes. Its protective properties, such as being UV-light absorbent, an antioxidant, and a good sorbent of pesticides and biodegradability in the environment, make it appropriate for pesticide formulation. Due to these properties plus low cost, it has been intensively studied as a carrier in the controlled-release formulations of many types of pesticides (Wilkins, 1990). These studies have included the adsorption capacity of kraft lignin (Riggle & Penner, 1994) and the release kinetics of lignin-based formulations (Wilkins, 1999).

Lignin has been successfully used as a controlled-release agent for a variety of pesticides in matrix systems (Dellicolli, 1980; Chanse & Wilkins 1987; Cotterill & Wilkins, 1996; Ferraz et al., 1997). Two possible release mechanisms were reported to operate in lignin-based formulations: (1) diffusion of active ingredient through the matrix and (2) hydrolysis of ester links formed between the phenolic groups in lignin and the carboxyl group in the active agent during the formulating process. The first mechanism was further elaborated in the release of diuron (Cotterill et al., 1996) and 2,4-D (Ferraz et al., 1997) from various lignin-based matrixes and related to the physical-chemical properties of the lignins obtained from various sources (hard- or softwood) and isolation methods in which mineral acids (e.g., H_2SO_4 or HCl) were employed for lignin precipitation.

The focus has been on soda and, especially, kraft lignins and their modified products from sulfur-based wood-pulping processes. Organosolv pulping uses environmentally friendly aqueous organic solvents, such as ethanol, under elevated temperatures and pressures (Lora et al., 1989) and yields easily isolated sulfur-free lignins that are less condensed than the kraft lignins. These new lignins have important beneficial properties, form a new generation of raw materials, and are expected to be available in large quantities (Faix, 1992). The average molecular weights of organosolv lignins obtained from *Pinus caribaea hondurensis* sawdust were found to be related to the properties of solvent mixtures employed in pulping (Balogh, 1992). More recently, Alcell lignin, produced using ethanol, has been reported to have a significant proportion of a very low molecular weight fraction (Thring, 1996). Organosolv lignins have properties (especially low average molecular weight and high purity) significantly different from alkali lignins, and thus the nature of controlled-release matrixes made from these lignins may also differ. The release patterns of bromacil from matrix granules based on Alcell lignin and some of its fractions have been found to be different from other lignins (Zhao & Wilkins, 1999). To gain a better understanding of the effect of molecular weight, and other properties, of organosolv lignin (Alcell lignin) on release characteristics, the lignin (Alcell) was modified using solution fractionation, including sequential solvent extraction and solvent-mixture precipitation with various solvent systems. The resulting fractionated lignins were employed as carriers to prepare matrix granules with the soil-applied herbicide, bromacil, as a model compound using a melt process. The release characteristics of those lignin-based matrix granules

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Table 1. Fractionation of the Organosolv Lignin (Alcell Lignin) by Sequential Solvent Extraction

fraction	solvent	δ (MPa ^{1/2})	yield (w/w, %)	water-sol. lignin content determined: ^a		data reported ^b			δ^e
				in deionized water (w/w, %) \pm SD	in bromacil soln (w/w, %) \pm SD	yield (w/w, %)	M_w^c (g/mol)	M_n^d (g/mol)	
fr1	diethyl ether	15.4 ^f	17.5	39.1 \pm 0.31	61.8 \pm 3.55	27	720	480	1.5
fr2	methanol	29.7 ^f	62.1	14.1 \pm 0.13	31.0 \pm 2.23	53	2410	1040	2.3
fr3	insolubles		17.6	0.79 \pm 0.05	3.78 \pm 0.45	18	6950	2400	2.9
losses			2.8			2.0			
original lignin		28 ^g	100	16.5 \pm 0.79	31.9 \pm 1.16	100	3300	900	3.7

^a The data were taken at 30 °C. See text for the details. ^b Values were taken from Thring et al. (1996). ^c Weight-average molecular weight. ^d Number-average molecular weight. ^e Polydispersity. ^f Values of solubility parameters (δ) of the solvents used for extraction (Barton, 1983). ^g The solubility parameter was calculated for Alcell lignin (Ni & Hu, 1995).

Table 2. Fractionation of the Organosolv Lignin (Alcell Lignin) by Solvent-Mixture Precipitation

code	solvent–water mixture (ratio of 1/10)	lignin yield ^a (w/w, %)	loss ^a (w/w, %)	δ (MPa ^{1/2}) ^b	water-sol. lignin content deter'd in deionized water ^c (w/w, %) \pm SD
L_{wat}	deionized water	95.7	4.3	47.8	16.4 \pm 0.26
L_{HCl}	2M HCl	96.2	3.8	47.8	16.2 \pm 0.43
L_{ace}	acetone	93.5	6.5	45.27	12.5 \pm 0.49
L_{dio}	dioxane	93.0	7.0	45.32	12.2 \pm 0.31
L_{pyr}	pyridine	92.4	7.6	45.43	11.6 \pm 0.62
L_{meth}	methanol	91.8	8.2	46.14	10.9 \pm 0.30
L_{HAc}	acetic acid	89.2	10.8	46.47	8.1 \pm 0.17

^a The yield and loss are expressed on percentage of parent Alcell lignin weight. ^b The Hildebrand's solubility parameters were calculated considering the volume fraction of each mixture component of the solvent systems (Barton, 1975). ^c The data were taken at 30 °C. See text for the details.

were investigated in vitro and were related to the properties of the fractionated lignins and the fine structure of the matrixes.

MATERIALS AND METHODS

Materials. The hardwood organosolv lignin (Alcell lignin, Lora et al., 1989) was provided by Repap New Brunswick, Inc. (New Brunswick, Canada). Alcell lignin [C₉H_{7.26}O_{2.17}(OCH₃)_{1.15}] is a fine, brown, free-flowing powder obtained as a major byproduct from ethanol/water cooks of mixed hardwoods (15% poplar, 50% maple, and 35% birch) in the organosolv pulping process. All analytical grade solvents were obtained from Fisher Scientific, U.K. and were used as received without further purification. Bromacil [5-bromo-3-sec-butyl-6-methyluracil] (purity, 97%) was obtained from Griffin Corporation (Valdosta, Georgia). Bromacil is a nonselective herbicide for total weed and brush control on noncrop land and for selective control of annual and perennial weeds and grasses in citrus and pineapple plantations (Tomlin, 1995). Bromacil standard (purity, 98%) was purchased from Greyhound (Birkenhead, England).

Fractionation of Lignin. Sequential Solvent Extraction. Alcell lignin was fractionated by sequential solvent extraction with diethyl ether and methanol according to Thring et al. (1996). The properties of the three fractions of lignin are summarized in Table 1. **Solvent-Diluted HCl Mixture Precipitation.** The mixed hardwood organosolv (Alcell) lignin (20 g) was added separately to each of the solvents (40 mL): acetone, dioxane, pyridine, methanol, and glacial acetic acid. Each of the mixtures was gently stirred in a sealed flask at ambient temperature for 48 h in the dark. The resulting mixture was precipitated at pH 0.37 in 2 M ice-cold dilute hydrochloric acid (400 mL), except for the acetic acid–lignin mixture which was poured into ice-cold water. The precipitate was filtered on a Buchner funnel and thoroughly washed with deionized water until the pH of the filtrate was neutral. Alcell lignin (20 g) was also stirred with ice-cold dilute HCl (400 mL) or water only (400 mL), filtered, and washed with water as before. The precipitated lignins were dried in vacuo at 40 °C for 24 h and kept in a desiccator for further use. The details of this precipitation–fractionation are in Table 2. **Water-Soluble Contents of Solvent-Fractionated Lignins.** Each of the fractionated lignins (25 mg) was accurately weighed and dissolved in

200 μ L of dioxane in a glass vial. The lignin solution was then added drop by drop into 300 mL of water (30 °C) with magnetic stirring. Residues of lignin solution left in the vial were completely transferred by rinsing with the stirring solution four times. After being vigorously stirred (2 min), an aliquot of the suspension was filtered through a nylon filter membrane (diam, 25 mm; pore size, 0.45 μ m; Whatman). The concentration of the lignin in the filtrate was measured at 277 nm on a spectrometer (Unicam 8625). To investigate the effect of the presence of bromacil on dissolution of water-soluble lignin, the water-soluble lignin content of the three sequential solvent-fractionated lignins plus the Alcell lignin was also determined in a saturated bromacil solution. The saturated bromacil solution was prepared by dissolving excess bromacil powder (purity, 97%) in deionized water, in a water bath (30 °C), with magnetic stirring overnight. The resulting suspension was filtered on a Buchner funnel, and the filtrate was used for the determination of water-soluble lignin content using the aforementioned method. The concentration of water-soluble lignin and bromacil in the solution was analyzed simultaneously by HPLC using a Phenomenex column (Spherisorb 5 ODS (2), 150 \times 3.2 mm, 5 μ m) and a diode array detector (Gilson, 170) at 280 nm. An isocratic regime of 55% acetonitrile in water was used as a mobile phase at a flow rate of 1 mL/min. All of the samples were analyzed in three replicates. The ether-soluble fraction, fr1, was used to prepare a standard curve for the water-soluble lignins.

Water Solubility of Water-Soluble Lignin. The water-soluble lignin was obtained by solid-phase extraction of a lignin solution of fr1 which was prepared following the same method previously described for the determination of water-soluble lignin content. A cartridge (Oasis HLB plus; 0.5 g Waters) was activated by methanol (5 mL) and water (5 mL). After 300 mL of lignin aqueous solution was eluted, the cartridge was washed with 5 mL of 5% methanol in water, and then the lignin was eluted with 5 mL of methanol twice and evaporated to dryness. The dried water-soluble lignin was weighed, and its aqueous solubility was measured by gradually adding deionized water until complete dissolution was observed. The experiment was done in two replicates.

Formulations. Preparation of Lignin-Based Matrix Granules. The lignin (Alcell lignin and all its fractions) as a fine powder (1 g) and bromacil (1 g) were weighed and thoroughly mixed for 5 min. The mixture was then heated on a hot plate

at 150–160 °C for 10 min. After being cooled, the resulting glass was crushed and sieved. The granules (0.7–1.0 mm) were used for release kinetics. A code for each modified lignin-based matrix was used: BL_x, where B is bromacil and L_x is the modified lignin.

Determination of bromacil Content of Granules. Triplicated samples of bromacil–lignin granules (10.0 mg) were treated with ca. 9 mL of acetone in a 10 mL volumetric flask in a sonicator for 30 min. Acetone was then added to make up to 10 mL at 20 °C. The mixture was filtered through a nylon membrane filter (diam, 13 mm; pore size, 0.45 μm; Whatman) and analyzed in triplicate by GC-FID using a SUP–Herb fused silica capillary column (column i.d., 0.53 mm; column length, 15 m; film thickness, 0.50 μm) (Supelco U.K., Dorset, U.K.). The conditions were as follows: He carrier gas, 15.7 mL/min; air, 450 mL/min; hydrogen, 45 mL/min; injector, 250 °C; column, 210 °C; and detector, 280 °C. A split mode was used at the ratio of carrier gas flow to split vent flow of 1/20. The retention time for bromacil was 1.6 min.

Measurement of Herbicide Release. Bromacil release from the lignin-based granules (50 mg) was studied in vitro at 30 °C in 300 mL reagent bottles using a controlled-environment incubator orbital shaker (New Brunswick Scientific, Edison, NJ) at 150 rpm. Immersion water was sampled at intervals and completely replaced with fresh deionized water (300 mL) in order to maintain “sink” conditions. The samples collected were filtered through a cellulose nitrate membrane filter (diam, 13 mm; pore size, 0.45 μm; Whatman) prior to HPLC analysis and were analyzed by HPLC using a Phenomenex column (Spherisorb 5 ODS 2, 150 × 3.2 mm, 5 μm) and a diode array detector (Gilson, 170) at 280 nm. An isocratic regime of 55% acetonitrile in water was used as a mobile phase at a flow rate of 1 mL/min.

Measurement of Release of Water-Soluble Lignins. *Spectrometric Analysis.* The water samples collected during the release of bromacil were also assayed using UV/vis spectrometer (Uvicam 8625) at 280 nm. The water-soluble lignin content in the solution was calculated on the difference between the total absorbance and the absorbance contributed by bromacil at 280 nm.

Gravimetric Analysis. The total release of water-soluble lignin during the course of the release of bromacil was also determined using gravimetric analysis. The matrix granules collected at the end of in vitro release experiment were accurately weighed after drying to constant weight at 30 °C. The cumulative percentage release of water-soluble lignin was calculated according to the following equation:

$$M_L/M_{L,0} = \left(1 - \frac{M_F + M_R}{M_I - M_0}\right) \times 100$$

where M_L is the total amount of lignin released during the course of bromacil release (mg), $M_{L,0}$ is the initial amount of lignin in the matrix granules before the release of water-soluble lignin (mg), M_0 is the initial amount of bromacil in the matrix granules before the release of bromacil (mg), M_I is the initial weight of matrix granules used in the in vitro release experiment (mg), M_R is the total amount of bromacil released (mg), and M_F is the final weight of the dry granules after the release of bromacil and water-soluble lignin.

Scanning Electron Microscopy. The freshly prepared lignin-based matrix granules were carefully cut to expose the cross-section without deformation of the granules. The cut granules were mounted with the cross section facing upward on double-side tape, sputter-coated with gold, and examined in a Cambridge Stereoscan (Model S240, U.K.) microscope at 6 KV. The granules collected during and at the end of the release experiment were dried at 35 °C and examined using the same method.

RESULTS AND DISCUSSION

Fractionation of Organosolv Lignin. *Sequential Solvent Extraction.* Sequential solvent extraction has

been successfully used to separate and characterize lignin in terms of molecular weight distribution and group functionality (Thring & Chornet, 1993; Thring et al., 1996). In this study, an organosolv lignin (Alcell lignin) was fractionated into three molecular mass groups by sequential solvent extraction with diethyl ether and methanol according to Thring et al. (1996). The heterogeneity of the organosolv lignin (Alcell lignin) is clearly shown in Table 1. A lower yield of ether-soluble fraction (fr1) and a corresponding higher yield of methanol-soluble fraction (fr2) were found compared to the data reported (Thring et al., 1996). The diethyl ether-soluble fraction (fr1) was reddish brown, greasy, and soft with visible granular particles coalesced together. The methanol-soluble fraction (fr2) was a dark brown, free-flowing powder and is the major fraction, comprising 62% of the Alcell lignin. The insolubles (fr3) were a black, charcoal-like free-flowing powder. The appearance of all three fractions were different from the original lignin, which is a free-running brown powder.

Solvent-Diluted HCl Mixture Precipitation. The yields of lignins from treatments with solvent systems and the corresponding weight losses during the solvent-diluted HCl mixture precipitation procedure are summarized in Table 2. The lowest yield of product (89.2%) was found for the acetic acid treatment, the highest yield (95.7%), for the lignin stirred with water at room temperature. The yields of the other lignin fractions follows in decreasing order: $L_{ace} > L_{dio} > L_{pyr} > L_{meth}$. The higher the yield of lignin, the lower the amount of lignin that had been removed. The losses of lignins could be related to the solvent from which the lignin was precipitated. Alcell lignin dissolved completely in dioxane and pyridine, partly dissolved in acetone, methanol, and acetic acid. When the lignin–solvent mixture was poured into dilute hydrochloric acid (2.0 N, 400 mL) or in ice-cold water (400 mL) for acetic acid-treated lignin, a part of the lignin remained dissolved and was removed during filtration. These losses increased with the slightly increasing solubility parameter of the mixture except for water (Table 2). This discrepancy might be due to the low solubility of lignin as a result of the low accessibility of water to the lignin (Goring, 1971). All of the solvent-mixture-fractionated lignins were fine, brown, free-flowing powders.

Water-Soluble Lignin. Alcell lignin has a low content of carbohydrates (<0.5%) and is free of sulfonic groups (Lora et al., 1989), being considered as a lignin of high purity. Therefore, it is unlikely that nonlignin impurities were removed during the precipitation process. The water-soluble lignin component of the fractionated lignins was quantitatively determined using ultraviolet spectrometry (Goldschmid, 1971) at 277 nm (Ahlgren & Goring, 1971; Sun et al., 1999). As can be seen from Tables 1 and 2, the water-soluble lignin contents varied with the fractionation methods, more so with the sequential solvent-extracted lignins than with the solvent-mixture-precipitated lignins, ranging from 39.1% (fr1) to 0.79% (fr3) for the former compared to 16.4% and 8.1% for the latter. Fraction fr1 had the greatest and fraction fr3 the lowest proportion of water-soluble lignins; thus, it can be assumed that the water-soluble lignins were of low molecular weight (Table 1). The water-soluble lignin content of Alcell lignin was found to equal the total of the individual water-soluble lignin contents of the individual three lignin fractions and their corresponding proportions (Table 3). This confirms

Table 3. Comparison of the Water-Soluble Lignin Dissolved from the Original Lignin with the Totals of the Contributions of the Water-Soluble Lignin Dissolved from the Lignin Fractions^a

frac.	water-sol. lignin cont. (w/w, %) \pm SD	water-sol. lignin (%) contrib. from lignin frac.	
		yield of frac. (w/w, %)	contrib. to original (w/w, %) \pm SD
fr1	39.11 \pm 0.31	17.5	6.84 \pm 0.05 ^b
fr2	14.10 \pm 0.13	62.1	8.76 \pm 0.08 ^b
fr3	0.789 \pm 0.05	17.6	0.14 \pm 0.01 ^b
original	16.48 \pm 0.79	100	15.74 \pm 0.14 ^c

^a All in water at 30 °C. ^b The product of the values in the 2nd and 3rd columns. ^c The sum of the above three values in this column.

the reliability of the method employed for the determination of water-soluble lignin in this study.

Alcell lignin has a significant portion (27%) of very low molecular weight fraction ($M_w = 724$ g/mol) soluble in ether (Thring et al. 1996). We found this to have a high water-soluble lignin content of 39% (Table 1). The water solubility of this water-soluble lignin, which was extracted from lignin solution in deionized water (pH \approx 5.5), was estimated as 1100 μ g/mL, resulting in its likely separation during precipitation.

As expected, the water-soluble lignin contents of all of the solvent-mixture-precipitated lignins were lower than that of the original lignin. The water-soluble lignin content of the solvent-mixture-precipitated lignins decreased with slightly increasing solubility parameter of the solvent mixture at pH 0.37 (except the lignins from treatment with water and diluted hydrochloric acid). The results suggest that this increase in solubility parameter would facilitate the dissolution of water-soluble lignin from the original lignin, leading to a lower yield of the resulting precipitated lignin containing a lower amount of low-molecular-weight lignin fraction. A similar interpretation was proposed that the high-molecular-weight fraction be extracted only when a certain amount of lignin has been removed (Balogh et al., 1992). The reason for the exception could be due to the poor accessibility of water to the soluble lignins in Alcell lignin during precipitation. Nevertheless, the yield of lignin products increased with decreasing amount of lignin being removed, resulting in an increase in water-soluble lignin content in the resulting fractionated lignins. Therefore, the decrease in yield of solvent-mixture-precipitated lignins could be due to the increasing removal of water-soluble lignins from the original Alcell lignin.

Compatibility of Fractionated Lignins with Bromacil. The compatibilities for blending lignin with pesticides are normally considered from the solubility parameter (δ) of each of the components incorporated in the matrix (Dellicolli, 1980; Chanse & Wilkins 1987). Polymers (including amorphous macromolecules) have a maximum solubility in solvents with δ -values closest to their own (Lindberg, 1960; Durrans, 1971). The solubility parameter of good solvents for lignin falls in the range of 20–23 MPa^{1/2} (Schuerch, 1952). In our study, all of the lignins completely dissolved in dioxane, dimethyl formamide, and dimethyl sulfoxide (data not shown), which possess solubility parameters ranging from 20.5 to 26.5 MPa^{1/2} and moderate hydrogen-bonding capacity. Therefore, all of the fractionated lignins have a solubility parameter similar to the Alcell lignin, with values ranging between 20.5 and 26.5

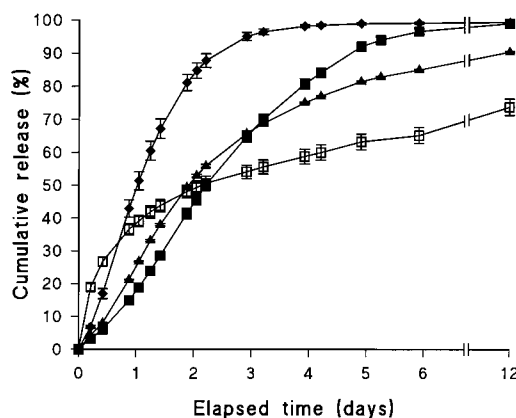


Figure 1. Release of bromacil from the matrix granules based on sequential solvent-extracted lignins and the original Alcell lignin: (◆) BL₀, 48.0% bromacil; (■) BL_{fr2}, 47.7% bromacil; (▲) BL_{fr3}, 48.7% bromacil; (□) BL_{fr1}, 48.9% bromacil. (Error bars represent the standard deviation of three replicates. Where error bars are not shown, the values of standard deviation are smaller than the data points.)

MPa^{1/2}. The solubility parameter of Alcell lignin was calculated as 28 MPa^{1/2} based on the lignin molecular formula (Ni & Hu, 1995). The δ value of bromacil was calculated as 26.6 MPa^{1/2}, on the basis of molecular group contributions of three cohesion energy density (CED) parameters and apparent molar volume (Meusburger, 1988). The similarity in the solubility parameters of fractionated lignins and bromacil signifies compatibility. As expected, for all of the lignins, a one-phase solution was formed with bromacil under melt conditions and transparent glassy matrixes after cooling. The matrix based on the ether-soluble fraction fr1 was the most plastic.

Release of Bromacil. Release from Matrixes Based on Lignin Fractions from Sequential Solvent Extraction. The cumulative release of bromacil from the matrix granules based on the three fractions and original Alcell lignin is shown in Figure 1. The release profile of the ether-soluble fraction-based matrix (BL_{fr1}) was biphasic, with a rapid initial release of bromacil from the surface of granules and a slow second phase, distinct from the other release profiles. This initial "burst effect" could be interpreted as a fast release of bromacil from the surface of the matrix combined with a fast release of water-soluble lignin. In contrast, the other three matrix granules (except BL_{fr1}) showed a sigmoidal release pattern with an early depression of release.

The release from alkali lignin-based matrix granules has been related to the functional groups (hydroxyl, methoxyl, and carbonyl) and molecular weight of lignins (Cotterill et al., 1996; Ferraz et al., 1997). A good correlation was only found between T_{50} values (time taken for 50% release of diuron) and the mass percent of hydroxyl group in the lignins for a set of diuron–lignin matrix granules containing 50% active ingredient (Cotterill et al., 1996). For the release of 2,4-D, the release rate constant increased with increasing methoxyl, aromatic hydroxyl, and carbonyl groups, and decreased with increasing total hydroxyl, aliphatic hydroxyl, and molecular weight (Ferraz et al., 1997). Alcell lignin and the three fractions vary in molecular weight and functional groups and structure (Thring et al., 1996). Methoxyl group content of the three fractions increased with molecular weight. The phenolic hydroxyl group is the major part of the total hydroxyl content in both Alcell and all lignin fractions with the absence of

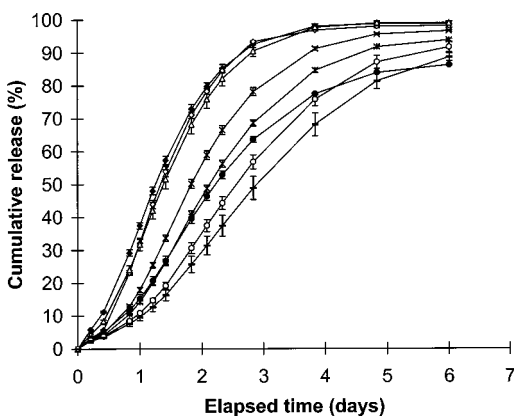


Figure 2. Release of bromacil from the matrix granules based on solvent-mixture-precipitated lignins and the original Alcell lignin: (◆) BL₀, 46.1% bromacil; (◇) BL_{HCl}, 45.9% bromacil; (Δ) BL_{wat}, 45.2% bromacil; (×) BL_{ace}, 46.1% bromacil; (*) BL_{dio}, 47.0% bromacil; (●) BL_{pyr}, 50.9% bromacil; (○) BL_{meth}, 47.4% bromacil; (–) BL_{HAc}, 46.5% bromacil. (Error bars represent the standard deviation of three replicates. Where error bars are not shown, the values of standard deviation are smaller than the data points.)

aliphatic hydroxyl groups in fr1 and the greatest amount of aliphatic hydroxyl groups in fr3 (Thring et al., 1996). Although the molecular weight and functional groups were not analyzed for the three fractions used in this study, the reported data (Thring et al., 1996) can be used as estimated values due to the similarity of these fractions to the reported results (Table 1). The molecular weight is likely to be the predominant factor, ranging from 720 g/mol for fr1 to 6950 g/mol for fr3 (Table 1) compared to functional groups such as the methoxyl which varied from 13.2% (fr1) to 17.5% (fr3). Importantly, the water-soluble lignin content decreased with increasing molecular weight, ranging from 39.1% to 0.79% for the low- and high-molecular-weight fractions. The molecular weight and its associated water-soluble lignin and fine structure of the matrix could be the major factor controlling the release of bromacil from the granules (which will be further discussed in the following section).

Release from Matrixes Based on Lignin Fractions from Solvent-Mixture Precipitation. The release of bromacil from various matrix granules based on the seven solvent-mixture-precipitated lignins was compared with that from the unmodified (Alcell) lignin matrix in Figure 2. The release of bromacil was slower from all matrix granules based on solvent-mixture-precipitated lignins than that from the original lignin. The release was particularly depressed for those granules at the early stage of release, as demonstrated by the set of sigmoidal curves, for all of the lignins (Figure 2). The extent of reduction in the release rates depends on the water-soluble lignin content of the precipitated lignins. The comparison between the depressed release of bromacil from solvent-mixture-precipitated lignin-based matrixes with the rapid release (burst effect) from L_{fr1}-based matrix (made from a lignin with 39% water-soluble lignin) suggests that the release material is related to the water-soluble lignin.

The influence of functional groups of lignins on the release rates could be less important compared to that of water-soluble lignin. When extracted from sawdust (*Pinus caribaea hondurensis*) using nine different organic solvents and 2 N hydrochloric acid (9:1) aqueous solution, all lignin samples isolated had very similar

Table 4. T_{50} Values and the Constants from Fitting the Generalized Model $M_t/M_\infty = kt^n$ to the Release Data of Bromacil from the Matrix Granules Based on Various Solvent-Mixture-Precipitated Lignins^a

matrix	$k \pm \text{SE}$ (day ⁻ⁿ)	$n \pm \text{SE}$	r^b	T_{50} (days) ^c	$T_{50-\text{BLx}}/T_{50-\text{BL0}}^d$
BL ₀	37.14 ± 0.49	1.28 ± 0.04	0.9996	1.26	1
BL _{wat}	31.63 ± 0.50	1.36 ± 0.04	0.9992	1.40	1.11
BL _{HCl}	31.38 ± 0.52	1.52 ± 0.05	0.9980	1.36	1.08
BL _{ace}	18.79 ± 0.49	1.58 ± 0.04	0.9989	1.86	1.48
BL _{dio}	15.16 ± 0.46	1.57 ± 0.04	0.9989	2.14	1.70
BL _{pyr}	16.68 ± 0.44	1.34 ± 0.03	0.9979	2.26	1.79
BL _{meth}	11.79 ± 0.41	1.53 ± 0.04	0.9985	2.57	2.04
BL _{HAc}	10.67 ± 0.36	1.43 ± 0.03	0.9982	2.94	2.33

^a The generalized model was fitted to the data up to 60% release of bromacil. ^b Correlation coefficient. ^c The time required for 50% release of bromacil. ^d The ratio of T_{50} values of various lignin-based granules to that of Alcell lignin-based granules.

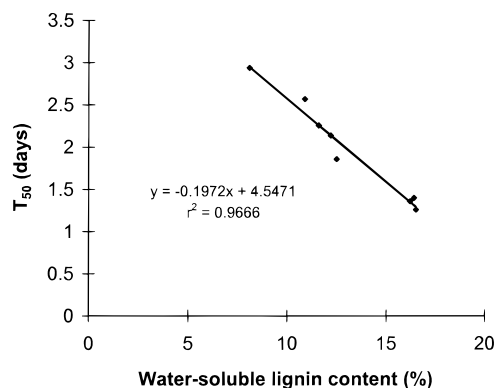


Figure 3. Plots of half-release times (T_{50} values) versus water-soluble lignin contents of various solvent-mixture-precipitated lignins.

functional group contents (Balogh et al., 1992). A high value of methoxyl group content occurred only in the methanol-HCl extracted lignin due to the reaction of the methanol with lignin during the extraction. Assuming the same reaction occurred to the methanol-HCl-precipitated lignin L_{meth} in this study, it could lead to an increase in release rates from the corresponding matrix granules BL_{meth} (Ferraz et al., 1997). On the contrary, the release was the slowest but one among the solvent-mixture-fractionated lignins. Therefore, a hypothesis is proposed that the release rate of bromacil is primarily governed by water-soluble lignin (Table 2). This will be further supported by considering the release of water-soluble lignin in the following discussion.

To facilitate comparison, the T_{50} value, the time required for 50% release of bromacil was calculated on the basis of the constants (k , n) obtained from the fitting of the generalized model $M_t/M_\infty = kt^n$ (Ritger & Peppas, 1987) in Table 4. Bromacil was released from the matrix granules based on the precipitated lignins in the decreasing rates of BL₀ > BL_{HCl} ≈ BL_{wat} > BL_{ace} > BL_{dio} > BL_{pyr} > BL_{meth} > BL_{HAc} (Table 4). A linear relationship with a high correlation was observed between the T_{50} values and the water-soluble lignin content of the solvent-mixture-precipitated lignins used as a carrier in the matrix granules (Figure 3), suggesting that the release rates of bromacil could be related to the water-soluble lignin in the precipitated lignins. Water-soluble lignin could affect the release of bromacil by increasing the porosity in the matrix as it is released and by increasing the water uptake of the matrix. By removing all of the soluble lignin from the Alcell lignin, it may be possible to slow this process to provide a matrix granule

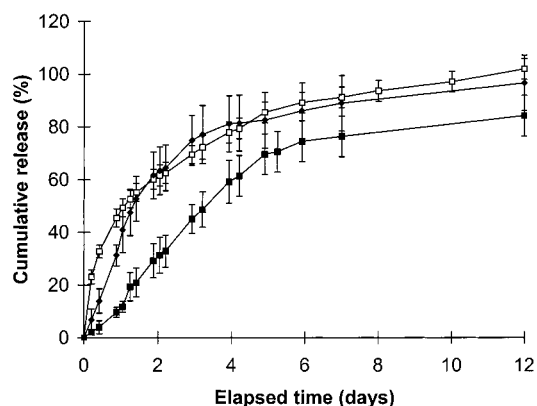


Figure 4. Release of water-soluble lignin from the matrix granules based on sequential solvent-extracted lignins and the original Alcell lignin: (◆) BL₀, 8.57% water-soluble lignin; (■) BL_{fr2}, 7.37% water-soluble lignin; (□) BL_{fr1}, 20.0% water-soluble lignin. (Error bars represent the standard deviation of three replicates. Where error bars are not shown, the values of standard deviation are smaller than the data points.)

Table 5. Constants from Fitting a Linear Model $y = mx + b$ to the Plots of the Cumulative Release of Bromacil versus the Cumulative Release of Water-Soluble Lignin

matrix	$m \pm SE$	$b \pm SE$	r^a
BL ₀ ^b	1.30 ± 0.01	0.41 ± 0.58	0.9978
BL _{fr2} ^b	1.32 ± 0.01	2.01 ± 0.42	0.9973
BL _{fr1} ^c	0.79 ± 0.02	0.32 ± 0.81	0.9998
BL _{fr1} ^d	0.59 ± 0.02	12.8 ± 2.16	0.9983

^a Correlation coefficient. ^b The linear model was fitted to the data up to 90% release of bromacil. ^c The linear model was fitted to the data up to 50% release of bromacil. ^d The linear model was fitted to the data ranging from 50 to 74% release of bromacil.

with a T_{50} value of 4.55 days, but still having a sigmoidal release profile.

Release of Water-Soluble Lignins. The release of water-soluble lignin from the matrix granules based on solution-fractionated lignins was monitored by both spectrometric and gravimetric analyses. The total release of water-soluble lignin determined by both methods was statistically similar and corresponded to the water-soluble lignin content, except for BL_{fr3} in which the amount released was greater than the measured soluble lignin content.

Sequential Solvent-Extracted Lignin Matrixes. The release profiles of water-soluble lignin are shown in Figure 4 for the matrix granules based on the low- and medium-molecular-weight fractions and the original lignin. The release of water-soluble lignin was fastest for BL_{fr1} and slowest for BL_{fr2}. An initial burst was found for the matrix BL_{fr1} (based on the low-molecular-weight fraction), whereas the early release of lignin was depressed for the other matrix granules. The release patterns of water-soluble lignin are similar to those of bromacil. This implies that the release of water-soluble lignin might be governed by similar mechanisms to those involved in the release of bromacil, which was indicated by the exponent n (Table 6). Although the water-soluble lignin content varied with the lignin fractions in the matrix granules, it only changed the release rates to a small extent, as indicated by the T_{50} values. For example, the T_{50} value was 1.14 days for BL_{fr1} containing ca. 20% of water-soluble lignin, whereas it increased to 1.39 days (for BL₀, 8.2%) and 3.27 days (for BL_{fr2}, 7.1%). There are two possible reasons to account for these differences: (a) the relatively high water solubility of the lignin (1100 mg/L, 30 °C) and (b)

the interaction of water-soluble lignin and bromacil. It has been reported that the release rates from kraft lignin-based matrix granules increased with the a.i. content for the a.i. with low water solubility (Chanse & Wilkins, 1987), but did not change for the a.i. with high water solubility (Wilkins & Falconer, 1988). Interestingly, the water-soluble lignin content of three lignin fractions and the original lignin was higher when analyzed in saturated bromacil solution than in deionized water (Table 1). The cause of the increase is not known. Nevertheless, the release rates of water-soluble lignin were slightly greater for the matrix BL₀ containing more water-soluble lignin than for the matrix BL_{fr2} containing less water soluble lignin.

In this study, the relationship between the release of water-soluble lignin and that of bromacil was explored by plotting the cumulative percentage releases against each other at the same time intervals (Figure 5). For bromacil, the original content of all of the matrix types was almost the same (~50%, with small losses in the heating process), but that of the soluble lignin varied (Table 3). Surprisingly, the cumulative release of bromacil correlated well with that of soluble lignin. The release of water-soluble lignin was faster than that of bromacil from the matrix BL_{fr1}, as indicated by the slope ($m < 1$) in Table 5. This is due to the water solubility of water-soluble lignin (which is present to 20% of the matrix) being greater than that of bromacil (1100 mg/L compared to 914 mg/L (30 °C)). The reduction in the release rate of bromacil at the late stage could probably be related to structural changes in the granules for this particular matrix containing only 30% mass of insoluble materials. However, the release of water-soluble lignin was slower than that of bromacil for the other matrixes BL₀ and BL_{fr2} with similar slopes > 1 . This is possibly due to the low water-soluble lignin (~7–8%) and high bromacil (~50%) contents. The results suggest that the release of bromacil primarily is affected by the water-soluble lignin content in the granules and less by the release rates of lignin.

Solvent-Mixture-Precipitated Lignins. Only the total release of water-soluble lignin was measured over the experimental period (6 days), and this increased with increasing water-soluble lignin content in these fractionated lignins, the results (not presented) indicated that all of the water-soluble lignin was released. This suggests that the natures of the water-soluble lignin in all of the various lignin fractions were similar. Thus, the matrix granules based on Alcell lignin and its various fractionated lignins can be considered as a two-component releasing system for which the release rates of individual a.i. are related to their water solubility (Gerstl et al., 1998).

Release Mechanisms. To elucidate the release mechanisms operating in the matrix granules based on various solvent-fractionated lignins, the release data ($\leq 60\%$) were fitted to the generalized model (Ritger & Peppas, 1987), $M_t/M_\infty = kt^n$, where M_t/M_∞ is the fraction of pesticide released at time t , k is a constant incorporating the structural and geometric characteristics of the release system, and n is the release exponent indicative of the mechanism of release. The value of n varies with the geometry of the release devices. For a sphere, the value of n is equal to 0.43 for Fickian diffusion, >0.43 and <0.85 for anomalous diffusion, 0.85 for case II transport, and >0.85 for super-case II transport. For irregularly shaped matrix granules with

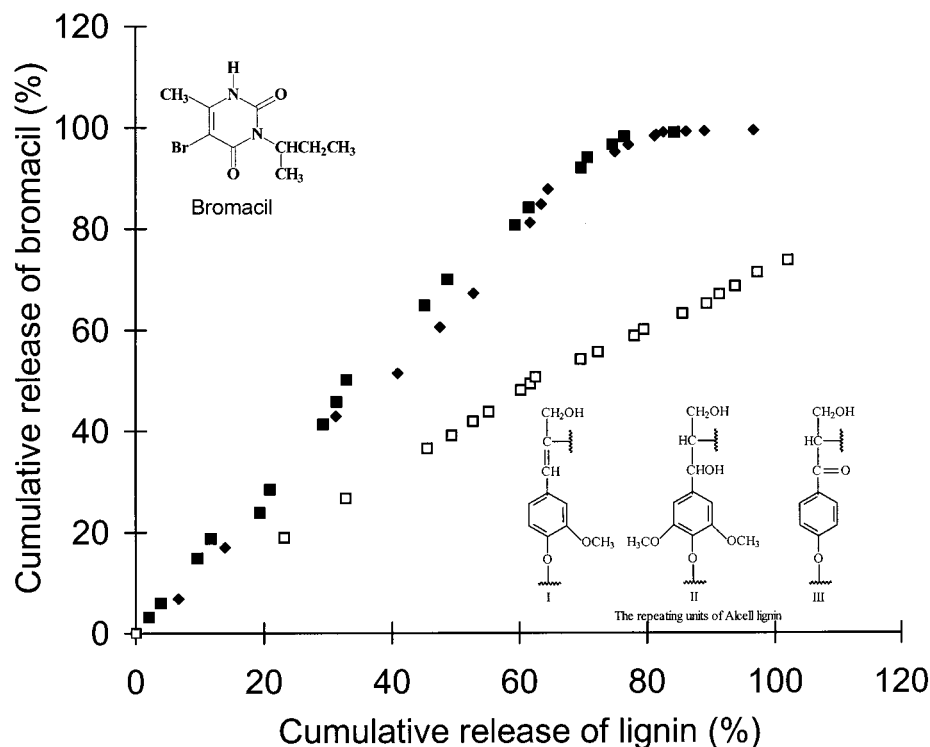


Figure 5. Plots of the cumulative release of bromacil versus the cumulative release of water-soluble lignin for sequential solvent-fractionated lignins and the original Alcell lignin: (◆) BL₀, 48.0% bromacil, 8.57% water-soluble lignin; (■) BL_{fr2}, 47.7% bromacil, 7.37% water-soluble lignin; (□) BL_{fr1}, 48.9% bromacil, 20.0% water-soluble lignin.

Table 6. T_{50} Values and the Constants from Fitting the Generalized Model $M_t/M_\infty = kt^n$ to the Release Data of Bromacil and Water-Soluble Lignin from the Matrix Granules Based on Sequential Solvent-Fractionated Lignins

matrix	$k \pm \text{SE} (\text{day}^{-n})$	gen'd model: ^a $M_t/M_\infty = kt^n$			$T_{50} (\text{days})^c$	$T_{50-\text{BL}_x}/T_{50-\text{BL}_0}^d$
		$n \pm \text{SE}$	r^b			
Release of Bromacil						
BL ₀	47.91 ± 0.53	1.15 ± 0.04	0.9991	1.04	1	
BL _{fr1}	37.68 ± 0.36	0.35 ± 0.01	0.9968	2.25	2.17	
BL _{fr2}	18.58 ± 0.44	1.22 ± 0.03	0.9986	2.25	2.17	
BL _{fr3}	25.22 ± 0.46	1.04 ± 0.03	0.9982	1.93	1.86	
Release of Lignin						
BL ₀	35.70 ± 2.60	1.00 ± 0.17	0.9909	1.40	1	
BL _{fr1}	47.32 ± 1.27	0.43 ± 0.04	0.9970	1.14	0.81	
BL _{fr2}	12.44 ± 0.66	1.17 ± 0.05	0.9946	3.27	2.34	
release of bromacil						
zero-order model: $M_t/M_\infty = k_1t + c$						
after 60%	$k_1 \pm \text{SE} (\text{day}^{-1})$	$c \pm \text{SE}$	r^b	$T_{100} (\text{days})^e$		
BL _{fr1}	1.67 ± 0.34	54.60 ± 2.55	0.9827	27.25		

^a The release data used for fitting the generalized model was not more than 60% ($\leq 60\%$). ^b Correlation coefficient. ^c The time required for 50% release of bromacil. ^d The ratio of T_{50} values of various lignin-based granules to that of Alcell lignin-based granules. ^e The time required for 100% release of bromacil.

polydispersity, the values of n for Fickian and case II transport are lowered to 0.30 and 0.45, respectively (Ritger & Peppas, 1987; Shukla et al., 1993). The values of k , n , and the correlation coefficient are summarized in Table 4 (sequential solvent-extracted lignins) and Table 6 (solvent-mixture-precipitated lignins). The values of the release exponent (n) were greater than 1 for all of the matrix granules except BL_{fr1}, indicating that the mechanism of bromacil release was super-case II transport. Only a few controlled-release systems have been reported to have release mechanisms of super-case II transport, such as the release of 4-nitrophenol from starch-UF matrix granules (Shukla et al., 1993), acetylsalicylic acid, sulfadiazine and indomethacin from

chitosonium malate matrix tablets (Akbuga, 1993), piroxicam from chitosan beads (Sezer & Akbuga, 1995), diclofenac sodium from encapsulated natural gum mini-matrixes including excipient (Sujja-areevath et al., 1996), and salmon calcitonin (sCT) from natural oligosaccharide gum-based tablets (Alur et al., 1999). The specific release mechanism was interpreted by the combination of the movement of the gel-glassy interface and the dissolution of penetrant into a glassy core (Shukla et al., 1993), or the combination of solute diffusion and polymer relaxation/dissolution (Alur et al., 1999), or the dissolution or erosion of the excipient (Sujja-areevath et al., 1996). Basically, the results were all related to the swelling and relaxation of long-chain

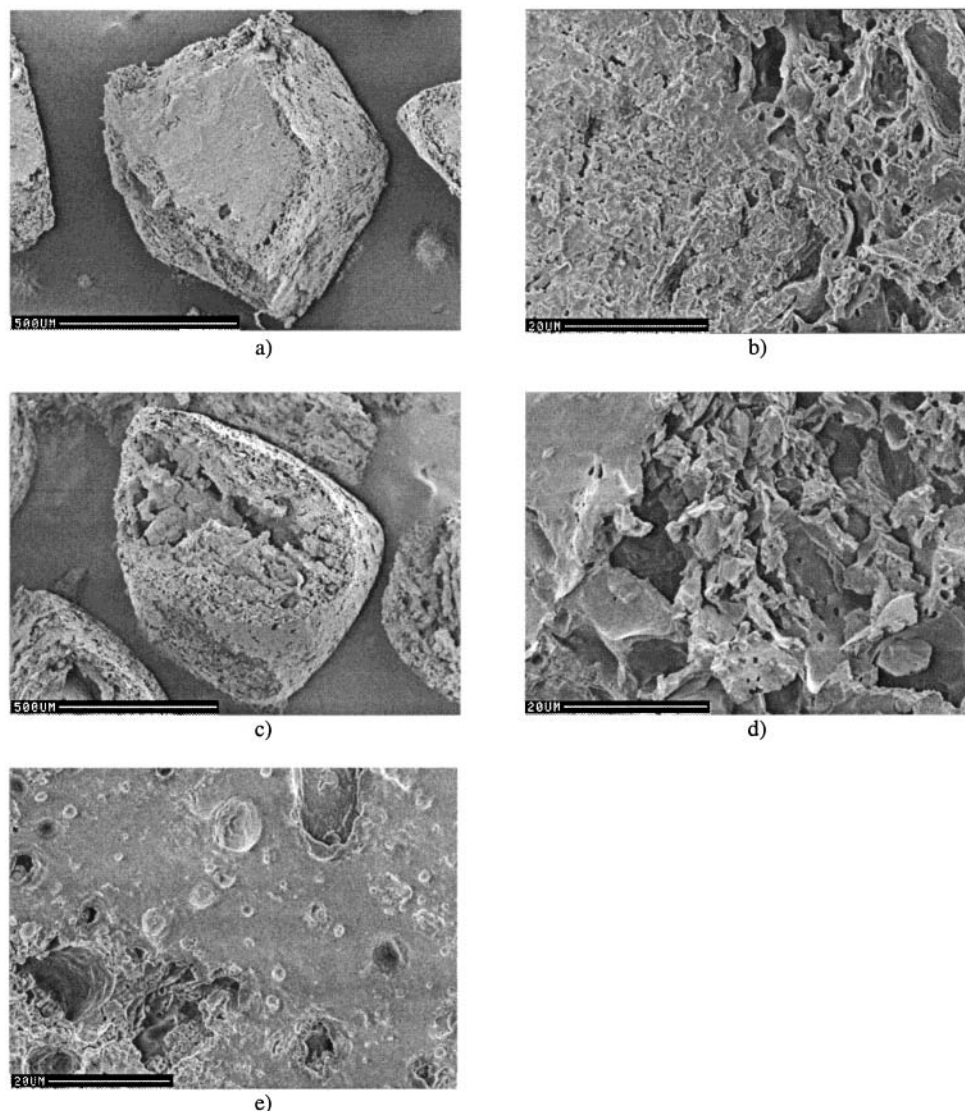


Figure 6. Scanning electron micrographs of cross sections of a BL_{fr1} granule after the release of bromacil: (a) 40% release of bromacil; (b) the close-up of the boundary layer between the swelling section and nonswelling section in part a; (c) 70% release of bromacil; (d) the close-up of the porous structure in part c; (e) the close-up of the surface of granule after 70% release of bromacil.

polymers, which could possibly correlate to water intake and osmotic effect (Shukla et al., 1993; Alur et al., 1999). However, these processes described in the foregoing are rapid and completed on the order of hours. In the case of the super-case II release observed with the lignin matrixes, the processes are much slower (over several days), and clearly, alternative mechanisms need to be sought. The lignin matrix, which shows minimal increase in volume with water uptake, retains its rigid structure through to complete loss of all releasable materials. Lignin, a macromolecule with a random structure and globular shape, lacks long chains which can change conformation in the uptake of water by the matrix.

For the case of the matrix granules based on fractionated lignins in this study, the release mechanism of super-case II might imply that the release of bromacil is governed by diffusion of pesticide and water-soluble lignin combined with some sort of fine structure change. The release could be related to the swelling and osmotic effect of the polymeric matrixes due to solutes, bromacil, and water-soluble lignin, present (Shukla et al., 1993) although offset by the high molecular mass of the soluble lignin. As the bromacil content was almost the

same for all matrix granules, the variation in water-soluble lignin content of the fractionated lignins would be responsible for any osmotic effect differences. Therefore, water-soluble lignin plays an important role in controlling the release of bromacil. The Alcell lignin-based matrix granules are hydrophobic in nature due to the high hydrophobicity of the lignin used as a carrier. Water uptake was substantially lower for these matrixes than that for alkali lignin-based matrix granules (Cotterill et al., 1996). The variation in osmotic effect and hydrophobicity of lignin could also account for the depression in bromacil release at the initial stage, where the greatest depression of release was observed for BL_{HAc} based on the lignin with the lowest water-soluble lignin content. The depression of bromacil release at the initial stage probably resulted from the time required to imbibe water into the matrix granules (Narisawa et al., 1997). With the removal of water-soluble lignin from Alcell lignin, the water uptake would be further reduced. For example, water uptake was 0.13 g/g for BL_{meth} (water-soluble lignin content 5.5%) compared to 0.22 g/g for BL_{HCl} (water-soluble lignin content (8.1%) after a 1.4-day hydration (experimental details not shown)). The hydrophilic water-soluble lignin would promote the

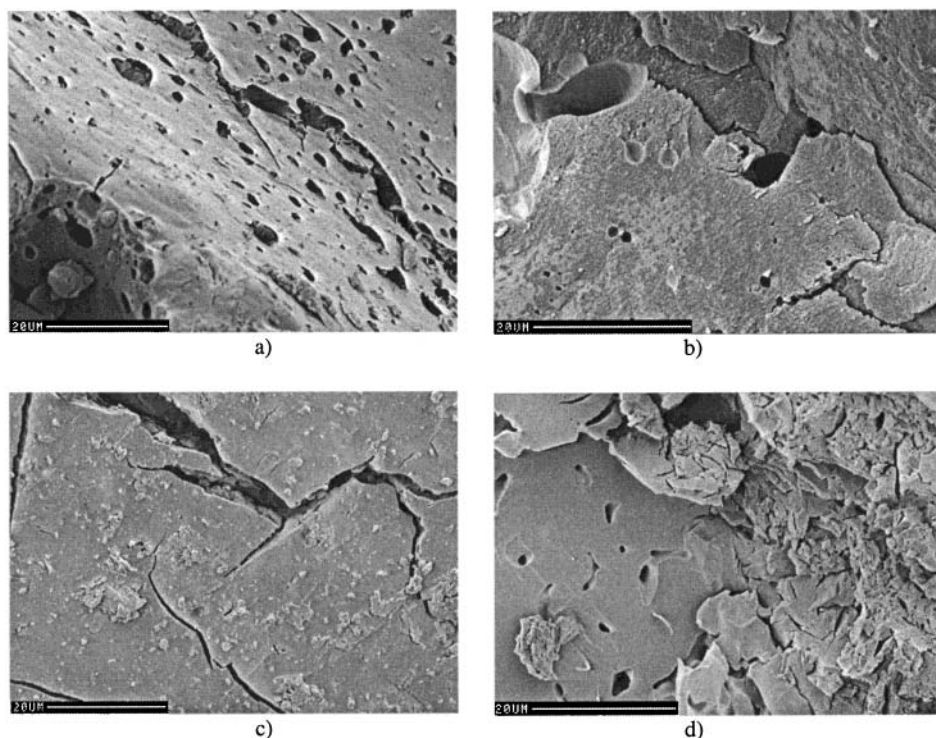


Figure 7. Scanning electron micrographs of the matrix granules after the release of bromacil: (a) the surface of a BL_0 granule after complete release of bromacil; (b) the cross section of a BL_0 granule after complete release of bromacil; (c) the surface of a BL_{fr3} granule after 90% release of bromacil; (d) the cross section of a BL_{fr3} granule after 90% release of bromacil.

ingress of water into the matrix, and its release would enhance the porosity and accelerate the pesticide diffusion. The swelling of the Alcell-based matrix is very limited (Cotterill et al., 1996). The increased porosity would result in a dramatic increase in water uptake and facilitate the diffusion of water into the glassy region, leading to much faster water diffusion into the glassy core compared to the movement of the gel–glass interface. In such a case, super-case II transport would occur at the early release stage (Shukla et al., 1993), implying that the release rate was increasing with time. Not surprisingly, the release rate constant (k) is the greatest for the matrix granules BL_0 based on the lignin with the greatest water-soluble lignin content (except for the matrix granules BL_{fr1}), whereas the k value was much reduced (4 times) for the granules BL_{HAc} based on the lignin L_{HAc} with least water-soluble lignin content (Table 4). For the matrix granules based on the lignin with extremely low water-soluble lignin content such as BL_{fr3} , there is a shift toward case II transport, indicated by the decrease in the n value (Table 6). In this case, the super-case II could be attributed to a coupling effect of the slow water intake at the early stage followed by substantial increase of porosity and water intake caused by the fast dissolution/diffusion of bromacil through glassy region. Therefore, the release of bromacil from most of the matrix granules based on solution-fractionated lignins could possibly be governed by the combination of diffusion of bromacil and water-soluble lignin and lignin relaxation/dissolution.

However, the matrix granules BL_{fr1} based on the low-molecular-weight fraction L_{fr1} has a bromacil release mechanism of Fickian diffusion. The shift of the mechanism from super-case II transport to Fickian diffusion is likely due to the marked difference in the hydrophobicity and water-soluble lignin contents. The hydrophobicity of the matrix could be increased considerably due

to the high water-soluble lignin content ($\sim 40\%$) of the lignin L_{fr1} , resulting in sufficient water intake which would facilitate the advance of the gel–glassy interface in the low-molecular-weight lignin matrix. The ease of hydration and swelling would allow free diffusion of bromacil from the matrix, leading to a Fickian diffusion as the mechanism controlling the release from the matrix granules BL_{fr1} based on low-molecular-weight lignin fraction L_{fr1} .

Fine Structure of the Matrix Granules Based on the Sequential Solvent-Extracted Lignins. It has been reported that various alkali lignin-based matrixes undergo swelling in contact with water and form a porous structure (Cotterill et al., 1996). The bromacil–lignin matrix granules based on the organosolv lignin and its fractionated products also showed swelling in contact with water. As illustrated in Figure 6a, for the matrix based on the ether-soluble fraction (L_{fr1}), with a relatively high content of water-soluble lignin, a swollen region appeared (in the cross section) with a porous structure on the outer part of the granule after 48-hour immersion (40% release) in water. The pore size is much greater in the spongelike structure than in the non-swollen region (right part of the close-up in comparison with the left in Figure 6b). A cavity with lumps of matrix within a porous structure as an outer shell formed by the time that 70% of the bromacil was released (Figure 6 c,d). With this matrix granule, early release of bromacil was rapid followed by very slow zero-order release. This may be explained by early dissolution from the surface (which generated a “skin”), and then later release was slowed by the presence of the outer layer. The permeability of the surface layer (as seen at 70% release; Figure 6 e) could be reduced as the soluble lignin and bromacil was rapidly released, possibly due to a change in surface pore structure. Therefore, the distinct difference in the fine structure for BL_{fr1} matrix

could give rise to the unique release profile compared to that of the other matrixes. The evidence for this assumption is that the release follows zero-order kinetics with a very high goodness of fit at the late stage of release (>60%) similar to a microcapsule (Table 6).

For the BL₀ and BL_{fr3} matrixes, either pores or cracks were formed throughout the matrixes during the release (Figure 7). Extensive pores can be seen on the surface, and exposed in cracks, of the BL₀ granules (Figure 7a), whereas the BL_{fr3} granules (Figure 7c) showed no pores at all. The BL₀ granule developed many pores which retained sharp edges even after complete release (Figure 7a), and the granules were hard and still brittle to an extent compared to the friable BL_{fr1} granules. The BL₀ granule, being fairly hydrophobic, delayed water uptake, but when this occurred, generated pores from the release of the water-soluble lignin and bromacil (at complete release; Figure 7a). However, an extensive pore structure was not seen in the cross section (after complete release; Figure 7b). Instead, a system of fractures was observed which may be responsible for the acceleration of release after the initial period when the release of bromacil (Figure 1) and soluble lignin (Figure 4) were delayed.

Matrixes based upon L_{fr3}, the high-molecular-weight fraction (M_w 6950) also showed surface cracks and no pores (Figure 7c) following 90% release of bromacil. The cross section of this matrix showed a broken structure, possibly as a result of the stresses produced on the interior as the bromacil (and very little soluble lignin) was released. This fracturing may have contributed to acceleration of release at the middle stage, but later, the rate slowed (Figure 1).

The use of SEM for studying the structure of these CR systems has been valuable. The release curves for the BL_{fr1} can be explained on the basis of the cross-sectional images at various release points. However, the explanation for the unique super-case II release from the other matrixes based on the sequential solvent extraction lignins is not apparent in these photographs.

CONCLUSIONS

Two of the most common solution fractionation methods such as sequential solvent extraction and solvent-mixture-precipitation were demonstrated to modify an organosolv (Alcell) lignin. The original and fractionated lignins were used to formulate herbicide-lignin matrix granules with bromacil as a model compound using a melt process. The release of bromacil from a granular formulation can be manipulated by the solution fractionation of the Alcell with various solvent systems. This generated a series of matrixes which all showed increasing release with time (super-case II transport), probably related to the initial hydrophobicity. This is the first report of such release kinetics applied to pesticide delivery and to apply to formulations with such a slow rate. Although evaluated using *in vitro* conditions, these granules could be expected to show similar increasing kinetics in soil conditions, as granules or as seed treatments, but with a slower overall release.

Another contrasting unique release profile was obtained for the matrix granules based on the low-molecular-weight fraction (fr1). The heterogeneity of this low-molecular-weight lignin seems to play a very important role in altering the release rates of the active ingredient for the matrix granules. The results obtained in this study could provide useful information for

selecting suitable release profiles of herbicides from organosolv lignin-based matrix granules for practical soil application and minimizing the potential environmental hazard associated with pesticide application.

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