

Sorption of Brilliant Blue FCF in soils as affected by pH and ionic strength

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Abstract

Brilliant Blue FCF has been frequently used as a dye tracer to stain flow pathways in porous media. As an ionic organic molecule, the dye interacts in a complicated manner with the solid phase. For an adequate interpretation of stained flow pathways, the sorption characteristics of the dye need to be better understood. In this study, we investigate the suitability of Brilliant Blue FCF as a dye tracer in vadose zone hydrology. The objectives were to test the effect of aqueous solution chemistry on dye absorption spectra, and to evaluate the effect of ionic strength and type of cations on dye sorption to soils. Batch sorption studies were conducted with three different soils and different ionic strengths of the background solution. Ionic strength was adjusted with either CaCl_2 or KCl . Sorption isotherms conformed to the Langmuir model, with the sorption capacity ranging over one order of magnitude. Substantial sorption was found for the soil sample with the highest clay content and the lowest pH. Increasing ionic strength led to increased sorption of Brilliant Blue FCF. The type of background cation, Ca or K, did not influence sorption. In aqueous solution, the absorption spectrum of Brilliant Blue FCF is not sensitive to pH nor ionic strength. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Brilliant Blue FCF; dye tracers; absorption spectrum; Langmuir adsorption; electrolytes, pH

1. Introduction

Brilliant Blue FCF has been proposed as a suitable dye tracer to visualize flow pathways in the vadose zone. The dye is one of the two blue colorants

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certified in the US for use in foods, drugs, and cosmetics (Marmion, 1991). As food dye, it possesses relatively low toxicity to organisms, and Brilliant Blue FCF is therefore an attractive compound to use in environmental studies, particularly because many other dye tracers in use are considerably more toxic than food dyes (Flury and Flühler, 1994). The bright greenish blue hue makes Brilliant Blue FCF readily visible in most soil and rock materials found in the vadose zone, discriminating it from yellow and red food colorants which are often more difficult to see in soil materials. The high water solubility and the dominantly anionic properties due to three sulfonic acid groups render the dye relatively mobile in most soils. The combination of the three characteristics — toxicity, visibility, and mobility — make Brilliant Blue FCF an appealing tracer.

Indeed, Brilliant Blue FCF has often been used as a dye tracer in vadose zone hydrology. The dye has been applied to visualize flow patterns in laboratory columns (Koch and Flühler, 1994; Aeby et al., 1997) and in field experiments (Pickering et al., 1988; Steenhuis et al., 1990; Flury et al., 1994; Natsch et al., 1996; Gjettermann et al., 1997; Petersen et al., 1997; Baveye et al., 1998; Forrer et al., 1999; Perillo et al., 1999). The non-toxic characteristics make the dye also a good dye tracer for instructional purposes (Butters and Bandarayanake, 1993). It is fair to say that Brilliant Blue is currently the most prominent dye tracer used to visualize flow pathways in vadose zone hydrological studies.

Tracer characteristics of Brilliant Blue FCF have been reported in terms of toxicity (Flury and Flühler, 1994) and sorption properties (Flury and Flühler, 1995; Perillo et al., 1998; Fahrenhorst et al., 1999; Ketelsen and Meyer-Windel, 1999). The sorption studies indicate that the dye can sorb considerably to soil materials. Sorption could be described by Freundlich isotherms at low concentrations in the range of 0.1 to 15 mg l⁻¹ (Flury and Flühler, 1995; Perillo et al., 1998) and by Langmuir isotherms at high concentrations in the range of 100 to 5000 mg l⁻¹ (Ketelsen and Meyer-Windel, 1999). The finding that sorption follows a Langmuir isotherm at concentrations typically used in tracer experiments indicates that sorption sites can fill up during the course of an experiment, which results in a time dependence of the sorption characteristics.

Sorption of Brilliant Blue FCF has been found to be positively correlated with clay content, but negatively correlated with organic carbon content (Ketelsen and Meyer-Windel, 1999). The pH is likely to play an important role in sorption due to the protonation and deprotonation of the dye's sulfonic acid groups; but pH in soils is usually not independent of other soil properties such as clay content, and has therefore not been unequivocally identified as a controlling factor in dye sorption (Ketelsen and Meyer-Windel, 1999).

The molecular properties of Brilliant Blue FCF as a charged organic molecule that consists of polar and non-polar portions call for a complex sorption process. The ionic properties should make the molecule's sorption susceptible to ionic strength, whereas the non-polar properties would call for preferential sorption to organic matter. Sorption studies indicate that hydrophobic interactions are much

less important than electrostatic or sorbate–mineral surface interactions (Flury and Flühler, 1995; Perillo et al., 1998; Ketelsen and Meyer-Windel, 1999).

The purpose of this study was to evaluate the suitability of Brilliant Blue FCF as a dye tracer for vadose zone hydrological studies. Specifically we (1) tested the effect of solution chemistry on dye absorption spectra in aqueous solution, (2) tested the effect of ionic strength and type of cations on dye sorption characteristics to soil, and (3) compiled and reviewed existing soil sorption data.

2. Materials and methods

2.1. Chemicals and equipment

Brilliant Blue FCF (C.I. 42090, C.I. Food Blue 2, FD & C Blue No. 1) was obtained in food grade quality from Warner-Jenkinson, St. Louis, MO. The purity of the dye used was > 90% on a weight basis according to the manufacturer. Because the exact level of purity is not known, dye concentrations have not been corrected for impurities. Properties of the dye are given in Marmion (1991) and Flury and Flühler (1995). Of relevance for this study are the relatively high water solubility of 200 g l^{-1} (at 2°C to 60°C), the low octanol water partition coefficient of $K_{ow} < 10^{-4}$, and dissociation constants pK_a of 5.83 for AH_2^0 and 6.58 for AH^- , where A^{2-} represents the completely dissociated molecule. The third dissociation constant is not known to the authors. Other chemicals used were obtained in analytical grade from standard suppliers.

Dye spectra and concentrations were measured in a quartz cuvette with a Hewlett Packard 8452A diode array spectrophotometer. All spectra were measured in solutions containing 8 mg l^{-1} (0.01 mM) Brilliant Blue FCF. Concentrations were determined at the dye's absorption maximum of 630-nm wavelength. All experiments were conducted in a temperature-controlled room at 20°C .

2.2. Absorption spectra

Absorption spectra of Brilliant Blue FCF in aqueous solution were measured as a function of pH, ionic strength, and type of background ions. For the pH study, dye was dissolved in bi-distilled water and the pH adjusted with HCl or NaOH. To test the effect of ionic strength and type of ions, dye solutions were prepared with different salts at the specified ionic strength, and the pH was adjusted to 7 with HCl or NaOH. The series of ionic strengths tested was 0, 10^{-5} , 10^{-4} , 10^{-3} , 10^{-2} , and 10^{-1} M for each of the salts CaCl_2 , MgCl_2 , NaCl, KCl, NaBr, Na_2CO_3 , Na_2SO_4 , Na_2HPO_4 . Spectra were measured in a 1-cm wide cell immediately after preparing the solutions.

2.3. Soil properties

Three soils with different pH, texture, and mineralogy were selected for the sorption studies. A summary of selected soil properties is shown in Table 1. Soil samples were air-dried and passed through a 2-mm sieve. For textural analysis, soil samples were treated with NaOAc solution to remove carbonates, iron oxides were removed according to Holmgren (1967), and particle sizes were measured with sieving and light diffraction (Mastersizer S, Malvern Instruments, Southborough, MA). The mineralogy was determined with a petrographic microscope and X-ray diffraction analysis. The non-crystalline iron content of the soils was determined by removing extractable amorphous iron with ammonium oxalate, using the procedure recommended by McKeague and Day (1966); the concentration of the aliquot was measured by atomic absorption analysis (Varian 220 Flame Atomic Absorption Spectrometer).

2.4. Adsorption isotherms

For staining purposes in soils, Brilliant Blue FCF has to be applied in concentrations up to 5 g l^{-1} . The sorption characteristics to soil should therefore be evaluated over a similar range of concentrations. Batch studies were performed with dye concentrations of 0.1, 1, 10, 50, 100, 200, 500, 1000, 2000, and 3000 mg l^{-1} . The experiments were run with three different ionic strengths for both Ca and K background ions using solutions of 0.005, 0.01, and 0.1 M CaCl_2 and 0.015, 0.03, and 0.3 M KCl. These concentrations correspond to ionic strengths of $I = 0.015$, 0.03, and 0.3 M. These ionic strengths do not consider the salts initially present in the soil material. The pH of the solutions was adjusted to 7 prior to mixing with the soil.

Soil samples and solutions with specified dye concentrations and ionic strengths were mixed in a 250-ml Erlenmeyer flask. The flasks were capped with a rubber stopper and shaken on a orbit shaker for 24 h. Initial tests comparing 24 and 48 h shaking times showed little differences ($< 1\%$) in the amount of dye sorbed to soil, so 24 h were assumed to be sufficient to reach sorption equilibrium. Roy (1993) mentioned that often differences $< 5\%$ within a 24-h interval are considered sufficient to assume equilibrium, and with our 1% difference we are well within this threshold. After shaking, the solutions were transferred into plastic centrifuge tubes and centrifuged at 10,000 rpm for 15 min. An aliquot of the supernatant was then used to measure pH and dye concentrations. Prior to the spectrophotometrical measurement, the solutions were passed through a hydrophilic syringe filter ($0.45 \mu\text{m}$, mixed cellulose ester). Filtration did not affect concentration measurements. With each set of experiments, blank dye solutions without soil as well as soil solution without dye were processed through the described protocol. Three replicates were run

Table 1
Specifications of soils used in sorption studies

Origin	pH ^a	Organic carbon (g kg ⁻¹)	Fe content ^b (μg kg ⁻¹)	Soil texture ^c				Munsell color	Mineralogy
				Clay (%)	Silt (%)	Sand (%)	USDA class		
Ritzville, WA	8.0	4.22	0.898	5.3	60.6	34.1	silt loam	2.5Y 6/3; 4/3 moist	quartz, calcite, illite, kaolinite
Vantage, WA	7.1	3.51	1.68	1.8	2.5	95.7	sand	2.5Y 5/3; 3/3 moist	quartz, plagioclase, alkali feldspar, dense minerals, lithic fragments, opaque minerals, biotite
Elk River, ID	4.5	3.16	5.59	12.3	72.0	15.7	silt loam	7.5YR 6/6; 4/6 moist	quartz, iron hydroxides, smectite, hydroxy-interlayered smectite, kaolinite

^a0.01 M CaCl₂ in a 1:1 (w/w) soil-solution ratio.

^bAmorphous iron extracted with ammonium oxalate.

^cExpressed on dry soil weight basis; clay < 2 μm, silt 2–50 μm, sand 50 μm–2 mm.

for each soil-solution combination. Neither the soil nor the dye blanks showed significant changes in concentrations after shaking, therefore, correction for background absorbance or decrease of dye concentration was not necessary. The mass of dye adsorbed to the soil particles was inferred based on the decrease in dye solution concentrations using mass balance considerations.

The experiments were performed at two different solid to liquid ratios. At low dye concentrations (0.1 to 10 mg l⁻¹) we used 10 g of soil and 60 ml of dye solution. At high dye concentrations (50 to 3000 mg l⁻¹) we used 30 g of soil and 30 ml of dye solution. The solid to liquid ratio had to be adjusted for accurate measurement of concentration differences in the liquid phase before and after shaking (Roy, 1993). By increasing the solid to liquid ratio, the relative amount of dye adsorbed increases, so that concentration differences between beginning and end of the batch study were well above the measurement error.

To evaluate the possible effect of particle concentrations when running the batch studies at different solid to liquid ratios, the so-called solids concentration effect (Honeyman and Santschi, 1988; McKinley and Jenne, 1991), we measured adsorption isotherms for a series of solid to liquid ratios (30 g/30 ml, 20 g/30 ml, 10 g/30 ml, 10 g/60 ml). The ionic strength of the solutions was adjusted to $I = 0.3$ M with KCl.

2.5. Data analysis

The experimental isotherm data were analyzed with the Freundlich and Langmuir isotherm models. The Freundlich model can be written as

$$C_a = K_F C_l^{1/n} \quad (1)$$

where C_a (mg kg⁻¹) is the concentration of chemical adsorbed, C_l (mg l⁻¹) the concentration in the liquid phase, and K_F (l kg⁻¹) and $1/n$ (–) are constants. The Langmuir model is given as

$$C_a = \frac{bK_L C_l}{1 + K_L C_l} \quad (2)$$

where b (mg kg⁻¹) is the maximum amount of chemical that can be adsorbed per unit mass of adsorbent, and K_L (l kg⁻¹) is a constant relating to the affinity between sorbate and sorbent. The Freundlich and Langmuir isotherms were fitted in their linearized forms to the experimental data. For the Langmuir isotherm, we used the linearization (e.g., Sparks, 1995)

$$\frac{C_l}{C_a} = \frac{1}{K_L b} + \frac{1}{b} C_l \quad (3)$$

3. Results and discussion

3.1. Effect of pH, ionic strength, and type of ions on adsorption spectrum

The absorption characteristic of Brilliant Blue FCF is insensitive towards solution pH and ionic strength (Fig. 1). The transmission spectra are not affected over the wide range of pH and ionic strengths values used. Fig. 1b shows the results for CaCl_2 , which is representative for all other salt solutions used. Marmion (1991) reported that Brilliant Blue FCF shows “very slight fading after 1 week” in solutions of pH 5, 7, and 8, and “slight fading after 1 week” in solution of pH 3. This indicates that the spectrum will change over time, although no quantitative assessment of the fading has been given. Compared to Indigotine (FD and C Blue No. 2, C.I. 73015), the other of the two FD & C certified blue dyes, Brilliant Blue FCF shows considerably better fading characteristics (Marmion, 1991).

3.2. Sorption isotherms

The results of the particle-density study indicate no significant effect of particle concentrations on isotherms; changing the solution to liquid ratio did not produce any discontinuity in the isotherms (Fig. 2).

Fig. 3 shows the effect of the soil characteristics on Brilliant Blue FCF sorption. There are clear differences between the sorption of the dye to the three soils. The three soils have been selected to represent differences in texture, pH, and mineralogical composition. The sorption affinity of the dye appears to be positively correlated with the clay content of the soils; sorption increases in the following order: Vantage (1.8% clay), Ritzville (5.3% clay), and Elk River (12.3% clay). This finding is in accordance with results from Ketelsen and Meyer-Windel (1999), who reported a strong positive correlation between maximum sorption capacity in the Langmuir isotherm and clay contents of soils.

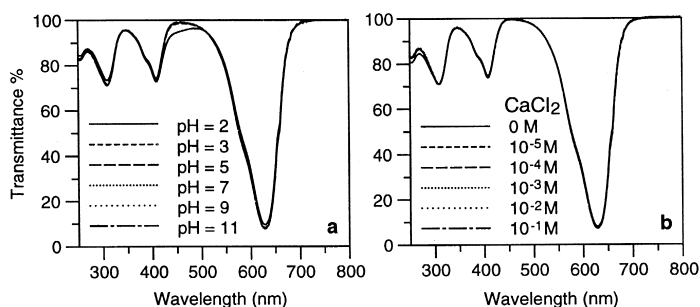


Fig. 1. Transmission spectra of Brilliant Blue FCF in aqueous solution for (a) different pH and (b) ionic strengths.

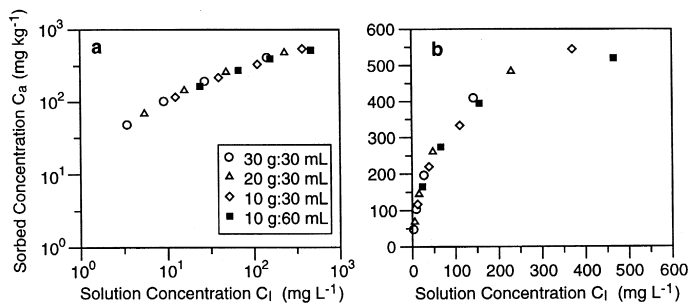


Fig. 2. Effect of solids concentration on sorption of Brilliant Blue FCF on Vantage soil. (a) Data in log–log scale, (b) data in linear–linear scale.

The mineralogy of the soils can also provide some explanation for the adsorption behavior of the three soils (Table 1). The Vantage soil mostly consists of primary minerals, whereas the Ritzville and Elk River soils contain clay minerals. The smectite composition of the Elk River soil might be responsible for the higher adsorption capacity than compared to the Ritzville soil, which has illite-type clay minerals.

The extractable iron content of the Elk River soil was about three times higher than that of the Vantage soil, and about six times higher than that of the Ritzville soil, which could be partially responsible for the differences in sorption capacities of the three soils.

The pH of the calcareous Ritzville soil is slightly alkaline, the Vantage soil has a typical neutral pH, and the Elk River soil is acidic, which is fairly common among soils that contain iron oxides (Table 1). The pH determines the degree of dissociation of the sulfonic acid groups and as such has direct influence on the net charge of the dye molecule. At the low pH of the Elk River soil, we expect the molecule to be predominantly in its neutral form, whereas in

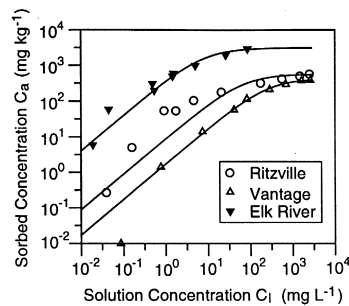


Fig. 3. Measured (symbols) and fitted Langmuir (lines) sorption isotherms of the three soils. The ionic strength in this example has been adjusted to $I = 0.015$ M with CaCl_2 . All standard deviations of measurements are smaller than symbols.

the other two soils, the dye occurs mainly in its anionic forms. Qualitatively, our data are consistent with the presumption of increased sorption at low pH, although pH and soil texture may often interfere in their effect on sorption (Ketelsen and Meyer-Windel, 1999).

The type of background cation, Ca versus K, did not affect sorption behavior of Brilliant Blue FCF on either of the soils. Fig. 4 shows representative results for the Ritzville soil for different ionic strengths. There is no evidence that sorption differs as a function of cation type, and the suggestion of ion-pair formation of the dye with Ca (Flury and Flühler, 1995) cannot be supported with our data.

It is anticipated that for ionic molecules that do not sorb primarily by an electrostatic mechanism, sorption increases when the ionic strength of the background solution increases. Our experimental data indeed show more sorption of Brilliant Blue FCF when the ionic strength becomes larger (Fig. 5). The effect of ionic strength appears to be more pronounced for the Ritzville and

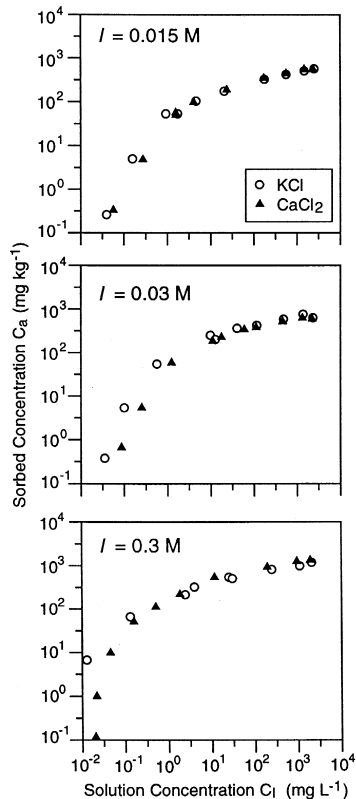


Fig. 4. Effect of ion type on sorption isotherm in Ritzville soil for different ionic strengths. All standard deviations of measurements are smaller than symbols.

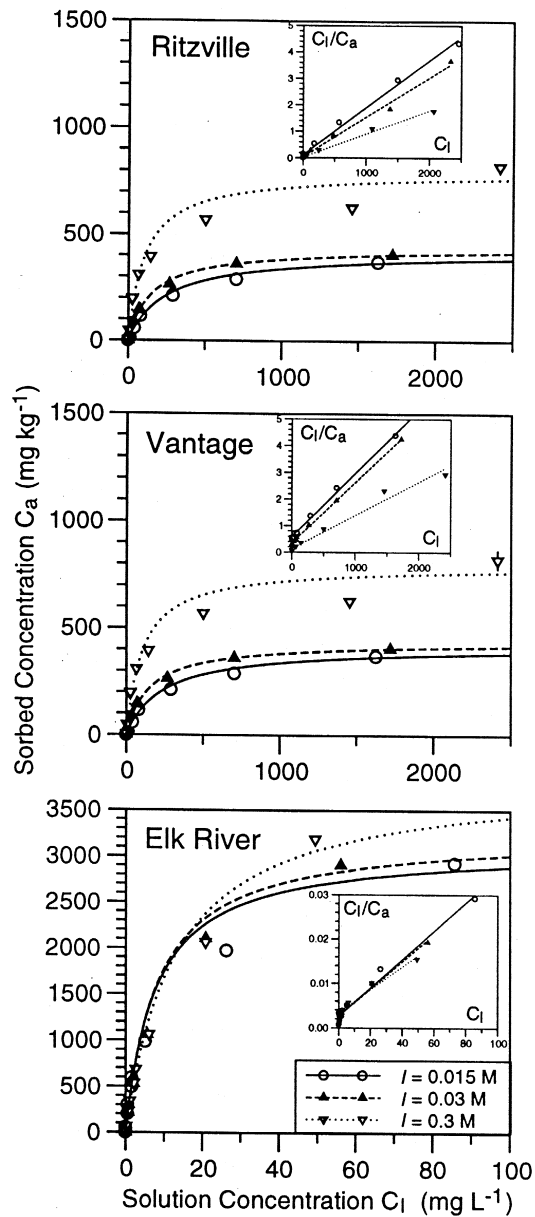


Fig. 5. Effect of ionic strength on sorption isotherm for the three soils. Measured (symbols) and fitted Langmuir (lines) isotherms. Ionic strength has been adjusted with CaCl_2 . Inserts show the linearized Langmuir isotherms used for the fitting. Standard deviations of measurements, when not shown in graphs, are smaller than symbols.

Vantage soils as compared to the Elk River soil. The ionic strength also affects the pH of the solution in the batch studies, with smaller pH for larger ionic

Table 2
Equilibrium pH of dye solutions at different ionic backgrounds

Soil	CaCl ₂			KCl		
	<i>I</i> = 0.015 M	<i>I</i> = 0.03 M	<i>I</i> = 0.3 M	<i>I</i> = 0.015 M	<i>I</i> = 0.03 M	<i>I</i> = 0.3 M
Ritzville, WA	8.0	7.8	7.4	8.1	8.1	7.9
Vantage, WA	7.1	7.1	6.8	7.1	6.9	6.6
Elk River, ID	4.5	4.3	4.2	4.4	4.3	3.8

strengths (Table 2). Considering the two pK_a -values of 5.83 and 6.58, the ionic-strength induced changes in pH are likely not a major factor in dye sorption.

The experimental data could reasonably well be analyzed with the Langmuir isotherm model. Fig. 5 shows the linear regression of Eq. 3 to the experimental measurements, and the corresponding non-linear Langmuir representation (Eq. 2). The coefficients of determination r^2 for the linear regressions were high ($r^2 > 0.97$), indicating that the Langmuir model was able to describe the experimental isotherms over the entire range of concentrations. The non-linear Freundlich isotherms (Eq. 1) did not produce good fits to the data, and results are therefore not shown.

Although the Langmuir model does not allow to infer any mechanisms of the sorption process, it provides some useful qualitative and quantitative measures for comparing the experimental scenarios. The Langmuir isotherms indicate that the soils have a limited capacity for sorption of Brilliant Blue FCF. The sorption capacity, represented by the parameter b , increases with ionic strength (Table 3). The increase in sorption capacity can be substantial: for Ritzville and Vantage soils, an increase of ionic strength from $I = 0.03$ to 0.3 M almost doubles the sorption capacity. Comparing the Langmuir parameters for CaCl₂ and KCl background ions confirms that the type of cation had no major effect on Brilliant Blue FCF sorption to our soils (values for KCl are not shown).

Table 3
Parameters of Langmuir isotherm. Ionic strength has been adjusted with CaCl₂

Ionic strength M	Ritzville		Vantage		Elk River	
	K_L (l kg ⁻¹)	b (mg kg ⁻¹)	K_L (l kg ⁻¹)	b (mg kg ⁻¹)	K_L (l kg ⁻¹)	b (mg kg ⁻¹)
0.015	0.0157	560.5	0.0041	420.7	0.1270	3115
0.03	0.0365	669.8	0.0065	439.9	0.1186	3268
0.3	0.0320	1144.2	0.0094	794.3	0.0760	3876

Coefficients of determination for linear regression of linearized Langmuir isotherm are in all cases $r^2 > 0.975$.

Table 4 summarizes literature data reported on Brilliant Blue sorption. At low liquid concentrations (0 to 15 mg l⁻¹), the sorption of Brilliant Blue FCF could be adequately described by a linear isotherm ($C_a = K_D C_1$), with the distribution coefficient K_D varying orders of magnitude for different soils. To compare the present study with results from Flury and Flühler (1995) and Perillo et al. (1998), we fitted the linear isotherm to our experimental data in the range of 0.1 to 15 mg l⁻¹. The Elk River soil stands out with a high K_D of 188.5 l kg⁻¹.

Table 4
Compilation of sorption coefficients for Brilliant Blue FCF

Soil	pH (0.01 M CaCl ₂)	Texture	Organic carbon (l kg ⁻¹)	K_D (l kg ⁻¹)	Langmuir K_L (l kg ⁻¹)	Langmuir b (mg kg ⁻¹)
<i>Flury and Flühler, 1995 (0.01 M CaCl₂; dye conc.: 1–5 mg l⁻¹)^a</i>						
Les Evouettes	5.7	silt loam	13.9	3.00	na ^b	na
Vetroz	7.1	silt loam	43.9	5.78	na	na
Lakeland	5.8	sand	4.3	0.19	na	na
<i>Perillo et al., 1998 (0.005 M CaCl₂; dye conc.: 0–15 mg l⁻¹)</i>						
Verndale Ap	5.3	sandy loam	12.4	4.34	na	na
Verndale Bt	5.4	sandy loam	5	23.95	na	na
Verndale C	5.7	sandy loam	0.2	4.59	na	na
<i>Germán-Heins and Flury, this study (0.01 M CaCl₂; dye conc.: 0.1–15 mg l⁻¹)</i>						
Ritzville	8.0	silt loam	0.898	24.36	na	na
Vantage	7.1	sand	1.68	2.46	na	na
Elk River	4.5	silt loam	5.59	188.5	na	na
<i>Ketelsen and Meyer-Windel, 1999^c (0.01 M CaCl₂; dye conc.: 100–5710 mg l⁻¹)</i>						
A2	6.5	silt loam	7.8	na	4.31	5690
D2	5.6	sand	8.9	na	1.42	220
F5	7.6	loam	1.4	na	4.71	8570
<i>Fahrenhorst et al., 1999^d (na M CaCl₂; dye conc.: 0–4400 mg l⁻¹)</i>						
F1-Ah1	3.3	clay	37	na	0.00083	5236
F1-B2	4.1	clay	5	na	0.00524	7752
<i>Germán-Heins and Flury, this study (0.01 M CaCl₂; dye conc.: 0.1–3000 mg l⁻¹)</i>						
Ritzville	8.0	silt loam	0.898	na	0.0365	670
Vantage	7.1	sand	1.68	na	0.0065	440
Elk River	4.5	silt loam	5.59	na	0.1186	3268

^aValues in parentheses indicate concentrations of background solutions and the concentration range of the dye in the liquid phase.

^bna: not available.

^cThree soils selected from 20 soils reported. The D2 and F5 soil samples represent extremes of b -values reported in Ketelsen and Meyer-Windel (1999).

^dParameters were determined from reported data in Fahrenhorst et al. (1999).

Extending the sorption experiments to larger concentrations (up to 5.7 g l^{-1}), the sorption isotherms become nonlinear, corresponding to Langmuir-type isotherms. The sorption capacity b of different soils can vary at least one order of magnitude. Based on a regression analysis with 20 soil samples, Ketelsen and Meyer-Windel (1999) found a positive correlation between sorption and the clay particle fraction. The data from other studies reported in Table 4 concur with this observation.

4. Conclusions

The strong non-linearity of the Langmuir isotherms has important implications for the use of Brilliant Blue FCF as a tracer in water and solute transport studies. When used for visualization purposes in most soils and sediments, Brilliant Blue FCF will have to be applied at concentrations in the order of a few grams per liter. During transport in the vadose zone, Brilliant Blue concentrations will be diluted, and as such dye concentrations will vary over many orders of magnitudes during a tracer study. The convex non-linearity of the sorption isotherm will lead to a self-sharpening tracer front in porous media (e.g., Bürgisser et al., 1993). This means that Brilliant Blue FCF fronts will likely be very sharp and produce a strong color contrast to the soil material.

Sorption of Brilliant Blue FCF to soil material increases with increasing ionic strength of the background solution. Since in tracer studies, the dye is often applied in combination with other tracers, such as Cl or Br salts, the ionic strength is an important factor to consider in such experiments. The simultaneous use of other ionic tracers will decrease Brilliant Blue FCF mobility. Since other ionic tracers travel with different mean velocity, leading to chromatographic separation of the tracers, the ionic strength of the background solution of Brilliant Blue FCF will change during the course of an experiment, thereby affecting the distribution coefficient of the dye between solid and liquid phases. Despite these disadvantages, we believe that, in terms of toxicity, visibility, and mobility, Brilliant Blue FCF may be one of the best compromises available to date as dye tracer for vadose zone hydrological studies.

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