LEACHING POTENTIAL OF NONSTEROIDAL ANTI-INFLAMMATORY DRUGS IN SOILS

JIAN XU,*†‡ LAOSHENG WU,‡ WEIPING CHEN,‡§ and ANDREW C. CHANG‡

†River, Estuarine and Coastal Environmental Research Center, Chinese Research Academy of Environmental Sciences, Beijing, 100012 China

‡Department of Environmental Sciences, University of California, Riverside, California 92521, USA

§State Key Laboratory of Urban and Regional Ecology, Chinese Academy of Sciences, Beijing, 100085 China

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Abstract—Nonsteroidal anti-inflammatory drugs (NSAIDs) in soils resulting from application of municipal wastewater or biosolids may migrate through soils intact or be transformed and reach groundwater. In the present study, the leaching potential of four NSAIDs (ibuprofen, naproxen, ketoprofen, and diclofenac sodium) in three U.S. cropland soils was evaluated, and the effect of CaCl_2 solution (as an index of salinity), dissolved organic matter (DOM), and polyacrylamide (PAM) amendment was investigated. The soils were spiked with selected NSAIDs, incubated for 24 h followed by 7-d storage in glass flasks, and then packed into stainless steel columns and leached with deionized water (DIW), 10 mM CaCl_2 , DOM (DOC 34 mg/L), and PAM solution (1.0 mg/L) by gravity. Initial concentrations of ibuprofen, naproxen, ketoprofen, and diclofenac sodium in the three packed soils were 1.93 to 2.07, 1.74 to 2.27, 1.79 to 2.16, and 1.99 to 2.13 mg/kg, respectively. Maximum concentrations of the above NSAIDs in column effluents were 1.23, 0.92, 0.69, and 1.12 mg/L, respectively, when the soil was leached with 10 pore volumes of water, which occupied 17.4, 11.1, 9.6, and 15.2% of the total chemicals in each soil column. Dissolved organic matter or PAM solution did not facilitate the NSAIDs release from soils. The CaCl_2 solution, however, reduced the amounts of NSAIDs leached from all three soils. Leaching of NSAIDs differed among the three tested soils. The results suggest that the leaching of NSAIDs through soil to water is significant, and the mobility of NSAIDs in soil is related to their chemicals' characteristics (such as pK_a values) and soil properties (such as soil organic matter and clay content). Amending soil with DOM or PAM does not significantly affect the leaching behavior of NSAIDs in soil, whereas increasing the salinity of the irrigation water may decrease the extent of contamination of groundwater posed by NSAIDs. Environ. Toxicol. Chem. 2010;29:800–807. © 2009 SETAC

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INTRODUCTION

Environmental fate and potential ecological harms of the active ingredients in pharmaceuticals and personal care products (PPCPs) have received much attention [1]. Among them, the nonsteroidal anti-inflammatory drugs (NSAIDs) with analgesic, antipyretic and anti-inflammatory effects are by far the most prescribed and used. Annually kilotons of NSAIDs are marketed in the United States. The unspent active ingredients and metabolic byproducts are excreted from the users' bodies ending up in municipal wastewater collection and treatment systems. Much of the expired products often is discarded and flushed down the sewers by consumers as well. Nonsteroidal anti-inflammatory drugs have been found in the water bodies downstream of the effluent outfalls and fields where biosolids were applied [2–9].

Soil modulates the flows of water, nutrients, and pollutants in and out of the terrestrial ecosystem. The biogeochemical cycling links the elements in the lithosphere and those in the biosphere. More importantly, soil is the habitat for the terrestrial biota, including humans. It is imperative that the potential of NSAID contamination of soils and groundwater be investigated especially where the reclaimed wastewater and biosolids are

applied [10–12]. Kinney et al. [13] reported that selected pharmaceutical ingredients persisted in soils irrigated with reclaimed wastewater for months (typical soil concentrations were ranging 0.02–15 $\mu\text{g/kg}$ dry soil). Nonsteroidal anti-inflammatory drugs, antibiotics, and other human pharmaceuticals and veterinary drugs were found in soils that had received biosolids [12,14], from which the fugitive chemicals may reach the groundwater. Analgesics, β -blockers, and antibiotics were found in groundwater at concentrations ranging from >10 to 1,100 ng/L [15]. Naproxen, an NSAID, was found in shallow groundwater below the fields where biosolids had been land applied [12]. To understand fully the environmental effects of pharmaceuticals in the soil, their leaching potential has to be investigated.

Dissolved organic matters (DOM) enhance the aqueous solubility of nonpolar organic pollutants, thus their mobility in the soil profile [16–19]. It is relevant to consider the role of DOM on soil profile transport of NSAIDs, because both reclaimed water and biosolids are sources of soil-borne organic carbon. Polyacrylamides (PAM) are water-soluble amendments used to reduce water repellence, enhance infiltration rates, and minimize surface runoff of irrigated soils [20]. They will probably further affect the leaching potential of the PPCPs and NSAIDs [20,21].

In the present study, laboratory experiments were conducted to investigate the leaching potential of four NSAIDs, namely, ibuprofen, naproxen, ketoprofen, and diclofenac sodium, in

* To whom correspondence may be addressed
(xujian@cras.org.cn).

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packed soil columns. Specifically, the present study investigated desorption kinetics of soil-borne NSAIDs, evaluated the extent of NSAIDs transport in soil profiles, and examined effects of salinity, DOM, and PAM application on NSAIDs mobility in soils.

MATERIALS AND METHODS

Chemicals and soils

The pharmaceutical ingredients used for the experiments (Table 1) were >98% free of purities. Dissolved organic matter stock solution was prepared by dissolving humic acids in deionized water to a concentration of 34 mg DOC/L, representing the average DOM level in the compost leachates [19]. The solution of 10 mM CaCl_2 was prepared to represent the salinity effects on the irrigated soils. This concentration is usually used to represent the salt level in irrigation water [22]. The granular anionic PAM, supplied by the Celanese Corporation, had an average molecular weight of 10 to 15 million Da/mol, with 21% NH_2 group substituted by OH group. The PAM stock solution was prepared by dissolving the chemical in deionized water to 1 mg/L, the typical amendment level of irrigation water. When organic solvents were needed, pesticide-grade acetone, ethyl acetate, and dichloromethane were used. Analytical-grade anhydrous sodium sulfate was desiccated at

400°C for 4 h. For chemical analyses, *N*-tert-butyldimethylsilyl-*N*-methyltrifluoroacetamide (MTBSTFA) was the derivatizing reagent.

Three soils, Arlington sandy loam (mixed, thermic haplic durixeralfs, ASL), Imperial silty clay (semectitic, calcareous, hyperthermic typic torrifluvents, ISC), and palouse silt loam (mixed, superactive, mesic pachic haploxerolls, PSL) were selected (Table 2). The sample soils representing the surface layer (0–20 cm) of the profile were mixed, air dried, and hand crushed to pass through a sieve with 2-mm openings.

Soil treatment

The soils were treated to contain 2 mg/kg of the targeted pharmaceutical ingredients in the following manner: 350 g aliquots of air-dried soils were placed in 500-ml conical flasks, spiked with target chemicals in ethyl acetate solution, and mixed. The solvents were evaporated at room temperature for 4 h in a darkened fume hood. The soils were then equilibrated with deionized water at 70% of the soil's water-holding capacity and incubated at 20°C for 24 h. Following incubation, soils were allowed to dry out in the fume hood for 7 d. Aliquots (5 g) of each treated soil were analyzed by the extraction method described by Xu et al. [23], and concentrations of ibuprofen, naproxen, ketoprofen and diclofenac sodium in the three treated

Table 1. Chemical structure, K_{OW} , and $\text{p}K_a$ of the selected compounds

Compounds	CAS No.	Structure	Log K_{OW} ^a	$\text{p}K_a$ ^a
Ibuprofen	15687-27-1		3.97	4.91
Naproxen	22204-53-1		3.18	4.15
Ketoprofen	22071-15-4		3.12	4.45
Diclofenac-Na	15307-79-6		4.51	4.15

^a Vieno et al. [37].

CAS = Chemical Abstracts Service.

Table 2. Textural and chemical properties of the three test soils

Soil	Sand (%)	Silt (%)	Clay (%)	Organic matter (%)	pH	Cation exchange capacity (cmol/kg)
Arlington sandy loam	71	17	13	1.9	7.1	13.2
Imperial silty clay	11	47	43	2.5	7.5	30.5
Palouse silt loam	32	50	18	5.5	5.9	25.1

soils were determined as 1.93 ± 0.08 to 2.07 ± 0.11 , 1.74 ± 0.07 to 2.27 ± 0.21 , 1.79 ± 0.21 to 2.16 ± 0.01 , and 1.99 ± 0.13 to 2.13 ± 0.14 mg/kg, respectively (see Table 3).

Desorption in batch experiment

In triplicate, 10-g aliquots of finished soils were each mixed with 8 ml of deionized water in a 50-ml Teflon[®] centrifuge tube, which was capped and shaken at 20°C for 24 h, and centrifuged at 6,708 g of centrifugal force for 15 min. The supernatant volume decanted (~5 ml) was accurately measured. The targeted chemicals were extracted from the aqueous supernatant with 5 ml of dichloromethane by equilibrating the mixture in a 15-ml septum-sealed headspace vial in a reciprocal mechanical shaker for 1 h and afterward the moisture in the dichloromethane fraction was removed over anhydrous Na₂SO₄. The target chemicals were then concentrated by subjecting the extracts to a gentle stream of N₂ gas, derivatized with MTBSTFA, and analyzed by gas chromatography-mass selective detector (GC-MSD).

For effects of salinity, dissolved organic carbon, and polyacrylamide on the desorption of NSAIDs, the treated soils were extracted with, instead of deionized water, the prepared CaCl₂, DOM, and PAM solutions respectively. The NSAIDs remaining in the extracted soils were determined according to the method described by Xu et al. [23]. Briefly, soil samples were sonicated with acetone/ethyl acetate solvents, followed by solid-phase extraction cleanup and derivatization with MTBSTFA, and analyzed by GC/MSD. The limits of quantification (LOQ) of the method were 0.2 µg/kg for ibuprofen, 0.4 µg/kg for naproxen and ketoprofen, and 1.2 µg/kg for diclofenac sodium. The recoveries of ibuprofen, naproxen, ketoprofen and diclofenac sodium from soils were 103.4, 110.7, 89.0, and 89.1%, respectively.

Column leaching experiment

Procedures described by Guo et al. [19] were modified for the experiments. The soil columns for NSAIDs leaching were prepared by packing the treated soils into 15-mm-i.d. × 120-mm stainless steel columns. Aliquots of 22 g of soils were packed in each column to a bulk density of 1.55, 1.42, and 1.33 g/cm³ and pore volumes of 6.0, 7.2, and 8.0 cm³, respectively, for ASL, PSL, and ISC. The bottom end of the column was sealed with an aluminum plate, through which a 1-mm-i.d. × 6-cm stainless steel needle was positioned at the center to collect leachates. The top end was covered by a screw cap that was fitted with an acrylic tube through which leaching solutions of deionized water, 10 mM CaCl₂, DOM, or PAM solution were applied. The column was saturated and gravity drained at the constant water head of 1 cm. Ten pore volumes of leachates were collected at the average of 6, 7.5, and 8.5 h per pore volume for ASL, PSL, and ISC columns, respectively.

Nonsteroidal anti-inflammatory drugs in the leachates were extracted and assayed according to the previously described analytical protocols. After the experiment, soils from the columns were air dried and the remaining NSAIDs were determined.

Instrumental and statistical method

Target chemicals were assayed with an Agilent 6890N GC coupled to a 5975C MSD. The GC was equipped with an Agilent 7683B automatic liquid sampler and an HP-5MS GC column (30 m, 0.25 mm i.d., 0.25 µm film thickness). Helium was used as the carrier gas in constant-flow mode of 1.2 ml/min. Two microliters of sample was injected in pulsed splitless mode. Injector temperature was 250°C. The GC-MSD interface and the ion source temperatures were set at 280°C and 230°C, respectively. The GC oven temperature was kept at 50°C for 1 min, followed by the first ramp at 20°C/min to 120°C, second ramp at 10°C/min to 280°C, and held for 11 min. For quantification, the mass spectrometer was operated in the selected ion monitoring (SIM) mode with electron impact ionization voltage of 70 eV.

The two-tailed *t* test was used to compare the average concentrations between samples in the present study. A *p* value in this *t* test of less than 0.05 means the difference is significant.

RESULTS AND DISCUSSION

Water release of NSAIDs in soils

When NSAIDs in the soils were extracted by deionized water, the equilibrium concentrations of the aqueous phase for ibuprofen, naproxen, ketoprofen, and diclofenac sodium were 1.02, 0.60, 0.46, and 0.92 mg/L, respectively, in ASL soil; 0.70, 0.26, 0.20, and 0.44 mg/L, respectively, in ISC soil; and 0.52, 0.18, 0.42, and 0.22 mg/L, respectively, in PSL soil. The NSAIDs detected in the aqueous phase depending on the soils accounted for 13 to 26% of ibuprofen, 4 to 13% of naproxen, 5 to 12% of ketoprofen, and 5 to 23% of diclofenac sodium of the total (Table 3).

The contents of NSAIDs in the CaCl₂ extracts showed no difference (*p* > 0.05) from those in the water extracts from the ASL and ISC soils, whereas, in the PSL soil, concentrations of NSAIDs in the CaCl₂ extracts were approximately half of those in the water extracts (Table 3). This suggested that higher salinity levels of the reclaimed wastewater would not enhance the leaching of NSAIDs in irrigated soils. The surface of soil materials is predominantly negatively charged in the normal soil pH range of 5 to 9. Selected NSAIDs in the present study are weak acidic pharmaceuticals, with *pK_a* values of 4.15 to 4.91. These chemicals may be partially deprotonated and be present in anionic forms in soil with pH values over 5.9. When ionic strength of the soil solution increases as the salinity of irrigation water rises, the resulting cations (i.e., Ca²⁺ in this case) will be

Table 3. Contents of nonsteroidal anti-inflammatory drugs (NSAIDs) released into water and remaining in soil (mg/kg soil)

Compound	Deionized water				CaCl ₂ solution				Dissolved organic matter solution				Polyacrylamide solution			
	Initial levels	Extract released ^a	Soil remaining ^b	Loss ^c	Extract released ^a	Soil remaining ^b	Loss ^c	Extract released ^a	Soil remaining ^b	Loss ^c	Extract released ^a	Soil remaining ^b	Extract released ^a	Soil remaining ^b	Loss ^c	Extract released ^a
Arlington sandy loam																
Ibuprofen	1.93(0.08)	0.51(0.04)	1.05(0.01)	0.37(0.13)	0.59(0.01)	0.91(0.02)	0.43(0.10)	0.50(0.05)	1.07(0.02)	0.36(0.15)	0.50(0.05)	1.15(0.01)	0.50(0.05)	1.15(0.01)	0.28(0.14)	0.50(0.05)
Naproxen	2.27(0.21)	0.30(0.03)	1.61(0.02)	0.37(0.26)	0.39(0.01)	1.53(0.03)	0.35(0.25)	0.31(0.02)	1.41(0.01)	0.55(0.24)	0.30(0.02)	1.63(0.02)	0.30(0.02)	1.63(0.02)	0.34(0.25)	0.30(0.02)
Ketoprofen	1.97(0.14)	0.23(0.03)	1.36(0.02)	0.39(0.19)	0.28(0.3)	1.46(0.04)	0.23(0.21)	0.23(0.03)	1.31(0.05)	0.43(0.22)	0.22(0.02)	1.32(0.02)	0.22(0.02)	1.32(0.02)	0.44(0.18)	0.22(0.02)
Diclofenac	2.01(0.06)	0.46(0.04)	0.90(0.04)	0.65(0.12)	0.45(0.03)	0.85(0.02)	0.70(0.10)	0.48(0.03)	1.08(0.03)	0.45(0.12)	0.45(0.05)	0.93(0.05)	0.45(0.05)	0.93(0.05)	0.63(0.15)	0.45(0.05)
Imperial silty clay																
Ibuprofen	2.07(0.11)	0.35(0.03)	1.29(0.02)	0.42(0.16)	0.36(0.03)	1.22(0.02)	0.49(0.16)	0.32(0.02)	1.41(0.01)	0.34(0.14)	0.33(0.02)	1.37(0.06)	0.33(0.02)	1.37(0.06)	0.37(0.19)	0.33(0.02)
Naproxen	1.74(0.07)	0.13(0.02)	1.37(0.02)	0.24(0.11)	0.13(0.02)	1.44(0.02)	0.16(0.11)	0.11(0.01)	1.52(0.03)	0.11(0.10)	0.11(0.01)	1.48(0.01)	0.11(0.01)	1.48(0.01)	0.15(0.08)	0.11(0.01)
Ketoprofen	2.16(0.01)	0.10(0.01)	1.79(0.03)	0.27(0.06)	0.10(0.02)	1.64(0.01)	0.42(0.04)	0.08(0.01)	1.75(0.04)	0.33(0.06)	0.08(0.01)	1.62(0.03)	0.08(0.01)	1.62(0.03)	0.46(0.05)	0.08(0.01)
Diclofenac	1.99(0.13)	0.22(0.01)	1.12(0.06)	0.64(0.20)	0.20(0.01)	1.10(0.01)	0.69(0.15)	0.19(0.01)	1.17(0.02)	0.63(0.15)	0.19(0.01)	1.10(0.03)	0.19(0.01)	1.10(0.03)	0.69(0.17)	0.19(0.01)
Palouse silt loam																
Ibuprofen	2.07(0.10)	0.26(0.02)	1.40(0.03)	0.40(0.15)	0.14(0.01)	1.53(0.03)	0.40(0.14)	0.25(0.01)	1.30(0.02)	0.51(0.13)	0.27(0.02)	1.47(0.04)	0.27(0.02)	1.47(0.04)	0.33(0.16)	0.27(0.02)
Naproxen	1.94(0.08)	0.09(0.01)	1.61(0.04)	0.24(0.13)	0.04(0.01)	1.75(0.05)	0.14(0.14)	0.09(0.01)	1.61(0.02)	0.24(0.10)	0.09(0.01)	1.56(0.01)	0.10(0.01)	1.56(0.01)	0.28(0.10)	0.10(0.01)
Ketoprofen	1.79(0.21)	0.21(0.01)	1.33(0.02)	0.25(0.24)	0.10(0.01)	1.49(0.01)	0.19(0.23)	0.20(0.01)	1.25(0.03)	0.34(0.25)	0.22(0.02)	1.41(0.01)	0.22(0.02)	1.41(0.01)	0.16(0.24)	0.22(0.02)
Diclofenac	2.13(0.14)	0.11(0.01)	1.37(0.04)	0.65(0.19)	0.05(0.01)	1.56(0.02)	0.52(0.16)	0.11(0.01)	1.28(0.04)	0.75(0.18)	0.11(0.01)	1.22(0.03)	0.11(0.01)	1.22(0.03)	0.79(0.17)	0.11(0.01)

^aThe portion of NSAIDs recovered in the extracts, on soil mass basis.^bThe content of NSAIDs remaining in soil after extraction.^cThe content of NSAIDs lost in the extraction process.

Data in parenthesis are standard deviations of triplicate measurements.

electrostatically attracted by the negative soil surfaces, thereby reducing the negative surface charge and increasing sorption of anionic organic compounds [24–26]. Lu et al. [22] found that an increase in salt level in the application solution greatly reduced the mobility of anionic polyacrylamide in soil. Williams et al. [27] also found that higher salinity in the soil could be the reason for some of the increased sorption of carbamazepine.

When DOM solution was used to extract the NSAIDs from the treated soils, measured concentrations of ibuprofen, naproxen, ketoprofen, and diclofenac sodium in the extracts did not show much difference ($p > 0.05$) compared with the water extracts (Table 3). The transport of organic contaminants in the soil matrix may be facilitated by cotransport with mobile colloids such as DOM [16–18]. The results of the present study showed that DOM did not further enhance the release of selected NSAIDs from the soils. The soil K_{OC} values of selected NSAIDs were low, from 100 to 400 cm³/g, and thus had relative low affinities with DOM constituents [19,28,29]. A similar trend was observed when the treated soils were extracted by the PAM solution. Polyacrylamide, being an anionic surface active reagent, is able to reduce the adsorption rates and amounts of anionic herbicides adsorbed by competing for the adsorption sites [21]. In this respect, the presence of PAM in the water should enhance the release of NSAIDs from the treated soils. However, the PAM-laced irrigation water did not cause greater release of the NSAIDs compared with simply water alone. Physically, PAM may stabilize the soil surface structure and pore continuity. When it is strongly adsorbed onto the surface of soil particles and forms a film on the soil surface, it may retard the release of chemicals from the inside soil particles [30]. The outcomes showing that amounts of NSAIDs extracted by the PAM-laced solution were not significantly different from those of the water extracts may simply be a result of the two processes cancelling out one another.

Leaching patterns of NSAIDs from soil columns

The leaching curves of four selected NSAIDs for the three incubated soils are shown in Figure 1. For the ASL soil columns, the highest concentrations of the four selected NSAIDs were found in the first pore volume of solution. Their concentrations dropped sharply in the second pore volume of solution and were negligible thereafter. The release potential under the four solutions was different. For the same NSAID compound, the concentrations in the first pore volume of effluents generally followed a descending order: DOM > DIW > PAM > CaCl₂. The leaching potentials of ibuprofen and diclofenac sodium with DOM and DIW solutions were quite close and greater than those under PAM solutions. For naproxen and ketoprofen, the leaching potentials with DIW and PAM solutions were similar but less than those with DOM solutions. In all cases, the leaching potentials of the four selected NSAIDs with CaCl₂ solution were far less than those with the other three solutions, indicating that the higher salinity of the reclaimed wastewater would retard the leaching of NSAIDs in irrigated soils.

The leaching patterns of the four selected NSAIDs in the PSL soil columns were quite different from those in the ASL soil columns. The concentrations of ibuprofen and naproxen peaked in the second pore volume of DIW, DOM, and PAM solutions and then gradually decreased and approached a

Fig. 1. Concentrations of nonsteroidal anti-inflammatory drugs in effluents from soil columns leached with deionized water (open circles), CaCl_2 (solid circles), dissolved organic matter (solid triangles), and polyacrylamide (open triangles) solution. Error bars represent standard deviations of triplicate measurements.

minimal plateau, whereas, with leaching with CaCl_2 , the highest concentrations of ibuprofen and naproxen were observed in the first pore volume of effluents. Under the four solutions, concentrations of ketoprofen decreased gradually with increased pore volume of solutions. The release of diclofenac sodium from PSL soil columns with DIW, DOM, and PAM solution was totally different from that of the other three NSAIDs. Concentrations of diclofenac sodium were kept at relatively high levels, with small fluctuations from the second to the fifth pore volumes, and then decreased slowly. Overall, the release potentials of the four selected NSAIDs with DIW, DOM, and PAM solutions did not show a significant difference ($p > 0.05$) but were greater than those under CaCl_2 solution.

Leaching of the four selected NSAIDs in the ISC soil columns followed a similar pattern; namely, concentrations

of the four selected NSAIDs in the pore volume of the four solutions gradually decreased. The leaching potential with the four solutions generally followed a decreasing order with $\text{PAM} > \text{DIW} > \text{DOM} > \text{CaCl}_2$. Compared with the leaching potentials in the ASL and PSL soil columns, there was much less difference of the leaching potential under the four solutions.

The different appearances of the leaching curves indicated that the release of NSAIDs from soil was significantly affected by the soil characteristics, such as soil organic matter content, clay content, anion exchange capacity, and microporosity. When incubated in soils, NSAIDs may be adsorbed on soil particles, entrapped in soil intra-aggregate micropores [31], and partitioned into soil organic matter and may form persistent residues. The ASL soil had low organic matter content. The sorbed compounds remained on the soil particle surface by

electrostatic interactions or entrapped in soil intra-aggregate micropores. Insofar as the preloaded NSAIDs in soil columns were not strongly associated with soil particles (predicted from their K_d values in the three soils [28,29]), the initial loading of solution leached out most readily desorbable NSAIDs from soil particles. That may be why the concentrations of NSAIDs sharply decreased after the first pore volume of leachate in ASL columns. The PSL soil had a higher OM content of 5.45% and thus a stronger retention of NSAIDs. Consequentially, there was a lag (i.e., one pore volume) between the movement of the water front and the dissolution of NSAIDs. This may be attributable to the release of the entrapped chemicals in soil micropores, because of a faster movement of water in interaggregate paths than in intraaggregate pores [32], and the slow dissolution from soil organic matter-associated NSAIDs. The kinetics of dissolution were not apparent from the outcomes of stationary extraction experiments, and the equilibrium concentrations of the NSAIDs in the three soil extracts were not significantly different. Unlike the case for ASL and PSL soils, concentrations of NSAIDs in effluents from ISC soil columns decreased gradually. Nonsteroidal anti-inflammatory drugs, for instance, ibuprofen, have been reported to be stronger adsorbed in the clayey soil [33]. Desorption of NSAIDs may be increased under better solution-particle contact conditions and longer solution-particle contact time. Because of the fine texture of ISC soil, it took a longer time to leach a pore volume solution from soil columns (~8.5 h in the present study). The extended contact time allowed the continuous release of NSAIDs from soil columns.

Leaching potential of NSAIDs from the soil columns

To evaluate further the leaching potential of the four selected NSAIDs, the cumulative amounts of NSAIDs leached in the 10 pore volumes of effluents were calculated. The cumulative ibuprofen amounts from the effluents in the 10 pore volumes of DIW, CaCl_2 , DOM, and PAM solutions, on the soil mass basis, were 0.35, 0.12, 0.39, and 0.20 mg/kg, respectively, accounting for 6 to 20% of the overall ibuprofen in the ASL soil columns. In the PSL soil columns, the cumulative leaching was 1.16, 0.55, 1.02, and 1.10 mg/kg, respectively, accounting for 27 to 56% of the overall ibuprofen. In the ISC soil columns, the cumulative leaching was 0.83, 0.38, 0.77, and 0.84 mg/kg, respectively, accounting for 18 to 41% of the overall ibuprofen. In each type of soil, the amount of ibuprofen leached by CaCl_2 was significantly ($p < 0.05$) lower than with the other three solutions. There was no significant difference ($p > 0.05$) between the amounts of ibuprofen leached by the DIW, DOM, and PAM solutions in most cases. These results are in agreement with those from the batch experiments in showing that DOM or PAM does not facilitate ibuprofen leaching and that CaCl_2 solution reduces the release of NSAIDs from soils.

The cumulatively leached amounts of naproxen in the 10 pore volumes of DIW, CaCl_2 , DOM, and PAM solution were 0.26, 0.053, 0.39, and 0.28 mg/kg in the ASL soil columns; 0.35, 0.07, 0.31, and 0.31 mg/kg in the PSL soil columns; and 0.18, 0.12, 0.19, and 0.19 mg/kg in the ISC soil columns, respectively. The amounts of leaching accounted for 2 to 17%, 4 to 18%, and 7 to 11%, respectively, of the overall naproxen in the ASL, PSL, and ISC soil columns. These figures were much lower than those for ibuprofen, indicating that the leaching

potential of naproxen was not as great as that of ibuprofen. Cumulatively, 0.21, 0.03, 0.28, and 0.17 mg/kg of ketoprofen was leached from ASL soil columns; 0.40, 0.15, 0.32, and 0.32 mg/kg from PSL soil columns; and 0.10, 0.06, 0.09, and 0.12 mg/kg from ISC soil columns, by 10 pore volumes of DIW, CaCl_2 , DOM, and PAM solution, respectively. They accounted for 2 to 22% of the total ketoprofen in soil columns. For the leached amounts of diclofenac sodium in the effluents from each soil column, cumulatively 0.41, 0.17, 0.46, and 0.27 mg/kg from ASL; 0.70, 0.24, 0.64, and 0.60 mg/kg from PSL; and 0.18, 0.12, 0.21, and 0.27 mg/kg from ISC were observed, which accounted for 6 to 33% of the total diclofenac sodium in soil columns.

The experimental results confirmed that DOM or PAM solution did not facilitate the leaching of NSAIDs from soils and illustrated that leaching of NSAIDs from soils could be significant, depending on the sorption tendency of these chemicals to soil particles. Conditions favoring the chemical's desorption, such as longer solution-particle contact time (e.g., Imperial silty clay soil in the present study), would increase the chemical's leaching. In addition, the soil dry-wet cycles in realistic fields may accelerate the decomposition of chemicals associated with organic matter, consequentially increasing the chemical release from soils [16,34]. In the deeper soil layers, the microbial activities are generally low, so these contaminants may persist in the aquifer over a longer time. Therefore, a long-term risk for groundwater contamination by NSAIDs in soils should be taken into account.

Dissipation of NSAIDs

Dissipation of NSAIDs through degradation or volatilization is an important factor affecting their transport in soils. The residual NSAIDs in the soils after column leaching with 10 pore volumes of solutions were analyzed. The amounts of NSAIDs lost during the experiment processes were then estimated by subtracting the amounts leached by solution and the amounts remaining in the soil columns from the initial loading. The results are summarized in Table 4. Degradation half-lives of test chemicals were obtained from our previous research [28,29].

During the water-leaching process, approximately 26, 31, and 34% of the overall ibuprofen was lost in the ASL, PSL, and ISC soil columns, respectively. Calculated with the first-order decay equation with a half-life of 7.2 d, the degradation in the experimental duration contributed to 21, 26, and 29% of the total loss of ibuprofen in the ASL, PSL, and ISC soil columns, respectively. Accordingly, approximately 23, 26, and 43% of the overall naproxen was lost in the three types of soil columns during the water-leaching process. Naproxen was reported to have comparable dissipation kinetics in soils that varied widely in properties, and the effects of soil mineral and organic matter content as well as pH on its dissipation rate in soils were quite limited [12]. Calculated with the half-life of 7.6 d, the degradation in the leaching processes contributed to 20, 25, and 28% of the total loss of naproxen in the ASL, PSL, and ISC soil columns, respectively. For ketoprofen, about 30, 36, and 36% was lost in the ASL, PSL, and ISC soil columns, respectively. By calculation with the first-order decay model with half-life of 8.0 d, approximately 20, 24, and 27% of total ketoprofen was lost during the leaching experiment by degradation. Approximately 35, 40, and 44% of total diclofenac sodium was lost

Table 4. Nonsteroidal anti-inflammatory drug (NSAID) residues in soils after column leaching experiments (mg/kg)

NSAIDs		Arlington sandy loam	Imperial silty clay	Palouse silt loam
Ibuprofen	Deionized water (DIW)	1.07 (0.13)	0.54 (0.36)	0.27 (0.13)
	CaCl ₂	1.30 (0.45)	0.94 (0.42)	0.86 (0.38)
	Dissolved organic matter (DOM)	1.03 (0.27)	0.59 (0.28)	0.41 (0.22)
	Polyacrylamide (PAM)	1.12 (0.28)	0.53 (0.16)	0.33 (0.15)
Naproxen	DIW	1.25 (0.33)	0.81 (0.24)	0.82 (0.14)
	CaCl ₂	1.66 (0.52)	1.04 (0.31)	1.29 (0.26)
	DOM	1.22 (0.10)	0.85 (0.16)	0.95 (0.50)
	PAM	1.30 (0.21)	0.82 (0.14)	0.92 (0.28)
Ketoprofen	DIW	1.17 (0.22)	1.28 (0.33)	0.76 (0.22)
	CaCl ₂	1.33 (0.43)	1.26 (0.34)	0.99 (0.13)
	DOM	1.10 (0.27)	1.29 (0.53)	0.84 (0.10)
	PAM	1.21 (0.39)	1.24 (0.47)	0.87 (0.35)
Diclofenac sodium	DIW	0.91 (0.31)	0.94 (0.22)	0.58 (0.23)
	CaCl ₂	1.14 (0.36)	0.99 (0.31)	1.03 (0.37)
	DOM	0.84 (0.11)	0.98 (0.36)	0.62 (0.33)
	PAM	1.03 (0.09)	0.83 (0.29)	0.66 (0.26)

Data in parenthesis are standard deviations of triplicate measurements.

during the water-leaching process in the three soil columns. From the calculation results by first-order decay model (with half-life of 5.0 d), approximately 29, 35, and 37% of the total diclofenac sodium was lost as a result of the degradation. It could be concluded that degradation during the leaching process was the main reason for the loss of selected NSAIDs in soil columns. Similar conclusions could also be reached for the other three leaching solutions (Table 4).

The above mass-balance calculation results revealed that there was a difference between the total NSAIDs loss and the loss from degradation, implying that some other removal processes may occur during the experiment. Selected NSAIDs have low Henry's law constants below 10^{-7} atm m³/mol [7], indicating their low potential to volatilize into air. This extra loss of NSAIDs may be due to the underestimation of degradation rates in the saturated soil columns. Half-lives of NSAIDs used in the present study were obtained by incubating the soil at room temperature at 70% field water-holding capacity. However, soils in the packed columns were always saturated with water, so greater quantities of chemicals were dissolved in the soil water of the saturated soil and were more bioavailable to microbial degradation. Increasing moisture has been found to increase the degradation of pesticides and other chemicals in soils [35,36]. In the calculations described above, we probably underestimated the degradation of NSAIDs in the soil columns.

Residual contents of NSAIDs in soils leached by DOM or PAM showed no significant difference ($p > 0.05$) compared with that in water-leached soils for most soil samples (Table 4), further strengthening the contention that DOM or PAM did not promote the release or the transport of NSAIDs in soil. It is noteworthy that the concentration of NSAIDs in CaCl₂-leached soils was obviously higher, indicating the weak ability of CaCl₂ solution to release NSAIDs from soils.

CONCLUSIONS

Investigation of the fate of pharmaceutical compounds in soils, especially leaching potential to contaminate groundwater, is essential to assessing their environmental risks. Experimental leaching results of NSAIDs in the present study clearly illustrate that the leaching patterns of these substances in soils varied

widely. It demonstrates that the leaching process of NSAIDs may last for a long time, depending on the amount of water passing through the soil profile. Dissolved organic matter has little influence on the mobility of NSAIDs in soil, and amendment with PAM also does not significantly influence the leaching. However, 10 mM CaCl₂ solution significantly reduced the leaching amount of NSAIDs from soils, suggesting that increasing the salt levels in the irrigation water may decrease the groundwater contamination risks posed by NSAIDs. To protect groundwater resources, leaching of NSAID residues should be taken into account.

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