

Elucidating the Fate of Organic Contaminants in Highly Basic Environments for Temperature Swing Solvent Extraction Desalination

Kinnari M. Shah, Julian van der Made, Kartik Chandran, and Ngai Yin Yip*



Cite This: *Environ. Sci. Technol.* 2025, 59, 23484–23496



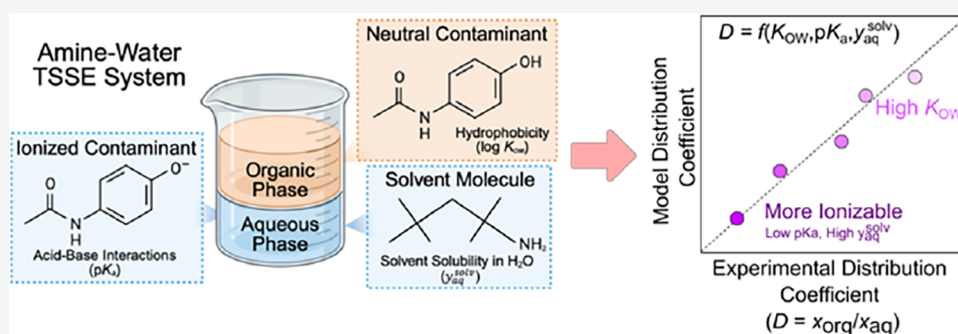
Read Online

ACCESS |

Metrics & More

Article Recommendations

Supporting Information



ABSTRACT: Temperature swing solvent extraction (TSSE) has been shown to effectively desalinate hypersaline brines. However, the fate of organic contaminants during TSSE remains poorly understood. This study elucidates the key physicochemical phenomena governing the equilibrium distribution of organic contaminants in biphasic solvent–aqueous systems relevant to TSSE. Distribution coefficients of organic analytes spanning roughly five orders of magnitude of hydrophobicity were systematically evaluated across five thermomorphic hydrophilicity amine solvents, at extraction and disengagement temperatures, and in hypersaline environments. While hydrophobicity has a principal role in governing distribution, acid–base interactions between the solvent and the contaminant were also found to be significant. Temperature typically has a minimal effect on conventional partitioning behavior but exerts a substantial influence in TSSE due to the thermal sensitivity of solvent solubility in water. Brine salinity does not uniformly affect distribution until the aqueous phases approach saturation, at which point the analytes are salted-out of the brine. A multiple linear regression analysis using K_{OW} , pK_a 's, and solvent solubility to model distribution achieved high accuracy ($R^2 = 0.93$), offering a practical framework for *a priori* determination of contaminant fate. These findings provide key mechanistic insights and design tools for TSSE solvent selection and process engineering.

KEYWORDS: distribution of organic contaminants, partitioning in basic environments, multiphase system behavior, temperature swing solvent extraction (TSSE), acid–base interactions, thermomorphic hydrophilicity amine solvents, hypersaline brines

INTRODUCTION

Hypersaline brines, with total dissolved solids of approximately >70,000 ppm, need to be properly treated and managed to prevent environmental damage.^{1–3} Oil and gas extractions, mining operations, textile manufacturing, leather tanning, inland desalination, thermoelectric power production, carbon dioxide storage, and landfills are prominent sources of these aqueous waste brines.^{1,4–8} When discharged into surface waters, the high salt contents and other contaminants present would damage ecosystems and pollute water sources.^{9,10} Desalinating these brines is a cost-effective and environmentally sustainable treatment option, reducing the liquid volume to enable efficient disposal and producing reusable water.^{1,4,11,12} However, the hypersalinity, high concentrations of mineral scalants, and presence of other foulants in the brines often pose insurmountable technical challenges to the

conventional desalination methods of reverse osmosis and thermal distillation.^{13–15} Temperature swing solvent extraction (TSSE) is an emerging technology for the desalination of hypersaline brines.^{16–20}

TSSE utilizes a solvent with thermally responsive hydrophilicity to extract water from the high-salinity feed stream. Salts, on the other hand, are largely rejected by the low-dielectric environment of the solvent. A moderate-temperature change stimulus triggers the solvent to switch from a

Received: July 15, 2025

Revised: October 7, 2025

Accepted: October 8, 2025

Published: October 23, 2025

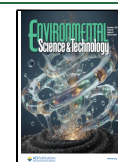


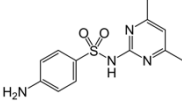
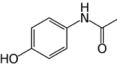
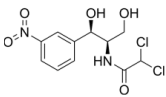
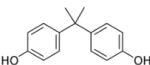


Table 1. Chemical Structures, Logarithms of Octanol–Water Partition Coefficients (K_{OW}), and Acid Dissociation Constants ($pK_{a,1}$ and $pK_{a,2}$) of Analytes Uracil, Caffeine, Sulfamethazine, Acetaminophen, Chloramphenicol, and Bisphenol A.^a

Compound (Abbreviation)	Chemical Structure	$\log K_{OW}$	$pK_{a,1}$ (25 / 70 °C) ⁴⁵	$pK_{a,2}$ (25 / 70 °C) ⁴⁵
Uracil (Ura.)		-1.07 ⁴⁶	9.23 / 8.57	13.38 / 12.20
Caffeine (Caff.)		-0.07 ²⁸	NA / NA	NA / NA
Sulfamethazine (Sulfa.)		0.28 ²⁸	6.99 / 6.64	NA / NA
Acetaminophen (Aceta.)		0.46 ⁴⁶	9.46 / 8.79	NA / NA
Chloramphenicol (Chlor.)		1.14 ²⁸	10.89 / 10.02	13.60 / 12.33
Bisphenol-A (BPA)		3.32 ⁴⁶	9.78 / 9.02	10.4 / 9.63

^a“NA” denotes “not applicable”.

hydrophilic state to a hydrophobic state. As a result, the solubility of water in the organic extract is lowered, driving water to disengage, and the demixed product water can be recovered. The solvent is simultaneously regenerated and recycled back into the process. TSSE is both membrane-less and nonevaporative, thereby avoiding the technical challenges that hamper conventional methods in brine desalination.¹⁸

Real hypersaline brines commonly have complex water chemistries. While inorganic salts constitute the majority of total dissolved solids, organic carbon compounds, heavy metals, oil and grease, particulates, and surfactants can also be present.¹ Organic contaminants are particularly relevant to produced waters from oil and gas operations, textile wastewater, coal-to-chemical wastewater, and landfill leachate.^{4,5,7,21} Concentrations of organics in real hypersaline brines often vary over several orders of magnitude, e.g., 10–1000 mg/L.^{8,22–24} At such non-negligible concentrations, these solutes have the potential to impact product water purity and taint the makeup of the recycled solvent stream. TSSE studies generally use single-electrolyte solutions (of sodium chloride) to simulate hypersaline streams. The few investigations that used actual field samples focused on proof-of-concept demonstration or inorganic ion transport.^{25–27} As such, there are significant gaps in our fundamental understanding of the fate of organic contaminants in the TSSE desalination of real brines.

Furthermore, while the distribution of neutral organic compounds in multiphase systems is well-studied,²⁸ the behavior of ionizable chemicals is poorly understood.^{29–31} In particular, fundamental studies investigating the distribution of organic contaminants in highly basic environments are lacking. Amines are good solvent candidates for TSSE because water solubility in the solvent is high and changes sharply with

temperature.^{32,33} However, amines are also very basic, often with pK_a 's > 10, and have significant solubility in water. Many organic compounds that typically remain neutral in octanol–water systems will ionize in the basic environment of the aqueous phases of TSSE. Elucidating the underlying mechanisms governing the distribution of organics within amine–water systems relevant to TSSE can also shed light on the role of acid–base interactions on the distribution of organic contaminants for many environmentally relevant systems, including sediments, soils, and wastewater sludges.^{29–31,34}

This study systematically investigates the distribution behaviors of organic analytes in amine solvent–aqueous systems across a parameter space relevant to TSSE desalination, with the overarching objective of contributing to a more complete framework for understanding partitioning equilibrium. Mole fractions of six model organic compounds, spanning almost five orders of magnitude in hydrophobicity, were carefully evaluated in equilibrated organic solvent and aqueous phases. Distribution coefficients are analyzed against key analyte physicochemical properties, and factors influencing the fate of organic contaminants are assessed. Evaluating different temperatures and a range of feed concentrations reveals how acid–base interactions impact the phase affinity of the analytes. Next, the effect of solvent on the analyte distribution is investigated using five amines with distinct molecular structures and thermophysical attributes. Differences in partitioning behavior between salt-free and saline environments are characterized, and the underlying salting-in and salting-out mechanisms are explored. Finally, implications of the study's findings for the desalination of real hypersaline brines using TSSE are discussed, and we consider the potential

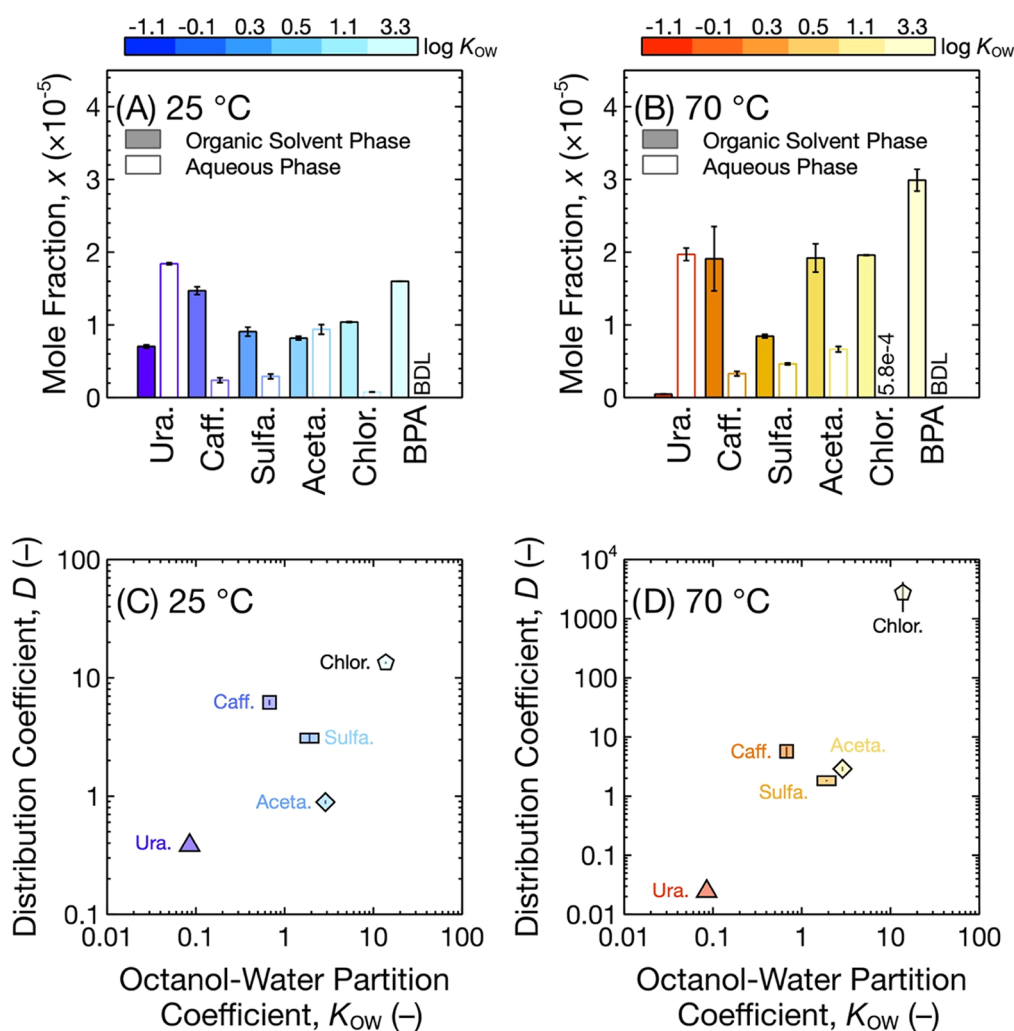


Figure 1. Equilibrium analyte mole fractions at (A) 25 and (B) 70 °C in the organic solvent and aqueous phases (filled and open columns, respectively). Analytes uracil, caffeine, sulfamethazine, acetaminophen, chloramphenicol, and bisphenol A are abbreviated as Ura., Caff., Sulfa., Aceta., Chlor., and BPA, respectively. Darker shades of blue (25 °C) and orange (70 °C) represent analytes with lower octanol–water partition coefficients, K_{OW} , as indicated by the color bar legends (with $\log K_{OW}$ labeled). Distribution coefficients, D (eq 1), as a function of analyte K_{OW} at (C) 25 °C and (D) 70 °C. Triangle, square, rectangle, diamond, and pentagon symbols denote uracil, caffeine, sulfamethazine, acetaminophen, and chloramphenicol, respectively. Note that both axes are on logarithmic scales and that the vertical axis scales are dissimilar. The 100 mg/L analyte aqueous feed solutions were equilibrated with equal weights of solvent *tert*-octylamine (TOA). Bisphenol A was not detectable in the aqueous phase of the mixtures at both temperatures and hence is not represented in plots (C and D); “BDL” denotes “below detection limit”. Data and error bars are means and standard errors of triplicate experiments.

broader impacts for understanding the distribution behavior of ionizable compounds in a wider range of systems.

MATERIALS AND METHODS

Materials and Chemicals. Solvents *tert*-octylamine (TOA, 95%), *N,N*-dimethylcyclohexylamine (DMCHA, 99%), *N*-ethylcyclohexylamine (ECHA, $\geq 99\%$), dipropylamine (DPA, 99%), and triethylamine (TEA, $\geq 99.5\%$) were used as received from MilliporeSigma (Burlington, MA). These solvents were chosen for their distinct chemical structures and properties, and all have been well-studied in the existing TSSE literature.^{18,35–39} Although diisopropylamine is commonly used in TSSE studies,^{18,36,37,39} the solvent is fully miscible with salt-free aqueous feeds at 25 °C and was, therefore, not evaluated here. The chemical and structural properties of the solvents are summarized in Table S1 of the Supporting Information.

Model analytes of uracil, caffeine, sulfamethazine, acetaminophen, chloramphenicol, and bisphenol A were chosen to span a wide range of octanol–water partition coefficients (Table 1). In addition, these organic analytes represent common environmental contaminants with well-defined characterization methodologies using high-performance liquid chromatography (HPLC).^{40–44} Aqueous analyte feeds containing uracil ($\geq 99\%$, Thermo Fisher Scientific, Waltham, MA), caffeine (USP standard grade, Thermo Fisher Scientific), or acetaminophen (USP standard grade, MilliporeSigma) were prepared by dissolving the solid organic chemical in deionized (DI) water obtained from an ultrapure water purification system (Milli-Q, Millipore, Billerica, MA). Stock solutions containing sulfamethazine ($\geq 99\%$, MilliporeSigma), chloramphenicol (97%, Thermo Fisher Scientific), or bisphenol A ($\geq 99\%$, MilliporeSigma) were prepared by dissolving the powdered organic compound in methanol (certified ACS grade, Thermo Fisher Scientific); appropriate quantities of

these stock solutions were gently evaporated in glass media bottles, and the remaining precipitates redissolved in DI water to produce the aqueous analyte feeds. The low volatilities and high boiling points (>150 °C) of the selected analytes ensured compatibility with this experimental procedure and the HPLC analysis. Dilute analyte feed concentrations between 10 and 1000 mg/L were prepared to simulate concentrations in real hypersaline brines and avoid formation of dimers and other associated species.³⁴ For experiments with saline feeds, i.e., background of inorganic salts, sodium chloride (NaCl, ACS reagent grade, Alfa Aesar, Haverhill, MA) was introduced into the analyte feed solutions. The chemical structures and properties of the organic analyte compounds are summarized in Table 1.

Characterization of Analyte Concentrations. Equal weights of aqueous analyte feed solutions and solvent were equilibrated in glass media bottles. The mixtures were continuously stirred at room temperature (≈ 20 °C) for 30 min, followed by a minimum of 45 min of settling in a temperature bath at 25 or 70 °C. The phases were carefully sampled using glass pipettes, and a known sample weight was gently evaporated to remove all water and solvent before redissolving the residual solid analyte in either pure water (uracil and acetaminophen) or a 40% w/w methanol aqueous solution (caffeine, sulfamethazine, chloramphenicol, and bisphenol A). For all analytes except caffeine, a 75 mM HCl solution was added dropwise to reduce the sample pH below the analyte $pK_{a,1}$, i.e., such that the predominant speciation of the analyte would be neutral (Table 1). Analyte concentrations of the resulting samples were characterized using reverse-phase high-performance liquid chromatography (HPLC, UltiMate 3000 with a diode array detector and an Acclaim Polar Advantage II HPLC column, Thermo Fisher Scientific; method details are given in the Supporting Information.) The HPLC methods (Table S2) utilized enable detection of aqueous analyte concentrations between 20 and 1000 mg/L with a high degree of accuracy (Table S3). Detailed descriptions of the methods used to characterize water, solvent, and sodium chloride concentrations in the biphasic mixtures are provided in the Supporting Information. Partitioning of the analytes between the organic and aqueous phases is quantified using parameters defined by the International Union of Pure and Applied Chemistry (IUPAC). Distribution coefficient, D , is the ratio of mole fractions, x , of the total analyte, i.e., all speciations, in the organic to aqueous phases:

$$D \equiv x_{\text{org}}^{i,\text{total}} / x_{\text{aq}}^{i,\text{total}} \quad (1)$$

Partition ratio, K , is defined as the ratio of mole fractions of the neutral species of the analyte in the organic to aqueous phases:

$$K \equiv x_{\text{org}}^{i,\text{neutral}} / x_{\text{aq}}^{i,\text{neutral}} \quad (2)$$

In both eqs 1 and 2, the superscripts denote the total or neutral concentration of analyte i , while subscripts org and aq indicate organic and aqueous phases, respectively.

RESULTS AND DISCUSSION

Distribution of Organic Analytes in Basic Systems Deviates from Conventional Behavior in Octanol–Water Mixtures. Six model analytes were thoughtfully chosen to span ≈ 4.5 orders of magnitude of octanol–water partition

coefficients, K_{OW} , the most common quantitative measure of hydrophobicity for organic compounds.²⁸ The analytes, in order of increasing hydrophobicity (i.e., increasing K_{OW}), are uracil, caffeine, sulfamethazine, acetaminophen, chloramphenicol, and bisphenol A (abbreviated as Ura., Caff., Sulfa., Aceta., Chlor., and BPA, respectively, Table 1). These model analytes are also common environmental contaminants in wastewaters.^{40–44} Equilibrium distributions of the analytes between 100 mg/L aqueous feed solutions and *tert*-octylamine (TOA) solvent are shown in Figure 1, with darker shades of blue (25 °C) and orange (70 °C) representing more hydrophilic analytes (log K_{OW} 's are labeled in the color bar legends). TOA was chosen as the solvent because it has demonstrated good performance for TSSE, particularly in minimizing solvent loss.⁴⁷ The investigated temperatures of 25 and 70 °C are representative of the extraction and disengagement steps of the TSSE, respectively. All analytes were present in measurable concentrations in both the organic solvent and aqueous phases of the mixtures except BPA, which was below detection limits (BDLs) in the aqueous phases at both temperatures (Figure 1A,B).

At both temperatures, uracil has the lowest mole fractions (x) and BPA has the highest x values in the organic solvent phases (filled columns, Figure 1A,B; Tables S4 and S5 of the Supporting Information). The trend is reversed in the aqueous phases, with uracil having the largest mole fractions and BPA having the smallest x values (open columns, Figure 1A,B). BPA almost entirely distributes into the solvent phase, likely due to the analyte being more hydrophobic (log $K_{\text{OW}} = 3.32$, Table S1) than TOA itself (log $K_{\text{OW}} = 2.58$).⁴⁸ Within these bookend K_{OW} values for uracil and BPA, however, the relationship between analyte hydrophobicity and mole concentrations in each phase is nonmonotonic. For example, at 25 °C, the mole fraction of caffeine in the organic solvent phase is greater than that in the aqueous phase, whereas the more hydrophobic acetaminophen (which is expected to distribute even more into the organic phase) has roughly equivalent concentrations in both phases.

K_{OW} is the most commonly used parameter to predict analyte distribution in environmentally relevant systems, e.g., sediments, soils, and wastewater sludges.²⁸ Hydrophobicity has been shown to be fairly indicative of the fate of analytes with log $K_{\text{OW}} > 3$ in biphasic mixtures of switchable solvent *N,N*-dimethylcyclohexylamine and water.⁴⁹ However, for the thermomorphic hydrophilicity of amines and the wide range of K_{OW} 's considered here, hydrophobicity alone is not able to fully account for the equilibrium trends. This can be readily visualized from the distribution coefficient, D (a ratio of total analyte mole fraction in the organic solvent to that in the aqueous phases, eq 1): although D generally increases with K_{OW} , the relationship is nonmonotonic, indicating that other physicochemical phenomena beyond hydrophilic–hydrophobic interactions are impacting distribution (Figure 1C,D). Note that D could not be determined for BPA as the aqueous phase analyte concentrations are below the detection limits. From the analysis in the next subsection, we put forth a cohesive explanation of the primary factors influencing distribution behavior in amine–water systems.

At 25 °C, the values of D span a range (0.383–13.4) similar to that of analyte K_{OW} 's (0.0851–13.8, excluding BPA), i.e., substituting the *n*-octanol organic solvent with *tert*-octylamine did not drastically alter the general trends in analyte distribution compared to the benchmark octanol–water

system. As the temperature increases to 70 °C, on the other hand, the range of D 's expands by three orders of magnitude to 0.0245–2730 while K_{OW} 's are considered to stay relatively constant.²⁸ Critically, the relationship between temperature and distribution is not uniform; D either increases, decreases, or remains constant with the temperature change. Mutual solubilities between TOA and water are highly temperature-sensitive. An increase from 25 to 70 °C, for example, results in a $\approx 50\%$ w/w decrease in TOA solubility in the aqueous phase (the change in the water content of the organic solvent phase is less dramatic).⁵⁰ Therefore, the solvation environments experienced by the analytes, e.g., polarity, change significantly within the organic and aqueous phases, yielding the observed dramatic changes in D . The specific mechanism by which temperature affects the analyte distribution behavior is further elucidated in a subsequent subsection. In addition, the analysis is further refined in another subsection for broader applicability across a range of solvents with different solubilities.

Distribution of Organic Analytes Is Principally Determined by Hydrophobicity and Acid–Base Interactions. As established in the preceding discussion, analyte distribution coefficients in the TOA–water system generally increase with the hydrophobicity of the organic compound, K_{OW} , with more hydrophobic solutes, by and large, preferentially distributing into the organic solvent phases of the biphasic TSSE mixtures. However, K_{OW} can only quantitatively explain approximately half of the variation in D (Table S6 of the Supporting Information). Thus, additional factors beyond hydrophobicity play an influential role in governing the distribution of organic compounds in the amine–water systems. TOA is a basic solvent with a $pK_{a,1}$ value of 10.7 (Table S1). In addition, significant amounts of TOA partition into the aqueous phases of the biphasic mixtures to yield considerably greater concentrations (≈ 9100 mg/L at 25 °C, Table S1) than the 100 mg/L analyte concentration of the initial feed solutions. As a result of the basicity and high relative solubility of TOA, the pH levels of the aqueous phases are driven by the partitioned amine and consistently >11.5 , above the pK_a 's of all investigated analytes except caffeine (Table 1). The organic analytes present in the aqueous phases will, hence, be predominantly deprotonated, i.e., conjugate bases, aside from caffeine, which will remain in its neutral form. More acidic organic compounds not specifically investigated in this study, e.g., containing carboxylic acid functional groups, will also deprotonate in these highly basic environments at the analyte concentrations considered. These acid–base interactions necessarily change analyte distribution behavior, as the activities (or chemical potentials) of each speciation of the compound, i.e., neutral or ionized, must be equivalent in both the organic solvent and aqueous phases at equilibrium.²⁸

The significant role of the analyte pK_a is validated by the t -statistics and p -value of a regression analysis, which reveals quantitative and qualitative relationships between D and the analyte properties of hydrophobicity, K_{OW} , and acid dissociation constants, $K_{a,1}$ and $K_{a,2}$ (Table 2, with coefficients and variables transformed into logarithmic space). The multiple linear regression yields $\log \hat{D} = 0.771 \log K_{OW} - 0.108 pK_{a,1} + 0.039 pK_{a,2} + 0.883$ (hat notation, $\hat{\Delta}$, signifies a modeled value). The coefficient (or, equivalently, the slope) of the K_{OW} variable is positive, indicating that D increases with hydrophobicity. This is consistent with the general understanding

Table 2. Coefficients of Multiple Linear Regression Analysis between Analyte Distribution Coefficient, D , in Biphasic *tert*-Octylamine–Water Mixtures at 25 °C and Analyte Properties of Octanol–Water Partition Coefficient, K_{OW} , and Acid Dissociation Constants, $K_{a,1}$ and $K_{a,2}$: $\log \hat{D} = 0.771 \log K_{OW} - 0.108 pK_{a,1} + 0.039 pK_{a,2} + 0.883$

parameter	slope	standard error	t -statistics	p -value ^a
$\log K_{OW}$	0.771	0.065	11.929	***
$pK_{a,1}$	−0.108	0.012	−8.955	***
$pK_{a,2}$	0.039	0.008	4.778	***
(intercept) ^b	0.883	0.067	13.250	***
multiple $R^2 = 0.932$; adjusted $R^2 = 0.917$				

^a***, **, and * indicate p -values <0.001 , 0.01 , and 0.05 , respectively.

^bVertical axis intercept of the regression equation.

that more hydrophobic compounds will prefer the lower-polarity organic solvent phase. Coefficients $K_{a,1}$ and $K_{a,2}$, on the other hand, serve to adjust D by reflecting the relative favorability of ionizable compounds to distribute into the aqueous phase, i.e., lowering D (Table S7). Deprotonated compounds are charged and, hence, will favor the higher relative permittivity of the aqueous phase over the low-dielectric constant environment of the organic solvent phase.^{36,51} Critically, even with simplistic linear fittings, hydrophobicity and acid–base interactions are sufficient to model D with a high degree of accuracy (adjusted $R^2 = 0.917$), providing convincing evidence that these analyte properties principally determine distribution in the investigated solvent–water system. The generalizability of this finding to other amine solvents with thermoresponsive hydrophilicity is examined in a later subsection.

The goodness of the regression fit is illustrated by the parity plot in Figure 2. Modeled distribution coefficients, \hat{D} , are plotted against the experimental values, with the dashed 45° line indicating perfect agreement between the model and experimental observation. In subsequent discussions, regression fits are primarily analyzed using parity plots, and regression tables are included in the Supporting Information. Despite differences in chemical structures and elemental compositions of the compounds (Table 1) and the relative simplicity of the multiple linear regression, \hat{D} values are well-predicted by the model for all of the organic analytes explored. Although D could not be calculated for BPA (concentration in the aqueous phase is below detection limits), the distribution coefficient should be greater than that of chloramphenicol, given that BPA concentrations are lower than chloramphenicol in the aqueous phases and higher than chloramphenicol in the organic phases. Indeed, the modeled \hat{D} values for BPA and chloramphenicol are 575 and 13.2, respectively, consistent with expectations. The regression model captures distribution behavior across a wide range of hydrophobicities and for both predominantly neutral (caffeine) and ionizable species. This versatility suggests that none of the evaluated organic analytes had any appreciable specific reactions with the solvent. Furthermore, the regression model is based solely on analyte physicochemical properties, thus offering a powerful tool for predicting the distribution behavior of a broad spectrum of organic contaminants in a TOA–water system. This analysis is expanded in the following subsections to provide a platform for *a priori* determination of D 's at different temperatures and for a range of solvents.

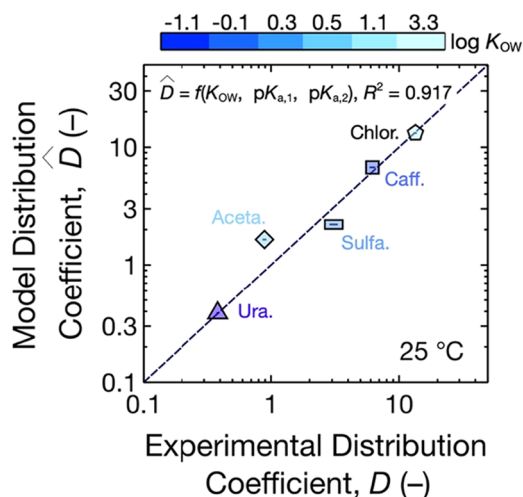


Figure 2. Parity plot comparing distribution coefficients, D , from experimental characterization and the regression model for organic analytes at 25 °C. The dashed 45° line signifies perfect agreement. Note that both horizontal and vertical axes are on logarithmic scales. Solvent *tert*-octylamine (TOA) was equilibrated with equal weights of aqueous feed solutions of 100 mg/L uracil, caffeine, sulfamethazine, acetaminophen, or chloramphenicol (triangle, square, rectangle, diamond, and pentagon, respectively). Darker shades of blue indicate analytes with lower octanol–water partition coefficients, K_{OW} , as denoted by the color bar legend (with $\log K_{OW}$ labeled). Bisphenol A was not detectable in the aqueous phase of the mixtures and is hence not represented in the plot. Data and error bars are means and standard errors, respectively, of triplicate experiments.

Shifts in Acid–Base Interactions due to Temperature Can Produce Drastic Changes in Distribution. Distribu-

tion of organic analytes in an octanol–water system is reported to be relatively insensitive to temperature over the environmentally relevant range ($\Delta K_{OW} < \approx 14\%$ between 5 and 45 °C).^{28,52–54} In the TOA–water system, however, D 's change for most of the compounds as the temperature increases from 25 to 70 °C, by as much as ≈ 2 orders of magnitude (Figure 3A and Table S8 of the Supporting Information). The large swings in D cannot be explained by the temperature dependence of K_{OW} alone. Further, while raising the temperature lowers pK_a consistently for the organic analytes (Table 1), the direction of the temperature effect on D is not uniform: the distribution coefficients of uracil and sulfamethazine decrease with increasing temperature, indicating that the analytes preferentially distribute into the aqueous phase, whereas the D 's of acetaminophen and chloramphenicol increase with temperature, i.e., elevated concentrations in the organic solvent phase. Caffeine is the sole organic analyte for which the D 's are statistically the same at both temperatures ($p > 0.05$). Critically, caffeine is also the only compound evaluated in this study that remains in its neutral form, i.e., does not ionize, in the TOA–water system.

Mutual solubilities of TOA and water are very sensitive to changes in temperature. TOA solubility in the aqueous phases decreases by $\approx 50\%$ w/w as the temperature increases from 25 to 70 °C.⁵⁰ Because less of the basic TOA solvent is mixed with water, the pH levels of the aqueous phases decline from ≈ 11.7 to ≈ 10.9 . As mentioned above, the pK_a 's of the organic analytes are lower at the elevated temperature (Table 1), which affects the ratio of ionized to neutral species for most analytes, thereby impacting distribution behavior. Because caffeine remains predominantly neutral at both temperatures, the compound is not impacted by the pH and pK_a changes. This is corroborated by the statistically indistinguishable distribution

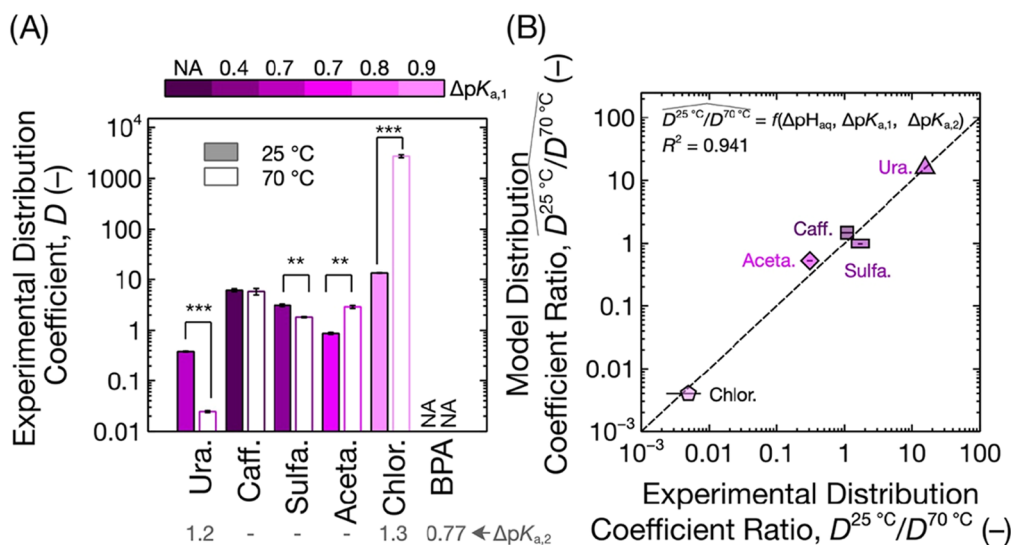


Figure 3. (A) Experimental distribution coefficients, D , at 25 and 70 °C (filled and open columns, respectively) in the TOA–water system for uracil, caffeine, sulfamethazine, acetaminophen, chloramphenicol, and bisphenol A. Lighter shades of violet represent analytes with greater changes in $pK_{a,1}$ between the low and high temperatures, as indicated by the color bar legend (with $\Delta pK_{a,1}$ labeled). Changes in $pK_{a,2}$ between the temperatures, where applicable, are indicated underneath the horizontal axis analyte labels. ***, **, and * designate p -values < 0.001 , 0.01 , and 0.05 , respectively. (B) Parity plot comparing the ratios of distribution coefficients at 25–70 °C, $D^{25\text{ °C}}/D^{70\text{ °C}}$ from experimental characterization and the regression model (the dashed 45° line signifies perfect agreement). Note that the axes for distribution coefficients and distribution coefficient ratios are on logarithmic scales. Aqueous feed solutions of 100 mg/L uracil, caffeine, sulfamethazine, acetaminophen, or chloramphenicol (triangle, square, rectangle, diamond, and pentagon, respectively) were equilibrated with equal weights of the solvent *tert*-octylamine (TOA). Bisphenol A was not detectable in the aqueous phase of the mixtures at either temperature, and hence, distribution coefficients could not be calculated (denoted “NA” for “not applicable”). For all plots in this figure, data and error bars are means and standard errors, respectively, of triplicate experiments.

coefficients at 25 and 70 °C; i.e., partitioning behavior of the analyte aligns with the widely established notion that distribution in an octanol–water system is insensitive to temperature. However, for the other investigated analytes, the temperature-driven changes in pK_a and aqueous phase pH have a substantial impact on distribution. Regression analysis reveals a significant relationship between the ratios of distribution coefficients at 25–70 °C, $D^{25\text{ °C}}/D^{70\text{ °C}}$, and the associated changes in aqueous phase pH levels, ΔpH_{aq} , and in organic analyte K_a 's, $\Delta pK_{a,1}$ and $\Delta pK_{a,2}$ (coefficients of the regression analysis are summarized in Table S9 of the Supporting Information). Importantly, parameters ΔpH_{aq} , $\Delta pK_{a,1}$, and $\Delta pK_{a,2}$ are sufficient to accurately model $D^{25\text{ °C}}/D^{70\text{ °C}}$ with the rudimentary multiple linear regression (Figure 3B), suggesting that the influence of temperature on acid–base interactions in the aqueous phases primarily determines changes in distribution behavior.

An alternative explanation for the temperature dependence of D may be that the trends are driven by changes in water contents of the organic solvent phase. However, on deeper analysis, we ruled out this possibility. As the temperature increases from 25 to 70 °C, the weight fraction of water in the TOA-rich phases, $y_{org}^{H_2O}$, decreases from 25.5 to 10.2% w/w; i.e., the organic solvent phase becomes more water-lean. The D 's of the more hydrophilic uracil and sulfamethazine decrease. On the other hand, the distribution coefficients of the more hydrophobic acetaminophen and chloramphenicol increase. If the change in water contents of the organic solvent phases, $\Delta y_{org}^{H_2O}$, is the principal factor underlying partitioning behavior on the basis of hydrophobicity, the value of D should also be expected to change for caffeine, which has a lower K_{OW} than sulfamethazine (i.e., less hydrophobic). Yet, caffeine distribution does not change between the low and high temperatures. Furthermore, the additional inclusion of parameters to capture the interaction between $\Delta y_{org}^{H_2O}$ and K_{OW} within the regression model did not yield statistically meaningful coefficients (results not shown). Thus, acid–base interactions in the organic phases and the sensitivity of the interactions to temperature are the principal factors governing the fate of organic contaminants.

Distribution Coefficient of Ionizable Compounds Increases with Concentration Because of Greater Deprotonation. Concentrations of organic contaminants in real hypersaline brines vary over several orders of magnitude.^{8,22–24} In octanol–water systems, the D 's (i.e., the K_{OW} 's) are relatively insensitive to changes in concentration so long as the solute remains present in dilute amounts; distribution behavior is concentration-dependent only when the solute content becomes sufficiently high that solute–solute interactions are no longer negligible (typically >0.1 mol/L).²⁸ To evaluate the potential influence of solute concentration on the partitioning behavior, distribution coefficients for aqueous feed solutions of 20, 100, 500, and 1000 mg/L analyte, i.e., dilute range (equivalent to 0.10 – 6.62×10^{-3} mol/L), were evaluated for acetaminophen and caffeine (Figure 4A,B, respectively). Despite acetaminophen concentrations being well in the dilute region, D monotonically increases with increasing feed concentrations (Figure 4A, with statistical significance indicated by asterisks, and Table S10 of the Supporting Information). In contrast, the D 's of caffeine remain statistically indistinguishable ($p > 0.05$, Table S10) across analyte feed concentrations of 100, 500, and 1000 mg/L (Figure 4B, left axis; p -value <0.05 between 20 and 100 mg/L is discussed

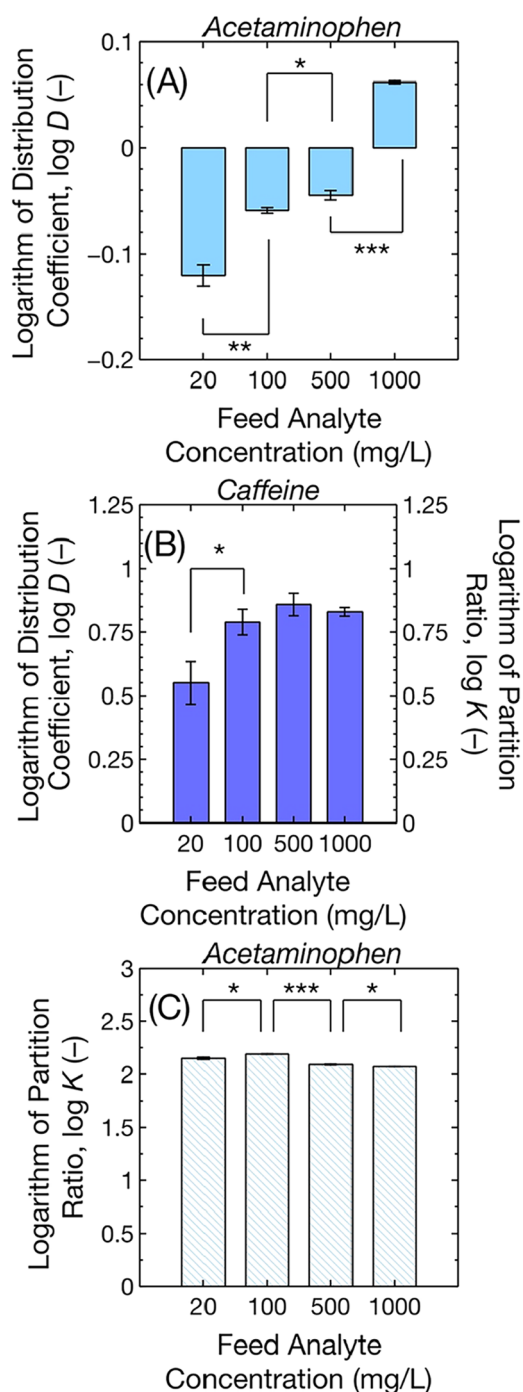


Figure 4. Logarithms of distribution coefficients, D (eq 1), i.e., all speciations, for (A) acetaminophen and (B) caffeine (left vertical axis) as a function of analyte feed concentration. Logarithms of partition ratios, K (eq 2), i.e., only neutral species, of (B) caffeine (right vertical axis) and (C) acetaminophen as a function of analyte feed concentrations. Note that because caffeine molecules remain neutral, i.e., do not protonate or deprotonate, in the investigated systems, the D and K are, therefore, equivalent. Solvent *tert*-octylamine (TOA) was equilibrated with equal weights of aqueous feed solutions of 20, 100, 500, and 1000 mg/L analyte. For all plots in this figure, data and error bars are means and standard errors, respectively, of triplicate experiments. ***, **, and * indicate p -values <0.001 , 0.01 , and 0.05 , respectively.

below). This discrepancy in analyte behavior and the dilute analyte concentrations indicates that acetaminophen distribu-

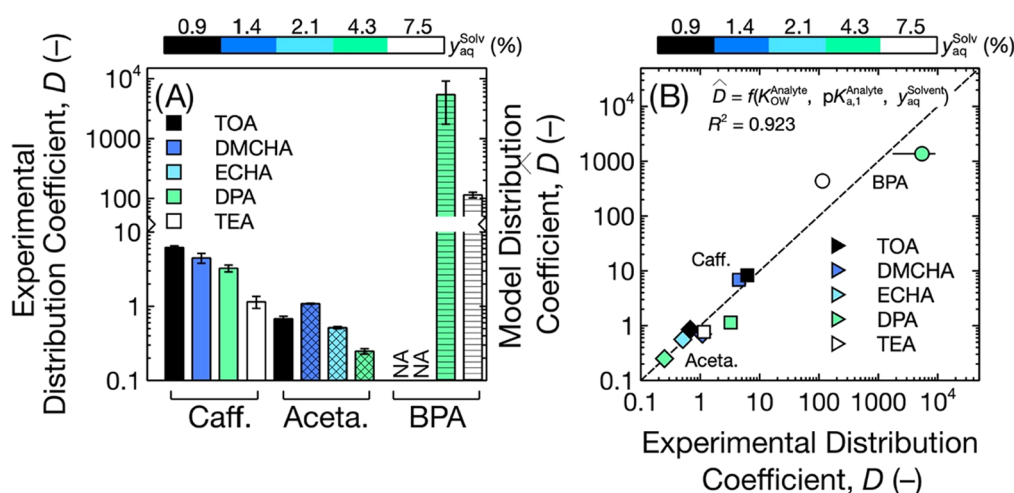


Figure 5. (A) Experimental distribution coefficients, D , for analytes caffeine, acetaminophen, and bisphenol A (solid, banded, and hatched columns, respectively) across amine solvents of *tert*-octylamine (TOA), *N,N*-dimethylcyclohexylamine (DMCHA), *N*-ethylcyclohexylamine (ECHA), dipropylamine (DPA), and triethylamine (TEA). Note that the vertical axis is on a logarithmic scale and has a break. (B) Parity plot comparing the D 's from experimental characterization and the regression model, with both axes on logarithmic scales. Square, diamond, and circle symbols denote caffeine, acetaminophen, and bisphenol A analytes, respectively. The dashed 45° line signifies perfect agreement. Aqueous feed solutions of 100 mg/L caffeine, 20 mg/L acetaminophen, or 100 mg/L bisphenol A were equilibrated with equal weights of solvents at 25 °C. Darker shades of green represent solvents with lower solubility in water, y_{aq}^{Solv} , as indicated by the color bar legend (with y_{aq}^{Solv} labeled). Bisphenol A was not detectable in the aqueous phase of the TOA and DMCHA mixtures; thus, distribution coefficients could not be calculated and are indicated by “NA” for “not applicable”. Caffeine and bisphenol A were not measured for ECHA, and acetaminophen was not measured for DMCHA. These solvent–analyte pairings are hence not represented in either plot. Data and error bars are means and standard errors, respectively, of triplicate experiments.

tion does not change with feed concentration as a result of solute–solute interactions. Instead, further analysis reveals that varying the analyte concentration alters the acid–base interactions in the aqueous phases of the amine–water mixtures and, in turn, shifts the D 's of ionizable compounds.

To separate out the effect of acid–base interactions on equilibrium, partition ratios, K , were evaluated (eq 2) for caffeine and acetaminophen (Figure 4B, right axis, and C). The partition ratio is determined using only the neutral form of the analyte. Because caffeine always remains predominantly neutral in this amine–water system, the D and K are equivalent. Hence, neither distribution nor partitioning behavior changes as the feed caffeine concentration is raised from 100 to 1000 mg/L ($p > 0.05$), matching the expected behavior of octanol–water systems. The ratios do increase as the initial caffeine is increased from 20 to 100 mg/L, but this rise might be due to measurements at low concentrations being more sensitive to experimental variations and uncertainties in sampling and HPLC methodology (as evidenced by a larger error bar for 20 mg/L).

The concentration of uncharged acetaminophen in the aqueous phase can be calculated by using pH in the Henderson–Hasselbalch equation. Analytes in the organic phase are approximated to be predominantly neutral,²⁸ as the low-dielectric constant environment of the amine solvent is highly unfavorable for ionized compounds.^{36,51} The partition ratios of acetaminophen do increase with analyte feed concentration but are practically indistinguishable (Figure 4C), again matching the behavior in octanol–water systems. The pK_a of acetaminophen is lower than that of the organic solvent TOA. As the analyte feed concentration increases, the aqueous phase pH slightly decreases, and the relative proportion of neutral acetaminophen concomitantly increases. For feed analyte concentrations of 20, 100, 500, and 1000 mg/L, the aqueous phase pH levels are calculated to be 11.73,

11.73, 11.71, and 11.69, respectively. Similarly, concentrations of neutral acetaminophen in the aqueous phase are theoretically determined to be 0.30, 0.30, 0.31, and 0.33 mol/L, respectively. The observed increase in D with increasing analyte feed concentration in Figure 4A is caused by the shift in acetaminophen speciation to the neutral form. Thus, the underlying mechanism for the concentration-dependence of the distribution coefficient for ionizable compounds is, again, acid–base interactions.

Distribution Coefficient Trends Negatively with Solvent Solubility in Water. To examine analyte distribution behavior across solvents with distinct chemical structures and properties, the D values of caffeine, acetaminophen, and bisphenol A (initial aqueous concentrations of 100, 20, and 100 mg/L, respectively) were assessed for five amine solvents of *tert*-octylamine (TOA), *N,N*-dimethylcyclohexylamine (DMCHA), *N*-ethylcyclohexylamine (ECHA), dipropylamine (DPA), and triethylamine (TEA). These amines exhibit thermoresponsive hydrophilicity and have been previously evaluated for TSSE.^{18,20,36,38,47} Molecular structures and thermophysical properties are summarized in Table S1 of the Supporting Information. Initial experiments were conducted using 20 mg/L acetaminophen aqueous feeds; however, the concentrations were increased to 100 mg/L for caffeine and BPA for improved measurement of these more hydrophobic compounds in the aqueous phases. Figure 5A shows the distribution coefficients, D (values available in Table S11 of the Supporting Information). Note that because concentrations of BPA in the aqueous phases were below detection limits for solvents TOA and DMCHA but measurable for DPA and TEA, the D 's could only be calculated for two of the solvents. Additionally, solvent–analyte pairings of caffeine–ECHA, bisphenol A–ECHA, and acetaminophen–DMCHA were not characterized and, thus, not presented. The combinations of solvent, analyte, and analyte concentrations were thought-

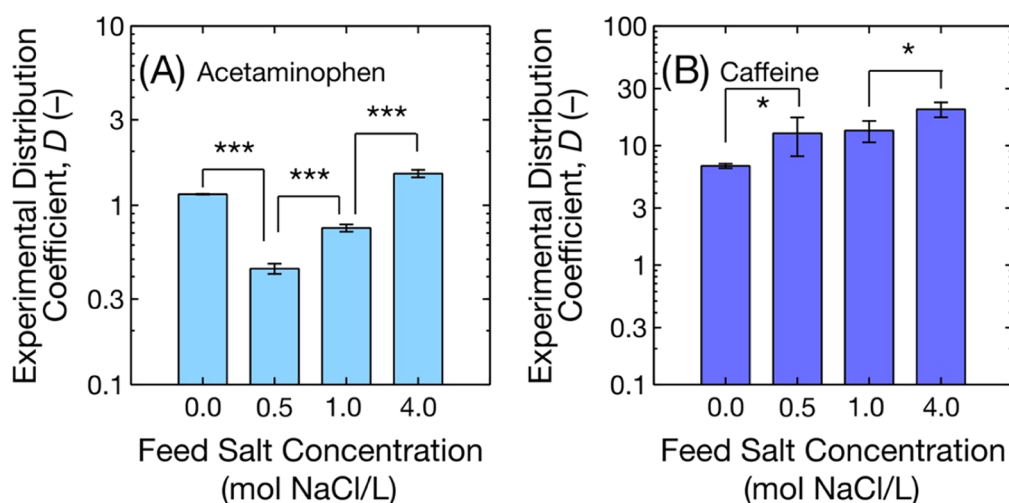


Figure 6. Experimental distribution coefficients, D , for (A) acetaminophen and (B) caffeine as a function of sodium chloride concentration in the feed solution. Note that the vertical axes are on different logarithmic scales. Aqueous feed solutions of 1000 mg/L analyte were equilibrated with equal weights of *tert*-octylamine (TOA) solvent at 25 °C. For all plots in this figure, data and error bars are means and standard errors, respectively, of triplicate experiments. ***, **, and * indicate p -values <0.001, 0.01, and 0.05, respectively.

fully chosen to balance the representation of different parameters while probing the robustness of earlier findings in this study. Distribution coefficients of caffeine and acetaminophen remain within an order of magnitude across the different solvents, ranging 1.15–6.20 and 0.25–1.09, respectively. The D 's of BPA are 5430 and 145 for the DPA and TEA systems, respectively, and are much more sensitive to changes in the relatively low concentrations of BPA in the aqueous phases (i.e., the denominator of eq 1 is small, yielding relatively larger error bars, e.g., BPA-DPA).

For all analytes, D generally trends negatively with amine solubility in the aqueous phases, $y_{\text{aq}}^{\text{Solv}}$ (labeled in the color bar legends of Figure 5, with darker shades of green signifying lower solubilities); i.e., the organic analytes preferentially distribute into the aqueous phases as the solubility of solvent in water increases. All of the solvents are basic, with pK_a 's ranging from 10.7 to 11.4 (at 25 °C, Table S1). However, the variation between K_a 's of the amines is narrower (4.2-fold) compared to solvent solubility in the aqueous phase, which spans from 0.91 to 7.5% w/w (8.2-fold). As such, $y_{\text{aq}}^{\text{Solv}}$ has a stronger influence on the aqueous phase pH than pK_a . Solvents that are more water miscible create a more basic aqueous phase and increase the ratio of ionized to neutral forms of the analyte. Because ionized species do not favor the low-dielectric constant environments of the organic solvent phases, the increase in $y_{\text{aq}}^{\text{Solv}}$ ultimately lowers D .

The regression analysis presented in Figure 5B highlights the significant influence of solvent characteristic $y_{\text{aq}}^{\text{Solv}}$ on analyte distribution, in addition to the importance of analyte properties K_{OW} and K_a identified earlier (Figure 2 and Table 2; $pK_{a,2}$ is not used in this regression analysis as only BPA has a second acid dissociation constant). The negative coefficient of the $y_{\text{aq}}^{\text{Solv}}$ variable is consistent with the analyte distribution trending negatively with solvent solubility in water (Table S13 of the Supporting Information). While the analyte properties can explain the majority of variation in distribution behavior (Table S12), the solvent-specific parameter $y_{\text{aq}}^{\text{Solv}}$ is helpful to account for changes in distribution across different solvents, with the coefficient of determination, R^2 , increasing from 0.866 to 0.930 after including $y_{\text{aq}}^{\text{Solv}}$ in the multiple linear regression.

Further, even though solvent solubility can be readily characterized, the parameter can alternatively be modeled using the solvent physicochemical properties of $K_{\text{OW}}^{\text{Solv}}$ and $pK_{a,1}^{\text{Solv}}$ with good accuracy ($R^2 = 0.975$, Table S14), thus eliminating the need for experimental measurements. Overall, the goodness of fit in Figure 5B across all investigated combinations (i.e., ≈ 5 orders of magnitude of D , three organic compounds with K_{OW} spanning >3 orders of magnitude and markedly dissimilar ionizability, and five different solvents) signifies that the principal factors governing partitioning are K_{OW} and K_a of the organic compound and $y_{\text{aq}}^{\text{Solv}}$ of the solvent.

Specific Ion–Analyte Interactions Determine Salting-In and Salting-Out Behavior. TSSE is applied to desalinate saline, and frequently hypersaline, streams. Hence, the distribution of any organic compounds present in the feed will be against the background of high inorganic salts. The introduction of salts to the biphasic system can cause salting-in or -out of the organic compounds. Salting-in is the phenomenon in which organic solutes become more soluble in the saline aqueous phases compared to a salt-free system and their D 's decrease. Salting-out describes the lowering of organic compound solubility in the aqueous phases by the salts, with D , thereby, increasing. To elucidate the role of salinity on D , we characterized the distribution of three analytes, caffeine, acetaminophen, and chloramphenicol, with saline feeds simulated by sodium chloride (NaCl) solutions at concentrations of 0.50, 1.0, and 4.0 mol/L to represent seawater, seawater desalination retentate, and hypersaline brine, respectively. A relatively high analyte feed concentration of 1000 mg/L was necessary to ensure measurable HPLC peaks with the large sample dilution ratios ($\approx 15\times$) required to avoid salt precipitation on the column.

Distribution coefficients as a function of feed salt concentrations using *tert*-octylamine as the solvent are presented in Figure 6. Chloramphenicol concentrations in the aqueous phases are below detection limits for all feed salt concentrations >0 mol NaCl/L, and thus, the D 's could not be plotted. The D for acetaminophen decreases from 1.15 to 0.44 as the feed salt concentration increases from 0 to 0.5 mol of NaCl/L (Figure 6A and Table S15 of the Supporting

Information). Although there is a slight increase of D to 0.75 in the 1.0 mol NaCl/L solution, the analyte is still salted-in compared to the salt-free solution ($p < 0.001$). Only at sufficiently high NaCl concentration of 4.0 mol/L is the organic compound salted out of the aqueous phase ($D = 1.5$, $p < 0.001$). On the other hand, caffeine (Figure 6B) and chloramphenicol (not presented), only exhibit salting-out behavior in response to the addition of salt, i.e., analytes prefer the organic solvent phase upon the introduction of salt (for the examined concentrations).

Although there is no universally accepted explanation for the salting-in and salting-out mechanisms,^{55–58} molecular interactions offer a useful framework for interpreting experimental observations. In the aqueous phase, electrolyte ions are preferentially hydrated over organic solutes by water molecules. An increase in salt concentration would, thus, decrease H₂O solvation of nonelectrolytes. Favorability of the nonelectrolytes to be in the aqueous phase is reduced and the organic phase is comparatively preferred, thereby increasing D .⁵⁹ Indeed, the distribution coefficients of caffeine monotonically increase with saline feed concentration (Figure 6B). In addition, more hydrophobic analytes are, on the whole, more easily salted out of aqueous feed solutions.^{60,61} Chloramphenicol, which has a K_{OW} that is orders of magnitude greater than caffeine and acetaminophen, is observed to be almost completely salted out of the aqueous phases when equilibrated with ≥ 0.5 mol NaCl/L aqueous feed solutions. However, interactions between salt ions and organic solutes are analyte-specific, and there are often outliers to these general trends.^{58,60,61} In the TOA–water–NaCl system, acetaminophen exhibited both salting-in and salting-out behaviors, depending on the ionic strength of the aqueous phase (Figure 6A). This suggests that such specific interactions between salt ions, organic analyte, water, and potentially even amine solvent molecules are significant in influencing the eventual distribution of the organic compound.

In this study, equal weights of solvent and aqueous feed solution were equilibrated in single batch experiments. Real TSSE operations will utilize higher solvent-to-feed ratios or multiple extraction cycles to achieve practical water recovery yields. Salt contents of the final raffinate, i.e., the aqueous effluent stream produced by the extraction step, will be in the hypersaline range or are likely near saturation; i.e., the D at 4.0 mol NaCl/L is more representative of the extraction step. Therefore, it is expected that organic contaminants in the feed will experience amplified salting-out, although only the more hydrophobic components might be completely ejected into the organic solvent phase. TSSE product waters are typically < 0.5 mol NaCl/L in equivalent salinity. Hence, the extent to which the organic solutes are recycled with the solvent rather than distributed into the product water will likely be more analyte-specific.

■ IMPLICATIONS

This study elucidates the key physicochemical phenomena that govern the partitioning behavior of organic contaminants in amine–aqueous systems. The hydrophobicity of the organic compound is a major determinant of distribution between the amine solvent and water, consistent with the established trends in phase affinity between *n*-octanol and water (analogously, lipophilicity/hydrophilicity). In general, more hydrophobic compounds will be present in the organic amine phases in higher proportions. Notably, organic contaminants with

octanol–water partition coefficients greater than that of the amine overwhelmingly distribute into the organic solvent phases. This feature can be strategically leveraged for the targeted remediation of organic contaminants from hypersaline brine through a rational solvent selection.

Amines are good candidates for TSSE due to the high and sharply temperature-dependent water solubility in the solvents.^{32,33} However, amines are also basic. In the aqueous phases of biphasic TSSE mixtures, the basicity can deprotonate organic contaminants that are ionizable at high pH levels. Therefore, acid–base interactions play a critical role in the distribution of organic compounds. Similar to electrolyte salts, which are highly rejected by the amine solvents, ionized organic compounds will be largely retained in the aqueous phases of TSSE. Different compositions and concentrations of organics in the brines and the specific amine solvent will alter the aqueous phase basicity and, in turn, modify the distribution behavior of the contaminants. The swing in temperature, a feature of the working principles of TSSE, will similarly change the partition equilibrium by shifting the aqueous phase pH. These findings can be generalized to solvents with high pK_a 's and significant solubility in water. For the corollary solvents with low pK_a 's (e.g., carboxylic acids for TSSE), the converse applies, with potential protonation of the organic compounds affecting the phase preference. Solvents that lack ionizable atoms, such as ethers and ketones, or those with negligible solubility in water can be expected to behave more similarly to octanol–water mixtures.

The regression analyses presented in this study accurately captured distribution behavior for a wide range of organic compounds across different amine solvents and at the extraction and disengagement temperatures of TSSE. Notably, the regression models are based solely on commonly reported analyte properties of octanol–water partition coefficient and acid dissociation constants, solvent physicochemical characteristics of solubility in water (or, alternatively, solvent octanol–water partition coefficient and acid dissociation constant), and the influence of temperature on these parameters. The robust predictive power using readily available thermophysical data highlights the potential of the approach for the *a priori* determination of the organic contaminant distribution broadly in amine–water systems. The analyses here employed relatively simple multiple linear regression. Applying more sophisticated models can enhance or expand predictive capabilities, for example, to model the ion- and analyte-specific effects of background salt on distribution in solvent–water–salt systems. Building off the foundation developed in this work, future studies can further probe the quantitative dependence of distribution coefficient on acid dissociation constants, octanol–water partition coefficient, and solvent solubility in water by investigating broader ranges of solvent–analyte–concentration combinations as well as examine distribution behaviors in systems with multiple organic contaminants, highly volatile solvents (e.g., dimethyl ether),^{62–64} volatile analytes, natural organic matter, and surfactants. The findings here can guide the rational design of the TSSE or other solvent-based processes for improved separation performance. Insights on the influence of solute properties (K_{OW} and pK_a) and solvent characteristics (γ_{aq}^{Solv} , K_{OW}^{Solv} , and $pK_{a,1}^{Solv}$) on partitioning behavior from this study advance our fundamental understanding of the fate of organic contaminants. This framework can inform the development of practical tools to more accurately predict the partitioning of

organic compounds in environmental, biological, and chemical settings, particularly in which acid–base interactions play a significant role.

■ ASSOCIATED CONTENT

SI Supporting Information

The Supporting Information is available free of charge at <https://pubs.acs.org/doi/10.1021/acs.est.5c09656>.

Chemical structures, logarithms of octanol–water partition coefficients, acid dissociation constants, and water solubilities of amine solvents investigated (Table S1); experimental method for characterization of biphasic mixture compositions (Table S2); molar balance of analytes between aqueous and organic phases (Table S3); and distribution coefficients and full regression tables for all experiments (Tables S4–S14) (PDF)

■ AUTHOR INFORMATION

Corresponding Author

Ngai Yin Yip – Department of Earth and Environmental Engineering, Columbia University, New York, New York 10027-6623, United States; Columbia Water Center, Columbia University, New York, New York 10027-6623, United States; orcid.org/0000-0002-1986-4189; Phone: +1 212 8542984; Email: n.y.yip@columbia.edu

Authors

Kinnari M. Shah – Department of Earth and Environmental Engineering, Columbia University, New York, New York 10027-6623, United States

Julian van der Made – Department of Earth and Environmental Engineering, Columbia University, New York, New York 10027-6623, United States

Kartik Chandran – Department of Earth and Environmental Engineering, Columbia University, New York, New York 10027-6623, United States; orcid.org/0000-0002-7526-3724

Complete contact information is available at: <https://pubs.acs.org/doi/10.1021/acs.est.5c09656>

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This material is based upon work supported by the National Science Foundation Graduate Research Fellowship (K.M.S.). Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

■ REFERENCES

- (1) Shah, K. M.; Billinge, I. H.; Chen, X.; Fan, H.; Huang, Y.; Winton, R. K.; Yip, N. Y. Drivers, Challenges, and Emerging Technologies for Desalination of High-Salinity Brines: A Critical Review. *Desalination* **2022**, 538, No. 115827.
- (2) Pramanik, B. K.; Shu, L.; Jegatheesan, V. A Review of the Management and Treatment of Brine Solutions. *Environ. Sci. Water Res. Technol.* **2017**, 3 (4), 625–658.
- (3) Ogunbiyi, O.; Saththasivam, J.; Al-Masri, D.; Manawi, Y.; Lawler, J.; Zhang, X.; Liu, Z. Sustainable Brine Management from the Perspectives of Water, Energy and Mineral Recovery: A Comprehensive Review. *Desalination* **2021**, 513, No. 115055.
- (4) Shaffer, D. L.; Arias Chavez, L. H.; Ben-Sasson, M.; Romero-Vargas Castrillón, S.; Yip, N. Y.; Elimelech, M. Desalination and Reuse of High-Salinity Shale Gas Produced Water: Drivers, Technologies, and Future Directions. *Environ. Sci. Technol.* **2013**, 47 (17), 9569–9583.
- (5) Correia, V. M.; Stephenson, T.; Judd, S. J. Characterisation of Textile Wastewaters - A Review. *Environ. Technol.* **1994**, 15, 917–929.
- (6) Sundarapandiyam, S.; Chandrasekar, R.; Ramanaiah, B.; Krishnan, S.; Saravanan, P. Electrochemical Oxidation and Reuse of Tannery Saline Wastewater. *J. Hazard. Mater.* **2010**, 180 (1), 197–203.
- (7) Shi, J.; Huang, W.; Han, H.; Xu, C. Review on Treatment Technology of Salt Wastewater in Coal Chemical Industry of China. *Desalination* **2020**, 493, No. 114640.
- (8) Moody, C. M.; Townsend, T. G. A Comparison of Landfill Leachates Based on Waste Composition. *Waste Manag.* **2017**, 63, 267–274.
- (9) Ahmad, N.; Baddour, R. E. A Review of Sources, Effects, Disposal Methods, and Regulations of Brine into Marine Environments. *Ocean Coast. Manag.* **2014**, 87, 1–7.
- (10) Estrada, J. M.; Bhamidimarri, R. A Review of the Issues and Treatment Options for Wastewater from Shale Gas Extraction by Hydraulic Fracturing. *Fuel* **2016**, 182, 292–303.
- (11) Burbano, A.; Brandhuber, P. Demonstration of Membrane Zero Liquid Discharge for Drinking Water System: Literature Review; WERF5T10. 2014.
- (12) Mickley, M. C. *Survey of High-Recovery and Zero Liquid Discharge Technologies for Water Utilities*; WaterReuse Foundation: Alexandria, VA, 2008.
- (13) Tong, T.; Elimelech, M. The Global Rise of Zero Liquid Discharge for Wastewater Management: Drivers, Technologies, and Future Directions. *Environ. Sci. Technol.* **2016**, 50 (13), 6846–6855.
- (14) Antony, A.; Low, J. H.; Gray, S.; Childress, A. E.; Le-Clech, P.; Leslie, G. Scale Formation and Control in High Pressure Membrane Water Treatment Systems: A Review. *J. Membr. Sci.* **2011**, 383 (1), 1–16.
- (15) Brogioli, D.; La Mantia, F.; Yip, N. Y. Thermodynamic Analysis and Energy Efficiency of Thermal Desalination Processes. *Desalination* **2018**, 428, 29–39.
- (16) Bajpayee, A.; Luo, T.; Muto, A.; Chen, G. Very Low Temperature Membrane-Free Desalination by Directional Solvent Extraction. *Energy Environ. Sci.* **2011**, 4 (5), No. 1672.
- (17) Guo, J.; Tucker, Z. D.; Wang, Y.; Ashfeld, B. L.; Luo, T. Task-Specific Ionic Liquid Enables Highly Efficient Low Temperature Desalination by Directional Solvent Extraction *ChemRxiv* 2020 DOI: [10.26434/chemrxiv.11840025.v1](https://doi.org/10.26434/chemrxiv.11840025.v1).
- (18) Boo, C.; Winton, R. K.; Conway, K. M.; Yip, N. Y. Membrane-Less and Non-Evaporative Desalination of Hypersaline Brines by Temperature Swing Solvent Extraction. *Environ. Sci. Technol. Lett.* **2019**, 6 (6), 359–364.
- (19) Barbosa, G. D.; Liu, X.; Bara, J. E.; Weinman, S. T.; Turner, C. H. High-Salinity Brine Desalination with Amine-Based Temperature Swing Solvent Extraction: A Molecular Dynamics Study. *J. Mol. Liq.* **2021**, 341, No. 117359.
- (20) Choi, O. K.; Seo, J. H.; Kim, G. S.; Hendren, Z.; Kim, G. D.; Kim, D.; Lee, J. W. Non-Membrane Solvent Extraction Desalination (SED) Technology Using Solubility-Switchable Amine. *J. Hazard. Mater.* **2021**, 403, No. 123636.
- (21) Moody, C. M.; Townsend, T. G. A Comparison of Landfill Leachates Based on Waste Composition. *Waste Manag.* **2017**, 63, 267–274.
- (22) Gregory, K. B.; Vidic, R. D.; Dzombak, D. A. Water Management Challenges Associated with the Production of Shale Gas by Hydraulic Fracturing. *Elements* **2011**, 7 (3), 181–186.
- (23) Correia, V. M.; Stephenson, T.; Judd, S. J. Characterisation of Textile Wastewaters—A Review. *Environ. Technol.* **1994**, 15, 917–929.

- (24) Shi, J.; Huang, W.; Han, H.; Xu, C. Review on Treatment Technology of Salt Wastewater in Coal Chemical Industry of China. *Desalination* **2020**, *493*, No. 114640.
- (25) Vásquez Salazar, E. E.; Hernández, G. R.; Vargas Saavedra, J. A.; Villegas Romero, H. J. Ethanol Extraction Desalination Test Using Pre-Treated Mine Wastewater Concentrated by Reverse Osmosis. *Desalination Water Treat.* **2024**, *317*, No. 100208.
- (26) Zhang, Y.; Jia, L.; Zhao, J.; Liu, X.; Dong, S.; Liu, C.; Cui, Y. Directional Amine-Based Solvent Extraction for Simultaneous Enhanced Water Recovery, Salt Separation and Effective Descaling from Hypersaline Brines. *Front. Environ. Sci. Eng.* **2024**, *18* (3), No. 32.
- (27) Boo, C.; Billinge, I. H.; Chen, X.; Shah, K. M.; Yip, N. Y. Zero Liquid Discharge of Ultrahigh-Salinity Brines with Temperature Swing Solvent Extraction. *Environ. Sci. Technol.* **2020**, *54*, No. 9124.
- (28) Sangster, J. M. *Octanol-Water Partition Coefficients: Fundamentals and Physical Chemistry*; John Wiley & Sons, 1997.
- (29) Disdier, Z.; Savoye, S.; Dagnelie, R. V. H. Effect of Solutes Structure and pH on the N-Octanol/Water Partition Coefficient of Ionizable Organic Compounds. *Chemosphere* **2022**, *304*, No. 135155.
- (30) Sigmund, G.; Arp, H. P. H.; Aumeier, B. M.; Bucheli, T. D.; Chefetz, B.; Chen, W.; Droge, S. T. J.; Endo, S.; Escher, B. I.; Hale, S. E.; Hofmann, T.; Pignatello, J.; Reemtsma, T.; Schmidt, T. C.; Schönsee, C. D.; Scheringer, M. Sorption and Mobility of Charged Organic Compounds: How to Confront and Overcome Limitations in Their Assessment. *Environ. Sci. Technol.* **2022**, *56* (8), 4702–4710.
- (31) Salthammer, T. Assessment of Methods for Predicting Physical and Chemical Properties of Organic Compounds. *Indoor Environ.* **2024**, *1* (3), No. 100031.
- (32) Davidson, R. R.; Smith, W. H.; Hood, D. W. Structure and Amine-Water Solubility in Desalination by Solvent Extraction. *J. Chem. Eng. Data* **1960**, *5* (4), 420–423.
- (33) Foo, Z. H.; Stetson, C.; Dach, E.; Deshmukh, A.; Lee, H.; Menon, A. K.; Prasher, R.; Yip, N. Y.; Lienhard, J. H.; Wilson, A. D. Solvent-Driven Aqueous Separations for Hypersaline Brine Concentration and Resource Recovery. *Trends Chem.* **2022**, *4* (12), 1078–1093.
- (34) Sangster, J. Octanol-Water Partition Coefficients of Simple Organic Compounds. *J. Phys. Chem. Ref. Data* **1989**, *18* (3), 1111–1229.
- (35) Davison, R. R.; Smith, W. H.; Hood, D. W. Phase Equilibria of Desalination Solvents: Water-NaCl-Amines. *J. Chem. Eng. Data* **1966**, *11* (3), 304–309.
- (36) Shah, K. M.; Dach, E.; Winton, R.; Fan, H.; Yip, N. Y. Phase Equilibria Insights into Amine-Water-NaCl Interactions in Liquid-Liquid Biphasic Systems for Temperature Swing Solvent Extraction Desalination. *Desalination* **2023**, *548*, No. 116259.
- (37) Ward, L. M.; Jarrell, S. K.; Monti, E. B.; Barbosa, G. D.; Danner, J. T.; Bara, J. E.; Turner, C. H.; Weinman, S. T. Substituent Effects on the Desalination Performance of Six-Carbon Amines in Temperature Swing Solvent Extraction. *Ind. Eng. Chem. Res.* **2025**, *64* (24), 12173–12184.
- (38) Barbosa, G. D.; Turner, C. H. Computational Assessment of an Amine-Based Solvent Library for High-Salinity Brine Desalination. *Ind. Eng. Chem. Res.* **2023**, *62* (20), 8033–8041.
- (39) Sappidi, P.; Barbosa, G.; Rabideau, B. D.; Weinman, S. T.; Turner, C. H. Molecular Simulation of High-Salinity Brines in Contact with Diisopropylamine and Tripropylamine Solvents. *Ind. Eng. Chem. Res.* **2021**, *60* (21), 7917–7925.
- (40) Shaaban, H.; Górecki, T. Fast Ultrahigh Performance Liquid Chromatographic Method for the Simultaneous Determination of 25 Emerging Contaminants in Surface Water and Wastewater Samples Using Superficially Porous Sub-3 Mm Particles as an Alternative to Fully Porous Sub-2 Mm Particles. *Talanta* **2012**, *100*, 80–89.
- (41) Ibáñez, M.; Gracia-Lor, E.; Bijlsma, L.; Morales, E.; Pastor, L.; Hernández, F. Removal of Emerging Contaminants in Sewage Water Subjected to Advanced Oxidation with Ozone. *J. Hazard. Mater.* **2013**, *260*, 389–398.
- (42) Lim, S.; Wu, Y.; Mitch, W. A. Transformation of Cyclic Amides and Uracil-Derived Nitrogen Heterocycles during Chlorination. *Water Res.* **2025**, *282*, No. 123639.
- (43) Melcer, H.; Klečka, G. Treatment of Wastewaters Containing Bisphenol A: State of the Science Review. *Water Environ. Res.* **2011**, *83* (7), 650–666.
- (44) Nguyen, L. M.; Nguyen, N. T. T.; Nguyen, T. T. T.; Nguyen, T. T.; Nguyen, D. T. C.; Tran, T. V. Occurrence, Toxicity and Adsorptive Removal of the Chloramphenicol Antibiotic in Water: A Review. *Environ. Chem. Lett.* **2022**, *20* (3), 1929–1963.
- (45) MarvinSketch was used for drawing, displaying and characterizing chemical structures, substructures and reactions, Marvin 17.21.0, Chemaxon. <https://www.chemaxon.com>.
- (46) U.S. Environmental Protection Agency. CompTox Chemicals Dashboard, <https://comptox.epa.gov/dashboard/> (accessed May 1, 2024).
- (47) Shah, K. M.; Billinge, I. H.; Dach, E.; Yip, N. Y. Advancing the Productivity-Selectivity Trade-off of Temperature Swing Solvent Extraction Desalination with Intermediate-Step Release. *Environ. Sci. Technol. Lett.* **2023**, *10*, No. 949.
- (48) Moldoveanu, S. C.; David, V. *Modern Sample Preparation for Chromatography*; Elsevier, 2021.
- (49) Lasarte-Aragonés, G.; Álvarez-Lueje, A.; Salazar, R.; Toledo-Neira, C. Application of Switchable Hydrophobicity Solvents for Extraction of Emerging Contaminants in Wastewater Samples. *Molecules* **2020**, *25* (1), No. 86.
- (50) Góral, M.; Shaw, D. G.; Mączyński, A.; Wiśniewska-Gocłowska, B.; Oracz, P. IUPAC-NIST Solubility Data Series. 96. Amines with Water Part 2. C7–C24 Aliphatic Amines. *J. Phys. Chem. Ref. Data* **2012**, *41* (4), No. 043107.
- (51) Griffiths, T. R.; Pugh, D. C. Correlations among Solvent Polarity Scales, Dielectric Constant and Dipole Moment, and a Means to Reliable Predictions of Polarity Scale Values from Current Data. *Coord. Chem. Rev.* **1979**, *29* (2–3), 129–211.
- (52) David, V.; Moldoveanu, S. C. Variation with Temperature of Octanol/Water Partition Coefficient for the Homologous Series from Benzene to Propylbenzene. *Sep. Sci. Plus* **2019**, *2* (12), 457–464.
- (53) Bahadur, N. P.; Shiu, W.-Y.; Boocock, D. G. B.; Mackay, D. Temperature Dependence of Octanol–Water Partition Coefficient for Selected Chlorobenzenes. *J. Chem. Eng. Data* **1997**, *42* (4), 685–688.
- (54) Lei, Y. D.; Wania, F.; Shiu, W. Y.; Boocock, D. G. B. HPLC-Based Method for Estimating the Temperature Dependence of n-Octanol–Water Partition Coefficients. *J. Chem. Eng. Data* **2000**, *45* (5), 738–742.
- (55) Grover, P. K.; Ryall, R. L. Critical Appraisal of Salting-Out and Its Implications for Chemical and Biological Sciences. *Chem. Rev.* **2005**, *105* (1), 1–10.
- (56) Hyde, A. M.; Zultanski, S. L.; Waldman, J. H.; Zhong, Y.-L.; Shevlin, M.; Peng, F. General Principles and Strategies for Salting-Out Informed by the Hofmeister Series. *Org. Process Res. Dev.* **2017**, *21* (9), 1355–1370.
- (57) Long, F. A.; McDevit, W. F. Activity Coefficients of Nonelectrolyte Solutes in Aqueous Salt Solutions. *Chem. Rev.* **1952**, *51* (1), 119–169.
- (58) Gregory, K. P.; Elliott, G. R.; Robertson, H.; Kumar, A.; Wanless, E. J.; Webber, G. B.; Craig, V. S. J.; Andersson, G. G.; Page, A. J. Understanding Specific Ion Effects and the Hofmeister Series. *Phys. Chem. Chem. Phys.* **2022**, *24* (21), 12682–12718.
- (59) Marcus, Y. Prediction of Salting-out and Salting-in Constants. *J. Mol. Liq.* **2013**, *177*, 7–10.
- (60) Endo, S.; Pfennigsdorff, A.; Goss, K.-U. Salting-Out Effect in Aqueous NaCl Solutions: Trends with Size and Polarity of Solute Molecules. *Environ. Sci. Technol.* **2012**, *46* (3), 1496–1503.
- (61) Ni, N.; Yalkowsky, S. H. Prediction of Setschenow Constants. *Int. J. Pharm.* **2003**, *254* (2), 167–172.
- (62) Deshmukh, A.; Wilson, A. D.; Lienhard, J. H. Electrically Powered High-Salinity Brine Separation Using Dimethyl Ether. *Ind. Eng. Chem. Res.* **2024**, *63* (18), 8341–8356.

(63) Deshmukh, A.; Foo, Z. H.; Stetson, C.; et al. Thermodynamics of Solvent-Driven Water Extraction from Hypersaline Brines Using Dimethyl Ether. *Chem. Eng. J.* **2022**, *434*, No. 134391.

(64) Foo, Z. H.; Deshmukh, A.; Wilson, A. D.; Lienhard, J. H. Harnessing Dimethyl Ether with Ultra-Low-Grade Heat for Scaling-Resistant Brine Concentration and Fractional Crystallization. *Chem. Eng. J.* **2024**, *489*, No. 151159.



CAS BIOFINDER DISCOVERY PLATFORM™

PRECISION DATA FOR FASTER DRUG DISCOVERY

CAS BioFinder helps you identify
targets, biomarkers, and pathways

Unlock insights

CAS
A division of the
American Chemical Society