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Oxygenated aromatic compounds from renewable resources: motivation, opportunities, and adsorptive separations

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Abstract

Over the last 50 years petroleum has become the primary feedstock for industrial organic chemical production. Over the next 50 years it is anticipated that there will be a growing use of renewable feedstocks in chemical manufacturing. In this review, the motivations for developing alternatives to petro-chemicals are discussed, and we highlight exciting advances in biotechnology that promise to make biomass-based feedstocks more attractive in the future. We argue that separations remain a key bottleneck to the recovery of organic chemicals from renewable resources. Finally, we consider our research to understand the mechanistic interactions responsible for adsorption onto polymeric adsorbents. We provide examples illustrating how knowledge of hydrogen-bonding interactions can be exploited for separating chemicals from renewable resources. We especially focus on oxygenated aromatic compounds (OACs) that are abundant in biomass-based feedstocks.
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Keywords: Adsorption; Lignin; Oxygenated aromatic compounds (OACs); Renewable resources; Separations

1. Introduction

It seems difficult to imagine that only 100 years ago renewable resources were the primary source of fuel and the major raw material for industrial organic chemicals [1]. Only 50 years ago, coal was a major chemical feedstock and when nylon ushered in synthetic polymers it was touted as being derived from coal, air, and water. Over the last 50 years, advances in petroleum processing and industrial organic chemistry have enabled petroleum to become a primary source of energy and the major feedstock for industrial organic chemicals [2,3]. In fact, over 90% (by tonnage) of all organic chemicals are derived from petroleum [3]. However, there is a growing interest in reducing dependence on petroleum and returning to the use of renewable resources to meet at least some of the demand for fuel and organic chemicals. In this review, we highlight the mounting incentives toward the use of renewable chemicals and briefly discuss the separations challenges that must be overcome before renewable resources can be more broadly utilized as a source of industrial chemicals. We especially focus on the recovery of oxygenated aromatic compounds (OACs) and review our research that suggests the potential of adsorption to overcome some of these separations challenges.

2. Motivation for change

2.1. Feedstock issues

The most obvious reason to reduce dependence on petroleum feedstocks is that petroleum is a finite resource. Although projections vary, most estimates indicate that over the next 10–40 years petroleum will become considerably less abundant and more expensive than it is today [4–7]. In addition to being finite, petroleum resources are also isolated to certain geographic regions of the world (i.e. the Middle East). Most countries outside these regions must import their petroleum and these imports can significantly affect national economies. For instance, the US imports a substantial fraction of its petroleum [8] and these imports account for 40% of the US foreign trade deficit [9,10]. In addition, many countries have biomass resources that could

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Nomenclature

C	liquid phase concentration (mmol/l)
D	partition coefficient
H	enthalpy (kJ/mol)
K	adsorption equilibrium coefficient
q	adsorbed amount of solute (mmol adsorbed/g sorbent)
R	gas constant
T	temperature (K)
Greek letters	
α	separation factor (Eq. (6))
Δ	increment
ν	IR wave number (cm^{-1})
Superscript	
$^\circ$	property at standard condition
Subscripts	
1	component one (Eq. (6))
2	component two (Eq. (6))
aqu	aqueous phase
max	saturated amount
org	organic phase
pore	pore phase

be converted into renewable feedstocks for fuels, chemicals, and materials. In fact, in some cases these 'resources' are nuisance wastes that pose a disposal problem. There are growing efforts to convert these 'wastes' into marketable products. Examples of current US efforts to convert 'wastes' into products include; Maryland's effort to convert crab wastes into the biopolymer chitosan, North Carolina's effort to convert livestock manure into methane, and California's effort to convert residues from its rice crop into fuel ethanol.

2.2. Safety, health, and environmental concerns for current processes and products

Many commercial chemical processes and products were developed nearly 50 years ago — before safety, health, and environmental (SHE) concerns were so prominent. Currently, SHE concerns are prompting a re-evaluation of many traditional process chemistries and products. For instance, many process chemistries have been based on the use of reactive reagents/intermediates. The risks associated with using reactive reagents is exacerbated by the fact that many chemical processes are operated on a very large-scale in order to achieve the economies-of-scales necessary to be profitable in the highly competitive chemical process industries. Mishaps with large-volumes of reactive chemicals can have disastrous consequences as demonstrated by the methyl isocyanate release in Bhopal, India, in 1984. To avoid such mishaps in the future, there has been a serious effort to develop inherently safer process chemistries [11] including the use of alternative raw materials [12]. Biotechnology is often viewed as an inherently safer alternative 'process chemistry' and some traditional chemical manufacturers (e.g. Dow, DuPont, and Monsanto) have moved aggressively into the life sciences [13–15].

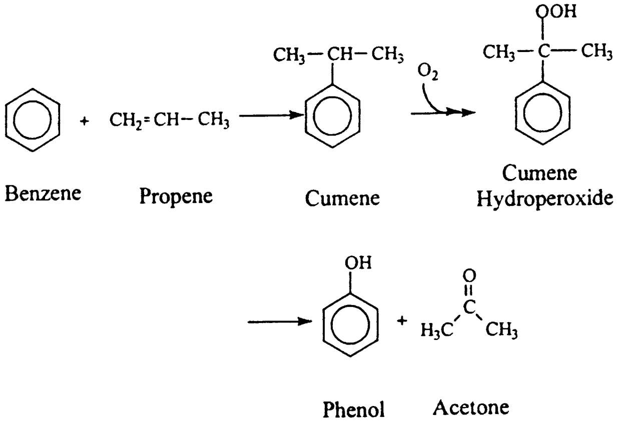
Synthetic chemical products are also undergoing scrutiny for a variety of reasons. In some cases scrutiny of a chemical's source appears to be simply a marketing tool (e.g. whether a highly purified food or flavor chemical is derived from a natural or synthetic source). In other cases, however, there are legitimate concerns on how functional properties have been built into synthetic chemicals. The alkylbenzene-derived surfactants provide a good example of how synthetic methods to confer functionality can lead to unforeseen and undesired consequences. For surfactant property, a molecule must have both hydrophobic and hydrophilic moieties. For alkylbenzene-derived surfactants, the alkyl group is hydrophobic while the polar 'head group' is either a sulfonate (for anionic surfactants), or ethylene oxide units (for neutral surfactants). Originally, the alkylbenzene sulfonates were synthesized from propene oligomers but these alkyl moieties were highly branched and poorly metabolized by microorganisms [16,17]. Since microbial metabolism is the primary mechanism for environmental degradation, the alkylbenzene sulfonates accumulated in the environment and caused considerable foaming in waste water treatment facilities and in discharge waters [18]. In the 1960s and 1970s, many countries converted to the use of more readily degraded linear alkylbenzene sulfonates (LABS). An additional issue with respect to biodegradation is that LABS have chiral centers and biodegradation rates may vary for individual enantiomers [19]. With respect to the non-ionic alkylphenol ethoxylates, branched alkyl units are still used. In the environment, some cleavage of ethoxy chains is observed but unfortunately the intermediates formed are reported to be more toxic and persistent than the parent compound [20,21]. Additional concerns have recently been raised of possible endocrine disrupting activities of alkylphenol ethoxylates [22]. These types of experiences are leading industry toward more natural means for conferring functionality. For instance, there have been substantial recent efforts to develop sugar and fatty acid-based surfactants [23].

In summary, SHE concerns are mandating change in the chemical process industry. Critics of the chemical industry suggest that this industry only changes when there is a direct effect on the financial 'bottom-line'. SHE concerns have begun affecting the 'bottom-line' through escalating costs for compliance with more stringent regulations [24,11]. Increasingly, SHE concerns are also being cast in financial terms as: risks for potential future liabilities, premiums for insurance coverage, and financial opportunities in green investment funds [25,26].

2.3. Current approaches for producing oxygenated aromatic compounds (OACs)

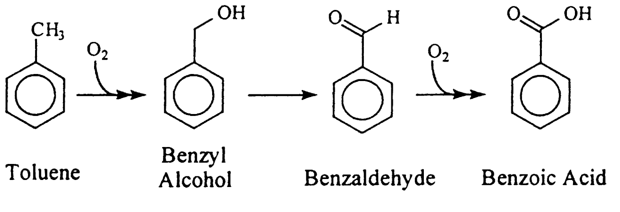
OACs suffer from the same concerns mentioned above. Namely, OACs are currently derived from non-renewable feedstocks, using process chemistries that are not entirely benign, and several synthetic OACs that have been developed to offer technically useful functionality also have undesirable SHE properties. With respect to feedstocks, traditional routes for manufacturing OACs begin with the petroleum-derived aromatic building blocks, benzene, toluene, or xylene.

Process chemistries for adding oxygen to aromatic hydrocarbons to obtain OACs are often indirect because of the difficulty of limiting oxidation to obtain partially oxidized intermediates (i.e. CO_2 and H_2O are the thermodynamically-favored products). For instance, the majority of the phenol synthesized worldwide is obtained by adding propene to benzene, followed by partial oxidation to yield the intermediate cumene hydroperoxide which is then cleaved to phenol and acetone [2].



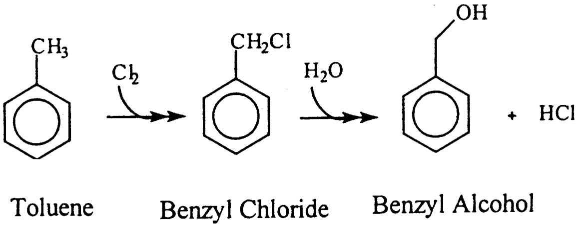
(R1)

The increased reactivity of the benzyl groups allows toluene to be partially oxidized to benzoic acid as shown in (R2). However, production of the intermediates benzyl alcohol and benzaldehyde is difficult.

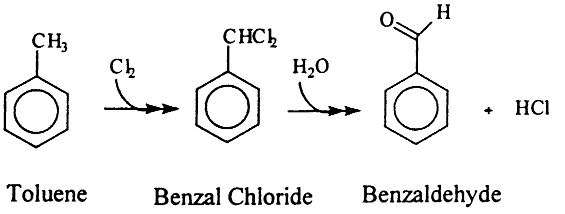


(R2)

In fact, the principal commercial routes to benzyl alcohol and benzaldehyde involve chlorination followed by hydrolysis as indicated in (R3) and (R4) [3]. There is considerable interest in reducing the generation of chlorinated intermediates — especially for the synthesis of non-chlorinated products.

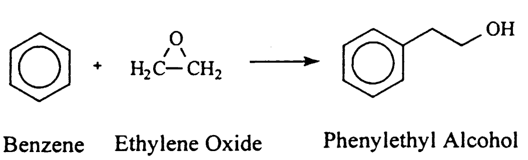


(R3)

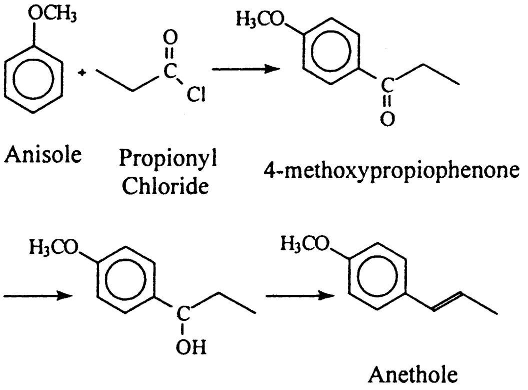


(R4)

Reactive reagents are often used for adding substituents to aromatics. For instance, (R5) and (R6) show that synthetic routes to the fragrance chemicals phenylethanol and anethole involve the use of ethylene oxide and propionyl chloride, respectively.



(R5)



(R6)

These examples illustrate that process chemistries developed for synthesizing OACs have shortcomings and opportunities exist for innovative and benign alternatives to traditional production methods.

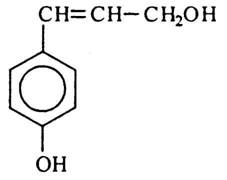
In addition to concerns for process chemistries, there are also concerns for several synthetic oxygenated aromatic products. OACs have been synthesized to confer a wide range of functional properties but there are growing concerns for some of their undesirable properties. As mentioned, the alkyl phenols are suspected endocrine disrupters. Similarly, bisphenol A, the monomer in polycarbonates and epoxy resins, is also a suspected endocrine disrupter [27]. Additionally, synthetic antioxidants (butylated hydroxytoluene and butylated hydroxyanisole) and phthalate ester plasticizers [28] are under increased scrutiny especially for uses in foods and medical products.

3. Opportunities for obtaining OACs from renewable resources

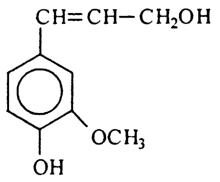
Interestingly, at the same time that synthetic OACs and their production methods are being questioned, scientific discoveries are opening exciting new avenues for obtaining OACs from biological sources. In the following, we summarize some obvious sources of natural OACs and then consider how advances in biotechnology may yield entirely new routes to OAC production.

3.1. Polymeric sources of OACs

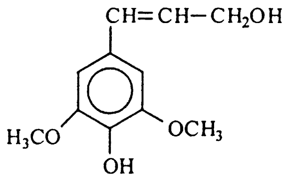
Lignin is the second (or third) most abundant biopolymer after cellulose (and possibly chitin) and lignin is the most abundant polymeric source of aromatics. Lignins are complex aromatic polymers biosynthesized from the three cinnamyl alcohol precursors, *p*-coumaryl, coniferyl, and sinapyl alcohols [29,30]. Commercially, lignins are generated in large amounts as wastes from the pulp and paper industry [31,32] and will likely also be generated as wastes if cellulose-to-ethanol processes become widely adapted. In nature, lignins are believed to play a structural role and lignification is also believed to protect trees from pathogen attack. There have been numerous efforts to convert lignins and lignosulfonates into products including adhesives, and binders [31,33,34]. There have also been efforts to develop lignin polymer blends [35,36] and lignin copolymers [37]. Despite these efforts, the large majority of waste lignins are burnt as a fuel.



p-Coumaryl Alcohol

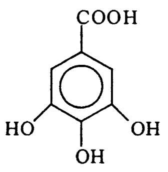


Coniferyl Alcohol

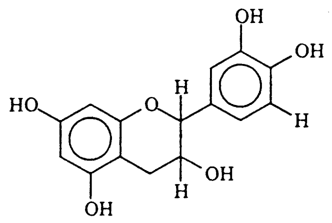


Sinapyl Alcohol

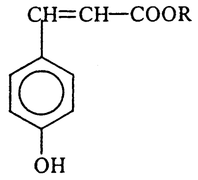
Plant tannins are another polymeric source of OACs. Tannins are typically classified into two groups depending on whether the polymer contains gallic acid derivatives (hydrolyzable tannins) or flavonoids, such as catechin (condensed tannins). Tannins are known to interact with proteins and metals and are believed to play a role in plant defense. For instance, it is believed that tannins bind to proteins and iron to make tannin-rich plant tissue less nutritious and less desirable for insect feeding [38–40]. Historically, tannins have been used in leather making and there remain some efforts to continue vegetable tanning operations given environmental concerns with chromium-based leather tanning [41]. Tannins have also been considered for the production of adhesives [42].



Gallic Acid



Catechin (flavan)



Hydroxycinnamic Ester

Suberins are polyesters consisting of polyaromatic and polyaliphatic domains. The aromatic domain consists of hydroxycinnamic acids — especially aliphatic esters and tyramine amides of ferulic acid [43,44]. In nature, suberins are believed to be important for plant structure and also to be a barrier to water loss and pathogen attack. There have been recent studies on developing suberin-based coatings [45] and viscosifiers [46], and suberin–urethane composites [47].

In addition to using polymeric OACs directly, there have also been efforts to convert these polymers into lower molecular weight products. Depending on the methods used, depolymerization can yield a variety of low molecular weight OACs. For instance, thermal treatment under oxidative conditions can yield aromatic aldehydes and acids, while reductive conditions leads to alkyl phenols, catechols, and guaiacols [32,48–50]. The most successful, and possibly only, example of the commercial conversion of lignins into a chemical product is the flavor chemical vanillin [51,52]. The critical problem appears to be that products of lignin depolymerization exist in a complex mixture and separating individual compounds from these mixtures is difficult.

3.2. Low molecular weight OACs from nature

Natural products offer a diverse array of functional properties that have been exploited for centuries to treat human maladies. In western medicine there has been an emphasis on identifying the chemical compound responsible for biological activity, and either using the chemical directly as a drug, or using it as a prototype for developing synthetic alternatives [53]. Advances in fermentation technology and later biotechnology enabled the production of microbial-derived drugs (antibiotics) and protein-based therapeutics that revolutionized the pharmaceutical industry. A similar revolution is underway in the agrochemical industry where discoveries of the chemicals responsible for natural communication and defense are enabling the development of environmentally safer chemicals for pest control. It seems that an analogous revolution may be emerging in the food industry where there is considerable research on identifying chemicals responsible for beneficial health-effects of some foods (see articles in the Journal of Agricultural and Food Chemistry). This interest is leading to the emergence of a functional-food (nutraceutical) industry.

Just as humans have looked to nature to provide chemicals, or prototypes for chemicals, that offer important functionality in medicine, agriculture, and foods, it seems plausible that nature could provide insights on conferring functionality for industrial chemicals [54]. Chemicals derived from nature are expected to be readily biodegradable. Similarly, chemicals that have been synthesized from natural precursors (sugars, fats, and amino acids) using linkages common in nature (glycosidic, ester, and amide) may also be more environmentally friendly. A couple examples of functionalities that could be obtained from natural OACs are antioxidants (e.g. tocopherols, flavonoids, and gallate esters) and colorants (e.g. flavanoids) [55].

3.3. Metabolic engineering to create OACs

Recombinant technology and metabolic engineering are providing new opportunities to enhance the production of specific compounds and possibly even to generate entirely new chemicals. Although biotechnology has been largely focused on medical applications, there are growing efforts to commercially exploit biotechnology for agriculture, food production, and chemical manufacturing [54,56]. With respect to OACs, there are diverse efforts underway to understand and manipulate the biosynthetic processes used for synthesizing aromatics. For instance, woody plants are being metabolically engineered to have altered lignins so they can be more readily pulped and bleached [29,57,58]. Also, biotechnology is being examined to generate forage legumes with altered tannin levels with the goal of improving forage quality and productivity in the beef, dairy, and sheep industries [40]. It seems plausible that analogous approaches could be exploited to generate transgenic plants engineered to produce desirable low molecular weight OACs [59–61], or to have lignins or tannins altered for industrially useful properties.

There has also been a substantial effort to understand and ‘engineer’ the shikimic acid (chorismic acid) biosynthetic pathway in microorganisms. This pathway is the primary route to the aromatic amino acids tyrosine, phenylalanine, and tryptophan and provides the biosynthetic intermediates for a variety of aromatic products. A group at the US National Institute of Standards and Technology is devoting considerable effort to understanding the thermodynamics and biochemistry of this pathway [62,63]. Also, Frost and co-workers have been examining how this pathway can be manipulated to produce a variety of compounds with interesting functional properties (e.g. vanillin, catechol, and 3-deoxyshikimic acid [64–67]). These, and other efforts, could enable the production of various OACs through fermentation processes.

4. Separations challenge for OAC recovery from renewable resources

A major hurdle to producing chemicals from renewable resources is separations. Distillation has become the separations operation of choice for industrial chemical manufacturing. Although distillation may be well suited for separating the volatile hydrocarbons common in petrochemical processing, distillation is not particularly well suited for separating chemicals from renewable resources. The heteroatoms (nitrogen and oxygen), generally lead to reduced volatilities while most streams generated from renewable resources contain a complex mixture of compounds. Adsorption is an alternative separations approach that has begun to make substantial in-roads in industrial separations [68]. However, adsorption suffers from one important limitation compared to distillation. It is difficult to achieve multiple-equilibrium-staged-contacting by simply contacting the two phases (solid and fluid) in a counter-current manner. To overcome this limitation while achieving multiple-equilibrium-stages, the operating mode for adsorptive separations is typically batch (e.g. chromatography), swing (e.g. pressure swing), or pseudo continuous (e.g. simulated moving bed). Unfortunately, these operating modes can be complex, and large-scale adsorption is only considered when alternative approaches cannot achieve a given separation.

Despite the difficulty in achieving multiple-staged contacting, adsorption offers one major potential advantage over distillation. While distillation uses a non-specific separating agent (heat), adsorption can exploit more specific sorbate–sorbent interactions to separate chemicals. For instance, adsorptive separations have been commercially exploited to separate molecules based on differences in: (i) molecular size and shape (zeolite molecular sieves for fractionating xylene isomers), (ii) charge (ion-exchange resins for separating amino acids), (iii) ability to complex with metals (Ca^{2+}-ions in zeolites or ion-exchange resins for fructose/glucose separation [69]), and (iv) interactions involving planar aromatics (styrenic sorbents for recovering cephalosporins [70]). We believe that adsorption would become a more practical separations alternative if sorbate–sorbent interactions were better understood and could be more effectively controlled. Specifically, better control of adsorption mechanisms could enhance binding selectivity (i.e. separation factors) and reduce the number of required equilibrium stages to achieve a given separation.

5. Hydrogen-bonding as an adsorption mechanism

We have been studying hydrogen-bonding as a specific, low-energy adsorption mechanism that can be exploited to confer selectivity to binding. To exploit hydrogen-bonding, we are studying an acrylic ester sorbent that has a carbonyl group that can serve as a hydrogen-bond accepting site as shown in Fig. 1. We are focused on polymeric sorbents because of the belief that they offer a more homogeneous surface chemistry and, thus, limit adsorption through undesired mechanism. For instance, the acrylic ester sorbent has groups that accept protons for the formation of a hydrogen-bond but this sorbent lacks hydrogen-bond donating groups. Additionally, Fig. 1 shows that we are studying hydrogen-bonding from the non-polar solvent hexane. The choice of solvent is critical and the mechanism for adsorption can vary depending on the solvent environment. For instance, molecular mechanics and experimental results from Mardis et al. [71] indicate that *p*-methoxyphenol adsorbs onto the acrylic ester sorbent through a hydrogen-bonding mechanism when hexane is the solvent, while adsorption from an aqueous solvent involves hydrophobic or van der Waals interactions. Presumably, this change in mechanism results from water's hydrogen-bonding abilities.

5.1. *Phenomenological evidence for a hydrogen-bonding adsorption mechanism*

Traditionally adsorption equilibrium is characterized by the adsorption isotherm. In our work, we generate isotherms using batch adsorption studies and as shown in Fig. 2, we generally confine our studies to the linear region of the isotherm in order to facilitate thermodynamic analysis. When adsorption is confined to the linear region and the intercept passes through the origin, the isotherm slope can be directly related to the adsorption equilibrium constant. For instance, if adsorption follows a Langmuirian model and adsorption is confined to the linear region, then this model simplifies to

$$q = \frac{q_{\max} C}{(1/K) + C} \approx K q_{\max} C \tag{1}$$

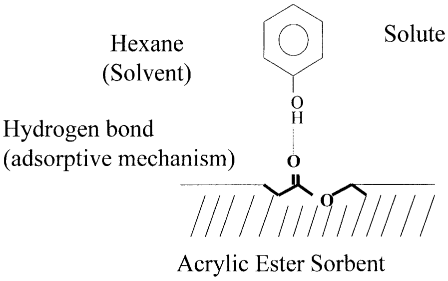


Fig. 1. Schematic illustration of the hydrogen-bonding adsorption mechanism with the acrylic ester (XAD-7) adsorbent. A small molecule analog of the binding site is highlighted in the schematic and this analog is used for spectroscopic investigation of the hydrogen-bonding mechanism.

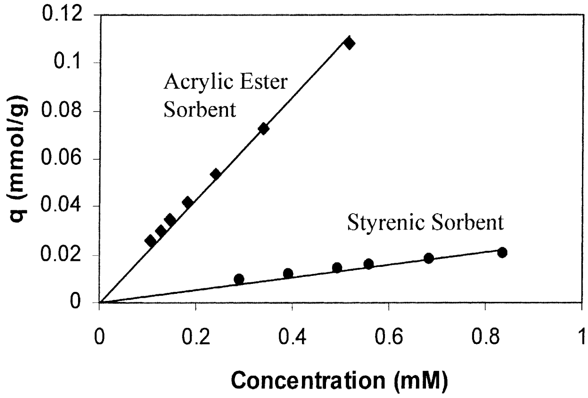


Fig. 2. Isotherms for *p*-cresol adsorption onto the acrylic ester (XAD-7) and styrenic (XAD-16) adsorbents. The specific surface areas for the acrylic and styrenic sorbents are reported to be 450 and 800 m^2/g, respectively. Isotherms are generally confined to the linear, low concentration region to facilitate thermodynamic analysis and the data are clustered in the region that allows most accurate analysis by spectrophotometry. These isotherms demonstrate the importance of adsorbent surface chemistry on adsorption equilibrium [85].

where K is an equilibrium constant for adsorption and $q_{\max}$ the adsorption capacity. To avoid the need to determine the adsorption capacity ($q_{\max}$) or even the shape of the isotherm, we characterize adsorption by an experimentally observed 'adsorption affinity':

$$\text{adsorption affinity} = \frac{q}{C} = K q_{\max} \tag{2}$$

Since $q_{\max}$ should be dependent only on the sorbent surface, then the adsorption affinity should be directly proportional to the adsorption equilibrium constant. We use this approach to compare the adsorptive behavior of various solutes. Additionally, by examining adsorption at various temperatures, it is possible to use the van't Hoff equation to determine the adsorption enthalpy:

$$\frac{\partial \ln(\text{adsorption affinity})}{\partial(1/T)} = -\frac{\Delta H^\circ}{R} \tag{3}$$

Initial evidence for a hydrogen-bonding adsorption mechanism was obtained by comparing the adsorption of various compounds from hexane onto the acrylic ester sorbent. Specifically, compounds with hydrogen-bond donating ability were observed to adsorb with higher affinities than compounds that are unable to form a hydrogen-bond with a carbonyl site [72,73]. Subsequent studies showed that the magnitudes and trends of the adsorption enthalpies were consistent with a hydrogen-bonding mechanism [74]. It is important to note that although adsorption studies provide thermodynamic information, they do not provide direct evidence for the adsorption mechanism.

In subsequent studies we used linear solvation energy relationships to provide phenomenological evidence for the hydrogen-bonding mechanism. Specifically, we examined a series of compounds and observed a correlation between the adsorption affinity and the compound's hydrogen-bond donor acidity [75–78] as shown in Fig. 3 [79]. This correlation provides additional phenomenological evidence for the hydrogen-bonding mechanism of Fig. 1.

5.2. Evidence for hydrogen-bonding from a small molecule analog of the sorbent binding site

Spectroscopic and molecular modeling approaches are commonly used to provide direct evidence of mechanistic interactions. Unfortunately, most spectroscopic approaches are not readily adapted to study mechanistic interactions leading to solute adsorption from a solution onto a porous sorbent. Additionally, molecular modeling approaches to study adsorption are often plagued by the uncertainties in the sorbent surface structure, or the computational cost of

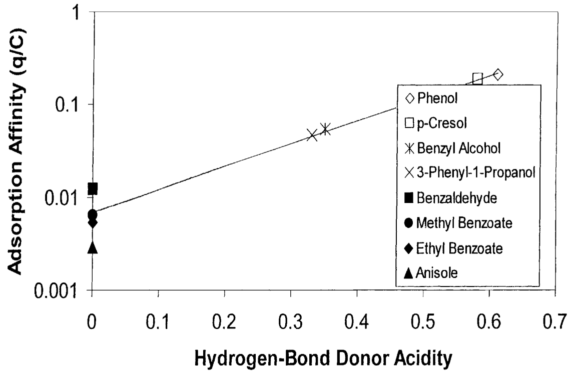


Fig. 3. Phenomenological evidence for the hydrogen-bonding adsorption mechanism. The affinity for adsorption is observed to correlate to a solute's hydrogen-bond donor acidity [79].

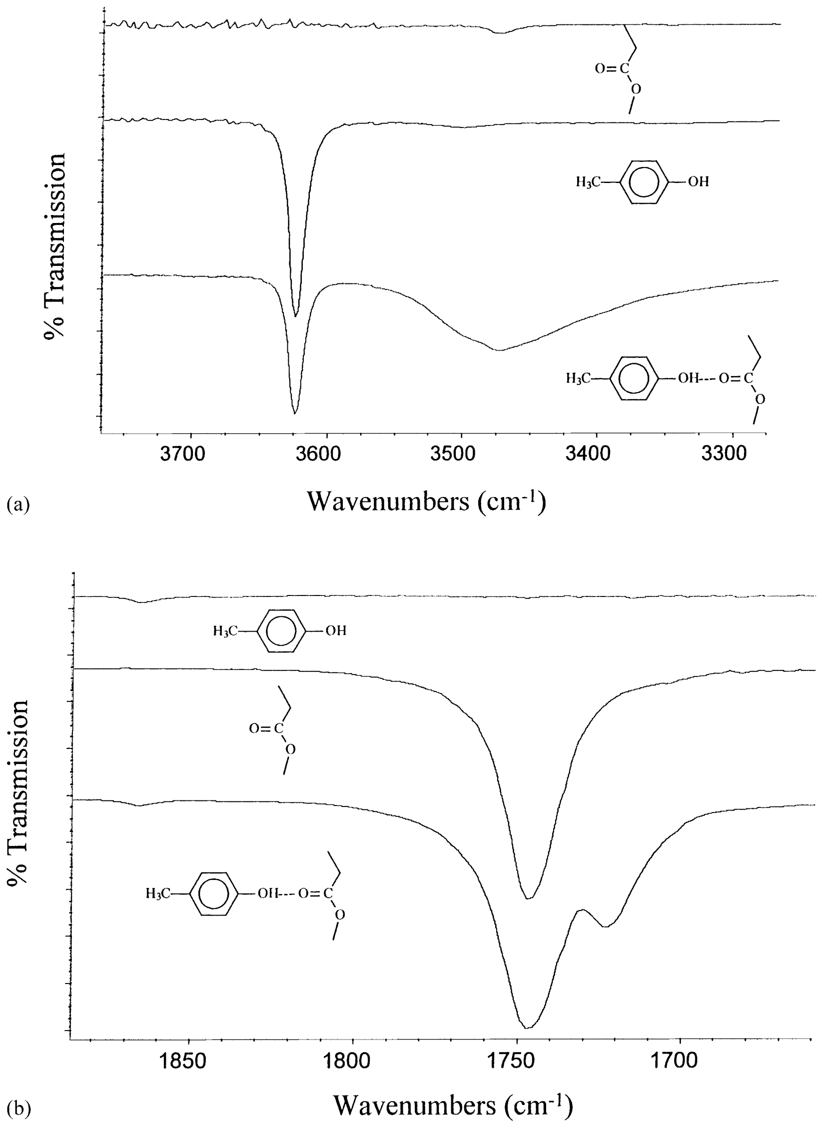


Fig. 4. IR evidence for hydrogen-bonding between *p*-cresol and ethylpropionate (EP), the small molecule analog of the acrylic ester's hydrogen-bonding site. Hexane solutions contained either *p*-cresol (20 mM), EP (50 mM), or both *p*-cresol and EP. (a) Specrta in the OH stretching region. (b) Spectra in the carbonyl stretching region.

modeling a macromolecular surface. To overcome these limitations a small molecule analog of the sorbent surface is often chosen and binding mechanisms are probed using this small molecule analog. As illustrated in Fig. 1, we selected ethylpropionate (EP) as a small molecule analog of the acrylic ester sorbent's binding site. Since EP is soluble in non-polar solvents (e.g. hexane), it is possible to exploit standard spectroscopic approaches to study solution phase hydrogen-bonding between individual OACs and EP.

The most common spectroscopic approach for studying hydrogen-bonding is infrared (IR) spectroscopy [80]. Fig. 4 shows IR spectra for hexane solutions containing either *p*-cresol (20 mM) or EP (50 mM) or both *p*-cresol and EP. In the absence of EP, Fig. 4a shows an absorbance peak at 3623 cm^{-1}, which is assigned to the stretching of the non-hydrogen-bonded hydroxyl group of *p*-cresol. When EP was added to the hexane solutions, Fig. 4a shows that a new peak appears at 3473 cm^{-1}, and this lower frequency peak is assigned to the hydroxyl stretching of the hydrogen-bonded–EP complex. In addition, Fig. 4b shows an absorbance peak at 1746 cm^{-1} for hexane solutions containing only EP. This peak is assigned to the carbonyl stretching of the unbound EP. When *p*-cresol was added to EP, Fig. 4b shows a new absorbance peak appears at 1723 cm^{-1}. This peak at 1723 cm^{-1} is assigned to the hydrogen-bonded carbonyl of the *p*-cresol–EP complex. The spectra in Fig. 4 indicates that an inter-molecular hydrogen-bond is formed between the phenolic hydroxyl of *p*-cresol and the carbonyl of EP.

A second spectroscopic approach that is employed for studying hydrogen-bonding is ^{1}H-NMR. Fig. 5 shows that the ^{1}H-NMR spectrum for *p*-cresol (10 mM) in deuterated benzene. As indicated in Fig. 5 the resonance for *p*-cresol's hydroxyl proton appears at 3.75 ppm. When EP was added to the solution, *p*-cresol's hydroxyl proton resonance shifts downfield, and the downfield shift increases with increasing EP (see insert in Fig. 5). Such downfield shifts are characteristic of hydrogen-bond formation.

Molecular modeling was also used to provide evidence for the hydrogen-bonding mechanism suggested in Fig. 1. The minimum energy conformations for various OAC–EP complexes were observed to have distances (<2.0 Å between the OAC's hydroxyl proton and EP's carbonyl oxygen) and angles (>140° for O–H–O) consistent with hydrogen-bonding [71,81,82]. Importantly, modeling has aided in the interpretation of spectroscopic results. For instance, quantum mechanical calculations indicated that IR frequency shifts were not adequate for distinguishing between two- and three-centered hydrogen-bonds of *o*-methoxyphenol [71]. Also, free energy calculations allowed the various IR peaks for flexible alcohols such as phenylethanol to be related to individual conformers in the population [81].

5.3. Relating small molecule studies to adsorption and direct evidence for hydrogen-bonding

The spectroscopic and computational studies provide definitive evidence for solution phase hydrogen-bonding between OACs and EP. To ensure that the observed solution phase behavior mimics adsorption, we examined various phenols and compared their solution phase hydrogen-bonding with EP to their affinity for adsorbing onto the acrylic ester sorbent. Solution phase hydrogen-bonding was quantified by the shift in the OH stretching frequency between the free and hydrogen-bonded species (i.e. $\Delta\nu = 3623–3473$ cm^{-1} in Fig. 4). Fig. 6 shows that for a variety of phenols, the adsorption affinity can be correlated to

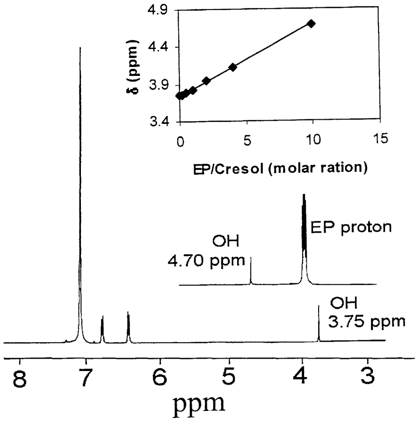


Fig. 5. ^{1}H-NMR evidence for hydrogen-bonding between *p*-cresol and ethylpropionate (EP), the small molecule analog of the acrylic ester's hydrogen-bonding site. Solutions were prepared in deuterated benzene with *p*-cresol (10 mM) and varying levels of EP. In the absence of EP, *p*-cresol's hydroxyl proton has a chemical shift of 3.75 ppm. When 100 mM EP is added to *p*-cresol, the chemical shift of the hydroxyl proton appears at 4.70 ppm. The insert shows the downfield shift in the proton resonance for the phenolic hydroxyl as a function of the added EP.

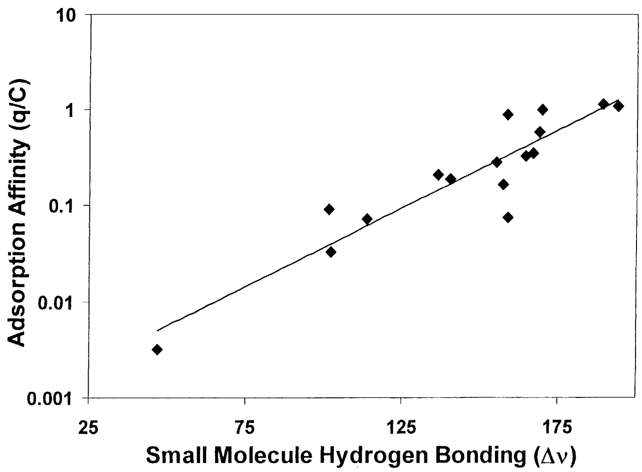


Fig. 6. Correlation between adsorption and small molecule hydrogen-bonding. Adsorption is quantified by the adsorption affinity, while small molecule hydrogen-bonding is quantified by the IR frequency shift in the hydroxyl stretching peak between the free and hydrogen-bonded species [83].

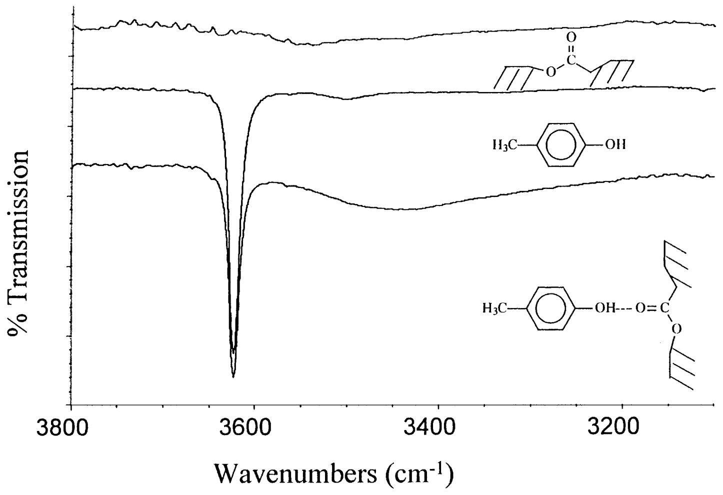


Fig. 7. Direct spectroscopic evidence for hydrogen-bonding between *p*-cresol and the acrylic ester sorbent (XAD-7). Crushed sorbent powder was suspended in hexane solutions in the presence and absence of *p*-cresol (20 mM).

solution phase hydrogen-bonding with EP [83]. This correlation between adsorption and small molecule hydrogen-bonding supports the use of EP as an experimental tool to study adsorption. Further, this correlation also supports the hydrogen-bonding mechanism of Fig. 1.

Currently, we are attempting to correlate results from molecular modeling with observed adsorption behavior. Ideally, modeling would allow calculation of equilibrium binding constants [84] that could be correlated to the equilibrium constants for adsorption (K in Eq. (2)). Initial results comparing phenols with alcohols show agreement in trends between the calculated binding constants with EP and the adsorption affinities with the acrylic ester sorbent [81].

To provide direct evidence for hydrogen-bonding between *p*-cresol and the acrylic ester sorbent, we added crushed sorbent directly to a hexane solution containing *p*-cresol and examined changes in the IR spectra. Fig. 7 shows that the control hexane solutions containing either the sorbent or *p*-cresol has no absorbance in the hydrogen-bonded OH stretching region. When the crushed sorbent and *p*-cresol were added together, Fig. 7 shows that a broad peak appears at 3450 cm^{-1} indicating that *p*-cresol has formed a hydrogen-bond with the acrylic ester sorbent. This result provides direct evidence for the hydrogen-bonding adsorption mechanism of Fig. 1.

6. Exploiting hydrogen-bonding for adsorptive separation

We have examined various examples of how a hydrogen-bonding mechanism could be exploited for adsorptive separations. In the following, we cite three examples relevant to the recovery/separation of OACs from renewable resources.

6.1. Fractionating OACs into four classes

Renewable polymeric materials (e.g. lignins) could provide a source of OACs if processes were available for de-polymerization and conversion into desired products, and if these products could be readily separated. As illustrated in Fig. 8, it seems possible that solid biomass could

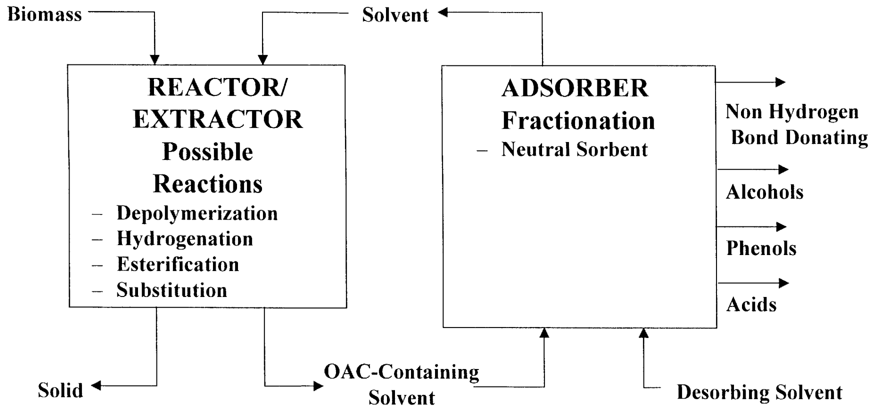


Fig. 8. Schematic for the conversion of biomass to low molecular weight OACs and the subsequent fractionation of these compounds by adsorption.

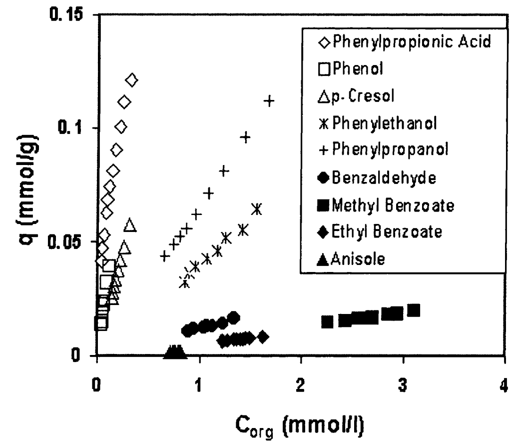
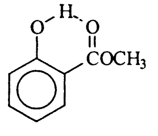


Fig. 9. Isotherms that illustrate differences in adsorption affinities for acids, phenols, alcohols, and non-hydrogen-bond donating OACs. All solutes were adsorbed from hexane onto the acrylic ester sorbent at 30°C [85].

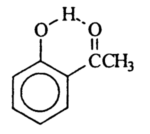
be subjected to conditions not only for its de-polymerization but also to generate hydrogenated, oxidized, esterified, or substituted QACs. Fig. 8 shows that the first step in recovery is extraction of the biomass to transfer low molecular weight species into a low dielectric fluid. Although various low dielectric fluids could be considered, hexane is a likely candidate because it is commonly used in the food industry (e.g. to extract vegetable oils and spices). Thus, we examined how various OACs adsorbed from hexane onto the acrylic ester sorbent [85].

Fig. 9 shows that the acid 3-phenylpropionic acid (i.e. hydrocinnamic acid) has a high affinity for adsorption onto the acrylic ester sorbent but the isotherm shows considerable curvature at higher concentrations. Phenomenological evidence indicates that curvature in this isotherm is due to solution phase interactions and not due to an approach to saturation as expected of Langmuirian behavior. Specifically, acids are known to self-associate to form hydrogen-bonded species such as cyclic dimers. Our evidence suggests that these solution phase self-association interactions compete with the hydrogen-bonding adsorption mechanism [85].

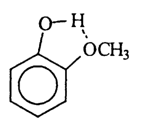
Phenols also adsorb with high affinities and these affinities vary depending on the specific phenol, as shown in Fig. 9. If a phenol has an electron-withdrawing substituent then adsorptive hydrogen-bonding is typically enhanced, while a phenol with an electron-donating substituent will typically form a weaker adsorptive hydrogen-bond. An *ortho*-substituent that can form an intra-molecular hydrogen-bond can dramatically disrupt adsorptive hydrogen-bonding [71,82,86]. The competition between intra- and inter-molecular hydrogen-bonding was studied with *o*-methyl hydroxybenzoate, *o*-hydroxyacetophenone, and *o*-methoxyphenol, and in these cases, the affinity for adsorption of the *ortho*-isomer was observed to be over an order of magnitude less than that of the corresponding *para*-isomer. As will be discussed, bulky *ortho*-substituents can also reduce the adsorptive hydrogen-bonding [87].



o-Methyl hydroxybenzoate



o-Hydroxyacetophenone



o-Methoxyphenol

In addition, Fig. 9 shows that aromatic alcohols (3-phenyl-1-propanol and 2-phenylethanol) adsorb from hexane onto the acrylic ester sorbent with about an order of magnitude lower affinity than that of phenols. This affinity difference should be sufficient to separate alcohols from phenols. In fact, a separation factor of 4 was experimentally observed for the preferential adsorption of *p*-cresol from a hexane solution containing both *p*-cresol and benzyl alcohol [74].

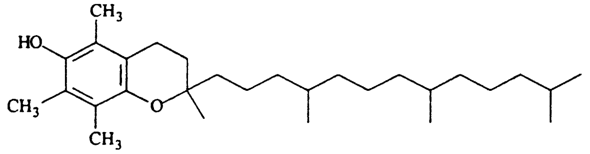
Finally, the compounds that cannot form a hydrogen-bond with the carbonyl site of the acrylic ester sorbent (benzaldehyde, methyl benzoate, ethyl benzoate, and anisole) adsorb from hexane with the lowest affinities (Fig. 9). For these compounds, adsorption is not due to hydrogen-bonding but rather correlates with the dipolarity/polarizability of the OAC [79]. Because of their poor adsorption, non-hydrogen-bonding compounds should be readily separable from acids, phenols, and alcohols.

The isotherms in Fig. 9 suggest that it may be possible to use hydrogen-bonding to fractionate OACs into four classes: (i) acids, (ii) phenols, (iii) alcohols, and (iv) compounds that lack hydrogen-bond donating abilities. Additionally, it may also be possible to enhance OAC fractionation in the desorption step. For instance, we examined how differences in acidity between carboxylic acids and phenols could be exploited for their selective desorption [85].

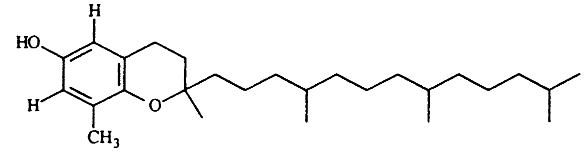
6.2. Separation of structurally similar OACs

Various low molecular weight chemicals could be obtained from renewable resources. However, one problem commonly encountered when recovering a natural product is that various structurally related compounds may also be present. This is the case for the natural antioxidant tocopherols (e.g. Vitamin E), which appear in oilseed crops in various forms. Since α-tocopherol is typically the most desirable anti-oxidant [88], there have been some efforts to separate α-tocopherol from the other forms. This separation is challenging because the only structural difference among the tocopherols is presence/absence of methyl groups at positions 5 and 7 of the chromoral ring. Earlier studies suggested that hydrogen-bonding of the phenolic hydroxyl was attenuated if bulky substituents were present in the *ortho*-positions. Presumably this attenuation in hydrogen-bonding resulted from steric effects since molecular modeling studies indicated that *ortho*-di-substituted phenols formed longer and less linear hydrogen-bonds [83,87].

We examined if such steric effects could be exploited for the adsorptive separation of tocopherols.



alpha-Tocopherol



delta-Tocopherol

Using FTIR and ^{1}H-NMR, we observed that both α-tocopherol and δ-tocopherol could form a hydrogen-bond with EP, the small molecule analog of the acrylic ester sorbent. Additionally, these spectroscopic studies indicated that α-tocopherol–EP hydrogen-bonding was less favorable than δ-tocopherol–EP hydrogen-bonding. These observations are consistent with the explanation that α-tocopherol–EP hydrogen-bonding is attenuated due to the flanking methyl substituents. Consistent with the spectroscopic studies, we observed that δ-tocopherol was preferentially adsorbed onto the acrylic ester sorbent from hexane solutions containing both α-tocopherol and δ-tocopherol. The separation factor observed in this study was 3.3 [89]. This study illustrates that by understanding and controlling the adsorption mechanism it is possible to exploit small differences in binding to obtain separations.

6.3. Exploiting a hydrogen-bonding mechanism in aqueous environments

There are many examples in which OACs exist in aqueous environments (e.g. fermentation processes) and separations will need to account for this solvent. As mentioned, a hydrogen-bonding adsorption mechanism cannot be directly exploited in aqueous solutions because of water's hydrogen-bonding ability [71]. Interestingly, nature has overcome this problem by enclosing hydrogen-bonding sites in non-polar environments. For instance, hydrogen-bonding can be used to confer selectivity to enzyme–substrate binding because the hydrogen-bonding site is located in the internal, low dielectric environment of the enzyme. We mimicked this behavior for adsorption by impregnating the non-polar solvent, hexane, into the pores of the acrylic ester sorbent as illustrated in Fig. 10. Importantly, hexane remains in the pores even when this impregnated sorbent is contacted with an aqueous phase. This system is reminiscent of impregnated styrenic sorbents used for extracting metals [90] and more recently for separating organics [91]. In studies with the styrenics, the porous polymer serves as a scaffold to hold the solvent. In our case, the acrylic ester sorbent serves both to provide a scaffold for the solvent, and to provide hydrogen-bonding interaction sites for adsorption.

As illustrated in Fig. 10, adsorption of solutes from an aqueous solution onto the impregnated acrylic ester sorbent involves two steps. The solute must first partition into the organic pore phase and then the solute can adsorb from the organic pore phase onto the sorbent's hydrogen-bonding site. The overall adsorption equilibrium can be expressed in terms of the individual steps by

$$\frac{q}{C_{\mathrm{aqu}}} = \frac{C_{\mathrm{org,pore}}}{C_{\mathrm{aqu}}}\frac{q}{C_{\mathrm{org,pore}}} = D\frac{q}{C_{\mathrm{org,pore}}} \tag{4}$$

where D is the distribution coefficient for the partitioning step, and the subscripts refer to the liquid phases. If adsorption is confined to the linear region of the isotherm, then the term on the right side of Eq. (4) is given by Eq. (2) for adsorption from the pore phase solvent.

$$\frac{q}{C_{\mathrm{aqu}}} = D\frac{q}{C_{\mathrm{org,pore}}} = D(Kq_{\mathrm{max}}) \tag{5}$$

Eq. (5) is valuable in understanding the behavior of the impregnated sorbent of Fig. 10, because it allows the observed equilibrium, q/C_{aqu}, to be related to the individual steps of partitioning, D, and hydrogen bonding, Kq_{max}. Also, Eq. (5)

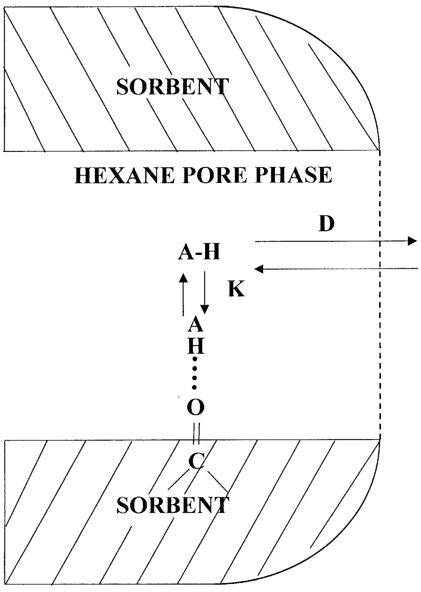


Fig. 10. Schematic of hexane-impregnated acrylic ester sorbent. As illustrated, adsorption onto this sorbent requires partitioning of the OAC from the aqueous bulk phase into the pore phase, and subsequent adsorption onto the polar site of the sorbent. The advantage of this impregnated sorbent is that the non-polar pore phase protects the hydrogen-bonding site from water [92–94]. This impregnated sorbent is analogous to enzymes that exploit polar interaction mechanisms (hydrogen-bonding or ion-pairing) by locating the binding sites in the low dielectric environment internal to the protein.

allows the observed behavior to be predicted from information of the individual steps of partitioning and adsorption [92]. Finally, this formalism can be extended to predict separation factors [93]:

$$\alpha_{12} = \frac{(q/C_{\mathrm{aqu}})_1}{(q/C_{\mathrm{aqu}})_2} = \frac{D_1}{D_2}\frac{(Kq_{\mathrm{max}})_1}{(Kq_{\mathrm{max}})_2} \tag{6}$$

Eq. (6) shows that the separation factor depends on both the relative partitioning from aqueous to organic pore phase, and the relative adsorption due to hydrogen bonding.

To test the behavior of the impregnated sorbent of Fig. 10, we examined the separation of *p*-cresol (1) and phenylpropanol (2). These solutes provide a rather rigorous test of Eq. (6) because partitioning and hydrogen-bonding have counter-acting influences on α_{12}. Specifically, phenylpropanol is preferentially partitioned from the aqueous phase into the hexane pore phase (2.6-fold), while *p*-cresol is preferentially hydrogen-bonded to the sorbent (4.6-fold). Because of the dominant role of hydrogen-bonding, adsorption in the system of Fig. 10, is expected to favor *p*-cresol and in fact the observed separation factor was 1.6. The second reason for choosing this experimental system is that it provides a test of whether the impregnated sorbent of Fig. 10 can offer advantages for separations. If the sorbent pores are filled with the continuous aqueous phase (and not impregnated with hexane) *p*-cresol and phenylpropanol adsorb similarly and the observed separation factor was less than 1.1. This compares with the value of 1.6 observed when the sorbent pores were impregnated with hexane [93].

The use of a non-polar pore phase allows the polar, hydrogen-bonding sites of the acrylic ester sorbent to be exploited for separations even in the presence of an aqueous continuous phase [94]. For solutes to adsorb onto the impregnated acrylic ester sorbent of Fig. 10 they must be capable of both partitioning into the non-polar pore phase and adsorbing onto the polar (e.g. hydrogen-bonding) sites of the sorbent. This coupling of operations (partitioning and adsorption) has also been extended to the coupling of ion-pair extraction and adsorption [95,96].

7. Areas for future advances in adsorptive separation

Despite a growing interest in recovering chemicals from renewable resources, there are substantial separations challenges that must be overcome. Adsorption (including ion-exchange) offers the potential to meet some of these challenges and there are two areas of investigation that we believe promise to have substantial impacts on adsorptive separations. First, is the ability to create more sophisticated binding sites. In the above examples it is seen that a single hydrogen-bonding mechanism can be exploited to confer selectivity to adsorption. It would be desirable if a binding site could be built that coupled multiple mechanistic interactions in a complementary manner. The use of multiple complementary interactions would likely increase both the binding affinity and binding selectivity. Unfortunately, there has been little understanding of how to design such a binding site a priori, while building such a site faces substantial synthetic challenges. These problems have been circumvented somewhat by the development of polymer imprinting [97–99]. More recently, combinatorial approaches have begun to emerge that may allow the rapid screening of a large number of candidate binding sites [100–102].

A second area that promises to impact adsorptive separations is the development of various tools to study mechanisms. Over the last decade there has been a growing use of spectroscopic methods to probe adsorption mechanisms. In addition to experimental tools, there is an increasing use of molecular modeling to study adsorption. Primarily, these approaches have been limited to statistical and molecular mechanics, although there is an emerging use of quantum mechanics for chemical engineering applications [103,104]. Given the ever increasing computer power, and the routine use of modeling in drug discovery, it seems reasonable to expect substantial use of modeling in studying adsorption mechanisms.

Acknowledgements

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