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Membrane Mediated Organocatalyst Separation Methodology

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ABSTRACT

Membranes were fabricated by Ring Opening Metathesis Polymerization (ROMP) of dicyclopentadiene with Grubbs catalyst. Organocatalysts were separated from organic molecules using these membranes. Acid or base was added to organic catalysts that increased the critical area of the organic catalysts to the size range (>0.5 nm^2) where membranes could retain them. The catalysts were too small to be retained by themselves, but the salts were in the range where PDCPD membranes could retain them.

Keywords: Membrane, Organocatalyst, critical area, separation.

INTRODUCTION

Organocatalysis is defined as the acceleration of chemical reactions through the addition of a sub stoichiometric quantity of an organic compound. Although organic molecules have been used for a long time in chemistry, their application in enantioselective catalysis has only emerged as a major concept in organic chemistry in the last few years [1-2]. Enantioselective organocatalysis has received a lot of attention in recent years and has become very important in the synthesis of chiral molecules. Even though Hajos first reported the use of organic molecules as catalyst back in 1974 (Figure 1) [3], the use of small organic molecules to catalyze organic reactions remained unexplored for a long time after that. The decade of 2000 saw organocatalysis emerging into prominence again in a large number of asymmetric reactions [4-9].

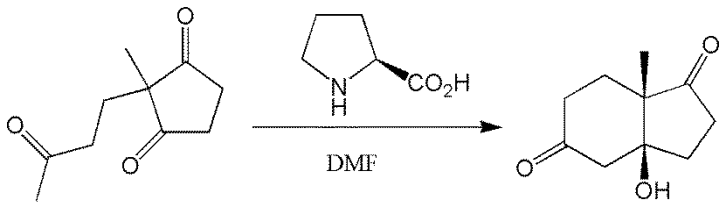

Figure 1*:* An example of an organic reaction catalyzed by L-proline

Organic catalysts can be broadly classified into four major classes. The first one is represented by biomolecules (e.g. proline, threonine and phenylalanine). The second class is represented by imidazoli dinone based organic catalysts. The third major class is based on hydrogen bonding including derivatives of binol and thiourea. The final class of organic catalyst is based on quarternary ammonium salts. Organocatalysts which have a secondary amine functional group undergoes catalysis by two vastly different mechanisms. One of them is the enamine mechanism where the active catalyst is an enamine nucleophile [10]. The second method is the iminium mechanism where the active catalyst is the iminium electrophile [4].

Organic catalysts have several advantages. The most important one is that it does not have any metals, so there is no need to remove any metals from the final product as with organometallic catalysts like palladium catalysts used in a lot of organic reactions. From that perspective, these catalysts are much less toxic as compared to the organometallic catalysts and that makes the synthetic process greener. These organic catalysts are not sensitive to moisture and oxygen which makes them much easier to use as compared to organometallic catalysts like $Pd_2(dba)_3$ and many other catalysts which are very sensitive to oxygen. These catalysts are readily available and are not overly expensive. For example, L-proline which is widely used as an organic catalyst costs $74 per mole, whereas organometallic catalyst like Pd $(OAc)_2$ costs $8980 per mole. Thus these organic catalysts are much attractive options for use in organic reactions nowadays.

Organic catalysts which are based on non-covalent interactions like hydrogen bonding helps low catalyst loading (down to 0.001 mol %)in organic reactions. On the other hand, an organic catalyst which covalently binds to substrates needs high catalyst loading (for proline catalyst usually 20-30%) [11]. Because of such high loadings of catalyst for an organic reaction, it is very important that these catalysts are separated from the organic product at the end of the reaction and recycled for multiple cycles to make the process more cost-effective. Organic catalysts are similar to the organic products in terms of structure, so their separation is not trivial. A lot of research has been done in the past few years to develop ways of easily separating these catalysts from organic products. The method used by a lot of researchers is to link an organocatalyst to a polymer support [9, 12-15]. The idea is this would allow easy separation of the catalysts from the products and facilitate their recycling for multiple cycles. Siegel showed that polymethylhydrosiloxane (PMHS) supported organic catalysts used in Diels-Alder reaction of dienes with α, β-unsaturated aldehydes gave products in high yield and high enantiomeric excess [16]. These catalysts were also recycled for five cycles without any loss of catalytic activity. Macmillan organocatalyst was immobilized onto polystyrene and Fe_3O_4 magnetic nanoparticles through copper-catalyzed alkyne azide cycloaddition reactions [17]. The immobilized catalysts were used in Friedel-Crafts alkylation reactions. These catalysts could be recycled for 6 cycles without any loss of catalytic activity. The disadvantage of using a polymer supported catalyst is the extra synthetic steps that you add to make the heterogeneous catalyst. Another method of separation is synthesizing bifunctional organic catalysts containing acid and basic sites with ionic liquid characteristics that make the catalyst selective as well as recyclable [18].

In this article we describe a method to separate organic catalysts from organic products using an organic solvent nanofiltration membrane based on polydicyclopentadiene (PDCPD). This is the first report of use of a membrane to separate commercially available organic catalysts from products without modifying them. The separation of commercially available organic catalysts without modifying them would make them more exciting than attaching catalysts to immobilized supports. Membranes are commonly used in industry to remove impurities from a mixture of molecules. Separations using membranes are a preferred method for industrial applications as it is a simple and less energy intensive way to purify molecules.

We recently developed size-selective membranes composed of highly cross-linked polydicyclopentadiene (PDCPD) [19, 20]. These membranes were fabricated by ring opening metathesis polymerization of dicyclopentadiene using Grubbs first generation catalyst at a monomer to catalyst ratio of 5000:1. These

membranes do not have well-defined pores but after swelling in organic solvents, they possess openings through which molecules may diffuse through. The distribution in size of these openings is not uniform and they are on nanometer to sub-nanometer scale. We studied the flux of a large number of molecules through PDCPD membranes and discovered that they selectively retained molecules having critical area higher than 0.50 nm^2 but allowed permeation of molecules below 0.38 nm^2. The critical areas were defined as the smallest cross-sectional area for each molecule in its lowest energy state. We observed that PDCPD membranes are a new type of size-selective membrane that separates organic molecules with molecular weights upto 600 g mol^{-1} based on their cross-sectional areas.

In this work we show that for the first time membranes can be used to separate organic catalysts from other molecules. This is an important advancement in the field of easy separation of organic catalysts from other organic molecules without having to modify the catalysts by extra synthetic steps. We show that organic catalysts are too small to be separated using PDCPD membranes, but when they form salts with carboxylic acids or bases that increase their sizes, PDCPD membranes can selectively retain these organic catalysts.

MATERIALS AND METHODS

Materials: Dicyclopentadiene, octylamine, diphenylpropionic acid, triphenylpropionic acid, Macmillan catalyst, L-proline, o-tert-butylthreonine, tetrabytylammonium hydroxide, *p*-dinitrobenzene, and solvents were purchased at their highest purity from Aldrich and Acros and used as received.

Characterization: ^{1}H NMR spectra were acquired using a Bruker DPX-500 at 500 MHz and referenced to TMS.

Fabrication of PDCPD membranes: A 20 mg mL^{-1} solution of Grubbs first generation catalyst was made using 1,2-dichloroethane. A sample of this solution (0.72 mL, 6.0 x 10^{-3} mmol of catalyst) was added to 12 mL of dicyclopentadiene heated to 40 °C. Heat was used to keep dicyclopentadiene (melting point 33 °C) a liquid. This solution was immediately placed between two glass slides with 100 µm thick paper as spacers along the edges. The sample was heated to 50 °C for 2 h and then removed from the glass slides. All PDCPD membranes used in this project were fabricated according to this method.

Permeation of octylamine and carboxylic acids through PDCPD (Table 1 and Figure 3): A PDCPD membrane was added to the apparatus to study permeation. CH_2Cl_2(25 mL) was added to the downstream side of the membrane and 25 mL of the same solvent was added to the upstream side of the membrane with 1 mmol of the molecule and 1.0 mmol of *p*-dinitrobenzene as an internal standard. Solvent on both sides of the membrane were stirred continuously at room temperature. At 24, 48, and 72 h a 1 mL aliquot of solvent was removed from solvent on both sides of the membrane. The aliquots were used to determine the concentration of the molecule and *p*-dinitrobenzene by ^{1}H NMR spectroscopy. The S_d/S_u values were found by the addition of known amounts of tetraethylene glycol to each aliquot to use the known concentration of tetraethylene glycol to calculate the concentration of the molecule of interest.

Permeation of octylamine and Macmillan catalyst salts with carboxylic acids through PDCPD (Table 2, Figure 5 and 6): A PDCPD membrane was added to the apparatus to study permeation. CH_2Cl_2(25 mL) was added to the downstream side of the membrane and 25 mL of the same solvent was added to the upstream side of the membrane with 1 mmol of the octylamine or Macmillan catalyst, 1 mmol of the carboxylic acid and 1.0 mmol of *p*-dinitrobenzene as an internal standard. Solvent on both sides of the membrane were stirred continuously at room temperature. At 24, 48, and 72 h a 1 mL aliquot of solvent was removed from solvent on both sides of the membrane. The aliquots were used to determine the concentration of the molecule and *p*-dinitrobenzene by ^{1}H NMR spectroscopy. The S_d/S_u values were found by the addition of known amounts of tetraethylene glycol to each aliquot to use the known concentration of tetraethylene glycol to calculate the concentration of the molecule of interest.

Permeation of L-proline, *o-tert*-butylthreonine and *p*-dinitrobenzene through PDCPD (Figure 8): A PDCPD membrane was added to the apparatus to study permeation. CH_2Cl_2: MeOH (v/v, 9:1 for proline, 8:2 for *o-tert*-butylthreonine, 25 mL) was added to the downstream side of the membrane and 25 mL of the same solvent was added to the upstream side of the membrane with 1 mmol of the molecule and 1.0 mmol of *p*-dinitrobenzene as an internal standard. Solvent on both sides of the membrane were stirred continuously at room temperature. At 24, 48, and 72 h a 1 mL aliquot of solvent was removed from solvent on both sides of the membrane. The aliquots were used to determine the concentration of the molecule and *p*-dinitrobenzene by ^{1}H NMR spectroscopy. The S_d/S_u values were found by the addition of known amounts of tetraethylene glycol to each aliquot to use the known concentration of tetraethylene glycol to calculate the concentration of the molecule of interest.

Synthesis of L-proline and *o*-tert-butylthreonine salts with tetrabytylammonium hydroxide: Proline or *o-tert*-butylthreonine (1 mmol) was dissolved in 20 mL MeOH. Tetrabutylammonium hydroxide (1 mmol) was dissolved in 8 mL MeOH. The solutions were combined and stirred for 20 min to allow the reaction to happen. After 20 min, $MgSO_4$ was added to the solution to remove the water formed during the reaction. The residue was removed by gravity filtration. The solvent was removed *in vacuo*.

Permeation of tetrabytylammonium salts of L-proline or *o-tert*-butylthreonine salts through PDCPD (Figure 9b). A PDCPD membrane was added to the apparatus to study permeation. CH_2Cl_2: MeOH (v/v, 9:1 for proline salt, 8:2 for *o-tert*-butylthreonine salt, 25 mL) was added to the downstream side of the membrane and 25 mL of the same solvent was added to the upstream side of the membrane with 1 mmol of the salt and 1.0 mmol of *p*-dinitrobenzene as an internal standard. Solvent on both sides of the membrane were stirred continuously at room temperature. At 24, 48, and 72 h a 1 mL aliquot of solvent was removed from solvent on both sides of the membrane. The aliquots were used to determine the concentration of the molecule and *p*-dinitrobenzene by ^{1}H NMR spectroscopy. The S_d/S_u values were found by the addition of known amounts of tetraethylene glycol to each aliquot to use the known concentration of tetraethylene glycol to calculate the concentration of the molecule of interest.

Critical areas of molecules (Table 3). The software used for these calculations was Spartan `08 V1.2.0. The model for each molecule was drawn in the software using a space filling model. The energy was minimized for each molecule using a semi-empirical AM1 to find the conformation with the lowest energy. Each molecule was thoroughly visualized to see which conformation had the lowest cross-sectional area. This method was also described in prior work [21].

RESULTS AND DISCUSSION

How the experiments were completed. PDCPD membranes were fabricated as described in the experimental section (Figure 2). These membranes were cross-linked by the first generation Grubbs catalyst. Dicyclopentadiene has two five membered rings and each of them contain one carbon-carbon pi bond. One of the pi bonds is more strained than the other. The ring opening metathesis polymerization of the highly strained pi bond yielded polymer and the ring opening of the less strained pi bond gave rise to the cross-links. In prior work it was shown that the degree of cross-linking for the PDCPD membrane was as high as 83% [19].

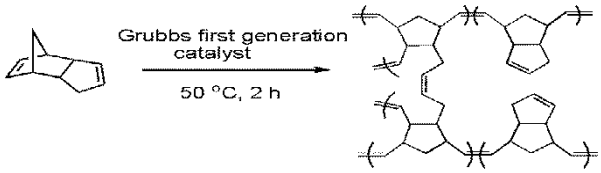

Figure 2. Ring opening metathesis polymerization of dicyclopentadiene with Grubbs 1st generation catalyst at 50 ˚C for 2 h to form PDCPD.

The experimental apparatus for studying the permeation of organic catalysts is shown in figure 3. A 100 µm thick PDCPD membrane was fabricated and placed between two glass parts. Both sides of the membrane were filled with solvent. The side where the molecules to be studied for flux were added was defined as the upstream side. The side of the membrane which only had solvent was defined as the downstream side. The molecules partitioned into the polymer, diffused through it and permeated on to the downstream side. The solvent on both sides of the membrane were constantly mixed using stir bars to ensure uniform concentrations on each side of the membrane. After a period of time, typically 24 h, well defined aliquots of solvent were removed from both sides of the membrane and the solvent was evaporated. An internal standard of tetraethylene glycol was added prior to analysis by ^{1}H NMR spectroscopy to allow the absolute concentrations of each molecule downstream and upstream to be measured.

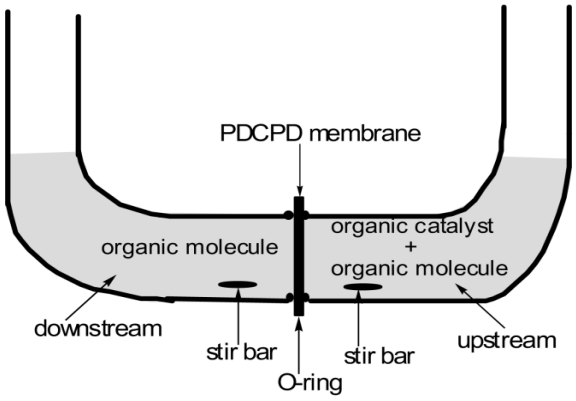

Figure 3. Schematic of the experimental apparatus for permeation experiments.

Separation of octylamine: The separation of octylamine from other organic molecules was chosen because of the similarity in functional group to most of the organic catalysts. They possess an amine group which is seen in all the imidazoline based organic catalysts. The initial test was to prove the concept that amines can be site-isolated by PDCPD membranes.

A mixture of octylamine and p-dinitrobenzene as an internal standard were added to the solvent on the upstream side of the membrane. The ratio of concentration of each molecule in the solvent on the downstream side (S_d) to the upstream side (S_u) was measured every 24 h. The S_d/S_u ratio was zero at the beginning of the experiment as the molecules were added to the upstream side only. The S_d/S_u ratio was equal to one when a molecule diffused such that the concentration was same on either side of the membrane. Both octylamine and p-dinitrobenzene equilibrated after 72 h (entry 1 in Table 1). This result was expected due to the small cross-sectional area of these molecules. From prior work in our group [19], it was known that diphenylamine readily permeated the membrane but triphenylamine did not permeate at any detectable level. Similarly, in our present work we observed that diphenylpropionic acid readily permeated the membrane after 48 h, but triphenylpropionic acid was not detected on the downstream side after 48 h (entry 2 and 3 respectively). The difference in permeation between diphenylpropionic acid (dpa) and triphenylpropionic acid (tpa) was due to the smaller cross-section area of diphenylpropionic acid (0.34 nm^2) as compared to triphenylpropionic acid (0.65 nm^2).

Table 1. Permeation of n-octylamine, diphenylpropionic acid, triphenylpropionic acid through PDCPD membrane.

Entry	Molecule	Molecule S_d/S_u			p-dinitrobenzene S_d/S_u		
		24 h	48 h	72 h	24 h	48 h	72 h
1	n-octylamine	0.770	0.747	1.00	0.876	0.993	1.08
2	diphenylpropionic acid	0.583	0.871	--	0.990	1.19	--
3	triphenylpropionic acid	0.00	0.00	--	0.486	0.931	--

A carboxylic acid was added to solvent on the upstream side of the membrane with octylamine to form a non-covalent bond (figure 4). Octylamine and the carboxylic acid formed a salt pair by transfer of the hydrogen from the acid to the nitrogen. These salts were stable and persistent in organic solvents. Both diphenylpropionic acid (dpa) and triphenylpropionic acid (tpa) had larger cross-sectional area than octylamine, so their addition increased the critical area of octylamine. It was hypothesized that the addition of carboxylic acid would increase the cross-sectional area of octylamine to reach the size range where it can be effectively separated from other molecules by PDCPD membranes.

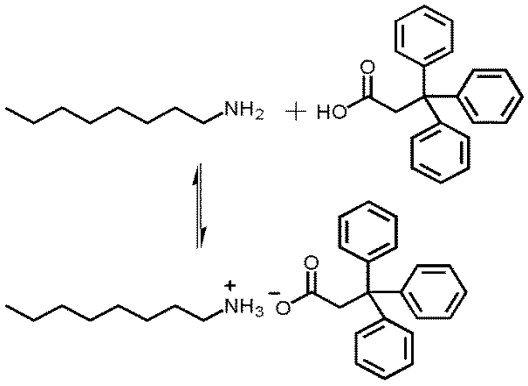

Figure 4. Salt of n-octylamine with triphenylpropionic acid

The results for the flux when a 1:1 molar ratio of octylamine: carboxylic acid was added to the solvent on the upstream side of the membrane was shown in table 2. The addition of diphenylpropionic acid made the flux of octylamine slower after 24 h, but it still equilibrated after 72 h. On the other hand, addition of triphenylpropionic acid made the flux of octylamine so slow that none of it was detected on the downstream side after 72 h.

Table 2. Permeation of salts of n-octylamine with diphenylpropionic acid and triphenylpropionic acid through PDCPD membrane.

	Molecule S_d/S_u			p-dinitrobenzene S_d/S_u		
Molecule	24 h	48 h	72 h	24 h	48 h	72 h
n-octylamine/ diphenylpropionic acid salt	0.230	0.677	1.00	0.793	0.993	0.993
n-octylamine/ triphenylpropionic acid salt	0.00	0.00	0.00	0.582	0.857	0.961

Not surprisingly the use of triphenylpropionic acid (critical area = 0.65 nm^2) stopped octylamine from permeating through PDCPD whereas the use of diphenylpropionic (critical area = 0.34 nm^2) acid did not affect the permeation of octylamine.

Separation of Macmillan organocatalyst: The results of the permeation of octylamine with addition of triphenylpropionic acid proved that other amines can be site-isolated from other organic molecules using this method. Macmillan organocatalyst is similar to octylamine due to the fact that both the molecules have an amine functional group. As shown in Figure 5a, Macmillan catalyst and diphenylpropionic acid had similar rates of permeation through PDCPD, but triphenylpropionic acid did not permeate through PDCPD even after 48 h.

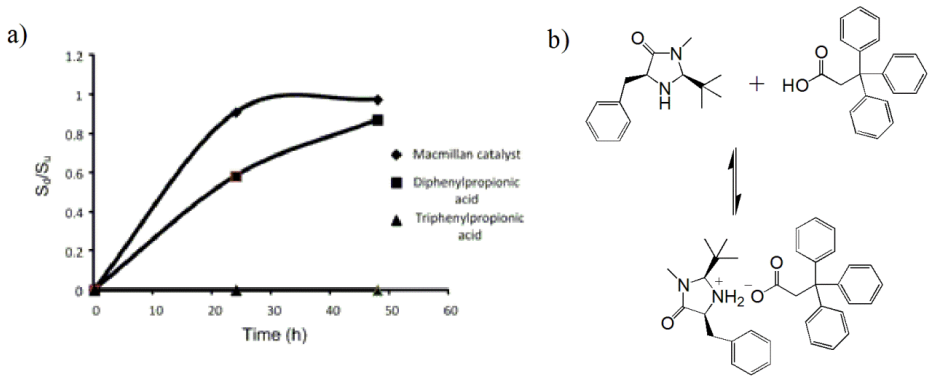

Figure 5. a) Graphical representation of permeation of Macmillan catalyst, diphenylpropionic acid and triphenylpropionic acid through PDCPD membrane. B) Salt of Macmillan catalyst with triphenylpropionic acid.

When 1:1 molar ratio of carboxylic acid was added to the Macmillan catalyst, the salt was formed by the transfer of the hydrogen from the acid to the nitrogen as shown by the triphenylpropionic acid salt of the Macmillan catalyst in figure 5b. As shown in figure 6, the salt with diphenylpropionic acid permeated through PDCPD and was equilibrated on both sides of the membrane after 72 h. The Macmillan catalyst salt with triphenylpropionic acid did not diffuse through the PDCPD membrane onto the downstream side even after 72 h. In both of the experiments *p*-dinitrobenzene permeated through PDCPD and it proved that the slow rate of permeation of the triphenylpropionic acid salt had nothing to do with the unusual properties of that one membrane.

Thus the use of triphenylpropionic acid forms a salt with Macmillan catalyst that has much slower rate of diffusion through the polymer as compared to other organic molecules like *p*-dinitrobenzene and the molecules studied in previous work. This method can be used to separate Macmillan catalyst from organic products after a reaction has been completed. This would also allow recycling of these expensive Macmillan organocatalyst.

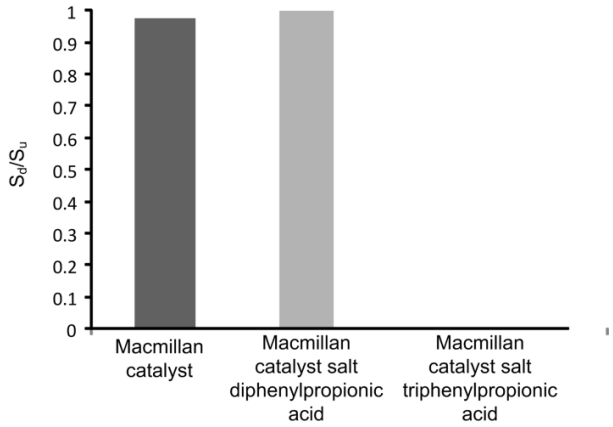

Figure 6. Bar graph representation of permeation of Macmillan catalyst and its salts with carboxylic acids through PDCPD membrane.

Separation of amino acids: Amino acids are organic compounds that consist of amine and carboxylic acid functional group. The amino acids which are commonly used as organic catalysts used in this study are L-proline and O-*tert*-butylthreonine as shown in figure 7. These catalysts are used for both intramolecular and intermolecular aldol reactions.

In neutral conditions they exist as a zwitterion with a positive charge on the nitrogen of the amine and the negative charge on the oxygen of the carboxylate group. All prior experiments used dichloromethane as the solvent on either side of the membrane. Both of these organic catalysts had poor solubility in dichloromethane but had good solubility in methanol.

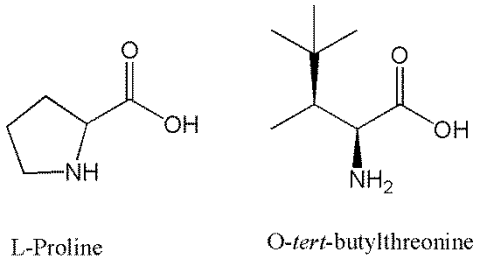

Figure 7. Structure of L-Proline and o-tert-butylthreonine

The flux experiment for L-proline was carried out in 9:1 CH_2Cl_2: MeOH and the experiment for o-*tert*-butylthreonine was carried out in 8:2 CH_2Cl_2: MeOH. The idea was to use minimum amount of methanol to dissolve these molecules because it has been shown in prior work that methanol is not a good swelling solvent for PDCPD. The results of the flux of L-proline and O-*tert*-butylthreonine (Figure 8) showed that while p-dinitrobenzene equilibrated on both sides of PDCPD membrane after 72 h, the rate of permeation through PDCPD membrane was very slow for both these organic catalysts. The S_d/S_u for L-proline after 72 h was 0.266 and S_d/S_u for O-*tert*-butylthreonine was 0.25.

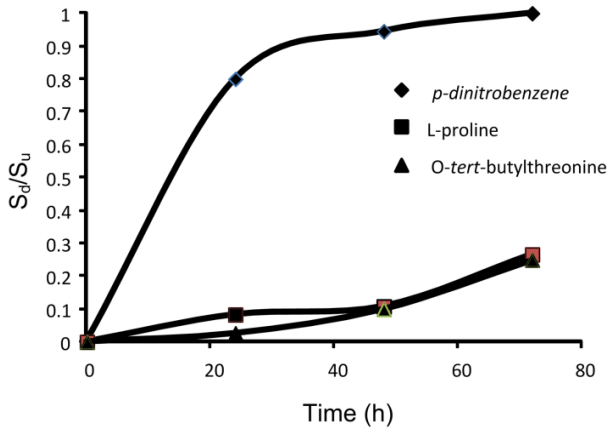

Figure 8. Permeation of L-Proline, o-tert-butylthreonine and p-dinitrobenzene (internal standard) through PDCPD membrane.

When a 1:1 mole ratio of a base like tetrabytylammonium hydroxide was added to the amino acid, a non covalent bond was formed as shown in figure 9a. The amino acid and the base formed a salt pair that was stable in organic solvents. From our prior work it was known that tributylamine does not permeate through PDCPD membrane. It was hypothesized that tetrabytylammonium hydroxide by itself will not permeate PDCPD and thus when it forms a salt with the amino acids it will slow down their permeation through PDCPD membranes. It was also hypothesized that it would be an easy way of separating these organocatalysts from the organic products.

The results for the flux when a 1:1 mole ratio of tetrabytylammonium hydroxide, was added to the solvent on the upstream side of the membrane has been shown in figure 9b. It showed us that without the addition of the base the permeation of the amino acids are pretty slow. It also showed us that the addition of tetrabytylammonium group increased the cross-sectional area of the salt enough to shut down its

permeation across the PDCPD membrane on to the downstream side after 72 h. In each of these *p*-dinitrobenzene equilibrated on both sides of the membrane after 72 h.

The experiment showed that the addition of tetrabytylammonium hydroxide can be used to separate organic catalysts like proline and o-tert-butylthreonine from organic products and thereby recycle the catalysts for further use.

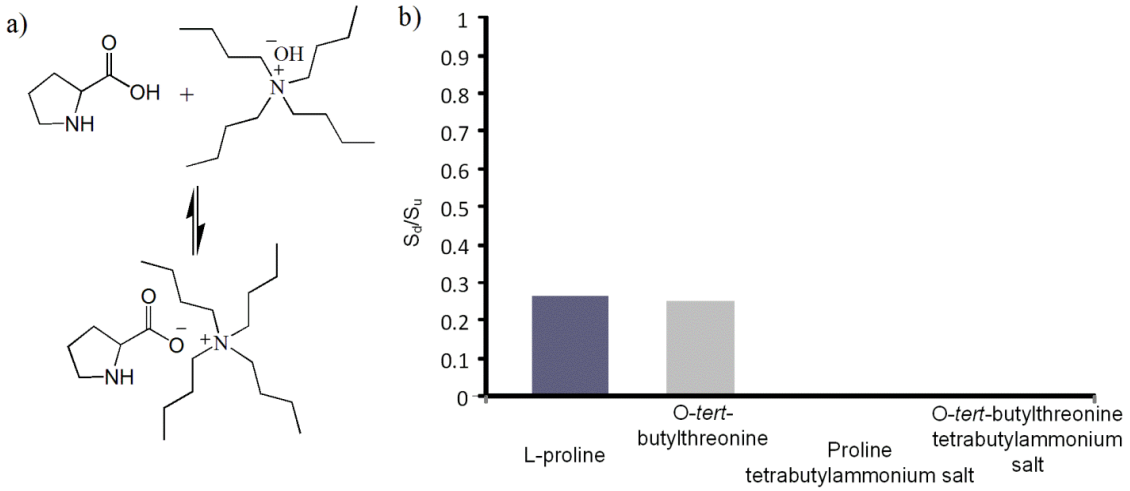

Figure 9. a) Salt of L-Proline with tetrabutylammonium hydroxide. B) Bar graph representation of permeation of L-Proline, o-tert-butylthreonine and their salts with tetrabutylammonium hydroxide.

M**easurement of critical area and the reason of separation using PDCPD membrane**: The permeation of a molecule across a polymer membrane mainly depends on two factors. The molecule must partition into the polymer membrane first, and after partitioning into the membrane it must have a considerable rate of diffusion inside the polymer. The well-known equation P= DS describes this relationship (P is the permeability, D is the rate of diffusion and S is the solubility of a molecule in the membrane). The partitioning coefficient is defined as the ratio of the concentration of a molecule inside a polymer divided by its concentration in the solvent when the system is at equilibrium. Our prior work showed that the fatty acid salts partitioned into the PDCPD similar to the fatty acids themselves [21]. It is hypothesized that the partition coefficient of octylamine and Macmillan catalyst will be similar to the partition coefficient of their salts with diphenylpropionic acid and triphenylpropionic acid. Even though the salts are charged but the charge parts should be encapsulated by the hydrophobicity of the phenyl rings in the acid. The slow rate of permeation of proline (critical area = 0.137 nm^2) can be hypothesized due to slower partitioning of the amino acid into the PDCPD membrane. But again the tetrabutylammonium salt of proline would have similar partition coefficient into the PDCPD membrane.

A difference in partition coefficient was not the reason for different rates of permeation between diphenylpropionic acid salt of Macmillan catalyst and triphenylpropionic acid salt of Macmillan catalyst. The second major factor that contributes to the rate of permeation of a molecule across a polymer is diffusion inside the polymer. Molecules that are smaller than the pores inside a polymer matrix can easily diffuse through the polymer, whereas molecules that are larger than the pores diffuse much slower through the polymer matrix. PDCPD was a highly cross-linked polymer and the rate of diffusion of molecules depended on their critical areas. In prior work, it was shown that molecules above a critical area of 0.50 nm^2 did not permeate PDCPD membranes but molecules with cross-sectional areas below 0.38 nm^2 did permeate.

The critical areas for the molecules in this study were calculated using Spartan `08 V1.2.0. The molecules were building and their energies were minimized using Spartan. The molecules were rotated until the

smallest rectangular cross-sectional area was found, and this value was labeled the critical area and reported in table 3. The critical area was measured because it was the smallest area for the pore that each molecule could diffuse through. For the salts, the energy of the carboxylic acids were minimized and docked in the same conformation with each molecule. The critical areas of the salts were calculated as described above.

Table 3. Critical areas of molecules were calculated using Spartan software

Molecule	Critical Area (nm^2)
n-octylamine	0.067
Diphenylpropionic acid	0.34
Triphenylpropionic acid	0.65
n-octylamine dpa salt	0.418
n-octylamine tpa salt	0.718
Macmillan catalyst	0.36
Macmillan dpa salt	0.424
Macmillan tpa salt	0.837
proline	0.137
Proline salt tetrabutylammonium hydroxide	0.699
Tetrabutylammonium hydroxide	0.558

It is important to note that there are other methods to measure critical areas like different shapes (i.e. sphere, square, oval, etc.) can be used and that will give different values for the critical areas. The variation in the method of critical area calculation is a reason why nanofiltration membranes use molecular weight cut-off instead of critical area cut-off. But the important thing to note is that the use of triphenylpropionic acid makes the critical area of the salts of octylamine and Macmillan catalyst greater than 0.5 nm^2 and therefore these salts have very slow rate of diffusion inside PDCPD. Similarly, tetrabutylammonium hydroxide makes the critical area of amino acid salts greater than the 0.5 nm^2 and that explains the very slow rate of diffusion and permeation across PDCPD membrane.

APPLICATIONS

This membrane mediated separation methodology of organocatalysts can be applied to a greener purification of these catalysts from the products as compared to distillation, column chromatography. This membrane mediated separation method is better as compared to the polymer supported organic catalyst separation method as it does not alter the structure of the catalyst.

CONCLUSIONS

The addition of triphenylpropionic acid and tetrabutylammonium hydroxide led to retention of important organic catalysts like Macmillan catalyst and L-proline respectively. The selective retention as compared to the organic products was because the acid and the base increased the critical areas of the organic catalysts to the size range (>0.5 nm^2) where PDCPD membranes could separate them. The catalysts by themselves were too small to be retained by the membrane, but the salts were in the range where PDCPD retains molecules. The formation of a non-covalent, reversible interaction between the molecules and the acid or the base led to a large difference in permeation across the polymer.

The separation of organic catalysts using membranes is an important advancement in this field of removal of organic catalysts from organic molecules. Membranes are widely used in industry for various applications regarding removal of impurities from a final product. The method of separation of organic catalysts as salts using polymer membranes would be exciting because by this method you can separate commercially available organic catalysts without modifying them with extra synthetic steps. This would also allow recycling of these catalysts for multiple cycles which would make the whole process more cost effective.

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