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Minimizing solvent waste in catalytic reactions in highly recyclable hydrocarbon solvents†

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This paper describes chemistry using organocatalysts in hydrocarbon solvents that minimizes solvent waste by using inexpensive, non-volatile, relatively inflammable, and easily recyclable poly(α-olefin)s (PAOs) as hydrocarbon solvents. These studies show that when substrates have limited solubility in PAO solvents, this issue can be addressed by adding a small amount of a cosolvent. Kinetic studies were also carried out and show that reactions carried out in PAOs are kinetically comparable to reactions in conventional non-recyclable hydrocarbon solvents. A range of strategies that separate and isolate products from reactions in PAOs using a polyisobutylene (PIB)-supported DMAP catalyst have been studied using four different catalytic reactions. In the most general procedure, the PAO phase containing a PIB-bound catalyst is separated from products by low energy liquid/liquid gravity separation. This can be accomplished using a minimal amount of a polar solvent. In another example, the product's low solubility leads to it precipitating during the reaction. In this case, a simple filtration recycles the PAO and a PIB-bound DMAP catalyst. We have demonstrated that the PAO phase containing a PIB bound DMAP catalyst can be recycled for at least 10 cycles without loss of activity. Our studies further showed that leaching of the PAO phase into polar solvents was orders of magnitude less than conventional hydrocarbon solvents such as heptane. The result is that the overall solvent waste generation is lower than for the same reaction carried out in conventional solvents.

Introduction

Solvents typically constitute the major mass fraction of any synthetic or homogeneously catalyzed reaction and are a major component of most synthetic processes. It is thus not surprising that there is great interest in developing greener and more sustainable alternatives for legacy solvents in synthesis and catalysis.[1–3] However, there is an ongoing need for new schemes and new media that can address this problem. Recently, considerable success has accrued to schemes that use surfactants enabling organic chemistry in aqueous media, and to schemes that use less conventional solvents like deep eutectic solvents and supercritical liquids like $scCO_2$.[4–6] Many new sustainable solvents have been developed and evaluated as alternatives to conventional solvents in other chemistry. Resources like the GSK tables of sustainable solvents provide chemists with a list of such solvents.[7] However, most of these solvents are volatile organic compounds that are not always easily recyclable. Nonetheless, since these solvents are derived from biological material, their combustion or degradation does not result in any net greenhouse gas generation (GHG) though there are GHG costs associated with these solvents' syntheses and use.[8] Our interests in solvents are a bit different and are focused on developing solvents or solvent systems that are highly recyclable. Highly recyclable solvents or solvent systems would in principle minimize the need to produce more chemicals and could be a step in what has been described as Moore's Law for Green Chemistry.[9] Recycling would also in effect amortize GHG costs associated with solvent synthesis.

We have suggested that poly(α-olefin)s (PAOs) can be alternatives to hydrocarbons like heptane and hexane. PAOs are prepared on large scale from α-olefins like 1-decene and 1-dodecene.[10–12] These α-olefins are most economically formed from petrochemical ethylene though they could be bio-based since they can also be prepared by renewable starting materials. Our initial studies looked at relatively viscous PAOs solvents that are mixtures of structurally and diastereomeric C_{40}, C_{50}, and C_{60} hydrocarbons formed by oligomerization of 1-decene.[13] Subsequent studies showed that lower viscosity C_{20}, C_{24}, C_{30}, and C_{36} PAO fractions were comparably recyclable and that these PAO fractions can be used in S_N2 chemistry, recycling a hydrocarbon phase-transfer catalyst more efficiently than heptane.[14] We also showed that the flash-point of these PAOs allowed us to substitute them for hexane or heptane to make 'safer' alkyllithium solutions and that products from

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reaction mixtures containing these solvents could be isolated without significant PAO contamination.[15] We have since shown that PAO and PAO solvent systems are useful extractants for removing trace organics from water.[16] These results suggested to us that PAOs could also be effective in other chemistry. The studies below explore these recyclable hydrocarbon solvents in a series of reactions using a recyclable analog of the nucleophilic catalyst 4-(dimethylamino)pyridine (DMAP) and describe various strategies that minimize solvent waste in these sorts of organocatalytic reactions.

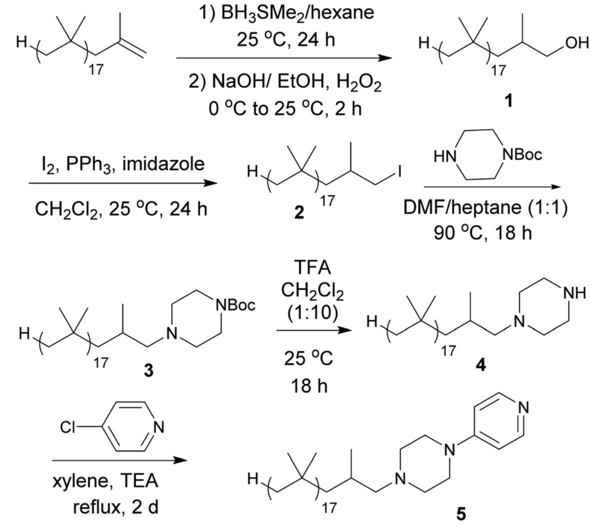
Results and discussion

Poly(α-olefin)s (PAOs) are inexpensive hydrocarbons that are commercially available on large scale.[10–12] While their industrial importance derives from their widespread use as base oils in industrial and automotive lubricants, we have proposed that they could have a role in green chemistry as safer recyclable solvents. In two preliminary studies, we showed that PAOs could be used in place of heptane in phase-transfer catalyzed S_N2 chemistry and that PAOs in place of volatile alkanes make alkyllithium reagents 'safer'.[14,15]

To evaluate PAOs in a broader setting, we here explore their use in organocatalytic reactions showing how PAOs and a catalyst anchored in PAO can be recycled and separated from products using a recyclable analog of the nucleophilic organocatalyst 4-(dimethylamino)pyridine (DMAP) as an example. We also kinetically compared the reactivity of this catalyst in heptane and PAO and to reactivity in PAO containing various cosolvents.

To demonstrate the utility of PAO in catalytic reactions, we chose to prepare a PAO soluble polyisobutylene (PIB)-bound version of 4-(di-methylamino)pyridine (DMAP), **5**, a commonly used nucleophilic catalyst that has been previously attached to many other soluble and insoluble polymer supports.[17–23] 4-(Dimethylamino)pyridine was chosen for this study because DMAP is an efficient catalyst for a variety of reactions[24,25] and would allow us to study a variety of substrates and products that could have varying solubility in PAO. Vinyl-terminated PIB was selected as a phase anchor for this organocatalyst because our prior studies showed that PAO was very effective both as a solvent for PIB-bound azo dyes and as a way to separate these PIB-bound azo dyes from polar organic solvents.[13] This phase selective solubility would ensure high levels of catalyst recovery in recycling studies.

The modified PIB oligomer DMAP-terminated catalyst (**5**) was synthesized starting with commercially available vinyl-terminated polyisobutylene (PIB) that had an M_n value of 1000 Da.[26] This synthesis (Scheme 1) first formed a hydroxy-terminated PIB oligomer (**1**). Compound **1** was next converted to an iodo-terminated PIB oligomer (**2**) by the Appel reaction. Then an excess quantity of Boc ($(CH_3)_3COC(=O)$–) protected piperazine was dissolved in DMF and added to a heptane solution of compound **2** under thermomorphic conditions to convert **2** into the Boc-piperazine-terminated PIB oligomer (**3**). Deprotection of **3** was carried out using trifluoroacetic acid to form the piperazine-terminated PIB oligomer (**4**). Finally, the oligomer PIB **4** was allowed to react with 4-chloropyridine in a nucleophilic aromatic substitution reaction to form the desired DMAP-terminated PIB oligomeric catalyst (**5**).

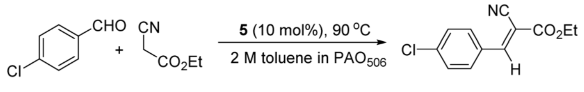


Scheme 1 Synthesis of a PIB-bound DMAP catalyst **5**.

We envisioned two scenarios that could demonstrate the utility of a PAO anchorable catalyst like **5** in a highly recyclable PAO solvent system. In the first, the starting material would be soluble but the product would be insoluble in this hydrocarbon solvent mixture. In this case, we would carry out a reaction and then separate the solid product from the solution. Recycling would only require the addition of fresh substrates.

A second scenario would involve a situation in which the starting materials and product would both be soluble in a PAO solvent system. In this case, we would isolate the product by using a liquid/liquid biphasic separation. Based on our past work, we would have to form a biphasic system using either a perturbant or by using a PAO-immiscible extraction solvent to isolate the product. This scenario would also require that any workup scheme would have to separate the product from the PAO and the catalyst **5** with minimal loss of the PAO or **5**. Ideally, this separation would minimize the amount of the required cosolvents.

The recyclability of PAO and catalyst **5** was first studied using a Knoevenagel condensation of 4-chlorobenzaldehyde, and ethyl cyanoacetate in PAO_{506}, a fully hydrogenated C_{36} trimer of 1-dodecene. This reaction (eqn (1)) used a 10 mol% loading of **5**



(1)

and was carried out for 6 h at 90 °C using 2 M toluene in PAO_{506} as a recyclable solvent system. Toluene was added so that the substrates would be soluble at a 0.3 M concentration. In this example, cooling the reaction mixture to room tempera-

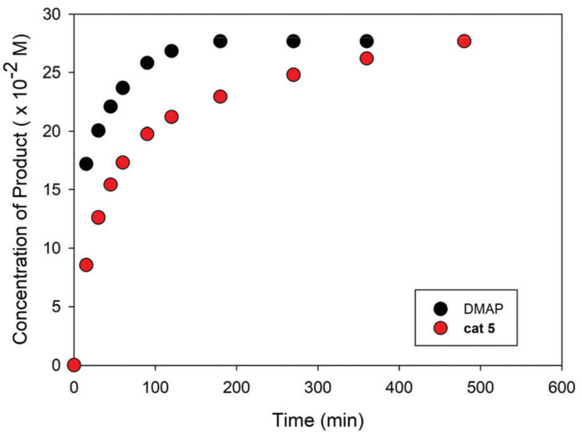
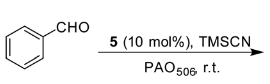


Fig. 1 Comparative plot for the reaction of 4-chlorobenzaldehyde and cyanoacetate using DMAP organocatalyst **5** in PAO_{506} in a Knoevenagel reaction forming a cyanoacrylate product.

ture led to self-separation of the product as a solid. This solid product was separated from the PAO_{506} and PAO_{506}-soluble catalyst by centrifugation and decantation. Fresh substrates were then added to the PAO_{506}/toluene phase containing **5** to effect a second cycle. This process of reaction/separation was repeated for 10 cycles with no significant decrease in volume of the PAO_{506} phase. Conversions in each cycle were analyzed by ^1H NMR spectroscopy and were 98%. While the product self-separated, the precipitated product did contain traces of PAO_{506}. Thus, the combined precipitate from these 10 cycles was triturated twice with 10 mL of heptane. The product so isolated was characterized using ^1H and ^{13}C NMR spectroscopy and had a melting point consistent with that in the literature.[27] The average isolated yield of the isolated product for these 10 cycles was 85%.

This experiment also allowed us to compare the activity of catalyst **5** to a conventional DMAP catalyst in this same 2 M toluene/PAO_{506} solvent mixture (Fig. 1). This comparison used a 5 mol% loading of **5** or DMAP and monitored the formation of cyanoacrylate by ^1H NMR spectroscopy over a 10 h reaction. The results in Fig. 1 show that **5** is comparable in activity to DMAP.

To further explore the utility and recyclability of PAO solvents in reactions catalyzed by **5**, we examined the addition of trimethylsilyl cyanide (TMSCN) to aldehydes in PAO_{506}. DMAP is one example of a commonly used catalyst for this reaction.[28] The starting materials TMSCN and benzaldehyde were soluble in PAO so a cosolvent was not required. This reaction was carried out using 10 mol% of catalyst **5** in 10 mL of PAO_{506} for 2 h at ambient temperature using 0.36 M TMSCN and 0.3 M benzaldehyde (eqn (2)). At this point, the conversion of benzaldehyde to products as measured by ^1H NMR spectroscopy was 100%. However, unlike the example in eqn (1), the products remained in solution. To isolate the product after the reaction was complete, 3 mL of acetonitrile was used to extract the product from PAO_{506} phase. The PAO_{506} phase containing **5** was then reused by adding fresh substrates. Ten cycles were carried out. The average percent yield per cycle after 10 cycles was 95%.



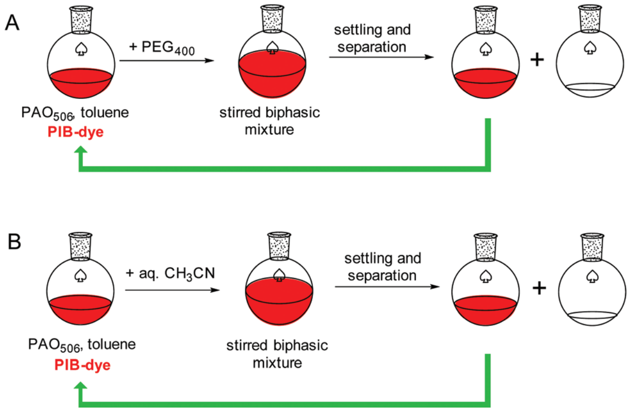
(2)

While substrates can be highly soluble in PAO and while product precipitation has precedent in other catalytic reactions we have studied using heptane soluble PIB-bound catalysts,[29,30] neither case is a general phenomenon in our experience. A more likely situation would be one where a cosolvent is needed to insure that the substrates are soluble in a hydrocarbon like a PAO. In those cases, the product or products too are likely to be soluble and practical schemes would be needed to separate the PAO and the PAO phase-anchored catalyst from the product when using a PAO solvent system.

Most of the catalytic reactions we have studied using recyclable PIB-bound catalysts also used cosolvents. In those cases, we typically used an equivolume mixture of heptane and a polar solvent. A liquid/liquid phase separation separated the heptane solution of a PIB-bound catalyst from the polar organic solvent phase after a temperature change or perturbant addition induced biphase formation.[31–36] However, while PIB-bound catalysts or other alkane soluble polymeric catalysts typically had >99.9% phase selective solubility in those separations and could be separated and recycled, some heptane partitions into the polar organic solvent during the liquid/liquid separation. The *ca.* 5–15% of the heptane that partitions into the polar organic solvent phase is typically removed along with the polar solvent at reduced pressure during product isolation. Thus, while the heptane is only partially recyclable, the products are not contaminated by heptane. That prior work also did not recycle other solvents either.

Our goal in this work was to use the low volatility and phase separability of PAO to maximize the recyclability of a hydrocarbon solvent and to minimize the use of other volatile solvents. However, while 5–15% heptane contamination of the products was not an issue in our earlier work, even small losses of 1–2% of the PAO solvent would pose a problem as the nonvolatile PAO would not be as removable as heptane. To avoid the requirement for an additional purification step, we expanded on a recent study of alkyllithium/PAO reactivity that isolated products with minimal PAO contamination[15] to develop procedures that could usefully separate PAO, a PAO phase-anchored catalyst, and a cosolvent from products with minimal PAO contamination of the product and product solution.

We studied two schemes to separate PAO from a PAO miscible cosolvent. The first (Scheme 2A) involved a liquid/liquid biphasic separation where we added an unfunctionalized PEG oligomer as a perturbing cosolvent. We chose PEG for two reasons. First, PEG (poly(ethylene glycol)) oligomers are one of the few widely used polymeric solvents and PEG is relatively inexpensive and nontoxic.[37,38] Second, poly(alkene oxide)s and polyolefins are immiscible. Second (Scheme 2B), we examined the use of a PAO-immiscible extraction solvent – acetonitrile. The idea was that a small amount of acetonitrile or acetonitrile with 5–10 vol% water would allow us to quantitatively recycle

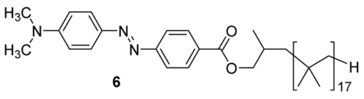


Scheme 2 Schemes A (using a PEG perturbant) and B (using acetonitrile as a immiscible polar solvent) for liquid/liquid separation to recycle a PAO phase from a product phase.

the PAO phase. Our prior work used PAO solvents as safer solvents for reactive alkyllithium reagents and we were able to isolate products without PAO contamination using an acetonitrile extraction step after removal of all the volatile solvents at reduced pressure.[15] However, those experiments typically only used a small amount of PAO and there was no effort to either recycle the PAO or to otherwise reduce the larger amounts of conventional solvents that were not recycled.

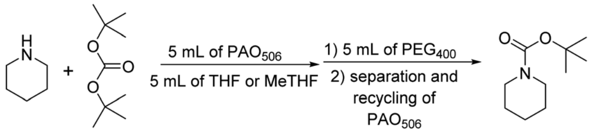
The experiments below address both those issues. To consider what more general schemes for PAO solvent and catalyst recycling might work, we first examined versions of these strategies looking at the separability of PAO_{506}, a cosolvent like toluene or tetrahydrofuran (THF), and a PIB-bound dye (as a PIB-bound catalyst surrogate). Once a separation strategy was established, we explored its practicality in a PIB-bound DMAP catalyzed reaction.

The initial experiments examining PAO immiscible perturbants that could be added to a mixture of PAO_{506} and toluene or THF to induce biphase formation. Unfortunately, addition of perturbants like sucrose, diethylene glycol, acetone, or ethylene diamine did not lead to phase separation of an equivolume mixture of PAO_{506} and toluene or THF. However, a biphase did form using PEG_{400} ($H(OCH_2CH_2)_8OH$) or PEG_{2000} ($H(OCH_2CH_2)_{45}OH$) as perturbants. In these experiments, addition of 5 mL of PEG_{400} or 5 g of PEG_{2000} to an equivolume mixture of PAO_{506} and toluene or THF led to a biphasic mixture where the *ca.* 5 mL of a PAO_{506} phase separated. When this experiment was carried out with a PAO_{506}/toluene or a PAO_{506}/THF solution containing a PIB_{1000}-bound dye **6** (*ca.* 10^{-3} M in dye), the perturbed reaction mixture separated such that visually all of the dye was in the PAO_{506} phase. This qualitative observation suggested that a PIB_{1000}-bound catalyst like **5** too could be recyclable with the PAO_{506} solvent.



6

To explore the viability of using PEG as a perturbing solvent in recycling PAO_{506} we studied Boc protection of an amine and a catalytic Boc protection of a phenol using **5**. In the first of these experiments, we examined the reaction of piperidine with Boc anhydride in a reaction that was carried out at room temperature for 2 h using 10 mL of an equivolume mixture of PAO_{506} and THF or 2-methyltetrahydrofuran (MeTHF) (eqn (3)). Then the miscible solution was perturbed by the addition of 5 mL of PEG_{400}. The product yields in the PEG_{400} phases were determined by ^1H NMR spectroscopy. Up to seven cycles could be carried out. The results showed that the PAO_{506} was fully recyclable through 7 cycles with THF as a cosolvents and through 4 cycles with MeTHF. The product yields averaged 98% in THF and 76% in MeTHF. We believe the slightly higher yield seen in THF *versus* MeTHF results from the fact that the recycled PAO_{506} phase contains more MeTHF than THF and that some product remains in the PAO_{506} phase.



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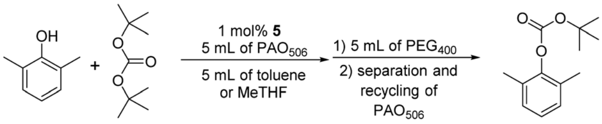
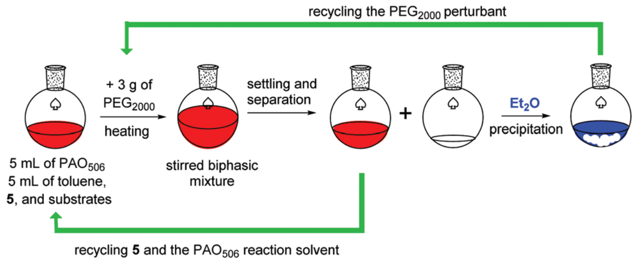
We next explored a similar Boc protection reaction in PAO_{506} using **5** as a catalyst with 2,6-dimethylphenol as a substrate (eqn (4)).



(4)

These studies involved using 10 mL of an equivolume mixture of PAO_{506} and MeTHF or toluene and were carried out for 3 h at room temperature using 1 mol% **5** as a catalyst. ^1H NMR spectroscopy indicated that the conversion of the starting phenol was quantitative. In these reactions the product was isolated by combining the PEG_{400}-rich phases from 5 cycles (*ca.* 7.6 mL per cycle). Water (100 mL) was added and the resulting aqueous phase was extracted 3 times with either diethyl ether if MeTHF was the reaction solvent or toluene if toluene was used as the reaction solvent. The organic phase was then extracted with once more with water and the organic solvent was removed at reduced pressure. The average yield of product for Boc esterifications catalysed by **5** in toluene was 86% and 87% for esterifications carried out in MeTHF.

While these initial experiments showed that we could recycle PAO_{506}, they used a large amount of PEG_{400} and other conventional solvents. Thus, we briefly explored schemes using recyclable PEG_{2000} in place of PEG_{400} (Scheme 3). This experiment also used **5** as a catalyst in Boc protection of 2,6-dimethylphenol. It recycled both the PAO_{506} and the PEG_{2000}. The reaction was carried out using 5 mL of PAO_{506} and 5 mL of toluene. The reaction was complete in 2 h based on ^1H NMR



Scheme 3 Liquid/liquid separation of a PAO_{506} phase from a product phase using a recyclable PEG_{2000} extraction solvent.

spectroscopy analysis for the disappearance of the starting phenol. At this point, 3 g of PEG_{2000} was added to the reaction solution. Brief heating dissolved the PEG_{2000} to form a biphasic mixture which was stirred. Then the mixture was allowed to settle. The less dense PAO_{506}-rich phase was separated from the more dense PEG_{2000}-rich phase and used in a subsequent cycle. The PEG_{2000} phase was then treated with 5 mL of diethyl ether to precipitate the PEG_{2000}. This precipitated PEG_{2000} too could then be reused as a perturbant in subsequent cycles. A total of 5 cycles was carried out with an average yield of product of 51% per cycle for 5 cycles suggesting that the product separates with the PEG_{2000} or is not extracted efficiently from the PAO phase. While this modification of a PEG-induced biphase formation recycled both the PAO_{506} and the PEG_{2000} and used a minimal amount of toluene, it did require significant amounts of diethyl ether. It was clearly a more complicated procedure compared to the cyanohydrin chemistry described above. Thus, we decided to further explore the strategy we used in the cyanohydrin reaction using aqueous acetonitrile as an extracting solvent as a simpler way to recycle PAO_{506} and the PAO-anchored organocatalyst **5**.

To examine how we might use a minimal amount of acetonitrile to extract products from a PAO solvent mixture, we dissolved the PIB-bound dye **6** in 10 mL of PAO_{506} containing 2 M toluene. The dye **6** was used as a surrogate for a PIB-bound catalyst with the expectation that it could be more easily detected than **5**. The end group of **6** is also more polar than **5** so leaching of **5** into a polar phase is expected to be less than that of **6** making 6 as good surrogate for **5**. We also prepared a 2 M solution of toluene in heptane. We then added 3 mL of acetonitrile, 3 mL of acetonitrile with 5 vol% H_2O, or 3 mL of acetonitrile with 10 vol% H_2O, examining the amount of heptane, PAO_{506}, or **6** that leached into the acetonitrile-rich phase (Scheme 2B) from PAO_{506} or toluene. Leaching of **6** was measured by UV-Visible spectroscopy and assumed that the extinction coefficient of **6** was the same in heptane and in the polar acetonitrile-rich phase. We also analyzed heptane and PAO_{506} leaching using ^1H NMR spectroscopy. Prior work[13,15] had already shown that PAO leaching into acetonitrile is minimal (*i.e.* <0.01%). However, we thought that the presence of a cosolvent like toluene could increase the amount of PAO_{506} or **6** that leaches into the polar phase. Our results shown in Table 1 indicate that the leaching of the PIB-bound dye is still low (0.07%) with acetonitrile alone and that leaching can be reduced to 0.03% using acetonitrile that contains some water. We also examined leaching of PAO_{506} into the acetonitrile phase and compared PAO leaching to leaching of heptane in an experiment using 2 M toluene in heptane instead of 2 M toluene in PAO_{506}. Those results in Table 1 show that PAO_{506} leaching was consistently almost 2 orders of magnitude less than heptane leaching and that PAO_{506} leaching is negligible using aqueous CH_3CN as the extraction solvent.

The Boc esterification of 2,6-dimethylphenol catalyzed by **5** was used to test how well this acetonitrile extraction protocol developed using the dye **6** would work in an organocatalytic reaction. This reaction was similar to eqn (4) and used 2 mL of a toluene solution of 3 mmol of 2,6-dimethylphenol and the Boc anhydride in 8 mL of PAO_{506} containing 1 mol% **5**. This reaction was complete after 2 h at room temperature. At that point, the PAO_{506} phase was extracted with 3 mL of acetonitrile containing 10% water. The PAO_{506} phase containing the catalyst was then recycled with fresh substrates for a subsequent reaction cycle. Ten cycles in total were carried out. We combined the acetonitrile extracts from each cycle and washed the combined material with brine to remove water. The acetonitrile was removed at reduced pressure to afford the product. The average isolated yield per cycle for 10 cycles was 88%. The ^1H NMR spectrum of the product so isolated showed that PAO_{506} did not contaminate the product. Moreover, the volume of the recovered PAO_{506} phase after 10 cycles was still *ca.* 8 mL indicating that this procedure did successful recycle the PAO_{506}.

Table 1 Leaching of heptane, PAO_{506}, and the dye **6** into acetonitrile and aqueous acetonitrile from a hydrocarbon solution containing 2 M toluene as a cosolvent

	Leaching into the polar phase (%)		
Non-polar phase (leachate)	CH_3CN	5% aqueous CH_3CN	10% aqueous CH_3CN
2 M toluene in heptane (heptane)[a]	5.6	2.7	1.2
2 M toluene in PAO_{506} (PAO_{506})[a]	0.06	0.03	0.02
2 M toluene in PAO_{506} containing **6** (**6**)[b]	0.07	0.05	0.03

[a] The leaching of heptane or PAO_{506} into the acetonitrile phase was monitored by ^1H NMR spectroscopy (see ref. 13). [b] The amount of leaching of **6** into the acetonitrile phase was monitored by UV-visible spectroscopy measuring the absorbance of **6** in the hydrocarbon phase (420 nm) and the absorbance of **6** in the aceto-nitrile phase (440 nm).

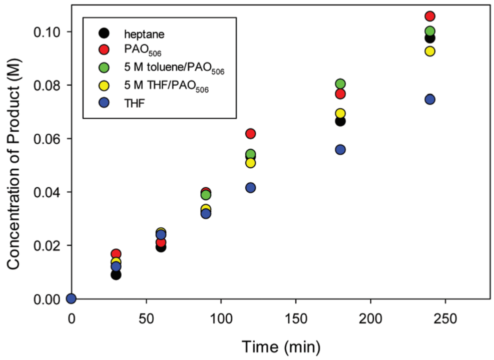
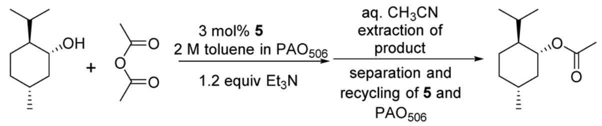


Fig. 2 Plots for formation of Boc-protected 2,6-dimethylphenol using catalyst **5** in heptane, PAO, PAO solvent mixtures, and THF.

We also kinetically compared the rate of Boc-protection of 2,6-dimethylphenol in PAO_{506} solvent systems with similar reactions in conventional solvents. These studies were carried out at 0 °C and used 0.5 mol% **5** as a catalyst with 0.2 M phenol and 0.24 M $(Boc)_2O$. A study of product formation for the initial 30–50% of the reaction showed that product formation was slightly slower in THF but that the reactions occurred at comparable rates in heptane, PAO_{506}, toluene/PAO_{506} and THF/PAO_{506} (Fig. 2).

While the two substrates in this reaction were not present at exactly the same concentration, a pseudo first order plot for the disappearance of the starting material for the first 30–40% of the reaction was linear (see ESI†) and allowed us to calculate rate constants. The results in Table 2 show that these reactions are actually slightly faster in nonpolar media. That result is consistent with others' observations.[39] However, the differences in rate between PAO, heptane, toluene, THF, PAO/toluene, or PAO/THF as solvents are modest (Table 2). Rates in heptane and PAO were very similar as was expected.

Finally, we investigated the recyclability of catalyst **5** in esterification of a secondary alcohol as shown in eqn (5) using the same acetonitrile extraction protocol that was effective in the phenol Boc protection and in the cyanohydrin chemistry. In this reaction, L-menthol was allowed to react with acetic anhydride in the presence



(5)

of PIB oligomer catalyst **5** (3 mol%) containing PAO_{506} and toluene as a cosolvent. The reaction proceeded at ambient temperature for 3 h. Under similar conditions in the absence of catalyst only *ca.* 4% acetylation occurred. Since the by-product acetic acid protonates and deactivates catalyst **5**, we added triethylamine in each cycle to reactivate catalyst **5**. In this case, the PAO_{506} and the catalyst **5** were fully recyclable for 10 cycles. The by-products from this reaction could be extracted from the acetonitrile solution of the product ester using a 10% NaCl solution. Removal of the acetonitrile at reduced pressure than afforded the product menthyl acetate that was pure based on ^1H and ^{13}C NMR spectroscopy. The combined products of 10 cycles showed that the isolated yield of menthyl acetate was 89% per cycle.

Table 2 Effects of solvent on the rate of Boc-protection of 2,6-dimethylphenol[a]

Solvent	Rate constant (min^{-1})
Heptane	6.0×10^{-3}
PAO_{506}	5.4×10^{-3}
5 M toluene/PAO_{506}	2.9×10^{-3}
5 M THF/PAO_{506}	2.4×10^{-3}
Toluene	2.5×10^{-3}
THF	1.9×10^{-3}

[a] Reactions were carried out at 0 °C using 0.2 M 2,6-dimethylphenol, 0.24 M $(Boc)_2O$, 0.5 mol% of **5** and were monitored using ^1H NMR spectroscopy.

Experimental procedures

General information

PAO_{506} (a hydrogenated trimer of 1-dodecene) was obtained from ChevronPhillips and used without further purification.[12] Polyisobutylene (alkene-terminated PIB) with a reported molecular weight (M_n) of 1000 Da was obtained from Texas Polymer Corporation (TPC) and used without further purification.[26] Other reagents were purchased from commercial sources and used without further purification. *p*-Methyl red-terminated PIB (**6**) was synthesized following procedures in a previous reports.[13,40] ^1H NMR and ^{13}C NMR spectra were recorded on a Bruker Advanced NEO 400 spectrometers operating at 400 MHz for ^1H NMR spectra, and 100 MHz for ^{13}C NMR spectra. Chemical shifts were calibrated and reported in ppm using an internal reference of $CHCl_3$ at 7.24 ppm for ^1H NMR and at 77.2 for ^{13}C NMR. UV-Visible analyses were obtained using a Shimadzu UV-2600 spectrophotometer.

Synthesis of hydroxyl-terminated PIB oligomer (1)

Alkene-terminated PIB (50.0 g, 50 mmol) was dissolved in hexane (200 mL). Then a 10 M solution of $BH_3–SMe_2$ (3.0 mL, 30 mmol) was slowly added into the reaction mixture and stirred at room temperature for 18 h. After the reaction was cooled to 0 °C, a solution of NaOH in EtOH and aqueous H_2O_2 was added dropwise to the hydroboration product. The resulting mixture was stirred for 2 h while it warmed from 0 °C to room temperature. The resulting biphasic system was separated and the hexane layer was extracted with water (3 × 200 mL) and washed with brine (2 × 200 mL). The hexane phase was then dried (Na_2SO_4), filtered, and the volatile solvents were removed using a rotary evaporator under reduced pressure to provide **1** (48.3 g, 95%) as a colorless oil. The product was used for next step without purification. ^1H NMR (400 MHz, $CDCl_3$): δ 3.46 (dd, J = 10.3, 5.4 Hz, 1H), 3.29 (dd, J = 10.2, 7.5 Hz, 1H), 0.97–1.40 (m, 181H). ^{13}C NMR (100 MHz,

$CDCl_3$): δ 69.6, multiple peaks between 56.8 and 59.5, 49.5, multiple peaks between 29.2 and 38.1, 20.0.

Synthesis of iodo-terminated PIB oligomer (2)

The hydroxyl-terminated PIB oligomer (**1**) (25.0 g, 24.6 mmol) was dissolved in 100 mL of CH_2Cl_2 and allowed to react for 24 h at room temperature with iodine (9.35 g, 36.8 mmol), triphenylphosphine (9.66 g, 36.8 mmol) and imidazole (2.50 g, 36.8 mmol). After removing the CH_2Cl_2 at reduced pressure using a rotary evaporator, the crude product was purified by column chromatography using hexane as an eluent to give **2** (22.7 g, 82%) as a colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$): δ 3.28 (dd, *J* = 9.4, 4.2 Hz, 1H), 3.15 (dd, *J* = 9.3, 6.8 Hz, 1H), 0.91–1.36 (m, 173H). ^{13}C NMR (100 MHz, $CDCl_3$): δ multiple peaks between 56.9 and 59.4, 52.1, multiple peaks between 29.1 and 38.1, 25.3, 24.0, 22.7, 20.8, 20.7, 14.2.

Synthesis of Boc-piperazine-terminated PIB oligomer (3)

A 50 mL heptane solution of the iodide-terminated PIB oligomer (**2**) (14.0 g, 12.4 mmol) was dissolved in 50 mL of a DMF solution containing 1-Boc-piperazine (15.0 g, 80.5 mmol). The resulting biphasic mixture was heated at 90 °C to form a monophasic mixture. After stirring for 24 h, the reaction mixture was cooled to room temperature to reform a biphasic mixture. The heptane layer was separated and extracted with CH_3CN (3 × 50 mL) and washed with brine (2 × 50 mL). The heptane phase was then dried with anhydrous Na_2SO_4 and filtered. The solvent was removed by using a rotary evaporator under reduced pressure. The crude product was purified by column chromatography using EtOAc : hexane (10 : 90) as an eluent to give **3** (10.65 g, 72%) as a pale yellow oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 3.33 (brs, 4H), 2.21–2.29 (m, 4H), 1.91–2.02 (m, 2H), 0.79–1.26 (m, 190H). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 154.8, 79.3, 67.4, multiple peaks between 51.3 and 59.4, multiple peaks between 26.3 and 38.1, 21.6.

Synthesis of piperazine-terminated PIB oligomer (4)

Compound **3** (7.61 g, 6.4 mmol) was dissolved in 30 mL of CH_2Cl_2 and 3 mL of trifluoroacetic acid. The reaction was stirred at room temperature for 18 h. The solvent was removed using a rotary evaporator under reduced pressure to yield an oily residue which was dissolved in 50 mL of hexane. The hexane phase was then washed with 1 M NaOH (3 × 50 mL) and brine (2 × 50 mL), filtered, and concentrated under reduced pressure using a rotary evaporator to afford **4** (6.58 g, 94%) as a colorless oil. The product was used in next step without further purification. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 2.79 (brs, 4H), 2.28–2.32 (m, 4H), 1.89–2.00 (m, 2H), 1.82 (brs, 1H), 1.61(brs, 1H), 0.92–1.35 (m, 166H). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 68.0, multiple peaks between 51.4 and 59.5, 46.1, multiple peaks between 29.2 and 38.3, 26.1, 21.6.

Synthesis of modified DMAP-terminated PIB oligomer (5)

Piperazine-terminated PIB oligomer (**4**) (3.00 g, 2.8 mmol) and triethylamine (2.2 g, 21.7 mmol) were added into 15 mL of xylene. 4-Chloropyridine (2.50 g, 22.0 mmol) was added and the reaction mixture was allowed to reflux for 48 h. After 48 h, the reaction was cooled down and the xylene was removed under reduced pressure using a rotary evaporator. The residue was dissolved with 50 mL of hexane and extracted with CH_3CN (3 × 50 mL), 1 M NaOH (2 × 50 mL) and brine (1 × 50 mL), filtered, dried (Na_2SO_4), and the hexane were removed at reduced pressure using a rotary evaporator. The oil that was isolated was then purified by basic alumina column chromatography using EtOAc : hexane (5 : 95) as an eluent to give **5** (1.95 g, 61%). ^{1}H NMR (400 MHz, $CDCl_3$) δ: 8.18 (d, *J* = 6.5 Hz, 2H), 6.56 (d, *J* = 6.6 Hz, 2H), 3.23 (t, *J* = 5.1 Hz, 4H), 2.39–2.50 (m, 4H), 1.97–2.07 (m, 2H), 0.92–1.34 (m, 160H). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 155.0, 150.2, 108.3, 67.2, multiple peaks between 57.1 and 59.5, 53.0, 51.3, 46.0, multiple peaks between 29.2 and 38.1, 26.4, 21.6.

General procedure of for Boc protection catalyzed by PIB-supported DMAP catalyst (5)

A mixture of 2,6-dimethylphenol (3 mmol) and di-*tert*-butyl dicarbonate (Boc_2O) (3.3 mmol) was dissolved in toluene (2 mL). PAO (8 mL) containing catalyst **5** (0.03 mmol, 1 mol%) was added and the resulting solution was stirred at room temperature for 3 h. After the reaction was complete, the product was isolated by extraction with 3 mL of 10% aqueous CH_3CN. The CH_3CN phase containing product was separated. Then fresh substrates were added to the PAO_{506} phase containing **5** for the next cycle without any toluene addition. After 10 cycles, the CH_3CN phases were combined, extracted with brine (2 × 20 mL), dried (Na_2SO_4), filtered, and the CH_3CN was removed at reduced pressure using a rotary evaporator to obtain the product. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.08 (bs, 3H), 2.25 (s, 6H), 1.60 (s, 9H). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 151.4, 148.5, 130.3, 128.7, 125.9, 83.0, 27.7, 16.1.

General procedure of 5-catalyzed esterification using acetic anhydride

L-Menthol (3 mmol), acetic anhydride (3.3 mmol), and triethylamine (3.6 mmol) were dissolved in 10 mL of 2 M toluene solution in PAO_{506} that contained 3 mol% of catalyst **5**. After 3 h stirring at room temperature, the product was isolated by extraction with 3 mL of 5% aqueous CH_3CN. The CH_3CN phase was separated and the PAO_{506} phase containing **5** was mixed with fresh substrates for a subsequent reaction cycle. After 10 cycles, the CH_3CN phases were combined, extracted with brine (2 × 20 mL), dried (Na_2SO_4), filtered, and the CH_3CN was removed at reduced pressure using a rotary evaporator to obtain the product. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 4.64–4.71 (m, 1H), 2.04 (s, 3H), 1.97–2.02 (m, 1H), 1.83–1.91 (m, 1H), 1.63–1.73 (m, 2H), 1.43–1.55 (m, 1H), 1.33–1.40 (m, 1H), 0.95–1.13 (m, 2H), 0.91 (dd, *J* = 6.6, 2.2 Hz, 7H), 0.77 (d, *J* = 7.0 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 170.4, 73.9, 46.9, 40.9, 34.2, 31.3, 26.2, 23.4, 21.9, 21.1, 20.6, 16.2.

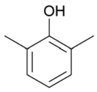
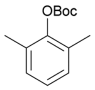
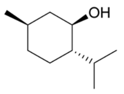
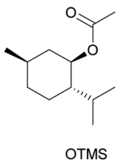
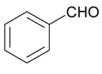
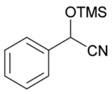
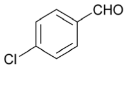
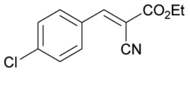
General procedure for the reaction between trimethylsilyl cyanide and benzaldehyde

Benzaldehyde (3 mmol) was dissolved in PAO (10 mL) containing catalyst **5** (0.3 mmol, 10 mol%). Trimethylsilyl cyanide (3.6 mmol) was then added and the reaction mixture so formed was allowed to stir for 2 h at room temperature. At that point, 3 mL of CH_3CN was added to extract the product from the PAO_{506} phase. The separated. PAO_{506} phase containing **5** was then mixed with fresh substrates for a subsequent reaction cycle. After 10 cycles, the CH_3CN phases were combined, extracted with a 10% NaCl solution (2 × 20 mL), dried (Na_2SO_4), filtered, and the CH_3CN was removed at reduced pressure using a rotary evaporator to obtain the product. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.22–7.34 (m, 5H), 5.36 (s, 1H), 0.088 (s, 9H). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 136.6, 129.6, 129.2, 126.2, 119.5, 63.9, −0.004.

General procedure for the Knoevenagel condensation reaction

4-Chlorobenzaldehyde (3 mmol) and ethyl cyanoacetate (3.9 mmol) were dissolved in a mixture of 2 mL of toluene and 8 mL of PAO_{506} containing 0.3 mmol (10 mol%) of catalyst **5**. The resulting reaction mixture was heated at 90 °C. After 6 h, the reaction was cooled to room temperature at which point the product precipitated. The precipitate was isolated by centrifugation (3000 rpm) for 30 min. The supernatant was decanted and the solution of toluene, PAO_{506}, and catalyst **5** was reused by adding fresh substrate for the next cycle. After 10 cycles, the combined precipitated product phases were washed with heptane (2 × 10 mL) and dried to yield the product, m.p. 88–91 °C (lit.[41] 89–90 °C). ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.84 (d, J = 8.6 Hz, 2H), 7.39 (d, J = 8.6 Hz, 2H), 4.30 (q, J = 7.1 Hz, 2H), 1.32 (d, J = 7.1 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 162.2, 153.4, 139.6, 132.2, 129.7, 115.3, 103.5, 62.9, 14.2.

Table 3 Summary of results using catalyst **5** in PAO_{506} and PAO_{506}/cosolvent systems where the PAO_{506} and the catalyst **5** was separated and recovered *via* a liquid/solid or a liquid/liquid separation for 10 cycles in various types of chemistry

Substrate	Product	Time (h)	Yield (%)
		3	88
		3	89
		2	95
		6	85

Conclusions

The results of these studies show that PAO solvents or solvent systems can be substituted for conventional solvents in a variety of DMAP-catalyzed reactions. These PAO solvent systems can be designed such that they and a PAO phase-anchored organocatalyst can be recycled for at least 10 cycles minimizing the amount of solvent needed for these catalytic transformations. By using PIB-bound version of the known catalyst DMAP that is useful in a variety of reactions, we were able to show that using these solvent systems is broadly useful in reducing solvent waste while affording products in good isolated yields (Table 3). In each of these four examples, no loss of the PAO solvent was seen over 10 cycles of the reactions catalysed by the DMAP analog **5**.

Conflicts of interest

There are no conflicts of interest to declare.

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