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Journal of Chromatography B, 807 (2004) 145–149
JOURNAL OF CHROMATOGRAPHY B
www.elsevier.com/locate/chromb

Application of polyethylene glycol-based aqueous biphasic reactive extraction to the catalytic oxidation of cyclic olefins

Ji Chen, Scott K. Spear, Jonathan G. Huddleston, John D. Holbrey, Robin D. Rogers*

Department of Chemistry and Center for Green Manufacturing, The University of Alabama, Tuscaloosa, AL 35487, USA

Available online 27 February 2004

Abstract

Glutaric acid and 1,2,3,4-butanetetracarboxylic acid (BTCA) have been synthesized by sodium tungstate catalyzed oxidation of the cyclic olefins: cyclopentene and 1,2,3,6-tetrahydrophthalic anhydride (THPA), using hydrogen peroxide in a polyethylene glycol (PEG)-2000/$NaHSO_4$ aqueous biphasic system (PEG-ABS). The production of glutaric acid and BTCA was found to increase from the monophasic to the biphasic regimes, and was found to be greatest at short tie-line lengths (TLLs), close to the system's critical point, yielding glutaric acid and BTCA in 73.1 and 82.5% yield, respectively. The results imply that mutual mixing or contact of the components is important, because the product dicarboxylic acids were found to increase from the monophasic side to the critical point and decrease from the critical point to more divergent regimes. The two reactions were compared with adipic acid synthesis from cyclohexene in terms of the cyclic olefin structure, and the partitioning of the dicarboxylic acid product in the ABS.

Keywords: Aqueous two-phase systems; Catalysis; Oxidation; Cyclic olefins

1. Introduction

Research and development in the use of alternative reaction media with an increased awareness of the need for 'Green Chemistry' have been spurred by the effect of several protocols, regulations, and laws such as The Montreal Protocol, The Superfund Amendments and Reauthorization Act (SARA), The Clean Air Act, and Toxic Substances Control Act, which govern the manufacturing, use and disposal of organic solvents [1]. It is our opinion that ABS should be investigated as potentially important green solvent systems, with reduced hazards to human health and the environment, compared to many aqueous–organic biphasic systems [2,3].

Aqueous biphasic systems (ABSs) have been used in biomolecular and particle separation [4–9] for almost 50 years. More recently, we have investigated the partitioning and separation of organic hydrocarbon species [10–13] and metal ions [14–17] in ABS to obviate the need for volatile organic solvents (VOCs) in liquid/liquid partitioning. Other researchers have now started to examine low molecular weight liquid polyethylene glycol (PEG) as new solvent systems for reactive chemistry, e.g., for osmium tetroxide catalyzed asymmetric dihydroxylation [18], polyoxometallate catalyzed aerobic oxidation [19], hydrolysis reactions [20,21], and as alternative phase transfer catalysts (PTC) [22]. ABS, on the other hand, have been largely ignored as "green reaction media" for chemical reactions, although a certain number of enzyme hydrolysis bioconversion reactions have been conducted in ABS [7]. Recently, however, we demonstrated how ABS can be used as a reaction media for aqueous biphasic reactive extraction (ABRE) in the synthesis of adipic acid from cyclohexene in a PEG/$NaHSO_4$ ABS [23].

We have used the term ABRE to describe the use of ABS as biphasic reaction media in which controlling the partitioning of reactants, catalysts, and products can be used to enable higher reaction yields, greater product selectivity, and easy separation of products [24]. Combining reaction and extraction in a single step, instead of separate unit operations, leads to greater process integration. Here, we expand our investigations to include the synthesis of glutaric acid and 1,2,3,4-butanetetracarboxylic acid (BTCA) via oxidation of cyclopentene or 1,2,3,6-tetrahydrophthalic anhydride (THPA) using an ABRE system comprised of PEG-2000 and $NaHSO_4$ in water.

* Corresponding author. Tel.: +1-205-348-4323; fax: +1-205-348-0823.
E-mail address: rdrogers@bama.ua.edu (R.D. Rogers).

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doi:10.1016/j.jchromb.2004.01.047

Glutaric acid is an important industrial by-product of adipic acid production, representing 2% of the output of a DuPont adipic acid plant [25]. It is a straight five-carbon chain dicarboxylic acid ($pK_1 = 4.33$, $pK_2 = 5.22$ at 25 °C) with high solubility in water (639 g/l H_2O at 20 °C) [26]. Currently, most industrial glutaric acid production processes use hot 50% nitric acid oxidation of cyclopentanone in the presence of vanadium pentoxide. This process results in the emission of N_2O, and is a considerable source of N_2O environmental pollution [26,27].

BTCA is an important intermediate in preparation of cellulosic reverse osmosis membranes, and chelating resins, and is a cotton textile cross-linking agent [28,29]. Both nitric acid oxidation and H_2O_2 oxidation have been used to synthesize BTCA from THPA [29,30].

Noyori and co-workers [31] recently demonstrated adipic acid, glutaric acid, and BTCA synthesis from catalytic oxidation of cyclohexene, cyclopentene, and THPA with hydrogen peroxide and sodium tungstate, in the presence of $[CH_3(n\text{-}C_8H_{17})_3N]HSO_4$ as a PTC. The use of H_2O_2 as a green oxidant for both homogeneous and heterogeneous reactions has been highlighted by some recent reviews [32,33]. PEG itself has some well-known advantages as a PTC. It is inexpensive, non-toxic, stable, and easily recovered by suitable organic solvent extraction or distillation of water or other corresponding solvents in PEG aqueous or organic solution [34].

2. Experimental

2.1. Chemicals and HPLC reagents

All reagents were purchased from Aldrich (Milwaukee, WI) and used as received. Water was purified using a Barnstead (Dubuque, IA) commercial deionization and polishing system.

2.2. Apparatus

The analysis of glutaric acid and BTCA were performed at room temperature using an AquaSep C8 reversed-phase column (150 mm × 4.6 mm I.D., 5 μm, 100 Å, ES Industries, NJ, USA). The HPLC system (Shimadzu Corporation, Kyoto, Japan) consisted of a LC-10AT pump, FCV-10AL VP gradient valve, DGU-14A in-line solvent degasser, SCL-10A system controller, Rheodyne auto injector, and SPD-10 AV UV-Vis detector. Data were collected and analyzed on a personal computer using Class VP software (version 4.2, Shimadzu).

2.3. Representative reaction procedure

A 250 ml round-bottomed flask equipped with a magnetic stir bar, a thermometer, and a reflux condenser was charged with 0.186 g (0.566 mmol) $Na_2WO_4{\cdot}2H_2O$, 12.5 g PEG-2000, 10 g $NaHSO_4$, and 30.0 g (441 mmol) 50% H_2O_2. Five milliliters of cyclopentene (density of cyclopentene 0.81 g/cm^3) or 9.26 g THPA (60.85 mmol) was added. The mixture was heated to 91 °C for 8–10 h, then cooled to room temperature. The dicarboxylic acids were analyzed by HPLC directly without further isolation from the mixture.

2.4. Product analyses

A series of glutaric acid and BTCA concentrations were used to make the working standard curve. Calibration curves were linear over the concentration range of 0–200 g/l for glutaric acid ($y = 6.92 \times 10^5 + 1.94 \times 10^5 x$, $r = 0.9952$) and 0 to 5 g/l for BTCA ($y = 1473 + 379283x$, $r = 0.9944$). In both cases, x is the dicarboxylic acid concentration, while y is the peak integration area. Analytical samples were made by dilution of 1 ml product mixtures with water to 10 ml final volume for glutaric acid, and to 50 ml final volume for BTCA without additional treatment. 20 μl samples were injected directly onto the HPLC column. The product yield was calculated from the calibration curve. 0.05 M and 0.1 M KH_2PO_4 was used as the mobile phase for glutaric acid and BTCA, respectively. The flow rate was 1 ml/min, and the UV detector was set at 210 nm. The product glutaric acid and BTCA were confirmed by comparing the retention time with that of a standard. The retention time for glutaric acid was 8.10 min, while the H_2O_2 peak appeared at 1.88 min; small peaks appearing at 3.10 min and 4.50 min were attributed to intermediates. BTCA corresponds to the peak with a retention time of 3.00 min, while the peak with retention time

Table 1
Reaction conditions and product yields in 50% H_2O_2

Batch no.	Mass of PEG/$NaHSO_4$[a] (g)		Yield (%)		
	PEG-2000	$NaHSO_4$	Glutaric acid	BTCA	Adipic acid[b] (purity, %)
1[c]	12.5	0	Trace	Trace	Trace
2	12.5	3.85	20.0	19.0	18.1 (98)
3	12.5	10	46.1	50.2	40.1 (95)
4	5.0	10	50.0	78.8	50.0 (97)
5	2.5	10	73.1	82.5	57.2 (98)

[a] Mass of PEG and $NaHSO_4$ added to 30 g of 50% H_2O_2.
[b] Data is taken from [23].
[c] Adjusted to pH = 1.6 with 0.1 M H_2SO_4.

1.82 min was H_2O_2; peaks appearing at 3.25 and 3.65 min were attributed to intermediates. Changes in PEG and salts were found to have no significant effects on elution time.

2.5. Determination of glutaric acid and BTCA partition coefficient

10 ml of batch 3 (Table 1) composition and 10 ml of batch 4 (Table 1) composition were prepared, and allowed to stand for 2 h until two clear phases were observed for each ABS. A volume ratio of PEG-rich top phase to salt-rich lower phase of 3 ml/7 ml was observed for batch 3 and 6 ml/4 ml was observed for batch 4. 0.5 g of glutaric acid was added to both ABS, and stirred until the glutaric acid dissolved completely. After equilibrium both phases were clear and no volume change was observed. 0.5 ml of each phase was removed and injected directly into the HPLC. The concentration of glutaric acid was calculated as described in Section 2.4. The partition coefficient was then calculated as the ratio of glutaric acid concentration in PEG-rich top phase to that in the salt-rich bottom phase. In a similar experiment, 0.025 g of BTCA was dissolved in each ABS and the partition coefficient was determined in a similar manner.

3. Results and discussion

Previously, we tested several PEG/salt ABS (e.g., PEG-2000 and $NaHSO_4$, Na_2SO_4, $(NH_4)_2SO_4$, and Na_2WO_4) as reaction media in the synthesis of adipic acid and found $NaHSO_4$ to be suitable [23]. Thus, in the current investigation of cyclic olefin oxidation, we studied PEG-2000/$NaHSO_4$/H_2O_2 ABS, containing Na_2WO_4 as the catalyst. The reaction compositions of ABS for each run are shown in Table 1 and are also plotted on the room temperature phase diagram in Fig. 1.

The effect of H_2O_2 on the PEG-2000/$NaHSO_4$ ABS is shown in Fig. 1. The binodal curve representing the

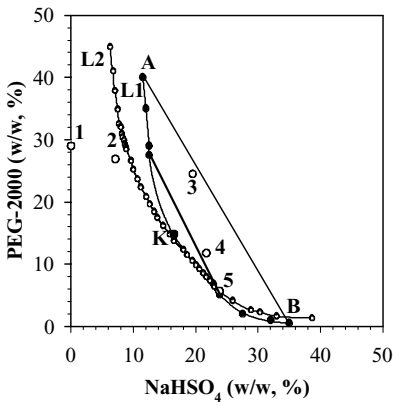

Fig. 1. Phase diagram for PEG-2000/$NaHSO_4$/50% H_2O_2 (L1) and a representative phase diagram for PEG-2000/$NaHSO_4$/H_2O (L2) at room temperature [23]. Compositions for each batch number given in Table 1 are represented by the symbol (○).

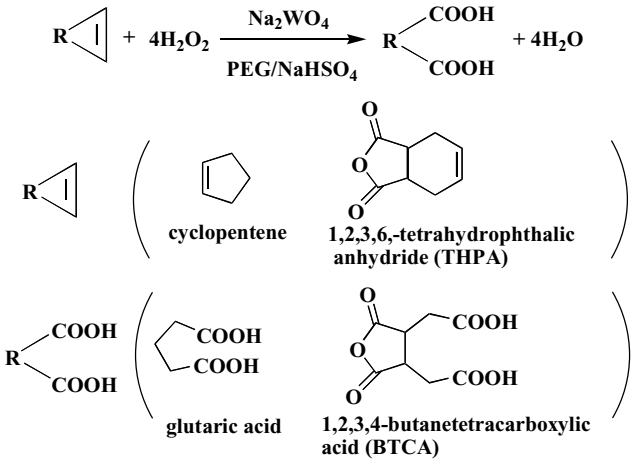

Fig. 2. Reaction scheme utilized in this work.

PEG-2000/$NaHSO_4$/H_2O_2/H_2O ABS (L1 in Fig. 1) is given as the weight percent PEG and $NaHSO_4$ of the total system composition. The second binodal curve (L2 in Fig. 1) represents the traditional three component PEG-2000/$NaHSO_4$/H_2O systems. In these systems, a biphase forms above the critical concentration, comprising a PEG-2000-rich top phase and $NaHSO_4$-rich bottom phase. The compositions of the two phases in equilibrium (e.g., A, B in Fig. 1) are connected by the tie line AB, such that any system composition along that tie line will phase separate into an upper phase of composition A and a lower phase of composition B. Since solute preference between the two phases can be affected by varying phase divergence described by the tie-line length (TLL), the differences in phase preference between precursor and product in a given reaction can be adjusted by controlling the ABS system composition [3,15].

In a typical reaction for this study (Fig. 2), an ABS consisting of PEG and $NaHSO_4$ in 50% aqueous H_2O_2 was prepared containing Na_2WO_4 as an oxidative catalyst. As the initial ABS composition of the reaction system was varied, large changes in product yield were observed (Table 1). These results are similar to those found for adipic acid production, except that here, higher yields were obtained for the production of glutaric acid and BTCA than for adipic acid under the same conditions.

Batch reactions were performed in several regions of the phase diagram as depicted in Fig. 1. Batch 1 (aqueous PEG-2000 without $NaHSO_4$, Table 1) produced only trace amounts of glutaric acid and BTCA as previously observed for adipic acid. This indicates that the reaction is not catalyzed simply by addition of pure PEG acting as a PTC. When $NaHSO_4$ was added (batch 2), but still in the monophasic area of the phase diagram, glutaric acid and BTCA yields increased. Although the binodal curve of PEG/salt ABS such as those used here will move towards lower concentrations of polymer and salt at higher temperatures [12,35], batch 2 was visually inspected at 91 °C and found to be monophasic.

Batch runs 3–5 were conducted in the biphasic region and showed increased production conversion of cyclic olefins to dicarboxylic acids. As shown in Table 1 and Fig. 1, at different batches and different TLL, yields were larger at shorter TLL (batches closer to the binodal L1), at lower PEG concentration, and at higher $NaHSO_4$ concentration. Batch 5 was close to the critical point, and glutaric acid and BTCA were obtained with yields of 73.1 and 82.5%, respectively. These results indicate that oxidation of cyclic olefins to dicarboxylic acid is greater under biphasic conditions, and that the reactivity is greatest closest to the critical point.

It should be noted that H_2O is a product of oxidation of cyclic olefins by H_2O_2, and this additional water will result in changes to the phase diagram during the course of the reaction. System compositions 3–5 (Table 1) became monophasic after the reaction. Thus, control of the water content in the ABS is another key parameter in optimizing an ABRE.

The increase of solubilization of reagents and decrease of tungstate catalyst concentration depend largely on the formation of the PEG-rich top phase [23]. Oxidation of olefins such as cyclohexene by H_2O_2 typically involves olefin epoxidation, two alcohol oxidations, Baeyer–Villiger oxidation, and multiple hydrolysis steps [31]. However, the key step to obtaining activity in this system seems to involve enabling catalyst, oxidant, and reagent to come into contact. The production of dicarboxylic acids under the monophasic conditions shown as batch 2 in Table 1 indicate a role for PEG as a PTC, presumably enhancing the solubility of organic reagents in the PEG/salt aqueous solution [36]. The results from batches 3, 4, and 5 under biphasic regions showed that the formation of the ABS actually improves reactivity; however, as the TLL is increased, the reaction yield decreased.

ABRE media in these cyclic olefin oxidation reactions can be regarded as a reaction solvent in which catalyst, oxidant, and reagents with disparate solubility characteristics are all solubilized and able to react in the PEG-rich phase of the ABS, and the reactivity appears to be controlled by the relative solubilities of all the components in the ABS PEG-rich phase. Comparing the different cyclic olefins, THPA is a solid with low solubility in pure water at room temperature, but will hydrolyze to a more water-soluble tetrahydrophthalic acid at elevated temperature [29]. Cyclopentene is more soluble in the PEG-rich phase than cyclohexene due to the smaller ring structure. Of the reactants in the PEG-rich phase, THPA is more soluble in this phase, and cyclopentene is more soluble than cyclohexene.

The results in Table 1 show that the product yields for the reactions increase in the order adipic acid < glutaric acid < BTCA at the same ABS compositions. The yields in these batch reactions appear to follow the solubilities of the initial starting materials in the PEG-rich phase, with the most soluble reagents resulting in the highest yields of products. This implies that the batch reactions did not reach equilibrium, and that optimization to monitor kinetics, and to consume all hydrogen peroxide at reaction completion will yield substantially better materials and could facilitate running reactions under semi-continuous batch conditions retaining the PEG-rich reaction phase in the reactor and replacing salt/product phase with salt/hydrogen peroxide after each reaction period.

Table 2
Partition coefficients[a] of glutaric acid and BTCA between the phases in ABS of compositions used in batches 3 and 4 (Table 1, Fig. 1)

ABS compositions	Glutaric acid	BTCA
10 ml batch 3	0.42	0.67
10 ml batch 4	0.78	0.92

[a] The partition coefficient is defined as the concentration in the top PEG-rich phase vs. that in the lower salt-rich phase. The analysis of glutaric acid and BTCA by HPLC was described in Section 2.

Table 2 shows the partitioning of commercial glutaric acid and BTCA in ABS having the same compositions as batches 3 and 4 in Table 1 and Fig. 1. Both glutaric acid and BTCA partition preferentially to the bottom salt-rich phase which suggests that this will benefit product and reactant separation. Thus, the data in Table 1 shows that the yield of both glutaric acid and BTCA were higher than adipic acid due to the more effective contact of all reagents and catalyst.

4. Conclusions

In this paper, we have demonstrated the controlled oxidation of cyclic olefins to dicarboxylic acids in an ABRE system. The control is made possible by manipulation of the ABS phase diagram simply by variation in the amount of PEG and salt utilized. These results confirm earlier results for the production of adipic acid under similar conditions.

Phase separation and the formation of the ABS resulted in much higher yields of dicarboxylic acid than in monophasic systems, and the yield appeared to be greatest at short TLL close to the critical point, with low PEG concentration, and high $NaHSO_4$ concentration. The higher solubility of THPA and cyclopentene than cyclohexene resulted in higher yields of glutaric acid and BTCA than adipic acid under these conditions. Nonetheless, this is not an optimized system and does not result in a clean separation of the soluble glutaric acid and BTCA. Further investigations are now underway to determine how to both optimize the system and to recycle the ABS components.

Acknowledgements

This research was supported by the Division of Chemical Sciences, Geoscience, and Bioscience, Office of Basic Energy Sciences, Office of Science, US Department of Energy (Grant DE-FG02-96ER14673).

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