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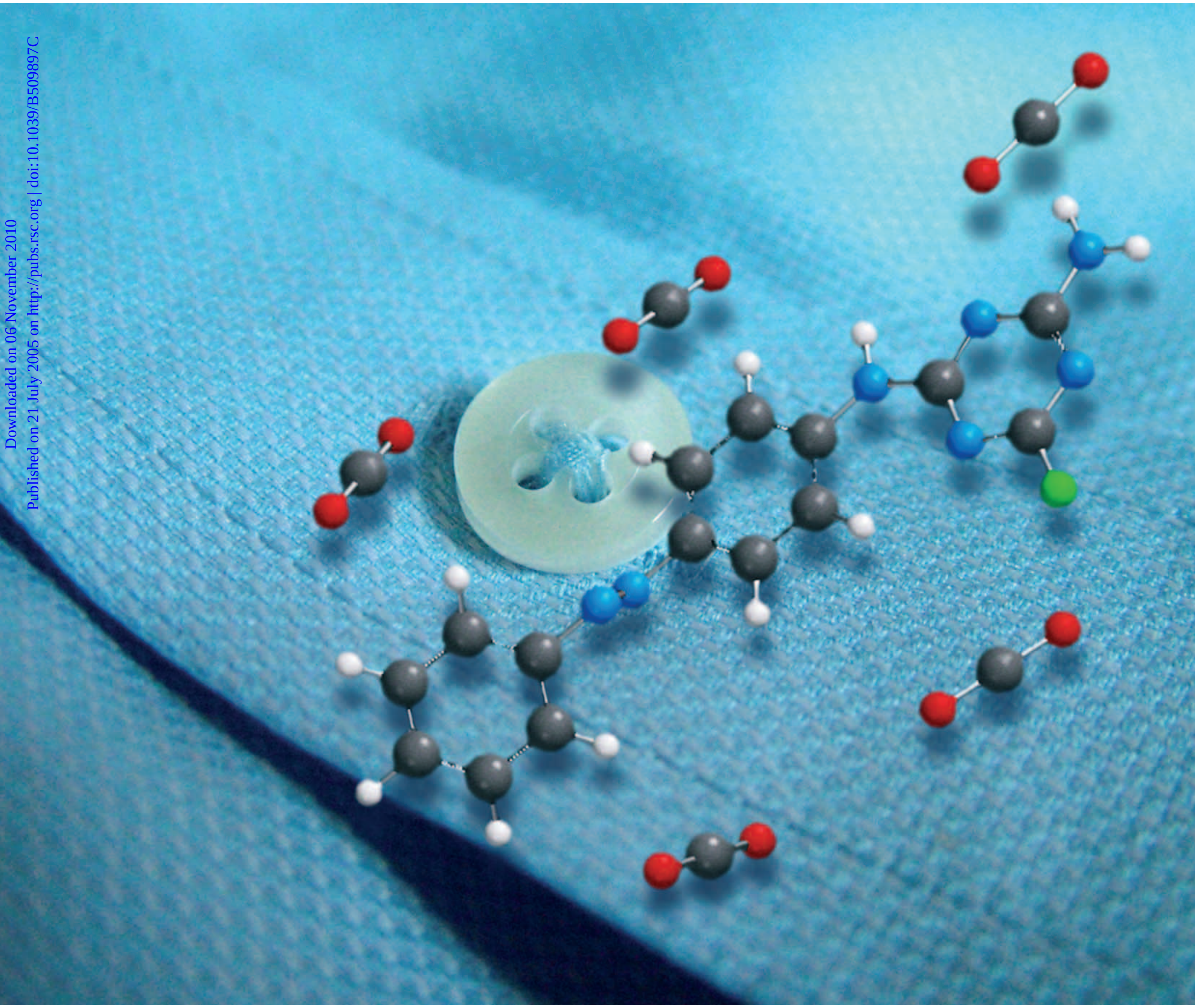

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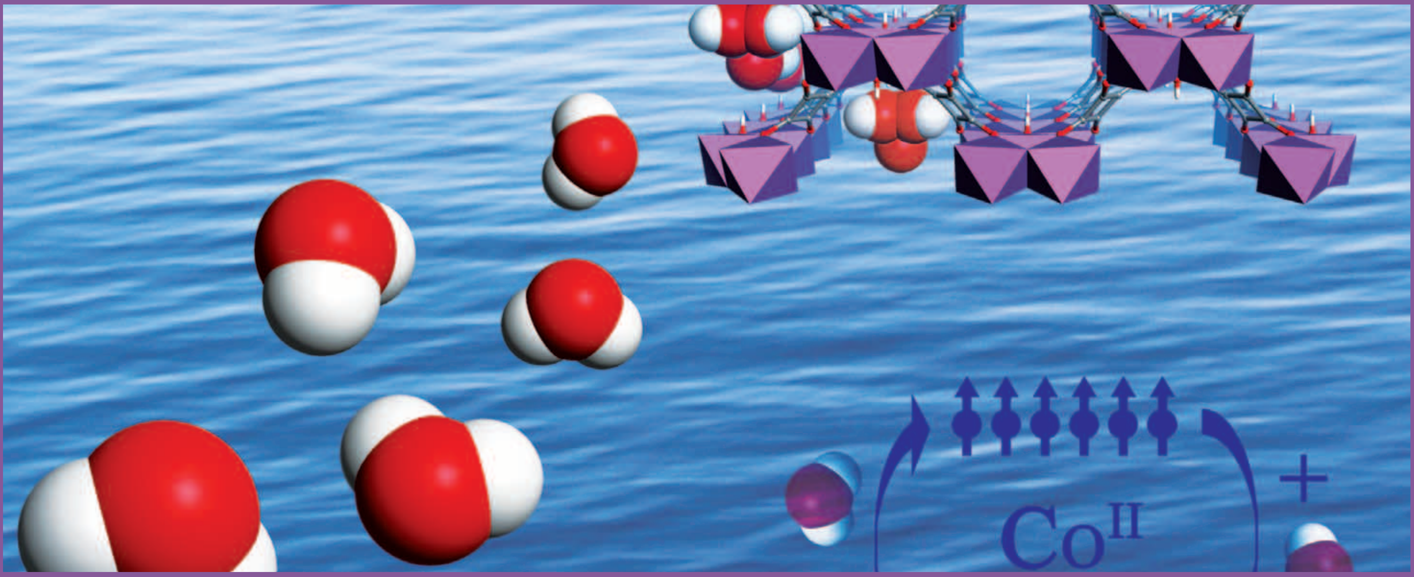
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Dyeing cotton in supercritical carbon dioxide has become viable as an alternative for water-based dyeing processes.

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Highlights

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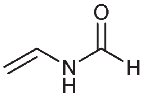

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COMMUNICATION

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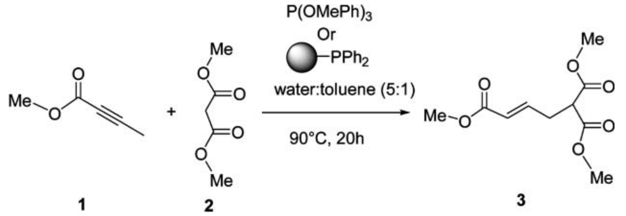
Efficient Trost's γ-addition catalyzed by reusable polymer-supported triphenylphosphine in aqueous media

Rachid Skouta, Rajender S. Varma and Chao-Jun Li*

A recyclable and efficient polymer-supported triphenylphosphine-catalyzed γ-addition of pronucleophiles to alkynoate was developed in aqueous media.



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'Green' composites using cross-linked soy flour and flax yarns

S. Chabba, G. F. Matthews and A. N. Netravali*

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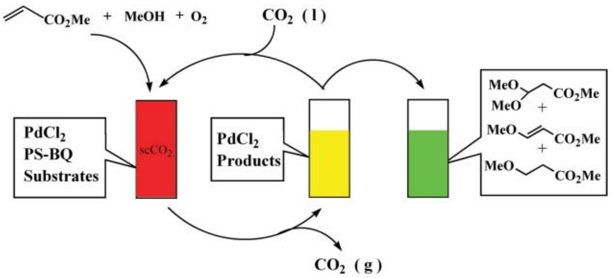
Zhao-Yang Wang, Huan-Feng Jiang,* Chao-Rong Qi, Yu-Gang Wang, Yao-Sen Dong and Hai-Ling Liu

Using polystyrene-supported benzoquinone as cocatalyst with palladium chloride, the acetalization of terminal olefins with electron-withdrawing groups was carried out smoothly in supercritical carbon dioxide under oxygen atmosphere.



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Terrence J. Connolly,* Patrick McGarry and Sunil Sukhtankar

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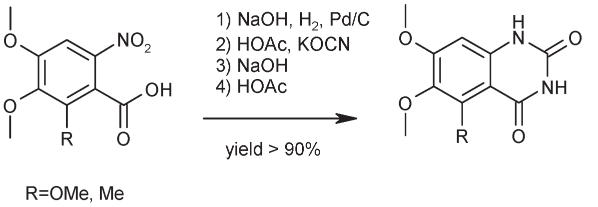

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M. V. Fernandez Cid,* J. van Spronsen, M. van der Kraan, W. J. T. Veugelers, G. F. Woerlee and G. J. Witkamp

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Arno Behr* and Qiang Miao

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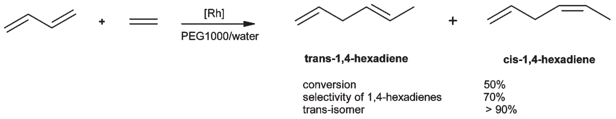

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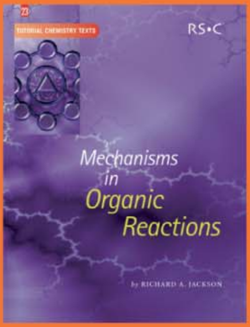
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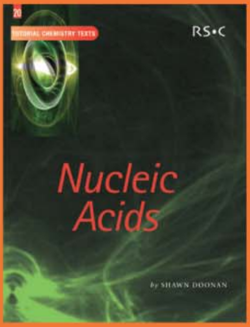
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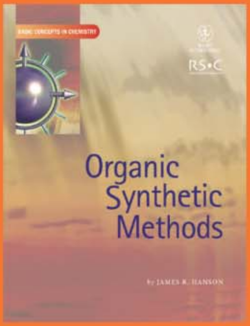
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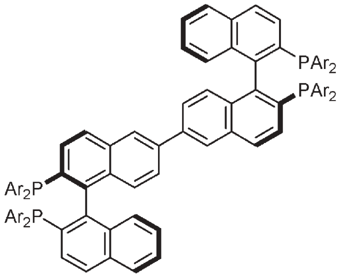
Highlights

DOI: 10.1039/b508813p

Markus Hölscher reviews some of the recent literature in green chemistry

Self-supported Noyori-type catalysts for asymmetric hydrogenation of ketones

One of the many possibilities to immobilize homogeneous catalysts is the generation of self-supported catalysts, which is attractive, when the desired catalyst obeys the following criteria: facile preparation, high stability, high density of catalytically active units, simple recovery/reuse and—with regard to asymmetric catalysis—excellent stereocontrol performance. One of the synthetic approaches which has not been validated until now, is the assembly of a chiral catalyst by heterocombination of different multitopic chiral ligands with metal ions. Ding *et al.* from the Shanghai Institute of Organic Chemistry very recently reported a promising contribution to the field.[1]



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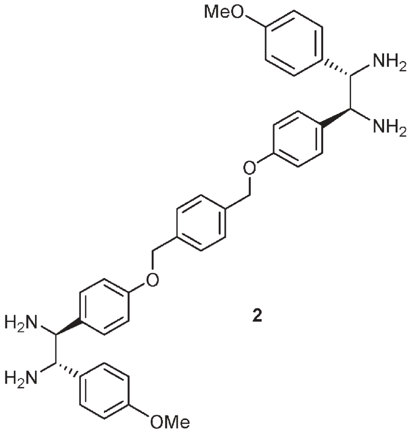
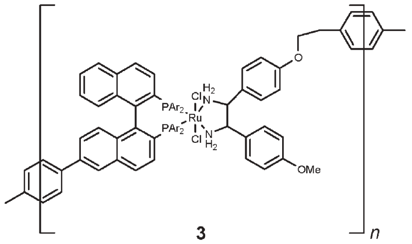




Ar = C_6H_5; 3,5-$(CH_3)_2$-CH_3

By combining diphosphane **1** and diamine **2** with Ru^{2+} ions the authors succeeded in forming polymeric complex **3** which proved to be an active and highly enantioselective catalyst for the hydrogenation of aromatic ketones, yielding up to 97.5% *ee* for 4-methyl-acetophenone. The catalyst is completely insoluble in 2-propanol and ICP spectroscopic analysis showed no detectable leaching of Ruthenium into the organic solution (<0.1 ppm). Also the control experiment using the supernatant of the catalyst showed that no hydrogenation of acetophenone was possible at all. Recycling experiments, showed no detectable loss of neither activity nor enantioselectivity for six consecutive runs, with slight loss of activity in the seventh cycle.

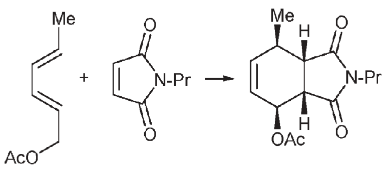
Increased hydrogen storage capacity in chemically activated MgH_2

Practically useful alternatives for carbon based fuels are highly desirable and hydrogen is generally considered to be a promising candidate. Especially interesting is the hydrogen/fuel cell technology, as nearly no emission of pollutants and greenhouse gases are to be expected, which is an important advantage. However, the utmost challenge for an introduction of hydrogen technology is still awaiting a convincing solution: Hydrogen storage. At present metal hydrides have poor gravimetric storage densities (*e.g.* 1.37 wt% for $LaNi_5H_6$), which fails by far to meet the desired capacity of 6–7 wt% needed for mobile storage applications. Also of practical importance is the H_2 absorption/desoprtion kinetics. Anderson, Edwards and Book *et al.* from the universities of Oxford and Birmingham investigated the influence of $LiBH_4$ on the absorption/desorption kinetics of MgH_2.[2] It had been shown before, that the hydrogen sorption kinetics of Mg and Mg-based alloys can be improved, when during preparation a nanocrystalline microstructure is generated through high velocity ball milling. Consequently the authors compared MgH_2, which was milled using appropriate conditions, with MgH_2, which was reacted with $LiBH_4$ prior to sorption experiments. As a third material they investigated untreated MgH_2. Interestingly it could be shown that $MgH_2/LiBH_4$ desorbs H_2 at 300 °C significantly faster than the other two materials (0.28×10^{-2} wt% s^{-1}), with milled MgH_2 showing similar behaviour as the $LiBH_4$ treated material. However, the high desorption kinetics were not obtained in the first run of subsequent absorption/desorption cycles; yet a stabilization of the kinetics behaviour was only achieved after the 4th run together with an appropriate heat treatment. Scanning electron micrograph images before and after absorption/desorption cycles showed that the $MgH_2/LiBH_4$ material had roughly the same particle size (*ca.* 2 μm) as the milled MgH_2, whereas the untreated MgH_2 consisted of much larger particles. But this is not the only prerequisite for fast desorption: By comparison with $NaBH_4/MgH_2$ materials it turned out that lithium is responsible for the fast desorption, its role however has not been clarified in detail yet.

Rate acceleration of organic transformations by reactions *on* water

More than just being an environmentally friendly solvent, water has many years ago been recognized for a unique characteristic, which is the substantial acceleration of organic reactions under certain conditions. It is generally assumed that

(1)



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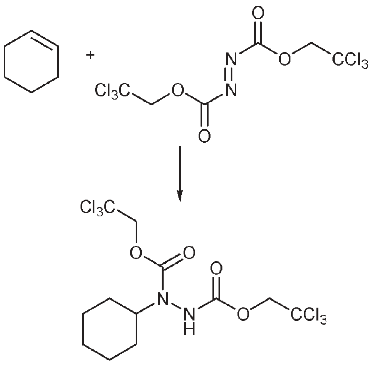

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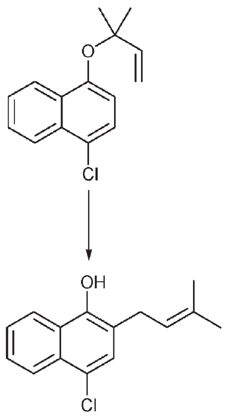

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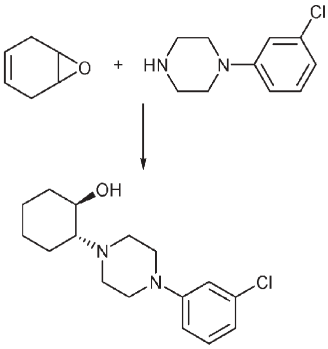
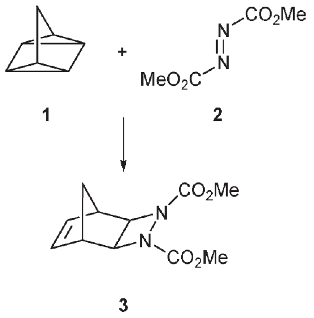


solubility (*i.e.* the complete dissolution of reactants in an appropriate and most commonly organic solvent to form a homogeneous solution) is required for efficient reaction. This dogma was challenged more than fifty years ago, when Breslow and Rideout showed that Diels–Alder reactions of nonpolar compounds proceeded at much higher rates in water than in organic solvents. In extending these initial hints Sharpless *et al.* from the Scripps Research Institute very recently investigated the influence of water on a variety of reactions in detail and obtained a unique result: Homogeneity is not needed at all for a reaction to proceed efficiently. As was shown for Diels–Alder (1) and for ene reactions (2) as well as Claisen rearrangements (3) and epoxide openings by nucleophiles (4), different organic solvents performed much poorer with regard to reaction rate than pure water.

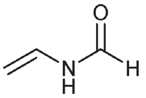
As an example the reaction of quadricyclane **1** with dimethyl azodicarboxylate **2** to form 1,2-diazetidine **3** was driven to completion in more than 120 h when toluene or EtOAc were used, whereas in the presence of protic solvents such as methanol only 18 h were required.



When the reaction was performed neat the time to completion was 48 h, but in pure water in which the reactants are insoluble only 10 min were needed. Interestingly homogeneity is not responsible in itself, as was indicated by a large isotope effect when H_2O was replaced by D_2O: the reaction time to completion rose to 45 min. Although these findings are of important practical meaning, the origins are not yet understood but under investigation.

Green industrial applications of *N*-vinylformamide

Acrylamide though being very well known to the chemistry market for its high molecular weight water soluble polymers might be one of the products which are displaced by environmentally more benign alternatives. In this case *N*-vinylformamide (NVF) could be the challenger and Sylvania, Ohio, based NVF producer Northaven Specialty Chemicals is the company that plans to introduce new applications of NVF into the market.



N-vinylformamide (NVF)

Like acrylamide NVF can be readily polymerized and copolymerized opening the possibility to create quite a number of interesting materials, as the amine group in the polymer backbone is amenable to functionalization. One of the visions which the entrepreneur focuses on is the synthesis of NVF/glucose copoylmers, which could be used as gels in the paper industry to enhance the "wet strength" of a slurry of cellulose during papermaking. This is a market with a high potential as the paper industry is moving away from halogen based processes to improve their environmental performance. Another application could be the usage of NVF gels as helper agents during the process of pumping oil out of the ground. Currently one of the products used are chromium(III)-based polyacrylamide gels, which does not work well in salt-water. The NVF gels perform much better and are usable at even high salt concentrations.

References

1 Y. Liang, Q. Jing, X. Li, L. Shi and K. Ding, *J. Am. Chem. Soc.*, 2005, **127**, 7694–7695.
2 S. R. Johnson, P. A. Anderson, P. P. Edwards, I. Gameson, J. W. Prendergast, M. Al-Mamouri, D. Book, I. Rex Harris, J. D. Speight and A. Walton, *Chem. Commun.*, 2005, 2823–2825.

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Efficient Trost's γ-addition catalyzed by reusable polymer-supported triphenylphosphine in aqueous media†

Rachid Skouta,[a] Rajender S. Varma[b] and Chao-Jun Li*[a]

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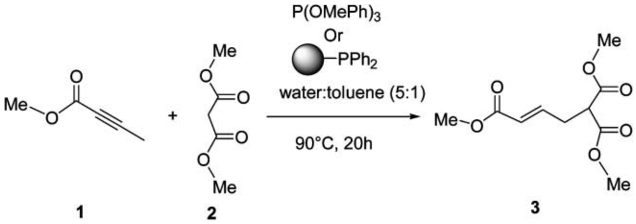
A recyclable and efficient polymer-supported triphenylphosphine-catalyzed γ-addition of pronucleophiles to alkynoate was developed in aqueous media.

Recently, great efforts have been made in developing chemical technologies that can intrinsically reduce or eliminate the use or generation of hazardous substances during the design, manufacture, and use of chemical products—Green Chemistry.[1] As a general objective of pursuing Green Chemistry for synthesis, we aimed at developing fundamental reactions that will bear the following green features: *(1) The reaction can be performed in aqueous media*,[2] which will provide various intrinsic benefits, such as the simplification of protection–deprotection steps, and ultimately the reduction of waste generation; *(2) the catalyst can be recovered and reused easily*, which will provide cost, environmental, and safety benefits in large scale manufacturing processes; and *(3) the reaction will have an "overall addition" (atom-economy)*,[3] which will eliminate intrinsic by-products for pollution prevention.

Despite the significant progress in homogeneous catalysis to date,[4] the demand for a highly active yet stable heterogeneous catalytic system is still very high.[5] Generally speaking, the most striking advantage of heterogeneous catalytic systems is the easy removal of catalysts from the reaction mixture which, in the case of sufficient stability, readily allows their reuse. There is also a great effort to develop organocatalysts[6] free of transition metals whose trace amounts of residue in the reaction products are sometimes undesirable for health and safety concerns (such as in the pharmaceutical industry).

The *Michael-addition* of α,β-unsaturated carbonyl and related compounds constitutes one of the most important fundamental synthetic reactions in organic chemistry.[7] On the other hand, Trost *et al.* developed the complementary *"γ-addition"* of nucleophiles to 2-alkynoates catalyzed by a phosphine.[8] In these reactions, a nucleophilic tertiary phosphine is first added to the triple bond of an electron-deficient alkyne and finally gets eliminated from the reaction product after a series of transformations; hence, the tertiary phosphine plays the role of the catalyst.[9] Zhang and Lu developed a series of reactions in which similar γ-additions of oxygen and carbon nucleophiles to electron-deficient allenes are also catalyzed by a tertiary phosphine.[10] However, previous γ-addition reactions required the use of homogeneous catalysts (triphenylphosphine) and benzene or toluene as organic solvent with an acetic acid–sodium acetate buffer as a proton shuttle as well as co-catalysts. In addition, the major limitation associated with common homogeneous catalytic reactions in high throughput synthesis is the removal of the homogeneous catalyst, which adds the step of purification to the synthesis. Herein, we report an efficient γ-addition of carbon nucleophiles to alkynoates bearing an electron-withdrawing group in aqueous media in the presence of a homogeneous catalyst (tris(*p*-methoxy phenyl) phosphine) or a heterogeneous catalyst (polymer-supported triphenyl phosphine) and without using any co-catalyst (eqn. (1)). In these systems, water serves both as a solvent and a proton shuttle. In the case of a heterogeneous catalyst, the polymer-supported triphenylphosphine can be recovered easily by a simple filtration and reused as a catalyst for subsequent reactions. Furthermore, inert gas atmosphere was not required for these catalytic reactions.



(1)

1. Homogeneous catalyst

The result of the initial screening experiments of different homogeneous phosphine-catalysts for the γ-addition of methyl 2-butynoate with dimethyl malonate, in the presence of water : toluene (1 : 1) as solvent mixture, showed that only tris(*p*-methoxyphenyl) phosphine gave 65% of the desired product (Table 1, entry 7). The use of triphenylphosphine as catalyst gave a modest yield (47%) (entry 6) of the desired product. Electron-rich phosphines (entries 1, 2 and 5) reduced the yield to around 25%. The use of an electron-poor phosphine-catalyst did not help the reaction either (entries 3 and 4). A bidentate phosphine catalyst was also tested and the desired product was obtained in only 36 to 42% yield (entries 8 and 9).

With tris(*p*-methoxyphenyl) phosphine as the optimized catalyst, different ratios of solvents were examined by using the γ-addition of methyl 2-butynoate with dimethyl malonate. It was found that the use of various ratios of water : toluene resulted in modest to high yields (entries 2 to 7, Table 2), whereas water alone as solvent gave 30% yield of the product (entry 1). When the ratio of water : toluene is (5 : 1) together with the use of 35% of the catalyst, the highest yield (82%) was obtained (entry 5). Reducing the amount

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[b] *National Risk Management Research Lab, U.S. Environmental Protection Agency, Cincinnati, Ohio, 45268, USA*

† Electronic supplementary information (ESI) available: Experimental details and characterization data for all new compounds. See http://dx.doi.org/10.1039/b506881a

Table 1 Catalyst screening for the γ-addition of methyl 2-butynoate with dimethyl malonate[a]

Entry	Catalyst (35 mol%)	Solvent[b]	Yield (%)[c]
1	$P(Bu)_3$	water : toluene (1 : 1)	25
2	$P(Cy)_3$	water : toluene (1 : 1)	25
3	$P(PhCl)_3$	water : toluene (1 : 1)	38
4	$P(PhCF_3)_3$	water : toluene (1 : 1)	16
5	$P(CH_2Ph)_3$	water : toluene (1 : 1)	21
6	$P(Ph)_3$	water : toluene (1 : 1)	47
7	$P(PhOMe)_3$	water : toluene (1 : 1)	65
8	Dppp	water : toluene (1 : 1)	42
9	Dppe	water : toluene (1 : 1)	36

[a] Dppp: 1,3-bis(diphenylphosphino) propane; Dppe:1,2-bis(diphenylphosphino) ethane. [b] The reaction was carried out at 90 °C for 20 h, methyl 2-butynoate (0.5 mmol), dimethyl malonate (0.5 mmol), 35% of different phosphine catalysts and 1 mL of solvent. [c] Reported yields were based on methyl 2-butynoate and determined by NMR using internal standard.

Table 2 Solvent screening for the γ-addition of methyl 2-butynoate with dimethyl malonate catalyzed by tris(*p*-methoxy phenyl) phosphine

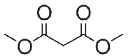
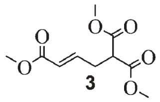
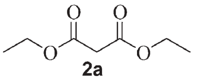
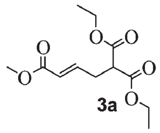
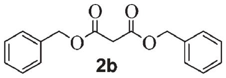
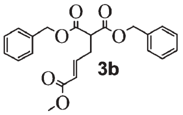
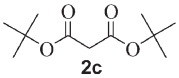
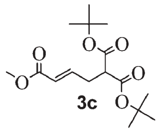
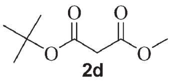
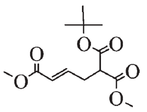
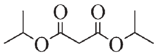
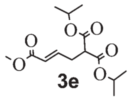
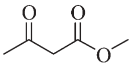
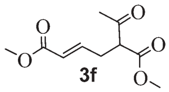
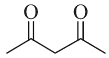
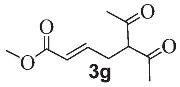
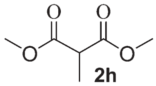
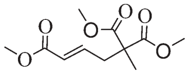
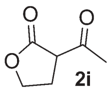
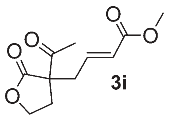
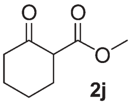
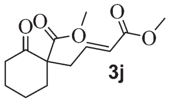
Entry	Catalyst (mol%)	Solvent[a]	Yield (%)[b]
1	35% cat	water	30
2	35% cat	water : toluene (1 : 1)	65
3	35% cat	water : toluene (1 : 2)	52
4	35% cat	water : toluene (2 : 1)	56
5	35% cat	water : toluene (5 : 1)	82
6	35% cat	water : toluene (10 : 1)	45
7	35% cat	water : toluene (20 : 1)	39
8	5% cat	water : toluene (5 : 1)	8
9	35% cat	water : ether (1 : 1)	56
10	35% cat	water : ether (5 : 1)	60
11	35% cat	water : ethanol (1 : 1)	25
12	35% cat	water : isopropanol (1 : 1)	21

[a] The reaction was carried out at 90 °C for 20 h, with methyl 2-butynoate (0.5 mmol), dimethyl malonate (0.5 mmol), tris(*p*-methoxy phenyl) phosphine as catalyst and 1 mL of solvent. [b] Reported yields were based on methyl 2-butynoate and determined by NMR using internal standard.

of the catalyst to 5 mol% in (5 : 1) of water : toluene gave only 8% yield (entry 8). Other co-solvents were also examined: water : ether (5 : 1) gave 60% (entry 10), whereas water : ethanol (1 : 1) and water : isopropanol (1 : 1), resulted in only approximately 25% of the desired product (entries 11 and 12).

Subsequently, various pronucleophiles were used for the γ-addition of methyl 2-butynoate by using a mixture of water and toluene (5 : 1) and tris(*p*-methoxyphenyl) phosphine as catalyst to give the desired products **3**–**3j** in good yields (57–90%) (Table 3). In general, all pronucleophiles for which pK_a < 16 provided good results. Introducing an alkyl group on the acidic carbon of the pronucleophile compromised the yield (compare entries 1 and 9). Both the lower kinetic acidity of the pronucleophile and the increased steric hindrance of the resulting nucleophile may be responsible for the reduction in yield. The steric effect was noticed (entries 3 to 6) when dibenzyl malonate **2b**, di-*tert*-butyl malonate **2c**, *tert*-butyl methyl malonate **2d** and diisopropyl malonate **2e** were used as pronucleophiles. Increasing the kinetic acidity by using β-keto ester **2f** (entry 7) and diketone **2g** (entry 8) restored the yields to 60–65%. Minimizing the steric hindrance by using a cyclic structure as in the case of 2-acetyl-γ-butyrolactone **2i**

Table 3 Homogeneous catalyst ($P(OMePh)_3$)-catalyzed γ-addition in aqueous media[a]

Entry	Pronucleophile	Product	Yield (%)
1	 **2**	 **3**	78
2	 **2a**	 **3a**	90
3	 **2b**	 **3b**	65
4	 **2c**	 **3c**	72
5	 **2d**	 **3d**	73
6	 **2e**	 **3e**	81
7	 **2f**	 **3f**	65
8	 **2g**	 **3g**	60
9	 **2h**	 **3h**	57
10	 **2i**	 **3i**	75[b]
11	 **2j**	 **3j**	70

[a] Conditions: The reaction was carried out at 90 °C for 20 h, with methyl 2-butynoate (0.5 mmol), different pronucleophile (0.5 mmol), tris(*p*-methoxy phenyl) phosphine as catalyst and 1.2 mL of mixture of water : toluene (5 : 1). [b] In all cases, only the *E* olefins are observed and isolated, except in the case of 2-acetyl-γ-butyrolactone (entry 10) which gave a mixture of *E* : *Z* (2 : 1).

Table 4 Effect of solvent on the γ-addition catalyzed by polymer-supported triphenylphosphine

Entry	Solvent[a]	Catalyst (mol%)	Yield (%)[b]
1	water	35% cat	29
2	water : toluene (5 : 1)	35% cat	75
3	water : toluene (10 : 1)	35% cat	55
4	water : toluene (20 : 1)	35% cat	45
5	water : toluene (5 : 1)	5% cat	17

[a] All reactions were carried out with methyl 2-butynoate (0.5 mmol) and dimethyl malonate (0.5 mmol) at 90 °C for 20 h in 1 mL of solvent. [b] Reported yields were based on methyl 2-butynoate and determined by ^{1}H NMR using an internal standard.

(entry 10) and 2-(methoxycarbonyl)cyclohexanone **2j** (entry 11) gave yields up to 70%.

2. Heterogeneous catalyst

For convenience, an inexpensive polymer-bound triphenylphosphine resin, readily available from a variety of commercial sources (*e.g.* Aldrich), was chosen as the catalyst. Different solvent systems were examined by using the reaction of methyl 2-butynoate with dimethyl malonate in the presence of the polymer-supported triphenylphosphine resin (Table 4). Ideally, the reaction should be performed in pure water. However, when water alone was used as solvent, the reaction gave 29% yield of the desired product (entry 1) with most starting material unchanged. This was attributed to the inefficient mixing of reactants on the solid surface. In order to increase the conversion, a small amount of co-solvent was added to facilitate the mixing of reactants. It was found that the use of a mixture of water and toluene (5 : 1) provided 75% of the corresponding γ-addition product (entry 2) in the presence of 35 mol% of polymer-supported triphenylphosphine as catalyst. No additional improvement was observed when the amount of co-solvent was further increased. On the other hand, decreasing the amount of co-solvent led to a sharp decrease in conversion. Lowering the amount of the catalyst to 5 mol % in (5 : 1) of water : toluene gave only 17% yield of the product (entry 5). As the polymer-supported triphenylphosphine catalyst can be recovered easily by simple filtration and reused, no further efforts were made to reduce the amount of catalyst.

2.1 Heterogeneous catalyst: recycle and reuse

As the polymer-supported triphenylphosphine catalyst can be recovered easily by simple filtration and reused, the efficiency of the heterogeneous catalyst was examined by using the reaction of methyl 2-butynoate with dimethyl malonate in the presence of the polymer-supported triphenylphosphine resin (Fig. 1). It was found that the polymer-supported triphenylphosphine resin, reused twice, gave 73% and 60% yield of the γ-addition products respectively. When the polymer-supported triphenylphosphine resin was reused for the third time, the γ-addition product was obtained in only 15% yield. By adding 5% of fresh polymer-supported triphenylphosphine resin, the yield of the desired product was increased to 32%.

To verify whether some leaching of the catalyst occurred during the studies, we performed ^{31}P NMR experiments of the organic extract with CD_2Cl_2 for each study. The studies were performed under an inert atmosphere (the mixture was bubbled with nitrogen for 10 min), using microwave irradiation as the source of energy (Fig. 1). The desired product was obtained in high yield (73% and 69% respectively) during experiments with the first and second catalyst recyclings respectively; whereas the yield dropped to 27% for the third reuse of the catalyst. By using ^{31}P NMR, the presence of the triphenylphosphine oxide (32.52 to 33.14 ppm) was observed in the organic extract after the second catalyst recycling.[11]

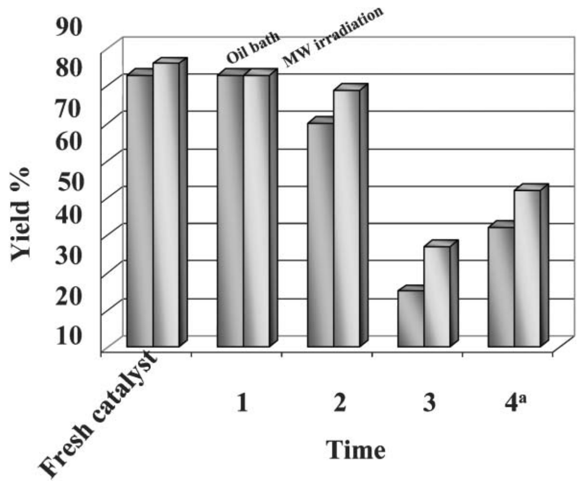


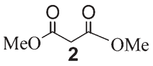
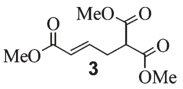
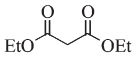
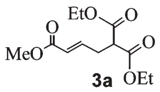
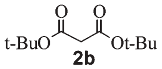
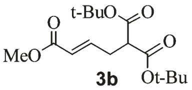
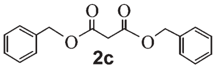
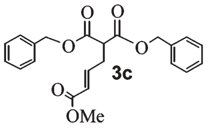
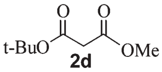
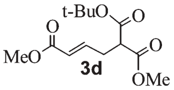
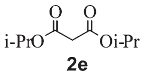
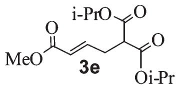
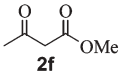
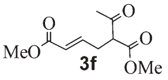
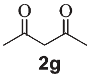
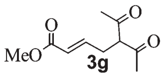
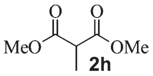
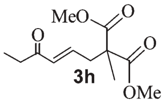
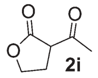
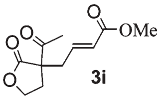
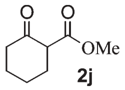
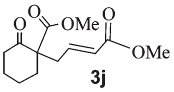
Fig. 1 Efficiency of reused polymer-supported triphenylphosphine catalyst for the γ-addition reaction of methyl 2-butynoate with dimethyl malonate in the presence of water : toluene (5 : 1). 1. Initial reaction with recycled catalyst; 2. Second reaction with recycled catalyst; 3. Third reaction with recycled catalyst; 4. Fourth reaction with recycled catalyst + 5 mol% of the fresh catalyst.

The solid state ^{31}P NMR spectrum of the polymer-supported triphenylphosphine (CPMAS spectrum) after the third recycling was also examined, which showed a 25.8 ppm signal corresponding to polymer-supported triphenylphosphine oxide.

Subsequently, various pronucleophiles were examined for the γ-addition with methyl 2-butynoate in a mixture of water and toluene (5 : 1) using polymer-supported triphenylphosphine resin as catalyst, under an alternative heating method (oil bath) and microwave conditions, to give the desired products **3**–**3j** in good yields (Table 5). In general, under an alternative heating method (oil bath), all pronucleophiles with pK_a < 16 gave satisfactory yields of the addition products. Introducing an alkyl group onto the activated methylene of the pronucleophile slightly compromised the product yield (compare entries 2 and 9). The use of di-*tert*-butyl malonate (**2b**) as a pronucleophile led to the low yield (30%) of the product, most likely due to the increased steric effect (entry 3). On the other hand, no significant variation was observed when dibenzyl malonate (**2c**), *tert*-butyl methyl malonate (**2d**) and diisopropyl malonate (**2e**) were used as pronucleophiles. Cyclic pronucleophiles such as 2-acetyl-γ-butyrolactone (**2i**) (entry 10) and 2-(methoxycarbonyl)cyclohexanone (**2j**) (entry 11) gave 81% and 55% yields of the γ-addition products respectively. Under microwave conditions at 150 °C, we obtained very high yields, in all cases, compared to the alternative heating method (oil bath) (Table 5). Additionally, we were able to reduce the reaction time of the γ-addition.

Mechanistically, the polymer-supported triphenylphosphine serves as a nucleophilic trigger,[12] similar to the triphenylphosphine

Table 5 Polymer-supported triphenylphosphine-catalyzed γ-addition in aqueous media[a]

			Microwave @ 150 °C		Oil bath
Entry	Pronucleophile	Product	Time/min	Yield (%)	Yield (%)
1	 2	 3	45	76	72
2	 2a	 3a	45	86	83
3	 2b	 3b	45	traces	30
4	 2c	 3c	45 × 2	82	76
5	 2d	 3d	45	55	61
6	 2e	 3e	45	67	71
7	 2f	 3f	45 × 2	72	61
8	 2g	 3g	45 × 2	97[b]	90[b]
9	 2h	 3h	45 × 2	65	67
10	 2i	 3i	45 × 2	96	81
11	 2j	 3j	45 × 2	61	55

[a] Conditions: all reactions were carried out either at 90 °C for 20 h and in MW 150 °C with methyl 2-butynoate (0.5 mmol), different pronucleophile (0.5 mmol), polymer-supported triphenylphosphine as catalyst and a mixture of water : toluene (5 : 1) as solvent (1.2 mL). [b] In all cases, only *E* olefins are observed and isolated, except for entry 8 which gave a mixture of *E* : *Z* (1 : 1).

catalyzed homogeneous system proposed by Trost *et al.*[8] wherein water functions both as the solvent and the proton shuttle.

In summary, we have demonstrated the use of commercially available polymer-supported triphenylphosphine as a catalyst for the efficient γ-addition of methyl 2-butynoate with different pronucleophiles in a mixture of water : toluene (5 : 1) without using any co-catalyst. The current method has the following distinct advantages in green chemistry: (1) The polymer-supported triphenylphosphine is recoverable and can be reused; (2) the proceeding of the reaction in aqueous media implies the simplification of the protection–deprotection reaction for acidic functional groups; (3) the γ-addition is highly "atom-economical";

and (4) the time of the reaction was reduced under microwave conditions.

Experimental

A typical experimental procedure is as follows: a mixture of polymer-supported triphenylphosphine (46 mg, 0.175 mmol, 3 mmol of triphenylphosphine per gram of resin, Aldrich), methyl 2-butynoate (0.5 mmol) and dimethyl malonate (0.5 mmol) in 1.2 mL water : toluene (5 : 1) was heated at 90 °C for 20 h or under microwave conditions at 150 °C for 45 min. The reaction mixture was cooled to room temperature and filtered through a glass frit to remove the resin. The resin was washed with ethyl acetate (3 × 5 mL). The combined organic fractions were washed with water (3 × 2 mL) and dried over anhydrous Mg_2SO_4. The solvent was removed *in vacuo*. In this case, the residue was pure as shown by NMR and GC-MS and needed no further purification.

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'Green' composites using cross-linked soy flour and flax yarns

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Environment-friendly, fully biodegradable, 'green' composites based on plant based fibers and resins are increasingly being developed for various applications as replacements for non-degradable materials derived from petroleum that are currently being used. Unlike petroleum, plant based proteins, starches and fibers are yearly renewable. In addition, these green composites may be easily composted after their life, completing nature's carbon cycle. In this study, soy flour (SF) was modified by cross-linking it with glutaraldehyde (GA). The cross-linked soy flour (CSF) polymer was characterized for its tensile and thermal properties. The effect of glycerol on the mechanical properties of the soy flour was characterized and optimized. CSF polymer showed improved tensile properties and thermal stability, compared to unmodified SF resin, for use as a resin to fabricate composites. Unidirectional green composites using flax yarn and CSF resin were fabricated and characterized for their tensile and flexural properties. The composite specimens exhibited fracture stress and Young's modulus of 259.5 MPa and 3.71 GPa, respectively, and flexural strength of 174 MPa, in the longitudinal direction. These properties seem to be sufficient for considering these green composites for indoor structural applications.

Introduction

Most of the conventional plastics used today are derived from petroleum. At the current consumption rate, the worldwide petroleum reserves have been estimated to last only for the next 50 years or less.[1] More than 60 billion pounds of plastic waste, mostly petroleum based, is discarded each year in the United States of America alone.[1] Most of this waste ends up in landfills. Biodegradable polymers produced from renewable resources such as plants, animals and microbes through biochemical reactions offer a convenient and environment friendly solution to the problem of plastic waste. Various biodegradable polymers such as starch, wheat gluten, zein, polyhydroxybutyrate-co-valerate (PHBV), whey protein, soy protein *etc.* have been explored for applications in composites.[2–7] Though wheat gluten and zein have been reported to form high strength films,[5,6] they are more expensive than soy protein.[8] Soy protein offers several advantages over synthetic polymers.[9] First, the soy protein purification process is benign and environment friendly. Second, these proteins can form ductile and viscous polymers that can be used as resins. Third, the cost of raw materials is low. Fourth, soybean is an annual crop and is abundantly available worldwide. In the 1930s, Henry Ford pioneered the use of soy protein for plastics and fibers.[10] Ford used soy plastic for various car parts such as gear shift knobs, horn buttons and window frames in an effort to produce an "all agricultural" car.[10] However, after the outbreak of World War II, most efforts and materials were reallocated to the war and research in soy plastics was abandoned. Also, the plastic molding technology of today was not available at that time. At present, because of the increased environmental awareness and stringent environmental laws, most manufacturers are looking towards 'greener' and more environment friendly alternatives for conventional polymers and composites.[11]

Soybean products are available commercially as defatted soy flour (SF), soy protein isolate (SPI) and soy protein concentrate (SPC). Chemically, SPI contains 90% protein and 4% carbohydrates, SPC contains 70% protein and 18% carbohydrates, while SF, which requires less purification, contains about 55% protein and 32% carbohydrate and is the least expensive variety. Soy protein is globular, reactive and often water soluble, as compared to helical or planar, non-reactive and water resistant synthetic polymers.[12] Soy protein consists of various polar and reactive amino acids such as cystine, arginine, lysine, hystidine, *etc.* which can be used for cross-linking it and improving the tensile and thermal properties. In this research, glutaraldehyde (GA) has been used as a cross-linking agent to modify SF. Several researchers have shown that GA reacts with the amine groups in protein, particularly in an alkaline pH, to form intermolecular cross-links.[13–15] Although GA can readily react with the amine groups, there has been no consensus on the reaction of proteins with GA. Different mechanisms have been proposed for explaining the reaction between GA and proteins. Blass *et al.*[15] have shown that monomeric GA binds irreversibly to proteins. Habeeb and Hiramoto[14] reported that GA reacted extensively with the α-amino group of glycine and the α- and ε-amino groups of lysine, while it only partially reacted with the α-amino groups of histidine and tyrosine. They also showed that the cross-linking of GA with proteins produced two species, monomers and aggregates. The monomers were a small component and had a sedimentation coefficient similar to the native protein.

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The aggregates were the products of intermolecular cross-linking and showed a three-fold increase in the sedimentation coefficient as compared to the native protein. Richard and Knowles[13] suggested that GA reacts with protein through an aldol condensation followed by a cross-linking reaction. They proposed that the smallest cross-link that can be formed between the protein molecule and GA would have five carbon atoms in a chain between two nitrogen atoms (from amine groups) similar to a double Schiff base formation.

Chabba and Netravali[16] cross-linked SPC using GA to form a suitable resin system. As a result of the cross-linking, the strength of the SPC resin increased significantly while the moisture absorption decreased. A typical structure of soy protein cross-linked with GA is shown in Fig. 1.[16] It was, however, difficult to assess the average degree of cross-linking because of the complexity of the chemistry. The cross-linking was judged based on the improved tensile strength and decreased fracture strain and moisture absorption after the GA modification as well as the significant increase in the viscosity immediately following the addition of GA to the SPC solution. Chabba and Netravali[17] also blended the cross-linked SPC with poly(vinyl alcohol) to improve its toughness. Other modifications of soy proteins have also been tried. Lodha and Netravali[18] used stearic acid to modify SPI. The mechanical and thermal properties of the resin were shown to improve with the stearic acid content. One of the main reasons for this improvement was the hydrophobic nature of the stearic acid which made the SPI resin less moisture absorbent.[18] In another modification, Lodha and Netravali[19] used Phytagel® to modify SPI and form an interpenetrating network (IPN) like structure. Because of the cross-linked IPN like structure the strength of the resin increased almost ten-fold to 60 MPa and the modulus increased nine-fold to about 900 MPa. Tummala *et al.*[20] have modified SF with polyester amide to fabricate composites using hemp fibers.

Natural 'lignocellulosic' (plant based) fibers, *e.g.* ramie, flax, hemp, kenaf, bamboo, *etc.*, are increasingly being used as reinforcement in both biodegradable and non-biodegradable polymers, to make them 'greener'.[11,21,22] Natural fibers offer several advantages over synthetic fibers, *e.g.* glass, graphite and aramids, in terms of low cost, low density, low energy consumption and no skin irritation.[23–26] Also, they are CO_2 neutral, biodegradable, compostable, and yearly renewable. In addition, bast fibers, derived from the stems of plants, also show good thermal as well as acoustic insulation properties because of their hollow nature.[23–26]

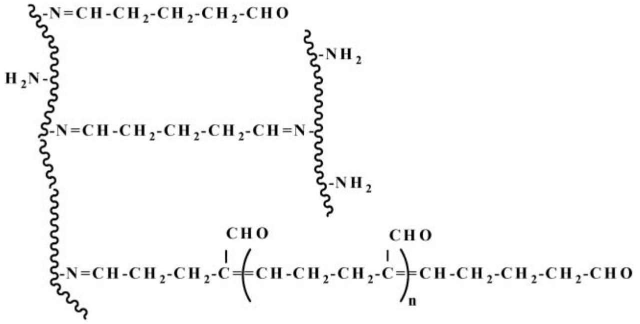

Fig. 1 Schematic of the glutaraldehyde (GA) cross-linked soy flour structure.

Mohanty *et al.*[22] fabricated biodegradable composites using twisted jute yarn and Biopol™ and showed a 150% increase in the tensile and impact strength of composites as compared to pure resin. Chabba and Netravali[16,17] fabricated unidirectional flax yarn as well as flax fabric reinforced green composites using GA cross-linked SPC as well as PVA blended resins. Both composites showed good tensile and flexural properties. Lodha and Netravali[27] used stearic acid modified SPI and ramie fibers to fabricate unidirectional green composites. Nam[28] also used ramie fibers to reinforce SPC. Both these efforts yielded composites with excellent mechanical properties. In the present research, spun flax yarns were used for fabricating composites. Use of twisted yarns in composites allows the fabrication of continuous length unidirectional composites (composite structures in which the fibers/yarns are aligned in one preferred direction within the polymer matrix/resin). In such composites, the maximum strength is observed in the longitudinal direction of the yarns.[29] The parallel laying of yarns (or fibers) is easy if the yarns (or fibers) are not short length and are continuous. Since flax fibers come in short lengths, 1 m or less, the only way to have them in continuous form is to spin (twist) them into yarns. Spun yarns also have some fiber ends protruding out, commonly referred to as yarn hairiness. In composites, hairiness may lead to better mechanical interlocking between fibers and the resin as the protruding fibers interlock the yarns or get deeply embedded into the resin, thus improving the fiber/resin interfacial bonding. Another advantage of using twisted yarns in composite manufacturing is the increased surface roughness of yarns compared to fibers, which further increases the fiber/resin interfacial strength due to increased mechanical interlocking.

In the present research, fully biodegradable, sustainable and environment friendly 'green' composites have been fabricated using cross-linked soy flour (CSF) resin and flax yarns. The tensile and flexural properties of the CSF resin and composites have been characterized. The tensile and flexural properties of the green composites have been compared with glass reinforced poly(propylene) composites.

Experimental

Materials

Soy flour was provided by Archer Daniels Midland Company, IL. Analytical grade glycerol and sodium hydroxide were obtained from Fisher Scientific, PA. Glutaraldehyde (GA), 25 wt% solution in water was obtained from Aldrich Chemical Company, Milwaukee, WI. All chemicals were used as received, without any further treatment. Flax yarn, in bleached form, was provided by Sachdeva Fabrics Pvt. Ltd., New Delhi, India.

Processing

To process SF powder into a suitable resin for fabricating 'green' composites, it was mixed with distilled and deionized water in a beaker in 1 : 9 ratio (by weight) and the desired amount of glycerol was added as a plasticizer. Without the plasticizer, SF was found to be brittle, weak and difficult to process into useful films. To study the effect of plasticizer (glycerol) content on the tensile properties of resin, different glycerol contents, 0%, 5%, 10% and 15% (w/w of SF) were used. The SF solution was homogenized using a magnetic stirrer for 15 minutes and then the pH of the mixture was adjusted to 11 ± 0.1, using 1N NaOH solution. The SF solution was again stirred for 15 minutes and then the beaker was transferred to a water bath maintained at 70 °C. The solution was 'pre-cured' by stirring for 27 minutes in a water bath at 70 °C, after which GA was added to the mixture and stirred for 3 more minutes at the same temperature. The final concentration of GA solution was 40% on an SF weight basis. This stage is referred to as pre-cured resin. With the fast cross-linking reaction, the viscosity of the mixture increased rapidly. The pre-cured solution was cast on Teflon® coated glass plates and dried at room temperature for 48 hours to obtain the resin sheets. Finally, the dried soy flour sheets were cured by hot pressing in a Carver hydraulic hot press, model 3891-4PROA00, at 120 °C for 25 minutes under a force of 178 kN. The cured, GA cross-linked SF polymer sheets were conditioned at standard ASTM atmosphere (65% r.h. and 21 °C) for 3 days before characterization of various properties. Based on the results, SF was cross-linked with 40% GA solution and 0% glycerol for composite preparation. This composition is henceforth referred to as CSF resin.

Analysis

Tensile properties of the cross-linked SF polymer sheets were characterized in accordance with ASTM D 882-97. Conditioned polymer sheets were cut into rectangular specimens of 110 mm × 20 mm dimensions. Three thickness measurements were carried out along the length of each specimen, and the average of these values was used for calculating the fracture stress and Young's modulus. The tests were performed on an Instron tensile tester, model 1122, at a strain rate of 1 min^{-1} and a gauge length of 50 mm. Thermogravimetric analysis of conditioned CSF polymer sheets was carried out using TA Instruments, Thermo-Gravimetric Analyzer (TGA), model 2050. The specimens were scanned in a nitrogen atmosphere from 25 °C to 400 °C at a ramp rate of 10 °C min^{-1}.

Flax yarn was characterized for its tensile properties such as Young's modulus and fracture stress and strain according to ASTM D 2256-97. Yarn specimens were conditioned at standard ASTM atmosphere for 5 days, prior to characterizing their properties. Individual yarn specimens were tested on an Instron testing machine, model 1122. A 100 mm length of yarn was used to determine the yarn diameter using an optical microscope. The same specimens were used for measuring tensile properties. Tests were performed using a gauge length of 50 mm and at a strain rate of 1 min^{-1}. Flax yarn linear density (mass per unit length, also referred to as yarn count) was measured according to ASTM D 1059-97.

Unidirectional composites were prepared using flax yarn and CSF resin. To prepare composites, flax yarn was wrapped tightly around a rectangular metal frame to achieve sufficient stress needed to maintain parallel alignment of the yarn strands. The entire frame was immersed in the pre-cured CSF resin for 30 minutes to allow the resin to impregnate the flax yarns as completely as possible. The pre-cured resin had the consistency of a thick paste. The frame was then taken out and specimens were oven dried at 35 °C for approximately 24 hours. The dried (uncured) composite specimens were removed from the frame and hot pressed (cured) and conditioned following the same procedure used for the CSF resin. The cured composites had approximately 60% yarn content, by weight.

The composite specimens were characterized for their tensile and flexural properties in the longitudinal direction in accordance with ASTM D 3039/D 3039M-00 and ASTM D 790-99, respectively. Tensile test specimens had a width of 10 mm and were tested at a gauge length of 20 mm. The flexural test specimens had a width of 10 mm and the tests were carried out using a span length of 25 mm. Tensile and flexural tests were performed at a crosshead speed of 20 mm min^{-1} (strain rate of 1 min^{-1}) and 2 mm min^{-1}, respectively.

Results and discussion

Fig. 2 shows the effect of glycerol content on the tensile properties of cross-linked SF resin containing 40% GA (10% solid GA content). As expected, increasing glycerol content from 0% to 15% increased the fracture strain from 3.6% to 31.7%. It also reduced the fracture stress and from 12.6 MPa to 6.7 MPa and Young's modulus from 525.6 MPa to 101.7 MPa. These results indicate that glycerol acts as a good plasticizer for CSF, leading to reduced brittleness and increased plasticity. Glycerol has been reported to increase the flexibility and extensibility of soy protein plastics by reducing the interaction between protein molecules.[3,16–19,30,31] Based on the tensile properties, 40% GA solution and 0% glycerol (CSF) was selected as the optimum blend concentration for use in composites. Although brittle, the CSF resin fracture strain was comparable to the flax yarn fracture strain, while the modulus and strength values were significantly higher, hence better tensile and flexural properties of the composites could be expected. In addition, glycerol has been shown to slightly reduce the fiber–resin interfacial bonding by acting as a lubricant between the fiber and the resin, thus affecting the

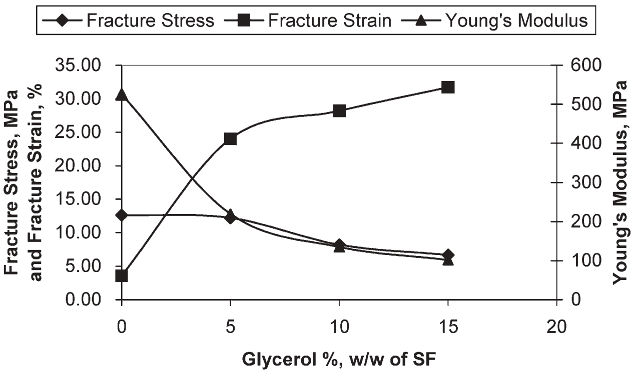

Fig. 2 Effect of glycerol on the tensile properties of modified soy flour resin.

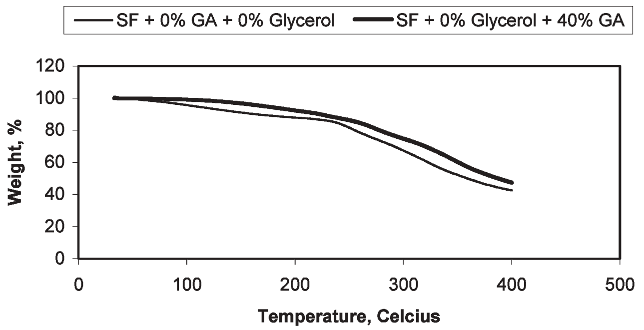

Fig. 3 TGA thermograms for SF and CSF resins.

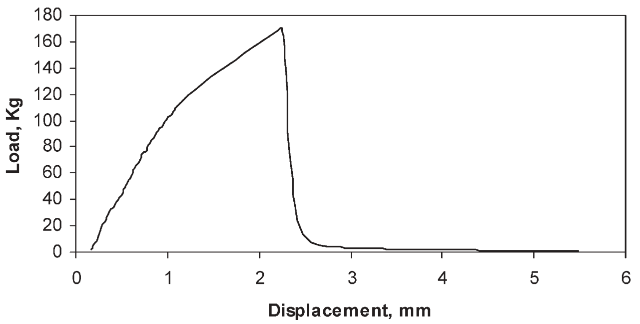

Fig. 4 Typical load *vs.* displacement plot for a tensile test of flax yarn reinforced CSF composites in longitudinal direction.

composite properties.[32] Without the cross-linking of SF with GA, it was difficult to fabricate composites with no glycerol.

Fig. 3 shows the typical TGA thermograms for the SF resin containing 0% glycerol and CSF resin, in a nitrogen atmosphere. The TGA thermogram for the CSF resin consistently shows less weight loss at all temperatures compared to SF resin, indicating a higher thermal stability than SF resin. The improved thermal stability of CSF resin is attributed to the cross-linking between GA and SF.[16,17] Also, it is clear from the plot that the CSF resin is very stable up to 120 °C, the processing temperature for yarn-reinforced composites. The weight loss up to 120 °C can be attributed mostly to the loss of moisture from the specimen.

The average linear density of the flax yarn was found to be 13.91 Ne (English count) or 382 denier. Tensile properties such as fracture stress, Young's modulus and fracture strain of flax yarn are summarized in Table 1. As can be seen from these data, there is a large variability in the fracture stress and Young's modulus values, which can be attributed to the variability in the flax fiber yarns and the variation of yarn diameter along its length. Most plant based fibers and their yarns show such high variation compared to synthetic fibers which tend to be much more uniform. The yarns used in this study were also brittle because of the high twist level.

Table 1 also summarizes the tensile properties of unidirectional yarn composites in the longitudinal direction. Fig. 4 shows a typical load *vs.* displacement plot for the tensile test of flax yarn reinforced CSF composites in the longitudinal direction. As can be seen from Fig. 4, the composite specimens attain their highest load and then fail catastrophically. In this case, the flax yarn reinforced composites increased the tensile strength by over 2000% (259.5 MPa) as compared to the CSF resin (12.6 MPa). The Young's modulus increased by over 700% to 3.71 GPa compared to 525.6 MPa for the resin. The strength of the flax yarn and good bonding between the flax yarns and CSF resin contribute to the high tensile properties. As mentioned earlier, about 32% of the SF is carbohydrate. This helps improve the fiber–resin interfacial bonding because of the similar chemistry containing polar glucose units. Simple rule of mixture[26] was used for predicting the longitudinal fracture stress and Young's modulus for flax yarn reinforced CSF composites. The fracture stress and Young's modulus values for composites calculated using rule of mixture were 221.9 MPa and 2.4 GPa, respectively, while the experimental values for the composite fracture stress and Young's modulus were 259.5 MPa and 3.71 GPa, respectively. These values are within the experimental variation.

Chabba and Netravali[17] reported the fracture stress and Young's modulus values of 126.1 MPa and 2.24 GPa, respectively, for flax yarn reinforced cross-linked SPC composites. The fiber weight fraction in that case was around 45% compared to 60% used in this study. They attributed lower tensile values to poor yarn orientation due to relaxation and voids in the composites. Nam and Netravali[4] have reported a strength of 271 MPa for unidirectional composites made using ramie fibers and SPC resin. Lodha and Netravali[27] have reported strengths of 267 MPa for ramie fiber reinforced composites made using stearic acid modified SPI resin. Flax yarn reinforced Phytagel® modified SPI resin composites were also reported by Lodha and Netravali.[19] In this case the composite strength was around 220 MPa. The results obtained in this study are within the range of properties reported by others. However, the CSF resin should be less expensive compared to modified SPI and SPC resins. These strengths are lower than the pre-stressed glass–polypropylene (PP) composites which had tensile strength and Young's modulus values of 774 MPa and 27 GPa, respectively.[33] However, the glass–PP composites had a density of 1.48 g cm^{-3} compared to about 1.3 g cm^{-3} for the green composites in this study. Also, it should be possible to improve the green composite properties further, using a similar pre-stressing technique.

Table 2 summarizes the flexural properties, at yield, of unidirectional yarn composites in the longitudinal direction. Fig. 5 shows a typical load displacement plot for a flexural test of flax yarn reinforced CSF composites in the longitudinal

Table 1 Comparison of tensile properties of flax yarn and composites

	Fracture stress/MPa	Young's modulus/GPa	Fracture strain (%)
Flax yarn	360.2 (20.3)[a]	4.8 (16.6)	13.0 (16.2)
Flax yarn reinforced CSF composites in longitudinal direction	259.5 (10.8)[a]	3.7 (23.7)	10.7 (5.6)

[a] Figures in parentheses are CV%.

Table 2 Flexural properties of flax yarn reinforced CSF composites in longitudinal direction

Flexural strength/MPa	Flexural modulus/GPa	Fracture strain (%)
174.5 (16.9)[a]	10.44 (27.4)[a]	2.6 (15.4)[a]

[a] Figures in parentheses are CV%.

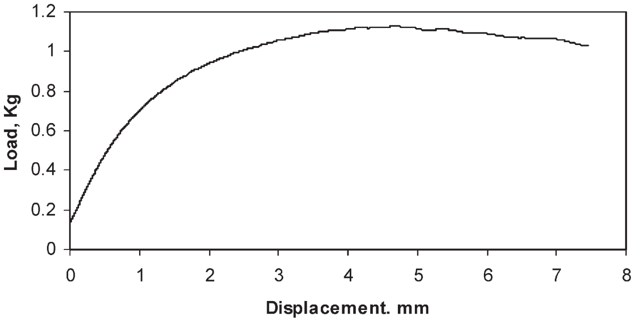

Fig. 5 Typical load *vs.* displacement plot for a flexural test of flax yarn reinforced CSF composites in longitudinal direction.

direction. Chabba and Netravali[17] reported the flexural stress and flexural modulus values of 86.1 MPa and 1.18 GPa, respectively, for flax yarn reinforced cross-linked SPC resin composites. Nam[28] fabricated unidirectional composites using ramie fiber and SPC resin. She reported flexural stress and flexural modulus values of 225 MPa and 12.3 GPa, respectively, in the longitudinal direction. Lodha and Netravali[27] have reported flexural stress and modulus values of 185 MPa and 13.9 GPa, respectively, for unidirectional composites made using ramie fiber and stearic acid modified SPI resin. Thus the flax yarn reinforced CSF composites fabricated in this research show flexural strength and modulus values comparable to fiber-reinforced composites using more expensive versions of soy protein. The flexural properties of green composites, however, are lower than 529 MPa and 27 GPa, for flexural strength and modulus, respectively, values obtained for the pre-stressed glass–PP composites.[33] However, in another case where the fibers were not pre-stressed, the flexural strength and modulus of glass–PP composites were 265 MPa and 11.7 GPa, which are very comparable to the values for green composites obtained in this study.[34]

Various SPI based resins have been characterized for their degradation in compost medium.[35] All were found to degrade within six months. The CSF used in this study, having similar chemistry to SPI and modified SPI resins, is also believed to be fully degradable making the flax yarn reinforced composites to be truly 'green'.

Conclusions

SF was successfully crosslinked with GA. Cross-linked SF (CSF) resin showed improved thermal stability and processability for manufacturing green composites. Flax yarn and CSF resin were used to fabricate fully biodegradable, environment friendly green composites. Flax yarn reinforced CSF composites, with 60% fiber weight fraction, exhibited improvements of over 700% in fracture stress and over 2000% in Young's modulus in the longitudinal direction as compared to the CSF resin. These composites can be used in secondary and, in some cases, primary structures in indoor applications.

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PS–BQ: an efficient polymer-supported cocatalyst for the Wacker reaction in supercritical carbon dioxide

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Using polystyrene-supported benzoquinone (PS–BQ) as cocatalyst with palladium chloride, the acetalization of terminal olefins with electron-withdrawing groups, *i.e.*, acrylate esters, acrylonitrile, methyl vinyl ketone and acrolein, was carried out smoothly in supercritical carbon dioxide under oxygen atmosphere.

Introduction

The Wacker reaction is a good way to produce methyl ketones *via* the Pd^{II}-catalyzed oxidation of terminal olefins.[1] In order to improve the activity of the catalyst in the Wacker reaction, many efforts have been made,[1] including (1) choice of solvents, such as *N*,*N*-dimethylformamide (DMF),[2] ethanol,[3] acetonitrile (CH_3CN),[4] and supercritical carbon dioxide ($scCO_2$),[5] (2) addition of hexamethylphosphoramide (HMPA),[6] (3) substitution for cocatalyst $CuCl_2$ (or CuCl) using benzoquinone (BQ),[4] ferric chloide,[7] heteropoly acid (HPA),[8] ironphthalocyanine (FePc),[9] and (4) the supporting of Pd^{II} catalyst by polymers.[10]

Of all the improvements to the Pd^{II}-catalyzed Wacker reaction, more and more importance has been attached to the utilization of BQ[11] instead of cocatalyst $CuCl_2$ (or CuCl) owing to two other advantages: (1) reducing the quantity of chlorine ion in the reaction solution, which is beneficial to avoid the erosion of metallic reactors and by-products caused by chlorination, and (2) preventing the interference of copper ion in the recovery of precious metal palladium from the remains. Therefore, the substitution of BQ for $CuCl_2$ in the Wacker reaction or similar oxidation of alkenes has been successfully reported by Bäckvall *et al.*[4,12]

However, as a small organic molecule, BQ can influence the separation of reaction products and recovery of palladium. If BQ could been fixed on polymer, the process would be simpler. Unfortunately, there have been only a few papers reported on BQ fixed on polymers and its application in the Wacker reaction in a long time.[13]

Many acetals, such as alkyl 3,3-dialkoxypropanoates, *β*-ketoacetals and *β*-cyanoacetal, are important intermediates in organic synthesis and have been used to synthesize a variety of compounds, including coumarins, porphyrins, spermine metabolites, loganin,[14] and active cyclic enaminone derivatives, drugs for prevention and treatment of ischemic heart diseases, dyes, pharmaceuticals and auxiliary agents in textile indusrties.[15] Of all the methods to prepare these compounds with 3,3-dialkoxy group, the Pd^{II}-catalyzed reaction between terminal olefins with electron-withdrawing groups and alcohols as a new type of Wacker reaction is the simplest one.[16]

In the initial stage, high yield of acetals, such as methyl 3,3-dialkoxypropanoate (92%), must be afforded in DMF and in the presence of expensive and toxic HMPA. Once HMPA was absent, the yield was only 46%.[14] As a green reaction solvent, $scCO_2$ has many well-known advantages.[5,17] Recently, replacing DMF with $scCO_2$ was realized in the synthesis of methyl 3,3-dimethoxypropanoate according to Hosokawa *et al.*'s work.[16] The result was successful as expected, and the conversion and selectivity was excellent, especially without the non-green reagent HMPA.[18]

Based on our previous work in $scCO_2$,[5,18,19] in this paper we wish to report the studies on application of polymer-supported benzoquinone (PS–BQ) to Pd^{II}-catalyzed acetalization of terminal olefins with electron-withdrawing groups in $scCO_2$.†

Results and discussion

Preparation and characterization of PS–BQ

The cocatalyst PS–BQ was prepared in three steps: chloromethylation of commercial polystyrene (PS) porous resin, alkylation of hydroquinone by chloromethylated PS, and oxidation of PS-supported hydroquinone with H_2O_2.

The results of every step were all successfully confirmed with IR and elemental analyses of chlorine. For example, chlorine content was more than 18.2% in chloromethyl PS porous resin; chlorine content in PS-supported hydroquinone was less than

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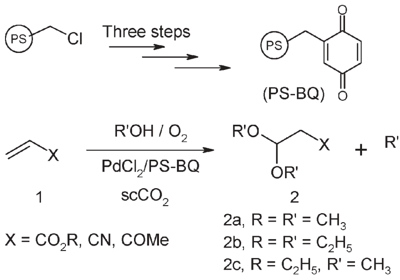
† Typical procedure: According to our previous work,[18] all reactions were carried out in a HF-25 autoclave. Catalyst $PdCl_2$ (0.15 mmol, 3 mol%), PS–BQ (2 mmol), MeOH (1 mL, 24.7 mmol) and methyl acrylate (5 mmol) were added into a 25 mL autoclave in sequence. O_2 and liquid CO_2 were pumped into the autoclave using a cooling pump to reach the desired pressure. Then the autoclave was put into an oil bath under magnetic stirring for the desired reaction time. After the reaction, the autoclave was allowed to cool to −30 °C. CO_2 was vented and the surplus was extracted with *n*-hexane or petroleum ether. The extract was filtered and condensed under reduced pressure. The product was analysed using GC (quantitative) and GC-MS, ^1H NMR and IR analysis (identification of products).



Scheme 1 Acetalization of acrylate esters, acrylonitrile, methyl vinyl ketone using $PdCl_2$/PS–BQ as catalyst.

0.3%, and absorption of CH_2Cl (1264 cm^{-1}) and C–Cl (670 cm^{-1}) in IR spectra disappeared, which indicated the alkylation of hydroquinone was almost entirely finished. After oxidation, the absorption of benzoquinone (1652 cm^{-1}) in PS–BQ was observed and HQ phenolic hydroxyl absorption (3505 and 1191 cm^{-1}) disappeared in IR spectra.

Acetalization of CH_2=CH–COOR and ROH

Using $PdCl_2$/PS–BQ as the catalyst, the acetalization of methyl acrylate (CH_2=CH–$COOCH_3$) with methanol was first investigated under oxygen atmosphere (Scheme 1). The results are shown in Table 1.

Since 1 mol BQ is equivalent to 2 mol $CuCl_2$ in the Wacker reaction of terminal olefins, the effective dosage of PS–BQ based on BQ was controlled to half the amount of $CuCl_2$ according to our previous work.[18] The yield and selectivity of the main product methyl 3,3-dimethoxypropanoate (**2a**, R=R′=CH_3) were very close to the result when cocatalyst $CuCl_2$ was used (Table 1, entries 1 to 3).

When the dosage of PS–BQ was reduced to 1 mmol, the yield and selectivity of **2a** were also manifestly declined (Table 1, entry 4). If the dosage of $PdCl_2$ was reduced to half of the normal amount, the decrease of yield was more remarkable, which indicated that $PdCl_2$ was the leading catalyst (Table 1, entry 5). Therefore, the suitable dosages of the catalysts should be $PdCl_2$ 0.15 mmol (3 mol% of methyl acrylate) and PS–BQ 2 mmol.

Extra methanol could promote partial dissolution of the inorganic catalyst in $scCO_2$,[18] but it was possible to slightly reduce the amount of methanol in the present reaction. We found that using equivalent amount of methanol and methyl acrylate the reaction was also obtained with excellent yield, even with excellent selectivity (Table 1, entry 6).

The experimental results showed that higher fluid densities were beneficial for the reaction. As the system pressure was high enough (7.83 MPa) to keep CO_2 in supercritical state, the conversion of methyl acrylate, the yield and selectivity of **2a** were almost very high. If the CO_2 pressure was high enough, the reaction at lower temperature—even room temperature (20–25 °C)—still gave satisfactory results (Table 1, entries 7 and 8).

To shorten the reaction time from 24 h to 12 h, the reaction gave the perfect result and the efficiency was remarkably improved (Table 1, entry 9).

When ethanol was used as the reagent in the acetalization of ethyl acrylate, it was obvious that acetal ethyl 3,3-diethoxypropanoate (**2b**, R=R′=C_2H_5) was obtained in lower yield and selectivity than that of the acetalization of methyl acrylate in methanol (Table 2, entry 4). This may be caused by the hindrance of R in CH_2=CH–COOR and ROH.

Acetalization of CH_2=CH–COOR and R′OH

In order to avoid transesterification between alcohol and acrylate ester during the acetalization, the acetalization of methyl acrylate was usually carried out with methanol, and ethanol was selected for ethyl acrylate.[16] An interesting phenomenon was observed when PS–BQ was substituted for $CuCl_2$. The transesterification did not occur in the acetalization of ethyl acrylate with methanol, and only ethyl 3,3-dimethoxypropanoate (**2c**, R=C_2H_5, R′=CH_3) was detected as the sole acetal product (Table 2, entries 2 and 3).

The acetalization of *n*-butyl acrylate with methanol or ethanol gave similar results, and no transesterification products were detected (Table 2, entries 5 and 6).

According to the classical Wacker oxidation mechanism,[11,20] it is inevitable to produce acidic substance (*e.g.*, HCl) in the reaction. The transesterification between alcohol and acrylate ester was easily carried out in acidic condition. But in our experiments, using PS–BQ instead of $CuCl_2$ may prevent this possibility, because the amount of chlorine was greatly reduced. This interesting phenomenon strongly revealed that

Table 1 Acetalization of methyl acrylate and MeOH using different catalysts in $scCO_2$ or compressed CO_2

Entry	Catalysts[a]	Temp/°C	Time/h	Pressure[b]/MPa	Mol ratio[c]	Conversion/%	Yield[d]/%			Selectivity for **2**[e]/%
							2	**3**	**4**	
1[f]	$CuCl_2$ 4 mmol[g]	40	24	13	4.94 : 1	99.1	87.9	1.6	2.5	95.5
2	$CuCl_2$ 4 mmol[g]	40	24	16	4.94 : 1	99.8	88.1	1.7	4.0	94.0
3	Normal	50	24	10	4.94 : 1	99.8	82.8	1.3	4.8	93.1
4	PS–BQ 1mmol[h]	50	24	8	4.94 : 1	98.5	54.3	8.0	7.2	78.1
5	$PdCl_2$ 1.5mol%[i]	50	24	8	4.94 : 1	100	39.5	2.3	5.0	84.4
6	Normal	50	24	13	2.00 : 1	99.8	93.9	0	0	100
7	Normal	R. T.[j]	24	7	2.00 : 1	55.6	35.8	0	0	100
8	Normal	R. T[j]	24	9	4.94 : 1	100	93.5	1.2	3.4	95.3
9	Normal	50	12	10	4.94 : 1	99.8	95.5	0.5	3.1	96.4

[a] Normal dosage was $PdCl_2$ 0.15 mmol (3 mol%) and PS–BQ 2 mmol exception for special explanation. [b] The reaction was carried out under the pressure of O_2 0.5 MPa, and the pressure shown in the table was the total system pressure. [c] Methanol to methyl acrylate. [d] By GC. [e] Selectivity = [**2**/(**2** + **3** + **4**)] × 100. [f] Data in entry 1 were cited from our previous work.[18] [g] In order to make a comparison, $CuCl_2$ was all used as cocatalyst in entries 1 and 2. [h] $PdCl_2$ 0.15 mmol. [i] PS–BQ 2 mmol. [j] Room temperature 20–25 °C.

Table 2 The results of acetalization of different acrylate esters using catalyst $PdCl_2$/PS–BQ in $scCO_2$

Entry	Acrylate Ester	Alcohol	Time/h	Pressure[a]/MPa	Mol ratio[b]	Conversion/%	Yield[c]/%			Selectivity for **2**[d]/%
							2	**3**	**4**	
1	Methyl acrylate	Methanol	12	10	4.94 : 1	99.8	95.5	0.5	3.1	96.4
2	Ethyl acrylate	Methanol	11	9	4.94 : 1	99.8	74.2	0	10.0	88.1
3	Ethyl acrylate	Methanol	12	10	4.94 : 1	100	84.5	0	9.1	90.3
4	Ethyl acrylate	Ethanol	12	8	3.44 : 1	100	77.6	0	17.0	82.0
5	*n*-Butyl acrylate	Methanol	12	8	4.94 : 1	78.9	77.8	0	1.1	98.6
6	*n*-Butyl acrylate	Ethanol	12	8	3.44 : 1	28.8	23.9	0.4	2.9	87.9

[a] The reaction was catalyzed by 0.15 mmol (3 mol%) $PdCl_2$ and 2 mmol PS–BQ at 50 °C and under the pressure of O_2 0.5 MPa, and the pressure shown in the table was the total system pressure. [b] Alcohol to acrylate ester. [c] By GC. [d] Selectivity = [**2**/(**2** + **3** + **4**)] × 100.

Table 3 Acetalization of different olefins with electron-withdrawing groups using catalyst $PdCl_2$/PS–BQ in $scCO_2$

Entry	Olefins	Time/h	Pressure[a]/MPa	Conversion/%	Yield[b]/%			Selectivity for **2**[c]/%
					2	**3**	**4**	
1	Methyl acrylate	12	10	99.8	95.5	0.5	3.1	96.4
2	Ethyl acrylate	12	10	100	84.5	0	9.1	90.3
3	*n*-Butyl acrylate	12	8	78.9	77.8	0	1.1	98.6
4	Methyl methacrylate	24	8	N[d]	—	—	—	—
5	Acrylic acid	12	9	N[d]	—	—	—	—
6	Acrylonitrile	12	9	100	79.1	0	0	100
7	Acrylamide	24	8	N[d]	—	—	—	—
8	Methyl vinyl ketone	12	8	100	76.8	13.4	0	85.1
9	Isopropylidene acetone	12	9	N[d]	—	—	—	—

[a] The reaction was carried out with methanol (mol ratio of alcohol to olefin 4.94 : 1), and catalyzed by 0.15 mmol (3 mol%) $PdCl_2$ and 2 mmol PS–BQ at 50 °C and under the pressure of O_2 0.5 MPa, and the pressure shown in the table was the total system pressure. [b] By GC. [c] Selectivity = [**2**/(**2** + **3** + **4**)] × 100. [d] According to above reaction procedure, none of **2**, **3** and **4**, or similar products, was detected.

some key steps in Pd^{II}/PS–BQ catalyzed acetalization are quite different from that in Pd^{II}–$CuCl_2$ catalyst system.

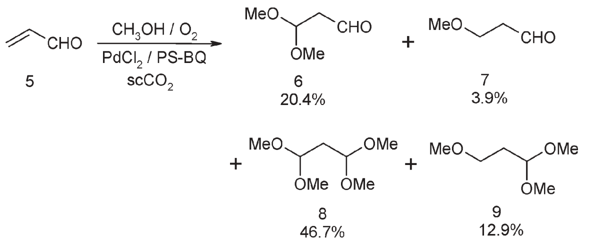
On the other hand, it is notable that the hindrance effect of the R group in CH_2=CH–COOR may affect the yield and selectivity remarkably. When the bulk of the R group became bigger and bigger, from methyl to *n*-butyl, the yield and selectivity decreased gradually (Table 2, entries 1, 3 and 5).

Acetalization of other olefins with electron-withdrawing groups

In Table 3 are shown the results using other olefins with electron-withdrawing groups as the substrates.

The acetalization reaction gave regular results with high yield and selectivity when terminal olefins acrylonitrile (CH_2=CH–CN) and methyl vinyl ketone (CH_2=CH–CO–CH_3) were employed (Table 3, entries 1 to 3, 6, 8, Scheme 2).

For methyl methacrylate [CH_2=C(CH_3)–$COOCH_3$], isopropylidene acetone [$(CH_3)_2C$=CH–CO–CH_3], acrylic acid (CH_2=CH–COOH), and acrylamide (CH_2=CH–$CONH_2$), no expected products were detected (Table 3, entries 4, 5, 7, 9). The hindrance of the methyl group in C=C bond of the formers might stop the reaction. The reason of the latters for giving no expected products is not clear.



Scheme 2 $PdCl_2$/PS–BQ catalyzed acetalization of acrolein with methanol

The acetalization of acrolein (CH_2=CH–CHO, **5**) gave a mixture of major acetal products (**6** and **8**) and minor Michael addition products (**7** and **9**) after the substrate was totally converted (Scheme 2). It is evident that the aldehyde group in acrolein was easily acetalized to yield **8** and **9** respectively.

In summary, it is a successful example to employ $PdCl_2$/PS–BQ as the catalyst for the acetalization of terminal olefins with electron-withdrawing groups, *i.e.* acrylate esters, acrylonitrile and methyl vinyl ketone. Importantly, the reaction is not only smoothly carried out with high yield and selectivity in $scCO_2$, but also makes the precious metal palladium and PS–BQ easily recyclable.

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An eco-efficient pilot plant scale synthesis of two 5-substituted-6,7-dimethoxy-1-H-quinazoline-2,4-diones

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Two 1-H-quinazoline-2,4-diones having substituents at the 5-position have been prepared on a pilot-plant scale using an eco-efficient process. The process started with the appropriately substituted *ortho*-nitrobenzoic acid and involved a catalytic hydrogenation, conversion of the generated aniline to a substituted urea, cyclization and precipitation of the desired 1-H-quinazoline-2,4-diones. The process is unique in that all stages of the process were conducted in water. The desired transformations were affected by manipulation of the pH of the reaction mixture, and addition of the necessary reagent. The products were isolated in near-quantitative yield and were analytically pure. The only waste streams were the aqueous filtrate and the noble metal catalyst. The process was demonstrated on scales up to 5 kg.

Introduction

The development of chemical processes that minimize environmental impact is a key driver for process chemistry groups.[1–3] The emergence of Sustainable Development and its acceptance into the corporate culture of chemical companies encourages the creation of more value with less impact. The principles of Sustainable Development as they pertain to synthetic organic and green chemistry have been discussed in detail recently.[4,5] Roche subscribes to the principles of Sustainable Development and, under the banner of Responsible Care, the process chemistry groups within Roche are encouraged to improve the environmental performance of the synthetic routes wherever possible.[6]

A recent publication by Dunn *et al.* (Pfizer) discussed the evolution of the chemical process used to manufacture sildenafil citrate from a medicinal chemistry route to a commercial route.[7] It highlighted the fact that the routes developed in medicinal chemistry are not eco-economical due to the large amount of waste generated relative to the amount of active pharmaceutical ingredient (API) prepared. This is usually offset by the fact that small quantities of API, typically a few grams, are produced using these initial discovery routes. As highlighted by Dunn *et al.*, optimization of a medicinal chemistry route by process chemists can have a significant impact in waste minimization.

Within the Roche global organization, Roche Palo Alto is a research site. The primary function of the Palo Alto chemical development group is to supply API for all pre-clinical and early clinical studies, typically up to Phase II, for the chemical entities under development at Roche Palo Alto. In this paper, one example of the work being done within Roche using Sustainable Development as a driving force is discussed. An eco-economical chemical process to two useful intermediates was developed that minimized the number of unit operations, waste streams and avoided VOC emissions by conducting all stages of the process under aqueous conditions and relying on a precipitation procedure to isolate the products.

Results and discussion

1-H-Quinazoline-2,4-diones are important intermediates in the pharmaceutical industry. The 6,7-dimethoxy derivatives are useful building blocks in the synthesis of alpha adrenergic receptor antagonists such as Prazosin (**1**), Alfuzosine (**2**) and RO3203546 (**3**). As part of the structure–activity relationship of sub-type selective alpha-1 adrenergic receptor antagonists,[8,9] 5-substituted quinazoline-2,3-diones **4a** and **4b** were required. The short-term goal was to develop a synthetic route to **4a** and **4b** that could be demonstrated in the Roche Palo Alto pilot plant.

Several methods to prepare quinazolinediones have been reported in the literature and are shown generically in Scheme 1. Mizuno has shown that 2-aminobenzonitriles can be converted to quinazolinediones using carbon dioxide in the presence of DBU (1).[10,11] Others have reported that 2-aminobenzamides can be converted to quinazolinediones using a direct carbonylation strategy (2)[12,13] or *via* generation of a urea intermediate and subsequent cyclization with ammonia release (3).[14,15] Conversion of 2-aminobenzoate esters to 2-ureido derivates followed by cyclization has also been a successful strategy (4).[16–20] In some of the latter cases, the intermediate ureido-esters were hydrolyzed to the corresponding carboxylic acid prior to cyclization. Several reports have shown that it is possible to begin the synthesis with anthranilic acids (5).[21–23]

Of the existing literature routes to quinazolinediones, the methodology developed by Pfizer's Hammen and Allen is particularly impressive.[19] It was demonstrated on a 100 kg scale, and afforded a near quantitative yield of 6,7,8-trimethoxy-(1H)-quinazolinedione from the methyl ester of 3,4,5-trimethoxy-2-nitro-benzoic acid. The process was telescoped from the starting nitrobenzoate ester to the quinazolinedione (*i.e.*, intermediates were not isolated) and only two

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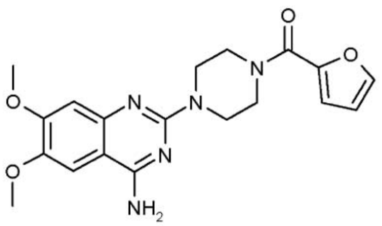

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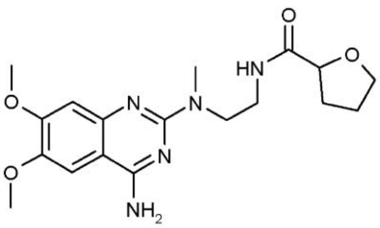

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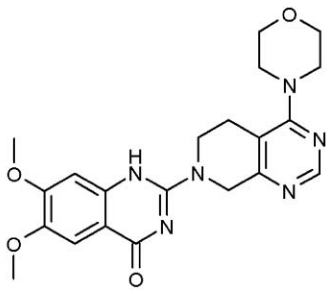

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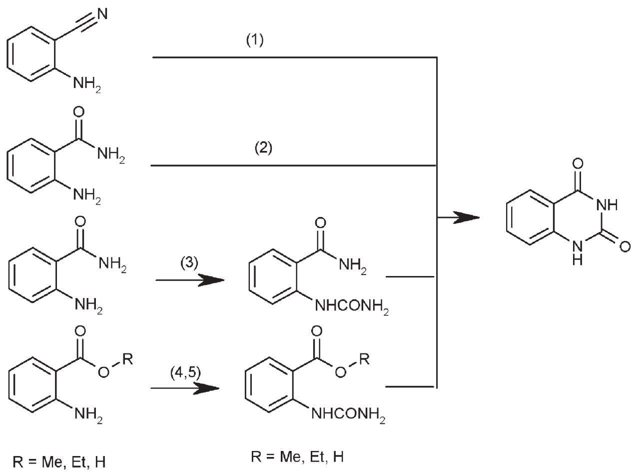


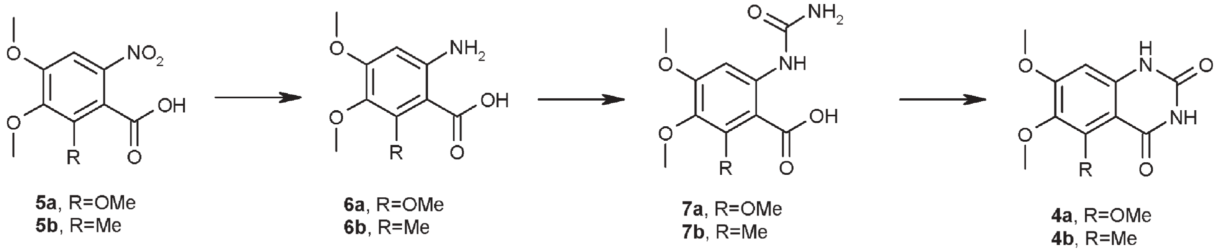
Scheme 1

solvents were used; 2-propanol and water. The propanol was used to dissolve the starting benzoate ester in order to perform the catalytic hydrogenation. When the reduction was complete, the ester was hydrolyzed and 2-propanol was replaced with water. The urea formation and subsequent cyclization were both performed in water.

Goto *et al.* recently reported the conversion of the sodium salt of 2-amino-4-chlorobenzoic acid to 4-chloro-2-ureidobenzoic acid with sodium cyanate and HCl under aqueous conditions.[24] Although the ureido-acid was cyclized under basic conditions, the sodium salt of the quinazolinedione precipitated under the reaction conditions. In order to isolate the quinazolinedione, the sodium salt was filtered, suspended in a 1 : 1 mixture of acetone and water, acidified with HCl and filtered again. Excellent yields were reported (94% yield) and the process generated 19.4 kg of 7-chloro-(1H)-quinazoline-2,4-dione at the 500 L scale.

When we started developing a method to prepare compounds **4a** and **4b**, we wanted to utilize 2-nitrobenzoic acids as the starting materials (Scheme 2). These compounds were safely prepared in high yield using methodology previously developed in this group[25] from commercially available[26] or easily prepared reagents.[27]

We were interested in improving on the published methodology and elevating the performance as a large-scale process, particularly with respect to green metrics. The goal was set to perform the entire sequence in water, which is an area of considerable interest in organic chemistry.[28,29] It was hoped that by manipulating the pH of the aqueous solution, we could accomplish each stage of the process in water, thereby avoiding the use of any organic solvents and eliminating intermediate unit operations such as distillations and filtrations. Conducting the catalytic hydrogenation in water was also appealing from a safety standpoint. The fire-related hazards associated with hydrogen due to its broad flammability range in air (4–75 vol%) are well documented.[30] Likewise, significant literature exists discussing the hazards of hydrogenation catalysts, especially when combined with flammable solvents.[31] The potential hazards associated with handling heterogeneous hydrogenation catalysts and performing hydrogenations on a large scale are greatly attenuated when a non-flammable solvent is used. From this perspective, there is no better solvent than water. The reduction of nitrobenzoic acids under basic, aqueous conditions does have literature precedent. In a paper on the hydrogenation of nitrophthalate salts, Merrill mentioned that *o*- and *m*-benzoic acids were reduced.[32] Although experimental details were not given, one can only assume that the same conditions used for reduction of the nitrophthalates (*i.e.* pH 8–9 aqueous solution



Scheme 2

of the acid in the presence of Raney nickel or platinum oxide at elevated pressure) were used to reduce the nitrobenzoates.

The hydrogenation of 2,3,4-trimethoxy-6-nitrobenzoic acid was evaluated on both the sodium and potassium salts. Using 1.2 equivalent of hydroxide base led to complete dissolution of the starting material in 10 volumes of water for the sodium salt at room temperature. The potassium salt required heating to 60 °C in order to completely dissolve in the same amount of water. The reduction to the anthranilic acid intermediate proceeded quite well in the case of the sodium salt, however the poor solubility of the potassium salt seemed to complicate the reduction and a significant (15% AN HPLC) impurity was formed.

Successfully reducing sodium salt **5a** to **6a** in water was the key step in the development of the telescoped eco-efficient process. When the reduction was complete, the hydrogen environment inside the vessel was purged and replaced with nitrogen. The mixture was then filtered over solka-floc[33] and the filtrate was combined with potassium cyanate (1.3 equiv.) in water.[34] The reaction mixture was cooled and acetic acid (1.2 equiv.) was added to the mixture as the temperature was maintained below 10 °C. The pH was maintained between 7.0 and 8.0. Above pH 8, urea formation was quite slow and below pH 6, a side reaction occurred. These observations were consistent with those reported by Hammen and Allen[19] and Goto *et al.*[24]

When carbamoylation was complete, the pH was adjusted to >13 with 50% sodium hydroxide and the mixture was heated to 50 °C until **7a** was consumed. When the cyclization was complete, the reaction mixture was cooled and the pH was lowered to *ca.* 8, which resulted in precipitation of **4a** as a white solid.

The same procedure was applied to 2-methyl-3,4-dimethoxy-6-nitrobenzoic acid and dione **4b** was generated with similar success.

During the lab scale experiments (5–25 g scales), the hydrogenation was very slow and required 2–4 days to fully convert to aniline derivatives **6a** and **6b**. These reductions were typically done in round-bottomed flasks using a magnetic stir bar and a hydrogen-filled balloon rather than in a Parr-shaker or pressure vessel. Although faster reductions likely would have occurred at higher hydrogen pressures, choosing to develop a process that required specialized equipment would have had a significant impact as the process was scaled up further. In a multi-purpose plant, such as the pilot plant in Palo Alto, there are a limited number of vessels capable of operating at high pressures. In order to maintain maximum flexibility, we chose to develop the hydrogenation using low hydrogen pressure.[35] In this case, the option to use many of the reactors in the pilot plant was available, as long as proper safety procedures were followed.

The first reaction to be scaled up to the pilot plant was the reduction of **5a**. Contrary to the observations in the lab, the reduction was quite fast, and required only 2 hours to convert fully to **6a**. One in-process sample taken from the reaction mixture after 40 minutes of being under a hydrogen atmosphere showed there to be 68% **5a** and 29% **6a** (area-normalized HPLC). Intermediates were not detected, which indicated the intermediates were reduced faster than the starting nitroaromatic under the reaction conditions. The only other in-process sample was examined after 2 hours, and it contained only product **6a**. The faster reduction was the result of more efficient mixing and better mass-transfer. The baffled reactor that was used in the pilot plant caused mixing in both horizontal and vertical planes.[36]

All other stages of the process performed as well on a pilot plant scale as they did in the lab. Over the course of the demonstration runs, the process generated **4a** in 90% yield on a 9 mole scale and **4b** in 98% yield on 20 mole scale. The process did not use any organic solvents, did not generate any vapor emissions from VOCs, and the only liquid waste stream was water, which contained some salts and traces of product related impurities. The aqueous waste streams generated were *ca.* 15 kg per kg of starting material, which is quite respectable for pharmaceutical products based on the E-factor metrics proposed by Sheldon.[37,38]

In summary, we have developed a green synthesis of two useful 1-H-quinazoline-2,4-diones. Our commitment to Sustainable Development and Responsible Care allowed us to adapt existing methodology and led to an eco-efficient chemical process that was demonstrated on a pilot-plant scale using two different substrates.

Experimental

Starting materials were prepared by nitration of the corresponding carboxylic acids,[25] which were commercially available, or prepared as described previously.[27] The catalyst used was Degussa type E-101 containing 10 wt% palladium (dry basis) on carbon. This catalyst is water-wet, and contains ~50 wt% water.

5,6,7-Trimethoxy-1-H-quinazoline-2,4-dione (**4a**): 2,3,4-trimethoxy-5-nitrobenzoic acid (2.35 kg, 9.1 mol) and palladium on carbon (245 g) were charged to a reactor. The vessel was inerted with nitrogen, then charged with tap water (23.5 L) and sodium hydroxide (870 g of 50% NaOH, 1.2 equiv.). The vessel was evacuated and flushed with nitrogen three times, then hydrogen was added to 5 psig. The mixture was stirred at ambient temperature until HPLC indicated that the reaction was complete (0% starting material, $>99\%$ product AN HPLC). The slurry was filtered over solka flok and the filtrate was charged to a clean reactor. Potassium cyanate (964 g, 1.3 equiv.) in water (2 L) was added and the vessel was fitted with a pH meter. Acetic acid was added slowly, and the pH was maintained between 6.8 and 8.0 and the temperature maintained below 10 °C. A total of 560 g (1.02 equiv.) of acetic acid was charged. In-process analysis (AN HPLC) indicated that the mixture had 96.1% urea intermediate (**7a**) and 2.0% aniline intermediate (**6a**). Sodium hydroxide (2.1 kg of 50% aqueous solution, 2.9 equiv.) was added to the solution, and it was heated to 50 °C. Additional NaOH (565 g, 0.8 equiv.) was added to maintain pH 13. After stirring at 50 °C for 18 h, HPLC analysis indicated that there was 96.1% **4a** and 0.9% **7a**. The reaction was cooled to 20 °C and the pH was lowered to 8.0 with acetic acid (2.9 kg). The product crystallized, and the slurry was cooled to 5 °C, then filtered, washed with water, and dried under vacuum in an oven with a nitrogen sweep at 70 °C overnight. 2.06 kg (90% yield) of dione **4a**, 99.9% AN by

HPLC was obtained. Anal. Calcd. For $C_{11}H_{12}N_2O_5$: C, 52.38; H, 4.80; N, 11.11. Found: C, 50.06; H, 4.55; N, 10.48%. mp 245.0–247.7 °C; MS: *m*/*z* (ESI): 253 ($M^{\bullet+}$+1); δ_H (300 MHz, DMSO): 10.8 (2H, br), 6.52 (1H, s), 3.84 (3H, s), 3.77 (3H, s) 3.70 (3H, s); δ_C (75 MHz, DMSO): 160.7, 158.7, 154.2, 150.4, 139.8, 138.0, 102.2, 94.3, 62.0, 61.2, 56.3 ppm.

5-Methyl-6,7-dimethoxy-1-H-quinazoline-2,4-dione (**4b**): 2-methyl-3,4-dimethoxy-6-nitrobenzoic acid (4.8 kg, 19.9 mol) and palladium on carbon (495 g) were charged to a reactor. Tap water (48 L) and NaOH (3.1 kg, 50% solution, 1.9 equiv.) were added and the vessel was inerted with vacuum–nitrogen cycles 3 ×. The reactor was placed under house vacuum and then pressured to 5 psi with hydrogen and stirred at ambient temperature overnight, after which time in-process analysis indicated that there was 0% starting material and >98% **6b**. The reaction mixture was filtered over solka flok and the filtrate was transferred to a clean reactor that was previously charged with potassium cyanate (2.1 kg, 1.3 equiv.). Acetic acid (2.37 kg, 1.9 equiv.) was added while the pH was maintained between 6.8 and 8.0. At the end of the addition, in-process analysis indicated that there was 1.0% **6b** and 95.3% **7b** (AN HPLC). NaOH (1.5 kg, 50% solution) was added and the mixture was heated to 55 °C. After stirring overnight, in-process analysis indicated there was 51.4% dione **4b** and 33% urea intermediate **7b** by HPLC AN. An additional charge of NaOH (2 kg of 50% aqueous solution) was made and the mixture was stirred at 55 °C for 20 h, when HPLC analysis showed there was 94.86% dione **4b** and 0.01% intermediate **7b** present. The reaction was cooled to 20 °C and acetic acid (4.02 kg) was slowly added until the pH was 6.5. The resulting slurry was cooled to 5 °C and the product was filtered, washed with water, and dried in a vacuum oven with a nitrogen bleed at 75 °C overnight. 4.62 kg (98.2% yield) of dione product, 99.7% AN by HPLC was obtained. Anal. Calcd. For $C_{11}H_{12}N_2O_4$: C, 55.93; H, 5.12; N, 11.86. Found: C, 54.27; H, 5.09; N, 11.44%. mp > 250 °C; MS: *m*/*z* (ESI): 237 ($M^{\bullet+}$ + 1); δ_H (300 MHz, DMSO): 8.5–12 (2H, br), 6.70 (1H, s), 3.84 (3H, s), 3.62 (3H, s) 2.56 (3H, s); δ_C (75 MHz, DMSO): 163.69, 157.53, 150.60, 142.62, 140.67, 133.64, 105.77, 96.69, 60.27, 56.04, 13.41 ppm.

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Solubility of several analogues of triphenylphosphine in carbon dioxide

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Homogeneous catalysts often have poor solubility in supercritical CO_2 ($scCO_2$) because they contain aromatic ligands such as PPh_3. The standard approach to this problem, adding fluorinated alkyl groups to the ligands, increases the cost and adds concerns about environmental persistence. Three fluorine-free strategies for increasing the solubility of PPh_3-analogs in $scCO_2$ have now been tested and two more soluble ligands identified.

Introduction

Homogeneous catalysis in environmentally benign solvents is a potentially industrially useful method for green chemistry, but only if the catalysts and ligands can be modified to make them soluble in these solvents. Much recent research has been directed towards the development of catalytic systems appropriate for use in water, ionic liquids, liquid polymers, and supercritical or liquid carbon dioxide[1,2] ($scCO_2$). Water and CO_2 are both cheap, abundant, nontoxic, and nonflammable, making them ideal alternative reaction media. For reactions requiring a nonpolar solvent, CO_2 is obviously preferred. However, carbon dioxide has low solubilizing power for numerous species including transition metal catalysts.[3,4] This is particularly troublesome for complexes having ligands containing multiple aromatic rings. Triphenylphosphine is a ubiquitous ligand in homogeneous catalysis and has, unfortunately, poor solubility in $scCO_2$.[5,6] Complexes of PPh_3 are much less soluble than the free ligand. Even though homogeneous catalysts do not need to be present in solution in large concentrations, the solubility of many such catalysts in CO_2 is problematically low. There is, therefore, interest in developing analogues of PPh_3 that have greater solubility in $scCO_2$.

Several strategies have been used to make phosphines and their complexes more soluble in carbon dioxide. Trialkylphosphines are known to be more soluble; trioctylphosphine is more than three times more soluble than PPh_3 (on a mole fraction basis at 47 °C)[5] despite its higher molecular weight. The use of trialkylphosphines as ligands instead of PPh_3 is a satisfactory solution if the greater basicity of the ligand does not decrease the activity of the catalyst.[7,8] Attachment of fluorine or fluorinated groups onto the aryl rings of PPh_3 has also been successful.[6,9] We sought to determine whether nonhalogenated groups could be used to increase the solubility of triphenylphosphine or other phosphines with similar electronic and steric properties. In particular, we chose to evaluate three strategies for making halogen-free CO_2-soluble phosphine ligands.

The first strategy to be evaluated in this study was the incorporation of ester-containing groups at one or more of the *para* positions of triphenylphosphine. It is known that ester-containing side-chains can increase the solubility of silicone polymers.[10] This may be due to a Lewis acid–Lewis base interaction which may favor the dissolution of the molecule in CO_2. Xiao's group[11] suggested that incorporation of an ester group may enhance the solubility of triphenylphosphine analogues in carbon dioxide but there are no data yet to confirm or refute that suggestion. Substituents containing multiple ester groups represent a further development of this strategy. Peracetylated sugars have been reported to be very soluble in CO_2,[12–14] and it has been suggested that peracetylated sugars could be attached to CO_2-insoluble small molecules to render them CO_2-soluble.[14]

The second strategy was the incorporation of Lewis basic groups into the aromatic ring; this could lead to favorable ligand–CO_2 interactions without the penalty of increased molar mass that is encountered in the first strategy. A number of studies have spectroscopically demonstrated the existence of such interactions in solutions of functionalized organics or in CO_2-expanded polymers; the functional groups included esters, ketones, phosphates, sulfoxides, amines, and amides.[15–18] Phosphines with heteroaryl groups might therefore be more CO_2-soluble than triarylphosphines.

The third strategy was to evaluate a phospha-adamantyl ligand that has similar electronic and steric properties to triphenylphosphine; under the assumption that the aryl rings in triarylphosphines are a major contributor to stabilization of the solid state by π-π stacking effects and that the substitution of two of these aryl rings by an adamantyl cage would eliminate such stacking effects and thereby increase solubility in CO_2.

In order to determine whether these strategies could lead to a phosphine of improved solubility, we chose six phosphines and compared their solubilities in carbon dioxide.

Experimental

General

All synthetic manipulations were performed under an inert and dry atmosphere using solvents dried and distilled from benzophenone ketyl, although CH_2Cl_2 was dried and distilled

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from CaH_2 instead. NMR spectra were acquired using a Varian 300 MHz spectrometer for ^1H and ^{13}C NMR spectra and a 400 MHz NMR spectrometer for the ^{31}P NMR spectra. ^1H and ^{13}C NMR chemical shifts are reported downfield from TMS but were acquired with residual protons of the solvent as the internal reference. $^{31}P\{^1H\}$ NMR chemical shifts are reported downfield from 85% aqueous phosphoric acid but were acquired with PPh_3 in $CDCl_3$ as an external reference at −5 ppm.

Phosphines **3a**, **5** and triphenylphosphine were commercially obtained and were used without further purification. Compounds **3b**, **3c**,[19] and **6**[20,21] were prepared as previously described. Compound **3e** was treated as a new compound because the only literature report[22] gave no spectral data.

General procedure for the preparation of phosphines 1, 2, and 4

To a stirred solution of 4-(diphenylphosphino)benzoic acid (0.82 g, 2.7 mmol) in CH_2Cl_2 (30 mL) were added 4-(dimethylamino) pyridine DMAP (0.18 g, 1.4 mmol) and 1,2,3,4-tetra-O-acetyl-β-D-glucopyranose (0.93 g, 2.7 mmol). The reaction mixture was brought to 0 °C after which 1,3-dicyclohexylcarbodiimide DCC (1.2 g, 5.8 mmol) was added and stirred for five minutes. The reaction mixture was brought to room temperature and stirred overnight. The solid precipitate was filtered off and the organic phase was washed three times with 0.1 M HCl and once with sat. $NaHCO_3$. The organic phase was dried over $MgSO_4$(s) and concentrated *in vacuo* to obtain the crude product. Pure product was obtained by column chromatography (SiO_2, 3 : 2 hexanes–EtOAc) which yielded a white solid (compound **4**). ^1H NMR ($CDCl_3$, 300 MHz) δ: 2.00 (s, 3H), 2.02 (s, 3H), 2.03 (s, 3H), 2.09 (s, 3H), 3.95 (m, 1H), 4.32–4.38 (dd, 1H, $^2J_{1,2}$ = 12 Hz, $^3J_{1,3}$ = 4 Hz), 4.47–4.52 (dd, 1H, $^2J_{2,1}$ = 12 Hz, $^3J_{1,3}$ = 3 Hz), 5.10–5.32 (m, 3H), 5.74 (d, 1H, $^3J_{6,5}$ = 8 Hz), 7.33–7.38 (m, 12H), 7.97 (d, 2H, $^3J_{arom}$ = 8 Hz). $^{13}C\{^1H\}$ NMR ($CDCl_3$, 300 MHz) δ: 21.0 (OAc), 21.2 (OAc), 62.0 (CH_2), 68.2, 70.5, 72.8, 73.0 (CH), 91.8 (CP), 128.8–129.8 (C_{arom}), 133.1 (C_{arom}), 166 ppm (C=O). $^{31}P\{^1H\}$ NMR ($CDCl_3$, 300 MHz) δ: −4 ppm.

Known[23,24] compounds **1** and **2** were prepared in a similar manner from 4-(diphenylphosphino)benzoic acid and the corresponding alcohol. They were identified by comparison of the ^1H NMR spectra with the literature reports.

Synthesis of 4,4′,4″-phosphinylidynetriphenol triacetate (3d)

To a stirred solution of tris(4-hydroxylphenyl)phosphine oxide (**3c**, 2.7 g, 8.2 mmol) in dry CH_2Cl_2 (160 mL) were added triethylamine (7.7 mL, 55 mmol), acetic anhydride (3.5 mL, 37 mmol), followed by catalytic DMAP (3.0 mg). The reaction mixture was allowed to stir overnight at room temperature. Work-up commenced with the addition of H_2O. The organic layer was then separated from the aqueous phase and concentrated. The aqueous phase was extracted three times with ethyl acetate. The four organic fractions were combined, washed with brine, and dried over $MgSO_4$. Filtration and concentration of the organic phase produced a white solid (2.7 g, 75% yield, mp 122–123 °C). ^1H NMR ($CDCl_3$, 300 MHz): δ 2.30 (s, 9H, Me), δ 7.20–7.24 (m, 6H, H_{arom}), 7.65–7.70 ppm (m, 6H, H_{arom}). $^{13}C\{^1H\}$ NMR ($CDCl_3$, 300 MHz) δ: 21.4 (Me), 122.2 (C_{arom}), 129.0 (CP), 134.0 (C_{arom}), 154.0 (CO), 169.0 (C=O). $^{31}P\{^1H\}$ NMR ($CDCl_3$, 300 MHz) δ: 27.5 ppm.

Synthesis of 4,4′,4″-phosphinidynetriphenol triacetate (3e)

To a stirred solution of **3d** (1.8 g, 4.1 mmol) in toluene (175 mL) were added Et_3N (11 mL, 79 mmol) and then dropwise trichlorosilane (4.8 mL, 79 mmol) at 0 °C. The reaction mixture was then slowly brought up to 110 °C and allowed to reflux overnight. The reaction mixture was then stirred with 30% NaOH at 60 °C. The aqueous phase was removed and extracted three times with toluene. These toluene fractions were combined with the organic phase, washed with brine, and dried over $NaSO_4$(s). Concentration of the organic phase and column chromatography (SiO_2, 1 : 1 hexanes–EtOAc) produced a white solid (1.2 g, 65% yield). ^1H NMR ($CDCl_3$, 300MHz): δ 2.30 (s, 9H, Me), δ 7.06–7.09 (m, 6H, H_{arom}), 7.27–7.34 (m, 6H, H_{arom}). $^{31}P\{^1H\}$ NMR ($CDCl_3$, 300 MHz) δ: −7.5 ppm.

Crystallographic analysis of 4,4′,4″-phosphinidynetriphenol triacetate (3e)

Crystals of **3e** were obtained by slow evaporation of a saturated solution of the phosphine in chloroform. A colorless needle of dimensions 0.36 × 0.11 × 0.08 mm was mounted in the 90(2) K nitrogen cold stream provided by a CRYO Industries low temperature apparatus on the goniometer head of a Bruker SMART 1000 diffractometer.[25] Diffraction data were collected with graphite-monochromated Mo Kα radiation employing a 0.3° ω scan and approximately a full sphere of data to a resolution of 0.77 Å. An empirical correction for absorption was applied using the program SADABS 2.10.[26] A total of 11388 reflections was collected, of which 1621 were unique (R(int) = 0.028) and 1557 had $I > 2\sigma(I)$. The structure was solved by direct methods (SHELXS-97[27]) and refined by full-matrix least-squares on F^2 (SHELXL-97[27]). The final difference map contained max and min peaks of height 0.39 and −0.24 e $Å^{-3}$, respectively (Table 1). CCDC reference number 266859. See http://www.rsc.org/suppdata/gc/b5/b502442k/ for crystallographic data in CIF or other electronic format.

Phase behavior measurements

The phase behavior measurements were performed at 295 K using a high pressure, variable volume windowed cell with a cylindrical sample volume (D.B. Robinson & Assoc.).

Table 1 Crystallographic data for phosphine **3e**

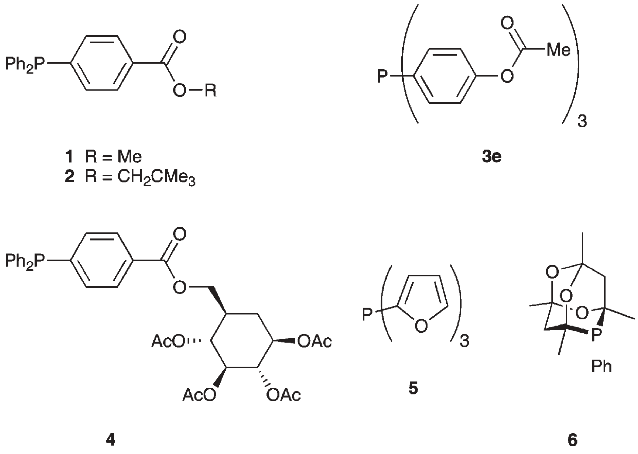
Formula	$C_{24}H_{21}O_6P$
M_w	436.38
Space group	$R3c$
a/Å	19.1098(8)
c/Å	10.2052(6)
Volume/$Å^3$	3227.5(3)
Z	6
$D_{calcd.}$/mg m^{-3}	1.347
μ/mm^{-1} (MoKα)	0.166
$R1$, $wR2$ [$I > 2\sigma(I)$]	0.0399, 0.1046
R indices (all data)	0.0421, 0.1066

Isothermal expansions and compressions of mixtures of specified overall composition were used to determine the two-phase boundary. A known amount of sample was introduced to the sample volume; high pressure liquid carbon dioxide was then metered in *via* a positive displacement pump. Addition of carbon dioxide was performed isothermally and isobarically by withdrawing the overburden fluid at the same time. Mixing was accomplished *via* a high intensity multi-blade stirrer fitted to the top of the view cell. The CO_2-sample mixture was pressurized and mixed until a transparent single phase resulted. The system was then slowly depressurized by withdrawing the overburden fluid and thus expanding the sample volume. The point at which the transmitted light through the sample was less than 10% of that through the initial solution was taken as the cloud point pressure of that mixture at that concentration. Measurements were repeated by repressurizing until a single, clear phase was observed and then depressurizing the system again. The average of 3–4 measurements was recorded as the cloud point pressure. Experiments were conducted over a range of compositions, thus the *P–x* diagram was established; typical variability in our cloud point measurements is less than ±7 bar.

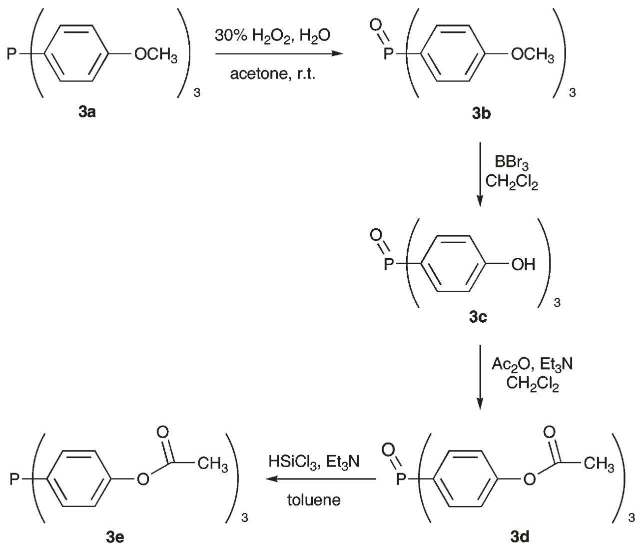
This method is ineffective for the measurement of the solubility of complexes at mass% concentrations below 0.5%.

Results and discussion

Of the six phosphines tested (Scheme 1), phosphines **1–4** contained ester groups. Phosphines **1** and **2**, containing a single ester group, had poor solubility in CO_2 even though the second of these had a neopentyl group which, it was hoped, would disrupt packing in the solid state. At 0.8 wt%, each phosphine failed to form a single-phase mixture with CO_2 even at 480 bar and 22 °C. The insolubility could indicate that the ester-group strategy is invalid, that the ester carbonyl must be further from the bulky aryl ring, or that more than one ester group is required to solubilize a triarylphosphine.



Scheme 1 The phosphines tested for solubility in carbon dioxide.



Scheme 2 The synthesis of 4,4′,4″-phosphinidynetriphenol triacetate (**3e**).

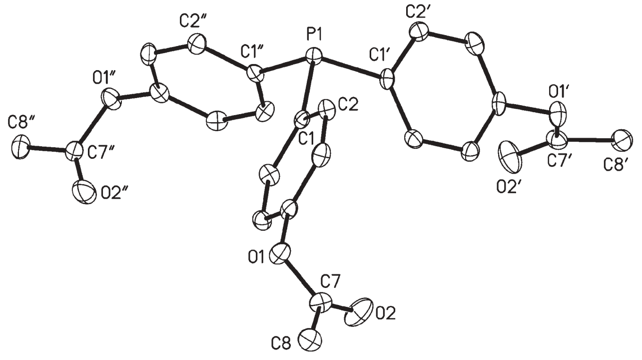


Fig. 1 The structure of 4,4′,4″-phosphinidynetriphenol triacetate (**3e**) with hydrogen atoms omitted. The thermal ellipsoids are shown at 50% probability.

Reversal of the ester group in structure 1, so that the carbonyl was further from the aryl ring, and incorporation of such ester groups on all three aryl rings of the triarylphosphine gave phosphine **3e**, which was still not particularly soluble in CO_2. This compound (synthesis in Scheme 2 and structure in Fig. 1) had a very high cloud point of *ca.* 500 bar at 25 °C and 0.1 wt% and failed to dissolve at any pressure (up to 550 bar) when tested at 0.5 wt%.

Better solubility was observed with a phosphine attached to a peracetylated sugar. Phosphine **4**, which contains a peracetylated sugar moiety on one aryl ring, had a much lower cloud point (Table 2) than those phosphines mentioned above. In comparison to PPh_3, phosphine **4** is much more soluble on a mass% basis and slightly more soluble on a mol% basis at

Table 2 Solubility data of phosphines **4** and **5** in CO_2 at 23 °C

Phosphine	Wt%	Mol%	Cloud point /bar
4	0.5	0.035	68.26
	1.0	0.070	115.8
	1.5	0.105	Insoluble
	4.0	0.280	Insoluble
5	0.5	0.095	124.8
	1.0	0.190	184.1
	1.5	0.285	227.5
	2.0	0.380	233.0

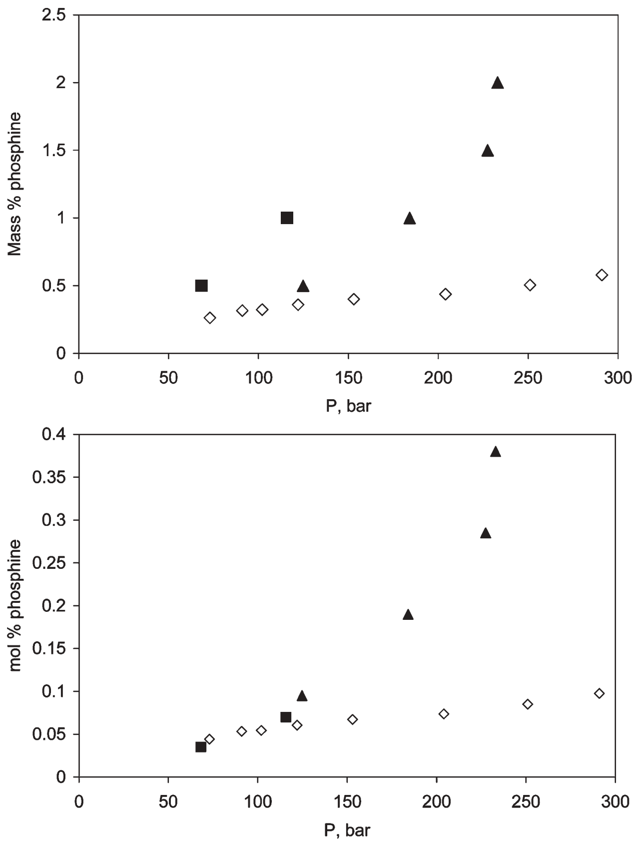


Fig. 2 Mass% and mol% solubility of PPh_3 at 27 °C (◇), **4** at 23 °C (■), and **5** at 23 °C (▲) in CO_2. Data for PPh_3 from reference 6, converted from mol L^{-1} solubility data using density data for pure CO_2.[29]

115.8 bar (Fig. 2). Unfortunately, when the mass% of **4** was raised to 1.5%, compound **4** failed to completely dissolve even at high pressure (600 bar). Solubility caps for peracetylated sugars have been seen before, due to a change in phase behavior from liquid–liquid to liquid–solid at higher weight percents.[28]

In order to test the effect of heteroaromatic rings as substitutes for the phenyl rings of PPh_3, the cloud point of commercially available tri(2-furyl)phosphine **5** was determined (Table 2). Tri(2-furyl)phosphine has been used[30–33] as a ligand for catalysis in CO_2 but of course it is not an exact substitute; it is less basic than PPh_3 and sterically smaller. The solubility data (Table 2), show that phosphine **5** is much more soluble than PPh_3 on a mol% and on a mass% basis. The greater solubility could be due to either the lower molar mass or a specific interaction between the ether oxygens and the carbon dioxide. The greater solubility supports the suggestion that this ligand should be used as a CO_2-soluble PPh_3-substitute in applications for which the slightly different steric and electronic properties are acceptable.

Quantitative measurements of the solubility of (2-pyridyl)-diphenylphosphine in CO_2 were not attempted because our preliminary competitive extraction experiments, in which CO_2 was used to partially extract phosphine from a 1 : 1 solid mixture of PPh_3 and (2-pyridyl)diphenylphosphine, showed that the two phosphines were extracted at comparable rates and therefore have comparable solubility.

Phosphine **6** was synthesized as previously described[20,21] in order to test the third strategy. This compound is more like PPh_3 than like a dialkylarylphosphine; it is air-stable,[34] only slightly larger than PPh_3 (cone angle 157° compared to 145°) and only slightly less basic (ν(CO) of $RhCl(CO)(L)_2$ is 1986 *vs.* 1965 cm^{-1}).[35] Unfortunately, it was found to be completely insoluble in CO_2 up to the limits of the equipment (660 bar, 25 °C).

It is generally anticipated that ligands that are more soluble than PPh_3 in CO_2 will form complexes which are more soluble than complexes of PPh_3. This has not been experimentally confirmed. The methods used in this research are not useful for the measurement of the solubilities of phosphine complexes because those solubilities are expected to be far below the detection limit. For example, the solubility of one complex, $NiCl_2(PPh_3)_2$, has been measured[4] by other methods to be 0.00021 mol% at 35 °C and 194 bar compared to 0.14 mol% for PPh_3 at 37 °C and 201 bar.[5]

Other factors can influence the solubility of phosphines and their complexes. The solubilities of such species in reaction mixtures may be significantly different from their solubilities in pure liquid or supercritical CO_2 due to the cosolvent effect, which is known[36] to enhance the solubility of aromatics in $scCO_2$. Also, temperature has a strong influence on the solubility of organic compounds in CO_2. At least at the higher pressures (typically over 120–150 bar), solubilities increase with increasing temperature.[37,38]

Summary

Three design strategies for CO_2-soluble analogs of PPh_3 have been tested. The first strategy, the incorporation of ester groups in a substituent attached to the *para* position of one or more of the phenyl rings, met with success only in the example of phosphine **4**, which contains a peracetylated sugar as a substituent. The second strategy, the incorporation of Lewis basic heteroatoms in the aromatic rings, met with greater success in the example of tri(2-furyl)phosphine, the most CO_2-soluble of the phosphines tested. The solubility of that phosphine may partly be due also to its lower molecular weight. The third strategy, ultimately unsuccessful, was to use a phosphaadamantyl ligand as a PPh_3-analog.

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Characterization of adsorption gels prepared from plant biomaterials

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The adsorption of Pb(II), Cu(II), Cd(II), and Zn(II) by new biomaterial gels synthesized in cross-linked reactions from agricultural wastes such as lemon, yuzu (*Citrus junos*), and coffee was investigated. Experimental data of adsorption equilibrium from the heavy metal solutions correlate well with Freundlich isotherm equations. The adsorption mechanism involved acid ion-exchange reactions between the heavy metal and the carboxylic acid of pectic acid in the lemon and yuzu gels, improving the amounts of Pb(II), Cu(II), Cd(II), and Zn(II) adsorbed onto the lemon and yuzu gels by approximately 5- and 6-fold, respectively. The maximum adsorption capacities of the yuzu and lemon gels for Pb(II) and Cu(II) were high. Among the biomaterial gels investigated, the lemon gel possessed the highest complexation ability with these heavy metals. In addition, the adsorption of nitrate ion (NO_3^-) was especially strong by the Pb(II)-adsorbed lemon gel, as shown by IR absorption spectrophotometry. These results indicate that lemon and yuzu gels can function, as new "green chemistry" adsorbents, which can be generated from recycled wastes, involve zero emissions, and provide effective recovery of precious resources.

Introduction

The 20th century was the age of the consumption of resources. However, the production of synthetic compounds that require the use of oil resources is a reason for concern. These production processes often result in toxic emissions to the environment, because microorganisms do not decompose products derived from fossil fuels. In addition, in air, soil, and aquatic environments, toxic metals cause severe health problems to animals and human beings across the globe.[1–3] Although many heavy metals are needed to sustain life, others cause health problems at various concentrations. Industrial activity has caused widespread pollution of soil by elements such as Pb, Cd, Cu, Hg, As, Zn, and also NO_3^-. Many reports have described health problems originating from the biological concentration of heavy metals in seafood, including *Minamata* disease and *Itai-itai* disease. *Minamata* disease is the result of methyl mercury accumulation in fish, which are then eaten. *Itai-itai* disease results in osteomalacia caused by cadmium ingestion. Exposure to lead in Israel and its effect on blood lead levels and the health of workers and children also have been reported.[4,5] Severe arsenic pollution in ground water and hot springs has been observed over large areas of West Bengal in India, Bangladesh, Inner Mongolia in China, and Japan after some mineral and chemical processes.[6,7] Major nitrate pollution problems have occurred by heavy use of agricultural fertilizers.[8] Lead is found throughout the environment, as it is a naturally occurring metal found in the earth's crust, however it is also contained in substances such as petrol, paint, and ceramic products, and released during the manufacture of batteries, solder and pipes, and cable covering. Lena *et al.*[1] reported that Pb concentrations in uncontaminated soils range from 2 to 200 mg kg^{-1}; however, soils from sites polluted by industrial and urban activities in Britain, France, Norway, and Japan contained Pb concentrations of 189 to 47 187 mg kg^{-1}. Leaching of these pollutants into water used as drinking water sources can raise the blood metal levels of infants and children to dangerous concentrations.[9,10] Several methods have been proposed for the removal of heavy metals, *e.g.* ion exchange, filtration, coagulation, and adsorption; however, the materials suggested for these methods often are prohibitively expensive and the processes can produce toxic emissions during the separation operations.

The 21st century has resulted in growing interest in recycling of resources. Concepts of green chemistry with the aim of zero emissions are becoming important in industrial activities. Heavy metal pollution in water systems can be removed to recover precious resources.[11,12] In an effort to develop products that aid recycling of heavy metals while following principles of green chemistry and zero emission, we examined new adsorbent materials that could be created at low cost. Exhausted coffee beans, green tea, black tea, Japanese coarse tea, and yuzu marc wastes are available in large quantities. Therefore, we investigated the adsorption of Cd(II) and Pb(II) at pH 2–6.7 onto biomaterials such as chitosan, coffee, green tea, black tea, Japanese coarse tea, yuzu, and aloe compared to adsorption by inorganic adsorbents such as activated carbon and zeolite.[13] High adsorptive capabilities were observed for all of the biomaterials at pH 4 and 6.7. Coffee, black tea,

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green tea, and coarse tea biomass had loading capacities of Cd(II) comparable to activated carbon and zeolite. Although activated carbon, zeolite, and chitosan are utilized in fields such as wastewater treatment, chemical and metallurgical engineering, and analytical chemistry, these adsorbents are costly. In contrast, processing of the test biomaterials was inexpensive, and all biomaterials except for chitosan adsorbed large amounts of Pb(II) and Cd(II) ions after pre-treatment by washing with water followed by drying. High adsorption capability for the removal of Cd(II) and Pb(II) ions by biomaterials prepared from cellulose biomass was found, showing promise for the development of a novel, low-cost adsorbent. The adsorption behaviour of the plant biomaterials could be categorized into three patterns: (1) coffee; (2) black tea, coarse tea, and green tea; and (3) aloe, yuzu, and chitosan. Adsorption of heavy metals on green tea, black tea, and coarse tea under acidic conditions did not occur. Metal adsorption on yuzu and chitosan occurred over a wide pH range, from strongly acidic to neutral solutions. The group (3) materials easily dissolved in acidic solutions. These differences can be attributed to the components of the biomaterials, suggesting that biologically active components, such as catechin in tea, alkaloid components in coffee beans, and D-glucosamine and pectic acid in yuzu, contribute to Cd(II) and Pb(II) adsorption. The effect of these components on the adsorption of heavy metals was greater than that of the biomaterial cellulose matrix. Although plant biomass can act as an effective adsorbent for the removal of heavy metals, dissolution can occur under acidic conditions, as in the cases of yuzu and chitosan. Thus, we attempted to cross-link the active compounds with the cellulose matrix to prevent elution of the component into the aqueous solution. In addition to the yuzu, the ability of lemon containing pectic acid to adsorb heavy metals was also examined. Here, we report the extent of adsorption of Cu(II), Cd(II), Zn(II), and Pb(II) onto cross-linked coffee bean, yuzu, and lemon to examine their efficiency as inexpensive and tractable biomaterial adsorbents for the removal of heavy metals.

Experimental

Chemicals

All reagents were analytical or extra-pure reagent grade purchased from Wako Pure Chemicals Company Ltd., Japan, unless otherwise noted.

Materials

A sample of crude yuzu residue, after extraction of citrus juice, was provided by Shizen Chiyuryoku Laboratories (Japan). Lemon was purchased commercially and the residue remaining after juice extraction in the laboratory used immediately. Coffee beans from Key Coffee Ltd. (Japan), yuzu (*Citrus junos*) epidermis powder from Shizen Chiyuryoku Laboratories (Japan), and activated carbon powder from Wako Pure Chemicals (Japan) were employed as adsorbents. Blended coffee obtained commercially was used after extraction with hot water and air drying. The preparation of the coffee beans has been described in a previous paper.[13]

Biomaterial gels

Synthesis of yuzu and lemon gels. Yuzu and lemon consist principally of cellulose, pectin substances, hemi-cellulose, chlorophyll pigments, and other low molecular weight compounds such as limonene and limonin. The synthesis of gels containing pectic acid and cellulose was conducted using the method of Yano.[14] Crude citrus residue (35 g) was ground for 30 s in a food processor, stirred in 500 mL of 80% aqueous ethanol for approximately 16 h at room temperature, and then filtered. The citrus fiber was obtained by ethanol extraction of the ground citrus. The yuzu and lemon fibers were freeze-dried to yield 6.5 g and 7.0 g, respectively. The fiber was placed in a flask with 200 mL of 50% aqueous acetone containing 160 mg NaOH (pH = 9) and stirred for 1 h at 25 °C. Fiber containing carboxylic acids was prepared by saponification of the methoxycarbonyl groups of pectin substances under the above conditions, followed by filtration. After the sample was washed with 100 mL of 50% aqueous acetone, it was swelled by addition of 60 mL dimethyl sulfoxide (DMSO) with 300 mL of 50% aqueous acetone for 1 h at 25 °C. To this solution was added 20 mL of epichlorohydrin, and the mixture was stirred for 1 h. Then, the cross-linking reaction was conducted at 50 °C for 3 h after addition of 50 mL 5 M NaOH solution to the mixture. After cooling to room temperature, the mixture was filtered and washed with 300 mL of 70% aqueous ethanol followed by 0.5 M HCl in aqueous ethanol to neutral pH. The cross-linked gel was then immersed in 200 mL distilled water in a flask, and the mixture stirred using a magnetic stirrer for 1.5 h at 50 °C, followed by filtration. The water-soluble components in the gels were removed and the residue freeze-dried to yield 4.8 g of yuzu gel and 5.6 g of lemon gel.

Synthesis of coffee gel. Coffee beans contain cellulose, lignin, and nitrogen-containing compounds such as caffeine, tannic acid, trigonelline, nicotic acid, and quinolic acid. These nitrogen-containing compounds in coffee bean residue were cross-linked using formaldehyde[15] to avoid solubility in acidic aqueous media. Washed and dried coffee bean residue weighing 20 g was placed in a flask with 200 mL of aqueous 0.1 M H_2SO_4 solution and 100 g of 35% formaldehyde was added. The mixture was stirred for 2 h at 60 °C.

After filtration, coffee bean residue was washed with distilled water in an ultrasonic washer until the solution achieved neutral pH, and then dried under air at 60 °C for 6 h. The cross-linked coffee gel is referred to as coffee gel.

Adsorption experiments. Adsorption experiments were carried out by a batch method. To investigate the effect of pH, a 1 g portion of each adsorbent (coffee, coffee gel, yuzu, yuzu gel, lemon, lemon gel, activated carbon) was added to 200 mL of 10 mg L^{-1} Cd(II), Cu(II), Pb(II), and Zn(II) nitrate solution adjusted to pH 2–7 with dilute nitric acid or aqueous ammonia, as required. The suspension was stirred for 24 h on a magnetic stirrer, and separated by filtration with a 0.45 μm membrane filter. The amount of Cd(II), Cu(II), Pb(II), and Zn(II) adsorption onto the adsorbents was determined by measuring the metal concentration in the resulting filtrate using a SAS 7500 Seiko instrument (Japan) atomic absorption spectrophotometer. IR spectra were recorded with a Jasco FT-IR-420 Fourier-transform infrared spectrophotometer (Japan) by the KBr method.

The adsorption isotherm experiments for Pb, Cd, Cu, and Zn for coffee, yuzu, lemon, and their corresponding gels, and activated carbon, were performed as follows. Adsorption experiments were conducted by a batch method. A 1 g portion of each adsorbent (coffee, coffee gel, yuzu, yuzu gel, lemon, lemon gel, activated carbon) was added to 200 mL of 10–1000 mg L^{-1} Pb(II), Cd(II), and Pb(II) or Zn(II) nitrate solution adjusted to pH 4 or pH 5 with aqueous ammonia. The suspension was stirred for 24 h on a magnetic stirrer, and separated by filtration with a 0.45 μm membrane filter. The amount of Cd(II), Cu(II), Pb(II), and Zn(II) adsorption onto the adsorbents was determined by measuring the metal concentration in the resulting filtrate using atomic absorption spectrophotometry.

After separation of the adsorbents from solution by filtration, the adsorbent was carefully transferred into a test tube and stoppered. The adsorbed heavy metals were dissolved in 5.0 mL of 0.1 mol dm^{-3} acetic acid by stirring with a test-tube mixer and the adsorbent was removed from the suspension by filtration. The amount of adsorption of Cd(II), Cu(II), Pb(II), and Zn(II) onto the adsorbents was determined by measuring the concentration of metals in the resulting filtrate by atomic absorption spectrophotometry.

Results and discussion

The pH dependence

The effect of pH on the adsorption behavior of Pb(II), Zn(II), Cd(II), and Cu(II) onto yuzu gel is shown in Fig. 1, which shows that the yuzu gel was effective for Cu(II) uptake over a pH range of 3–6. Pb(II) in aqueous solution was almost completely removed in the pH range of 2–6 by yuzu gel. In contrast, the adsorption of Cd(II) and Zn(II) varied widely at more neutral pH and was most effective at pH 4 and 5, respectively. Adsorption behavior of yuzu gel was similarly recognized in lemon and coffee gels. In our previous paper,[13] we studied the adsorption of Cd(II) and Pb(II) at pH 2–6.7 onto plant biomaterials such as coffee and yuzu. High adsorptive capabilities were observed except for strongly acidic solution. Since yuzu and lemon are easily dissolved in acidic solution, the measurement of the amount of heavy metal remaining in solution by atomic absorption spectrophotometer was difficult. However, lemon and yuzu gels prepared by cross-linking with epichlorohydrin are not soluble in acidic solution. Thus, it became possible that yuzu, lemon, and coffee could be utilized in wider pH ranges by turning into gel. Herein we set the pH of the solutions to the optimum working pH range for adsorption of metals onto yuzu gel, lemon gel, and coffee gel. The values were pH 4 for Pb(II), Cu(II), and Cd(II), and pH 5 for Zn(II).

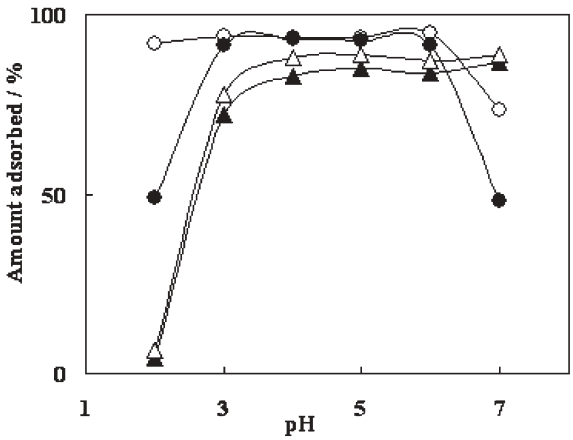


Fig. 1 Effect of pH on the adsorption of heavy metals onto yuzu gel, –○–: Pb, –▲–: Zn, –△–: Cd, –●–: Cu. Sample solution of 200 mL containing 2 mg heavy metal was adjusted to various pH's with diluted nitric acid or aqueous ammonia solution. The suspension with 1 g adsorbent was stirred for 24 h at room temperature.

Adsorption isotherms

The adsorption isotherms of Pb, Cu, Cd, and Zn were investigated for coffee, yuzu, lemon and their corresponding gels. The adsorption isotherms of Pb(II) and Cu(II) ions on several biomaterials are shown in Fig. 2 and Fig. 3, respectively. Adsorption capacity (q) and the amount (mg) of adsorbed metal per weight (g) of biomaterial, were determined from eqn. (1).[13]

$$q = (C_0 - C)/W \tag{1}$$

where C_0 and C are the initial and the final metal concentrations of the solution (mg $(200\ mL)^{-1}$), respectively, and W is the amount (1.0 g $(200\ mL)^{-1}$) of biomaterial.

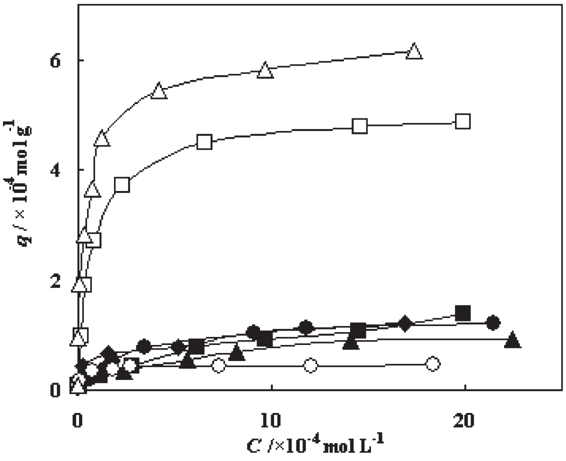


Fig. 2 Adsorption isotherm of Pb(II) on biomaterials and activated carbon. The adsorption experiments were carried out by a batch method. A 1 g sample of each adsorbent, –♦–: activated carbon (A. C.), –■–: yuzu, –▲–: lemon, –●–: coffee, –□–: yuzu gel, –○–: coffee gel, –△–: lemon gel, was added to 200 mL of sample solution containing Pb(II) from 10 mg L^{-1} up to 1000 mg L^{-1} adjusted to pH 4 with aqueous ammonia. The suspension was stirred for 24 h at room temperature. Units for q and C are mol g^{-1} and mol L^{-1}, respectively.

As shown in Figs. 2 and 3, the amounts of metal adsorbed onto yuzu and lemon gels were greater than those on the other biomaterials, especially for Pb(II) and Cu(II). It is particularly interesting that the q_{max} values which are the maximum

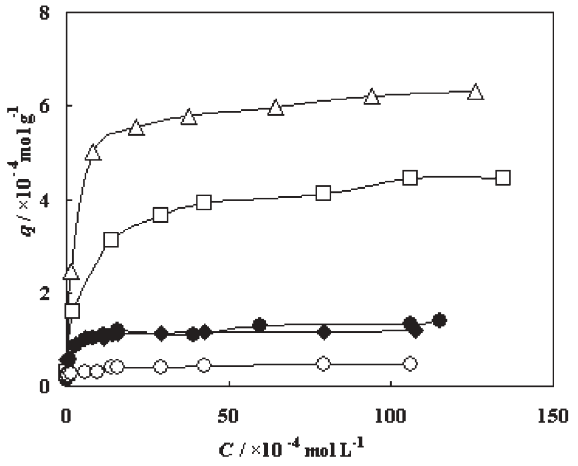


Fig. 3 Adsorption isotherm of Cu(II) at pH 4 on the adsorbents: –◆–: A.C., –●–: coffee, –□–: yuzu gel, –○–: coffee gel, –△–: lemon gel. The adsorption experiment methods and units for q and C are the same as those in Fig. 2.

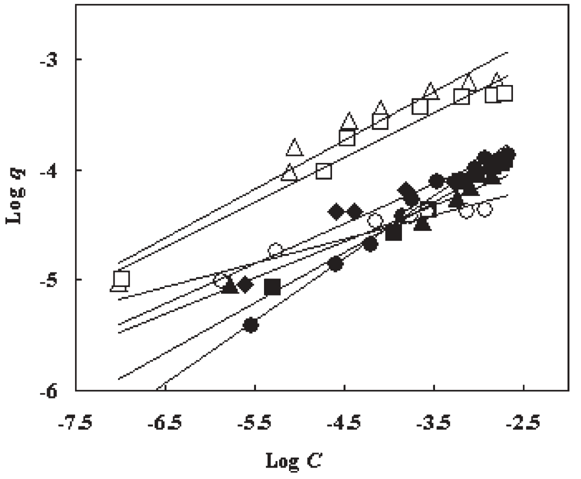


Fig. 4 Freundlich plots for Pb(II) adsorption at pH 4 on the adsorbents: –◆–: A. C., –■–: yuzu, –▲–: lemon, –●–: coffee, –□–: yuzu gel, –○–: coffee gel, –△–: lemon gel. Units for q and C are mol g^{-1} and mol L^{-1}, respectively.

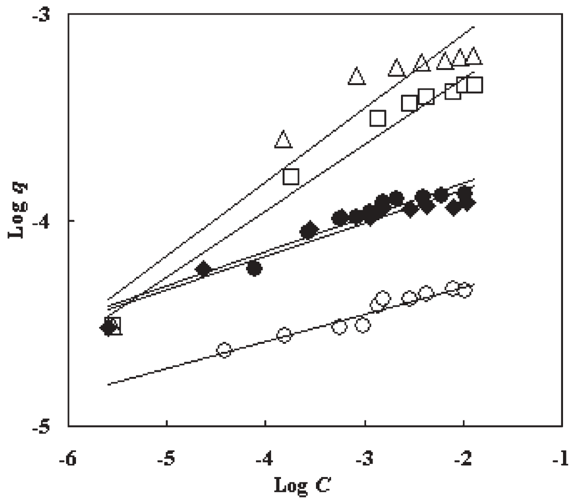


Fig. 5 Freundlich plots for Cu(II) adsorption at pH 4 on the adsorbents: –◆–: A. C., –●–: coffee, –□–: yuzu gel, –○–: coffee gel, –△–: lemon gel. Units for q and C are mol g^{-1} and mol L^{-1}, respectively.

adsorption capacities extracted from adsorption isotherms of yuzu and lemon gels were 2–3 times greater than those found for the other gels. The amount of heavy metal adsorbed on the coffee gel was the lowest of all the adsorbents, and it was decreased significantly by polymerization.

The Freundlich adsorption isotherm is generally applicable in the case of monomolecular adsorption of a single species from a liquid to a solid phase. The Freundlich adsorption isotherm can be expressed as:

$$q = kc^{1/n} \tag{2}$$

where q is the amount adsorbed (mol g^{-1}), c is the residual amount of solute in solution (M), k is and arbitrary parameter, and $1/n$ is an index of the affinity between adsorbent and adsorption sample. The Freundlich adsorption isotherms for Pb, Cu, Cd, and Zn ions exhibit an approximately linear relationship for all biomaterials and gels. The Freundlich adsorption isotherms for Pb(II) and Cu(II) ions on coffee, yuzu, lemon, their gels, and activated carbon (A. C.) are shown in Figs. 4 and 5, respectively.

The parameters obtained from four types (Pb, Cu, Cd, and Zn) of isotherms are summarized in Table 1. For all metal adsorptions, the adsorbents with large values for both k and q_{max} were yuzu and lemon gels. The maximum adsorption capacities (q_{max}) of Pb(II) and Cd(II) by lemon gel increased by more than 6.6-fold after cross-linking. The q_{max} values of yuzu

Table 1 Adsorption parameters with the adsorption isotherms and Freundlich equations for Pb(II), Cd(II), Cu(II), and Zn(II) adsorptions on biomaterials and gels

	Pb(II) pH 4			Cd(II) pH 4			Cu(II) pH 4			Zn(II) pH 5		
Adsorbents	q_{max}[a] × 10^{-4} /mol g^{-1}	k × 10^{-3} /mol g^{-1}	$1/n$	q_{max}[a] × 10^{-4} /mol g^{-1}	k × 10^{-3} /mol g^{-1}	$1/n$	q_{max}[a] × 10^{-4} /mol g^{-1}	k × 10^{-3} /mol g^{-1}	$1/n$	q_{max}[a] × 10^{-4} /mol g^{-1}	k × 10^{-3} /mol g^{-1}	$1/n$
Lemon gel	6.16	17.1	0.44	3.17	2.39	0.37	6.32	4.03	0.36	3.15	1.11	0.28
Yuzu gel	4.88	8.62	0.41	2.04	0.95	0.28	4.46	2.12	0.32	2.09	0.71	0.27
Coffee gel	0.45	0.23	0.22	0.41	0.09	0.12	0.45	0.09	0.13	0.12	0.12	0.03
A. C.	0.93	1.38	0.36	1.08	1.01	0.38	1.21	0.29	0.16	0.54	0.13	0.18
Coffee	1.21	5.62	0.57	1.09	0.78	0.33	1.41	0.32	0.16	0.58	0.01	0.15
Lemon	0.93	0.65	0.33	0.47	0.25	0.25						
Yuzu	1.38	2.04	0.46	0.41	0.29	0.32						

[a] q_{max} is the maximal adsorption capacity extracted from adsorption isotherms.

gel were more than 3.3-fold greater than those of yuzu. In contrast, the adsorption capacity of coffee gel prepared by polymerization was remarkably decreased, even though coffee demonstrated adsorption behaviour similar that of activated carbon.[13] The adsorption ability (k) and maximum adsorption capacity ($q_{\max}$) for Pb(II) and Cu(II) decreased in the following order: lemon gel $>$ yuzu gel $\gg$ coffee $>$ activated carbon $>$ coffee gel. The k and $q_{\max}$ values for lemon gel were more than 5–13 times those of activated carbon.

For Cd(II) and Zn(II), the values of k and $q_{\max}$ decreased in the following order: lemon gel $>$ yuzu gel $>$ coffee and activated carbon $>$ coffee gel. The $q_{\max}$ and k values for lemon gel were more than 2–8 times greater than those of activated carbon. The values of k and $q_{\max}$ for lemon gel increased in the following order: Pb(II) $>$ Cu(II) $\gg$ Zn(II) and Cd(II). Lemon gel also had the highest value of $1/n$ for Pb(II). Thus, the lemon and yuzu gels are effective adsorbents for Pb(II) and Cu(II) ion removal.

Characterization of plant biomaterial gels

The adsorption behaviour of lemon gel was especially interesting, indicating that lemon gel has a strong affinity for lead. In previous papers,[13,16] we reported that differing patterns of adsorption onto plant biomaterials could be attributed to the active components of these biomaterials. These gels appear to have a similar adsorption site; therefore IR absorption spectrophotometry was performed to characterize these gels. Fig. 6 shows the IR adsorption spectra of lemon gel, before and after adsorption of Pb(II), Cu(II), Cd(II), and Zn(II). Table 2 shows the final solution pH values after adsorption of Pb(II), Cu(II), Cd(II) and Zn(II) ions on various adsorbents.

The absorption bands at 3000–3600 cm^{-1} of lemon gel (A)–(E) were assigned to O–H bonds of macromolecular association, consistent with cellulose, and the sharp peak observed at 1750 cm^{-1} was attributed to a carboxylic acid C=O bond on pectic acid. The absorption band at 1750 cm^{-1} for Pb(II), Cu(II), Cd(II), and Zn(II) decreased in the following order: metal-free lemon gel (A) $>$ Zn(II) and Cd(II) adsorbed lemon gels, (E) and (D) $>$ Cu(II) and Pb(II) adsorbed lemon gels, (C) and (B). The strong peak that appears at 1665–1655 cm^{-1} for all lemon gels is the C=O stretching vibration of a carboxylic acid that participates in an intermolecular hydrogen bond. The absorption band at 1665–1655 cm^{-1} for all lemon gels increased in the following order: (B) and (C) $>$ (D) and (E) $>$ (A). This trend corresponds to the amount of each heavy metal adsorbed on the lemon gel. In addition, the spectra of the yuzu gel showed a similar tendency to the lemon gel. As shown in Table 2, the pH of the aqueous solution of the heavy metals adsorbed on yuzu and lemon gels after 24 h is remarkably acidic, while the pH of the solution using activated carbon did not change. From this experimental data, it is suggested that the adsorption of heavy metals on yuzu and lemon gels involves acid-type ion exchange between the carboxylic OH and a heavy metal ion. The interaction of the carboxyl group of pectic acid with a heavy metal ion forms a stable chelate comprising five rings.[17,18] Scheme 1 shows the adsorption mechanisms of heavy metals by yuzu and lemon gels.

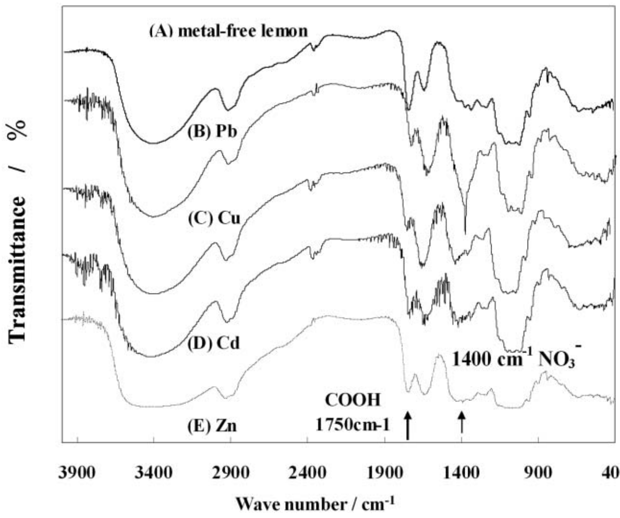
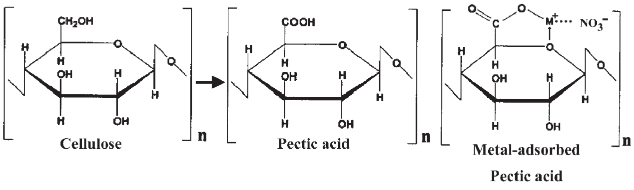


Fig. 6 FT-IR spectra of lemon gel, (A) metal-free lemon gel, (B) Pb(II) adsorbed lemon gel, (C) Cu(II) adsorbed lemon gel, (D) Cd(II) adsorbed lemon gel, (E) Zn(II) adsorbed lemon gel. Spectra were recorded with a Jasco FT-IR-420 Fourier-transform infrared spectrophotometer (Japan) by KBr method.

Table 2 The pH of solutions after 24 h for adsorption of Pb(II), Cu(II), Cd(II) and Zn(II) ions on various adsorbents (initial pH of solutions given in parentheses)

Adsorbent	Pb (pH 4)	Cu (pH 4)	Cd (pH 4)	Zn (pH 5)
Yuzu gel	2.34	2.33	2.52	2.60
Lemon gel	2.16	2.12	2.34	2.40
Activated carbon (A. C.)	4.14	3.81	4.58	4.54

The most interesting phenomenon is the appearance of absorption at 1400 cm^{-1}, which was assigned to NO_3^- vibration.[19] The absorption peaks of NO_3^- ions were sharp in spectra of lemon gels. Fig. 7 shows the FT-IR spectra of lemon gels before and after adsorption of Pb (II). This absorption characteristically appeared on Pb(II)-adsorbed lemon gel. Absorption spectrum strength of NO_3^- in Pb(II)-adsorbed lemon gel increased with the amount of Pb(II) adsorbed. In other words, the high value of NO_3^- uptake capacity of lemon gel may be due to the coordination effect of adsorbed Pb(II) with the carboxyl group of the pectic acid within the cellulose matrix. Nitrate is an essential source of nitrogen for the growth of plants, but can be toxic to humans, animals, and marine life. Fig. 8 shows the generation of nitrate ions during the nitrogen geocycle and its effects on the human body. Nitrate contamination in the environment comes mainly from manure, agricultural fertilizers and industrial effluents. Nitrate ions are



Scheme 1 Adsorption mechanism of heavy metals on yuzu and lemon cellulose matrix gels.

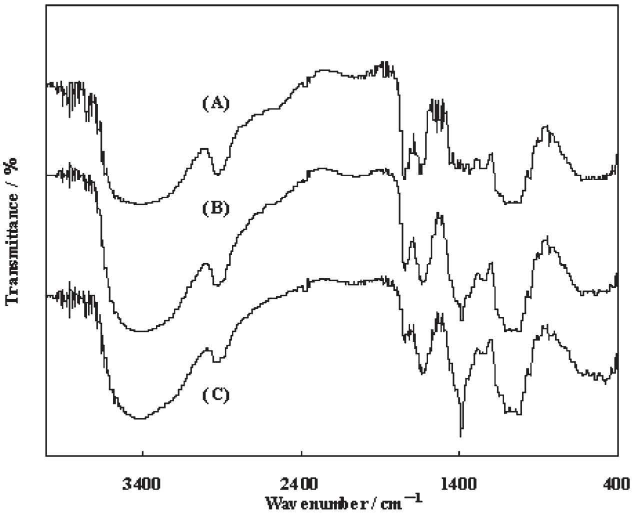


Fig. 7 FT-IR spectra of lemon gel, (A) metal-free lemon gel, (B) Pb(II): 0.46 mmol g^{-1} adsorbed lemon gel, (C) Pb(II): 0.62 mmol g^{-1} adsorbed lemon gel. Spectra were recorded with a Jasco FT-IR-420 Fourier-transform infrared spectrophotometer (Japan) by KBr method.

highly soluble in water, causing them to be washed from the soil into rivers, lakes, oceans, or groundwater. In Japan, 30% of the groundwater, which contains little naturally derived nitrate, is utilized for drinking. Recently, in Japan and Europe, the rising nitric acid concentration in the groundwater has been considered a major environmental problem. Nitrate pollution of land, ground water, and surface water has become a concern in both industrial and developing countries. Excess nitrate intake affects human health and can cause methemoglobinemia in infants[20] and react with amines to form carcinogens.[21]

Water quality standards of waterworks in Japan are measured as the sum of nitrite and nitrate nitrogen levels, which are 10 mg L^{-1} and 44 mg L^{-1} respectively, or less.

Table 3 Effect of diverse ions

	Lemon gel		Yuzu gel	
Ion	Amounts/ µmol g^{-1}	Recovery (%)	Amounts/ µmol g^{-1}	Recovery (%)
Pb(II)	10.1	104	10.1	105
Cu(II)	30.5	97	30.7	97
Cd(II)	15.2	86	15.2	85
Zn(II)	28.1	92	27.8	92

Hydrophobic anion exchange is utilized to remove nitrate and nitrite from groundwater.[20] To overcome the drawbacks of traditional treatment processes, many attempts have been made to remove nitrate and other anions using layered double hydroxides with Ni–Fe[19] and iron(III)-loaded chelating ion exchange resins having either an acidic or basic moiety as the functional group.[22–25] The abilities of iron(III)-loaded chelating pectic acid and alginic acid and their derivatives to complex the arsenious acid ion, phosphate, fluoride, and borate have been reported by Inoue *et al.*[26,27] and Haron *et al.*[28] However, treatment with these chelating ion exchange resins and polymers is expensive.

The ability of Pb(II)-adsorbed lemon gel prepared from agricultural lemon wastes to adsorb nitrate is of great interest because it can be prepared very inexpensively.

Effect of diverse ions

The effects of foreign ions often present in water samples on the adsorption ability of yuzu and lemon gels were examined using 100 mL sample solutions containing 1 mg each of Pb(II), Cu(II), Cd(II), and Zn(II) at pH 5. The analytical results are summarized in Table 3. The presence of 1.0 mg of common cations did not affect the determination of Pb(II) and Cu(II). The presence of Pb(II), Zn(II), and Cu(II) caused slight negative errors in the recovery of Cd(II). However, the concentrations of these ions are generally low in natural water samples. Quantitative recoveries were obtained for lemon and yuzu gels.

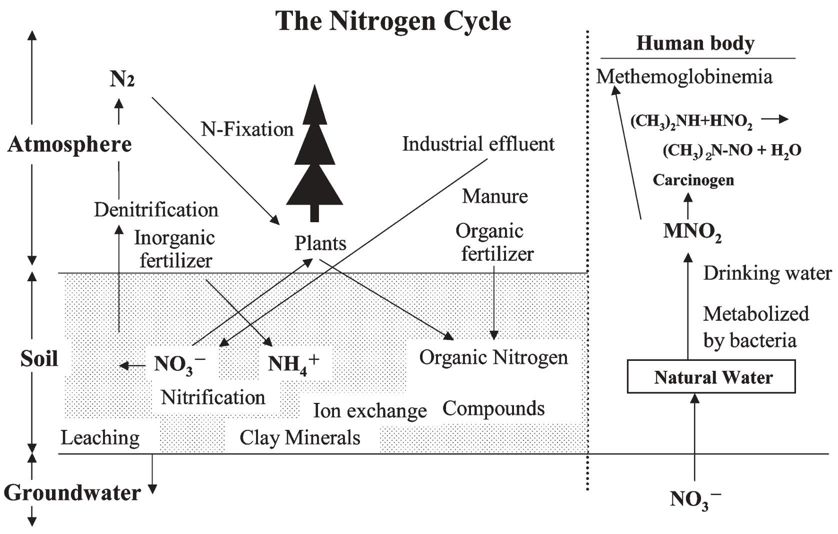


Fig. 8 The generation process of nitrate ions in the nitrogen geocycle and their effects on the human body.

Conclusions

Biomass gels derived from lemon and yuzu, prepared by cross-linking pectic acid to cellulose, effectively adsorbed heavy metals from aqueous solutions. The adsorption abilities of lemon gel and yuzu gel for Pb(II), Cu(II), Cd(II), and Zn(II) were about 5 and 6 times that found for lemon and yuzu, respectively. The maximum adsorption capacity of lemon and yuzu gels for Pb(II) and Cu(II) was high; among the biomaterial gels investigated, lemon gel possessed the highest complexation capacity for these heavy metals. The amounts of Pb(II), Cu(II), Cd(II), and Zn(II) adsorbed on lemon gel were approximately 3- to 6-fold greater than those for activated carbon. Thus, recovery of heavy metals by lemon and yuzu gels is an effective method involving zero emissions.

The adsorption of NO_3^- ions was particularly good for lead-adsorbed lemon gel. This method may prove beneficial for the selective removal of NO_3^- from industrial effluents and seawater. We conclude that lemon gel represents a form of plant biomass capable of recycling resources while achieving zero emission and following the principles of green chemistry.

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Ionic liquids as additives in the pig liver esterase (PLE) catalysed synthesis of chiral disubstituted malonates

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This report describes the first application of hydroxylated and epoxylated ionic liquids as additives in the enantioselective hydrolysis of prochiral diester malonates using pig liver esterase (PLE) as catalyst. Less than 1% of a hydrophilic functionalised ionic liquid, used in combination with 10% isopropanol/water is sufficient to enhance the activity of the enzyme by a factor of up to 4 and also to increase the enantioselectivity of the reaction. Immobilisation of the PLE on Eupergit® C enabled successful recycling of the enzyme system.

Introduction

Room temperature ionic liquids are salts with melting points below 100 °C.[1] These "green" solvents are non-volatile and therefore possible alternatives for environmentally unattractive organic solvents like *n*-hexane or dichloromethane. Another advantage is the possibility of designing a desired liquid with specific properties by modifying the anionic or cationic part of the salt, resulting in a change of the chemical and/or physical behaviour of the ionic liquid. However, at present the exact design rules are not completely understood. Tuning the ionic liquid enables polar and non-polar organic, inorganic, and polymeric compounds to be solubilised. For these reasons ionic liquids have recently gained much attention as attractive solvents in biocatalytic reactions.[2]

The application of ionic liquids in enzyme-catalysed reactions was first reported by Erbeldinger *et al.*,[3] who described the protease thermolysin catalysed synthesis of *Z*-aspartame, using a 1-butyl-3-methylimidazolium hexafluorophosphate ([BMIM]PF_6 : water (95 : 5)) two-phase system. The observed activities were similar to those obtained in conventional organic solvents, but the stability of the enzyme was increased. Following these initial results, further work has shown that ionic liquids usually do not deactivate enzymes as observed with polar organic solvents, although their polarities (measured with Reichardt's dye[4]) are similar to those of methanol, *N*-methylformamide or 2-chloroethanol. This facilitates the use of highly polar substrates and opens new possibilities for biocatalytic reactions.

In the last four years considerable attention has been attracted by lipase catalysed transesterification,[5] perhydrolysis[6] and ammoniolysis[6] reactions in ionic liquids, particularly using *Candida antarctica* lipase B (CAL-B), *Pseudomonas sp.* lipase (PSL) and *Pseudomonas cepacia* lipase (PCL), and examples of enhanced enantioselectivity have been reported. Other enzymes such as proteases,[7] glycosidases,[7] epoxide hydrolases[8] and redox enzymes[9] have also been tested in ionic liquids. In most of these cases, the ionic liquid was the sole or major solvent for the process. However in one example from Zhao and Malhotra,[10] the ionic liquid *N*-ethyl pyridinium trifluoroacetate was effective as a 15% v/v solution in water for the protease catalysed acetylation of amino acid esters. At this level, the ionic liquid still represents a considerable cost component for an industrial process.

The first, and to our knowledge, only application of a hydrophilic functionalised ionic liquid in an enzyme-catalysed reaction is the use of 1-(3-hydroxypropyl)-3-methylimidazolium glycolate as the sole solvent in the combined biological and chemical catalysed synthesis of oxycodone. This solvent proved to be capable of simultaneously dissolving the substrate, enzyme and cofactor.[11]

Despite the promising results achieved with ionic liquids in biocatalytic reactions, development to an industrial scale is still difficult. The commonly used imidazolium-based ionic liquids such as [BMIM]PF_6 or [BMIM]BF_4 are still relatively expensive, difficult to recycle, and are poorly described in terms of their toxicological properties. In addition, impurity levels and purification methods can have a major impact on the rate or selectivity of a biocatalytic process in an ionic liquid. For example, the enantioselective acylation of 1-phenylethanol in [BMIM]BF_4 was reported to give either $<5\%$ conversion[12] or up to 36% conversion,[13] depending on the purification method used in the synthesis of the ionic liquid. The presence of strongly coordinating anions, particularly chloride or nitrate, has a strong inhibitory effect on the enzyme activity.

Results and discussion

We considered that an ideal process would either use cheap, commercially available, nontoxic ionic liquids, or only use low concentrations of the ionic liquid component. We investigated the enantioselective enzyme-catalysed hydrolysis of prochiral disubstituted malonic acid esters, as the chiral

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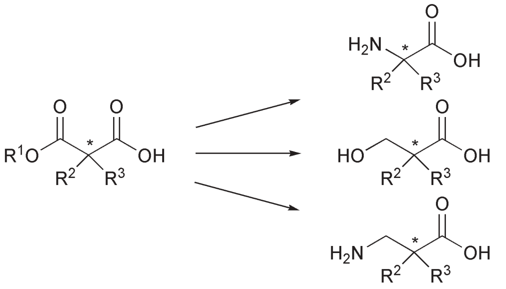
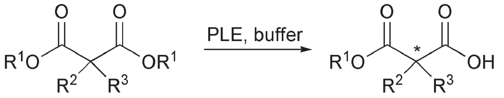
reaction products are well established key intermediates for pharmaceuticals. For example different amino acids or β-hydroxycarboxylic acids can be synthesised as shown in eqn. 1.[14]



(1)

One of the standard enzymes for this process is pig liver esterase (PLE), even though enantioselectivities and/or reaction rates vary depending on substitution pattern as shown in Table 1 (eqn. 2).[15]



(2)

Table 1 PLE catalysed hydrolysis of disubstituted malonates

	R^1	R^2	R^3	ee (%)	Conversion (%)
1	CH_3	CH_3	C_6H_5	78	90
2	CH_3	CH_3	p-$CH_3C_6H_4$	82	92
3	C_2H_5	CH_3	C_2H_5	20	—
4	C_2H_5	CH_3	n-C_5H_{11}	10	90–98[a]

[a] In the presence of 25% DMSO.

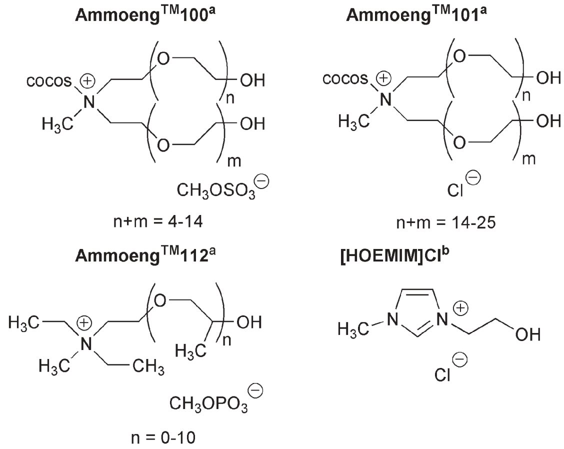
The enantioselectivities can be significantly improved by adding small amounts of alcohol co-solvents.[16,17] A detailed study of the reaction rate, however, revealed a reduction in reaction rate (although the final conversions achieved are still in a comparably high range), presumably due to inhibition of the enzyme by the co-solvent (see Table 2).

We have now found that this decrease in enzyme activity can be completely reversed by the addition of ionic liquids bearing one or more hydroxyl functional groups. The results presented in Table 3 show that, in combination with isopropanol (10%), small amounts of hydroxylated ionic liquids (Fig. 1) (<5%) are able to increase the enzyme activity by up to a factor of 4 compared to the reaction in water–isopropanol alone.

Table 2 Influence of different alcohols on selectivity and activity in the PLE catalysed hydrolysis of diethyl 2-phenyl-2-methyl malonate[a]

	Co-solvent	Time/h	ee (%)	Conversion[b] (%)
1	—	1.5	78	>90
2	20% Methanol	3	87	35
3	20% Ethanol	3	90	30
4	20% Isopropanol	3	95	>90

[a] 20 mM malonate, 30 mg PLE (40 units mg^{-1}), 50 mL reaction volume. [b] Yield measured as consumption of NaOH using a Titrinus automatic burette.



[a] Purchased from Solvent Innovation / Goldschmidt GmbH
[b] Synthesised on laboratory scale.

Fig. 1 Ionic liquids with hydroxyl groups.

As shown in Table 3, the enhancement of the enzyme activity depends on the numbers of hydroxy functions in the ionic liquid. Ammoeng™112 and 1-(3-hydroxy-ethyl)-3-methylimidazolium chloride ([HOEMIM]Cl) which contain one hydroxy group accelerate the reaction by a factor of *ca.* 2, whereas Ammoeng™100 and Ammoeng™101 which have two hydroxy functions increase the activity by a factor of 4, even at levels of 0.1%. The application of standard ionic liquids such as [BMIM]PF_6 results in practically no effect on enzyme activity and selectivity. Even the use of polyethyleneglycol as co-solvent, which is known to stabilize enzymes, results in lower activities compared to Ammoeng™100 or Ammoeng™101 (PEG 200, Table 3, entry 7). In addition to the enhancement of enzyme activities, higher enantioselectivities (ee up to 97%) were observed in reactions utilising Ammoeng™100 or Ammoeng™101.

Table 3 Influence of different ionic liquids on selectivity and activity in the PLE catalysed hydrolysis of diethyl 2-phenyl-2-methyl malonate[a]

	Co-solvent	Time/min	ee (%)	Conversion[b] (%)
1	—	95	78	>90
2	10% Isopropanol	200	95	>90
3	10% Isopropanol + 1% Ammoeng™112	95	95	>90
4	10% Isopropanol + 1% [HOEMIM]Cl	105	92	>90
5	10% Isopropanol + 0.1–5% Ammoeng™100	55	97	>90
6	10% Isopropanol + 1% Ammoeng™101	65	97	>90
7	10% Isopropanol + 1% PEG 200	110	92	>90
8	10% [BMIM]PF_6	180	78	>90

[a] 40 mM malonate, 40 mg PLE (40 units mg^{-1}), 50 mL reaction volume. [b] Yield measured as consumption of NaOH using a Titrinus automatic burette.

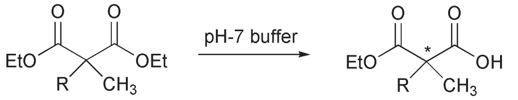
Table 4 PLE catalysed hydrolysis of different malonates[a]

	R	Co-solvent	Time/min	ee (%)	Conversion (%)[b]
1	p-$CH_3C_6H_4$	—	210	>96	>90
2	p-$CH_3C_6H_4$	10% Isopropanol + 1% Ammoeng™100	60	>96	>90
3	$CH_2C_6H_5$	—	210	n.d.	60
4	$CH_2C_6H_5$	10% Isopropanol + 1% Ammoeng™100	45	n.d.	>90

[a] 40 mM malonate, 40 mg PLE (40 units mg^{-1}), 50 mL reaction volume. [b] Yield measured as consumption of NaOH using a Titrinus automatic burette.

Another advantage, besides the increased activity and selectivity, is the possibility of utilising ionic liquids which contain strongly coordinating anions, *e.g.* Ammoeng™101. Because of the catalytic amounts of ionic liquid, the chloride content has little effect on the activity of the reaction (Table 3, entries 5 and 6).

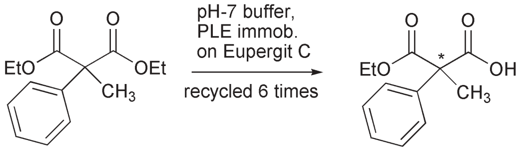
To extend the scope of the hydrolysis reaction, we investigated the PLE catalysed hydrolysis of a range of disubstituted malonates as shown in eqn. 3 (Table 4).



(3)

The results showed for both malonates a clear enhancement of the activity by a factor >3. Surprisingly, when the 2-methyl substituent of malonate was replaced with a larger group, an inhibition of the reaction was found on addition of hydroxylated ionic liquids.

To illustrate the industrial applicability of the process, the recycling of the enzyme has been investigated. Eupergit® C has been utilised as an effective industry-proven carrier material for the immobilisation of enzymes.[18] Eupergit® is a copolymer of methacrylamide, N,N'-methylene-bis-(methacrylamide) and two monomers containing oxirane groups. The oxirane groups react with the amino groups of the enzyme and generate a highly stable supported enzyme, as has been demonstrated for a broad range of enzymes including PLE. This system was applied to the hydrolysis of diethyl 2-phenyl-2-methyl malonate (Table 5, eqn. 4).



(4)

Table 5 The use of immobilised PLE in the hydrolysis of diethyl 2-phenyl-2-methyl malonate[a]

	Co-solvent[b] IL	Time/min	ee (%)	Conversion[c] (%)
1	1% Ammoeng™100	95	97	>90
1 Rec.-1	1% Ammoeng™100	105	n.d.	>90
1 Rec.-2	1% Ammoeng™100	105	97	>90
1 Rec.-3	1% Ammoeng™100	105	96	>90
1 Rec.-4	1% Ammoeng™100	105	n.d.	>90
1 Rec.-5	1% Ammoeng™100	130	n.d.	>90
1 Rec.-6	1% Ammoeng™100	145	97	>90
2	—	195	n.d.	>90

[a] 20 mM malonate, 1.36 g PLE on Eupergit C (295 units g^{-1}), 50 mL reaction volume. [b] +10% isopropanol. [c] Yield measured as consumption of NaOH using a Titrinus automatic burette.

The results showed that after the fifth cycle the activity decreases by *ca.* 10–20% per run. This could be explained by a possible deactivation and/or mechanical abrasion of the enzyme during the reaction. Compared to the reaction without the ionic liquid (entry 2), the reaction rate is about a factor of two higher.

Conclusions

The results presented in this work show that the selectivity and activity of the PLE catalysed hydrolysis of disubstituted malonates can be efficiently increased by addition of both isopropanol and a small amount (<1%) of a hydrophilic functionalised ionic liquid. The best results were achieved with 0.1% of Ammoeng™100 which contains two primary hydroxy groups at the end of two polyethylene chains. Interestingly, nearly no reduction of activity was found when ionic liquids containing halide anions, such as Ammoeng™101, were employed. No inhibition was seen with the low concentration of halide present, in contrast to previous results where high concentrations of ionic liquids containing strong coordinating anions were employed.[19] The process has been further improved by immobilisation of the PLE on Eupergit® C, which allowed the immobilised enzyme to be successfully recycled 6 times.

For the first time, catalytic amounts of hydroxylated and epoxylated ionic liquids have been used as additives in enzyme-catalysed processes, making such processes easier to transfer to an industrial scale. These reaction conditions are currently being transferred to other biocatalytic processes.

Experimental

Materials

Pig liver esterase was provided by Sigma-Aldrich and the immobilised form was obtained from Röhm. The ionic liquids (Ammoeng™100, Ammoeng™101 and Ammoeng™112) were purchased from Solvent Innovation or Goldschmidt GmbH. [HOEMIM]Cl was prepared according to the method of Fraga-Dubreuil and Bazureau.[20] The other chemicals and reagents were purchased from Aldrich or Acros and used without further purification.

Analysis

For the HPLC analysis of the malonates a chiral column OD was used. The separation of enantiomers was achieved with a flow of 0.25 mL min^{-1} at 240 nm, by using n-hexane : isopropanol : trifluoracetic acid (93 : 7 : 1.5) as the mobile phase. ^1H NMR and ^{13}C NMR spectra were recorded on a Bruker

DRX 500 operating at 500.13 and 125.77 MHz, respectively. Chemical shifts are reported in ppm with tetramethylsilane as internal standard (0 ppm). Data are reported as follows: chemical shift, multiplicity (s = singlet, t = triplet, br = broad, m = multiplet, coupling constant (Hz), integration, and assigment).

General procedure for the enzyme hydrolysis of disubstituted malonates

In a pH-stat (Titrinus) with a total volume of 50 mL a mixture of a buffer solution (0.1 M KH_2PO_4–K_2HPO_4) together with the respective co-solvents (ionic liquid, alcohol) were stirred at a temperature of 30 °C. The substrate concentration depended on the experiment and the amount of enzyme added. The hydrolysis was controlled by fixing the pH with the addition of a 0.1 M NaOH solution. The reaction was complete when one equivalent of NaOH had been added. At the end of the reaction, the aqueous solution was extracted with diethyl ether (2 × 50 mL). Afterwards the aqueous phase was acidified with HCl (1 M) to pH <2.5. The product was extracted with diethyl ether (4 × 50 mL) and the combined organic phases were dried over $MgSO_4$, filtered and concentrated under reduced pressure to yield the pure chiral malonates (HPLC and NMR analysis).

^{1}H NMR (2-phenyl-2-methyl ethyl malonate): $\delta = 1.25$ (3H, t, $^3J = 7.09$ Hz), 1.90 (3H, s), 4.25 (2H, m), 7.35 (5H, m) ppm.

Acknowledgements

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Ionic liquids as novel solvents for the dissolution and blending of wool keratin fibers

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1-Butyl-3-methylimidazolium chloride ionic liquid has been developed for the dissolution and regeneration of wool keratin fibers, which can be used to prepare wool keratin/cellulose blended materials directly.

Introduction

Ionic liquids have received much attention as green and designable solvents with the development of green chemistry and the requirement for environment protection. Many applications of ionic liquids in organic synthesis and catalysis have already been found.[1] Owing to their special structures compared to the traditional molecular solvents available today, ionic liquids possess many unique solubility characteristics. In particular, the 1-butyl-3-methyllimidazolium chloride ($BMIM^+Cl^-$) and dicyanamide ionic liquids have a strong ability to disrupt hydrogen bonds under relevant conditions and thus they can be used to dissolve biological macromolecules that are linked together by intermolecular hydrogen bonds such as carbohydrates, cellulose and silk fibroin. In 2002, Forsyth *et al.*[2] first used dicyanamide anion based ionic liquids as solvents for the dissolution of carbohydrates. Swatloski *et al.* reported that $BMIM^+Cl^-$ is an excellent solvent for the dissolution of cellulose,[2] and it was easy to prepare an up to 10 wt% solution by heating in an oil bath at 100 °C and 25 wt% using a microwave. In 2004, Phillips *et al.* reported that bombyx mori silk fibroin could be dissolved by $BMIM^+Cl^-$ under similar conditions.[3] Recently, Liu *et al.* reported that the ionic liquids based on the dicyanamide anion were highly effective aprotic solvents that can dissolve carbonhydrates such as glucose, starch and even cellulose in large amounts.[4]

Wool keratin fibers are one of the most popular natural biopolymers. Since the first wool keratin solution was prepared, its applications have been explored in many fields such as additives for animal feed, neatening reagents for wool or leather, wool regenerating blended materials and so on, besides its use as textile fiber. The applications mentioned above have been illuminated in detail in many patents.[5] It is worth noting that tons of non-spin wool fibers are discarded during wool weaving every year, and a mass of waste wool keratin textile fibers are discarded in our daily life. So from both an economic and environmental point of view, it is quite challenging to develop a simpler process to use and reuse these resources.

Wool keratin is a kind of unbranched polymer comprised of amino acids. It exhibits a stable three-dimensional conformation maintained by a range of noncovalent interactions (electrostatic forces, hydrogen bonds, hydrophobic forces) and covalent interactions (disulfide bonds), in addition to the peptide bonds between individual amino acids.[6] A key problem is to find a suitable reagent to destroy these interactions in terms of the dissolution of wool keratin. However, its complicated structure can't be directly dissolved by common solvents, and can only be dissolved by a mixture of solvent systems in which different components have different functions to disrupt the noncovalent and covalent interactions between the polypeptide chains. For example, a solvent can disrupt the noncovalent interactions and a reductant or oxidant can destroy the disulfide bonds. Multiple solvent systems have been utilized to prepare wool keratin solutions based on this principle,[5] such as carbamide/H_2O_2/H_2O and carbamide/2-mercaptoethanol.[7] In the process of the preparation of wool keratin/cellulose blended materials, the Cu-oxam metal complex system ($[Cu(NH_3)_4(OH)_2]$) was used as a common solvent for both wool keratin and cellulose,[8] and the reductant is necessary to increase the dissolution of wool keratin. However, the strong environmental impact of the metal complex waste solution and the difficulties encountered in removing Cu from the regenerated materials prompted us to develop a new dissolving process. In this paper, we report the dissolution of wool keratin fibers in ionic liquids and their potential applications in wool keratin/cellulose blended materials. To our knowledge this represents the first example of a single solvent able to dissolve wool keratin fibers.

Results and discussion

The strong ability of $BMIM^+Cl^-$ to disrupt hydrogen bonds makes it an attractive solvent for wool keratin. In our laboratory, we used different ionic liquids (including $BMIM^+Cl^-$, Br^-, BF_4^-, PF_6^-, and 1-allyl-3-methylimidazolium choride (AMIMCl)) to investigate the relationship of solubility for wool keratin and the structure of ionic liquids. All these ionic liquids were synthesized according to the literature and dried at 100 °C in a vacuum oven 48 h prior to the experiments.[9] Their structures were verified by ^{1}H-NMR, ^{13}C-NMR, MS, and IR.

The wool keratin fibers utilized in these experiments were commercial materials, and cleaned by an acetone/ethanol

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Table 1 Solubility of wool keratin fibers in ionic liquids

Ionic liquids	Condition/°C	Time/h	Solubility (wt%)
$BMIM^+Cl^-$	100	10	4
	130	10	11
$BMIM^+Br^-$	130	10	2
$AMIM^+Cl^-$	130	10	8
$BMIM^+BF_4^-$	130	24	Insoluble
$BMIM^+PF_6^-$	130	24	Insoluble

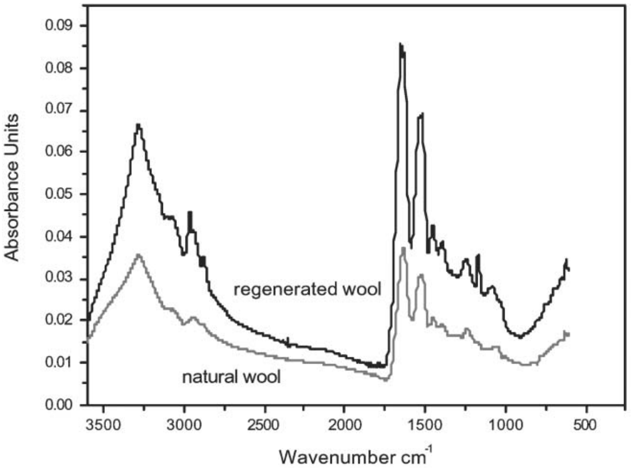

Fig. 2 IR comparison of natural wool keratin fibers and regenerated wool keratin.

mixture solvent system in a Soxhlet extractor for 48 h, then rinsed with distilled water and dried at 100 °C in a vacuum oven 12 h prior to solubility experiments. All dissolution experiments were performed in a 50 ml three-necked flask with mechanical stirrer under an inert atmosphere of N_2. The temperature of the dissolving process was controlled by an oil bath at the optimized temperature. The wool keratin fibers were added in portions of only 1 wt% of ionic liquid every time until the wool keratin fibers disappeared. The resulting wool keratin/ionic liquid solution was clear and viscous. From the solubility results listed in Table 1 we can conclude that temperature has a strong effect on the solubility, *e.g.* only 4 wt% dissolved at 100 °C over 10 h for $BMIM^+Cl^-$ and 11 wt% at 130 °C. The results show that the chloride anion ionic liquids have better solubility for wool keratin fibers than ionic liquids involving bromide anion or noncoordinating anions including BF_4^- and PF_6^-.

In order to further prove the dissolution of wool keratin fibers in ionic liquids, the 10 wt% wool keratin $BMIM^+Cl^-$ solution was taken to examine the crystal structure by wide-angle X-ray diffraction (WAXD). Fig. 1a shows a broad amorphous halo centered near a 2θ of 25°, but no typical diffraction pattern of α-keratins (with a prominent peak at 20.06° and a peak at 9.26°, corresponding to the crystalline spacing of 4.43 and 9.54 Å, respectively) is observed,[10] which indicates that the crystalline domains of wool keratin have been disrupted by the ionic liquid during the dissolving process, and have not regenerated, so the wool keratin fibers have been dissolved in the ionic liquid.

With the wool keratin ionic liquids solution obtained, we have explored the scope for processing of wool keratin from ionic liquids. First, the regenerated wool keratin was obtained from the 10 wt% wool keratin solution of $BMIM^+Cl^-$ ionic liquid by addition of methanol, ethanol or water with a rapid agitator. The regenerated wool keratin precipitated from methanol was examined with WAXD, IR (Fig. 2) and thermogravimetric analysis (TGA). The WAXD data (Fig. 1a) show that there is a prominent 2θ peak at 20.02° and several minor peaks that can be indexed according to the antiparallel β-sheet structure compared with the natural wool keratin fibers. The disappearance of the peak at 9.26° indicates that the α-helix structure is destroyed by the ionic liquid during the dissolving process and is not restored, which is in agreement with the results that methanol can induce the regeneration of the β-sheet structure of protein polypeptide chains.[11] The comparison of TGA of natural wool keratin fibers and regenerated wool keratin (Fig. 1b) indicates that the thermal stability of regenerated wool keratin is slightly superior to that of natural wool keratin fibers. The reasons need to be further explored. Then, we explored whether it is possible to cast wool keratin membranes from the wool keratin ionic liquids solution. The wool keratin membrane could be obtained by casting a wool keratin $BMIM^+Cl^-$ ionic liquid (10 wt%) solution onto a glass slide. Then the glass slide was soaked in the methanol bath overnight to allow the ionic liquid to diffuse from the membrane. However, the wool keratin membrane is very brittle. It is well known for biopolymers that blending is a common way to improve their mechanical properties. Furthermore, the

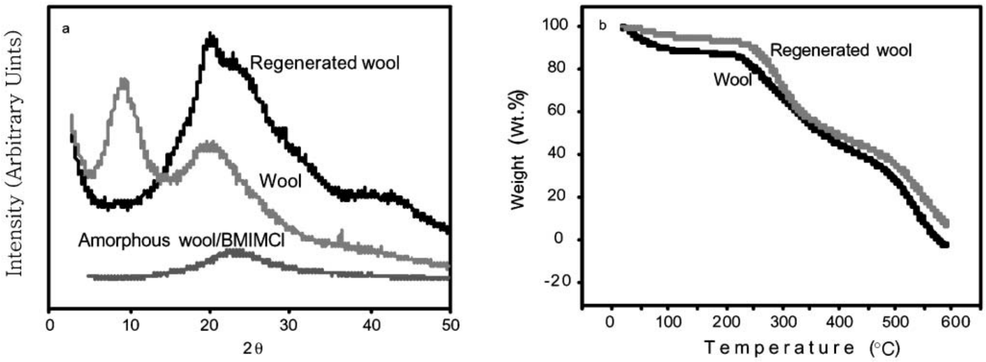

Fig. 1 a: WAXD comparison of wool keratin fibers and regenerated wool keratin and the 10 wt% wool keratin solution of ionic liquid; b: Thermal decomposition analysis comparison of wool keratin fibers and regenerated wool keratin.

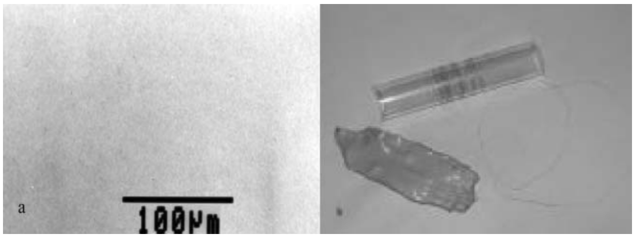

Fig. 3 a: SEM micrograph of wool keratin/cellulose (1/5, w/w) blended membrane; b: Picture of wool keratin/cellulose (1/5, w/w) blended membrane and fibers.

$BMIM^+Cl^-$ ionic liquid is also an excellent solvent for the cellulose. Here we prepared wool keratin/cellulose composite materials such as fiber, membrane using $BMIM^+Cl^-$ as solvent. The wool keratin/cellulose ionic liquid solution (10 wt%) with different ratios of wool keratin fibers and cellulose could be prepared easily at the above mentioned conditions. Taking the wool keratin fibers/cellulose (1/5, w/w) as an example, the blended membrane could be obtained by the same process of preparing the wool keratin membrane. The regenerated blended fibers could be obtained easily by syringing in the laboratory. The regenerated blended fibers were also soaked in the methanol bath overnight to remove the ionic liquid, and then immobilized on a glass bobbin to prevent recoiling and dried overnight at room temperature.

Fig. 3a shows the SEM micrograph of the surface of the blended membrane. The membrane displays a homogeneous structure, which exhibits a certain level of miscibility of the components. The membrane doesn't show residual fiber structure, further supporting the fact that the wool keratin fibers have been dissolved in the ionic liquid.

Conclusion

We have shown that $BMIM^+Cl^-$ is an excellent solvent for wool keratin. Compared with the natural wool keratin fibers' structure, the regenerated wool keratin from ionic liquids exhibits a β-sheet structure with the disappearance of the α-helix structure. Thermal stability of regenerated wool keratin is slightly superior to that of natural wool keratin fibers. The reasons need to be further explored. We have also shown the feasibility of preparing cellulose/wool keratin $BMIM^+Cl^-$ ionic liquid (10 wt%) solutions with different ratios of cellulose and wool keratin fibers, which can be used to cast a wool cellulose/keratin blended membrane and to spin blended fibers directly.

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Excellent dye fixation on cotton dyed in supercritical carbon dioxide using fluorotriazine reactive dyes

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Development of a water-free dyeing process for cotton is essential for the textile industry due to ecological and economical reasons. In this study, a dyeing method is described where cotton has been effectively dyed in supercritical carbon dioxide ($scCO_2$). Excellent dye fixation of 100%, and colour strength (*K*/*S*) values up to 30, were achieved in a small batch reactor and in a scale-up vessel. A series of non-polar reactive dyes with fluorotriazine as reactive group were synthesised at our laboratory. Fluorotriazines were found to be the best dyes for dyeing cotton and their reaction with cotton was improved by adding small quantities of acids to the reaction medium. H_3PO_4 and HAc were tested at different concentrations on cotton dyed with fluorotriazines. Evenly dyed pieces of cotton without any damage to the cotton fibres were observed in all experiments. An important step forward has been made for the future commercialization of a green process for industrially dying cotton in $scCO_2$. Elimination of water and its costly treatment can be now achieved in the cotton dyeing process.

Introduction

Traditional dyeing of textiles requires a large amount of water, nearly 100 kg of water per kg of textile. Considerable levels of salts and alkali are required when dyeing cotton with reactive dyes, producing huge quantities of polluted water, which is very costly to purify. Moreover, up to 40% of the reactive dye applied is hydrolysed during the dyeing process due to competitive reaction with hydroxyl anion nucleophiles. The high affinity of the hydrolysed dye molecules for the cotton demands an extensive wash-off after dyeing, consuming water and energy.[1] Furthermore, the scarcity of water in the near future places a boundary for the textile industry and requires research into alternative processes to improve the dyeability of cotton with reactive dyes.[2–4]

In order to reduce the usage of water and energy consumption, research has been carried out over the last two decades to develop a greener process for dyeing textiles.[5–7] As a result, supercritical carbon dioxide ($scCO_2$) has been chosen as dye solvent instead of water. The beneficial properties of supercritical carbon dioxide have been widely investigated and are applied to several processes;[8] among others, in extraction processes and as solvent for organic reactions.[9] Besides its green properties (non-flammable, relatively non-toxic and inert), $scCO_2$ has a higher diffusion rate (self diffusion as well as diffusion of dissolved compounds) and a lower viscosity than liquids[10] enhancing mass transfer phenomena; consequently the dye penetration into the fibres is facilitated, reducing dyeing times.[11] Since no water is used, the textiles do not need to be dried after dyeing saving a great deal of energy. As the dye molecules cannot be hydrolysed, no additional waste is created. Moreover, the remaining unreacted dye and supercritical carbon dioxide can be easily separated by simply lowering the pressure.

Synthetic fibres, such as polyester, have been successfully dyed in $scCO_2$[11–13] at laboratory scale; however, it has not been possible yet to dye cotton. Since 35% of the world market is represented by cotton,[14] development of a method for dyeing cotton is vital. Several studies have been done to improve the dyeability of cotton in $scCO_2$.[15–19] Often the improvements made use of chemicals or extra process steps that made the process less ecological and commercially viable as well.

To achieve a good dyeing performance, the properties of the dyeing medium should be considered. Supercritical carbon dioxide in combination with the natural moisture of the cotton becomes a moderately acidic medium.[20] Therefore, it is important to develop dyes that are able to react in an acidic medium with cotton. Non-polar reactive dyes have been used for natural textiles in $scCO_2$;[20,21] nevertheless, the cotton dyed with these dyes displayed a poor coloration and fixation. In our previous research[22] on the kinetics of a non-polar reactive dye, it was found that dyes with a monochlorotriazine reactive group would be more suitable to react with –OH groups in the presence of $scCO_2$ than dyes with a dichlorotriazine reactive group. A much greater improvement may result from the greater reactivity of F compared to Cl in S_NAr reactions, such as the one between a dye and cotton.[23] Therefore, superior reactivity and fixation with cotton than those observed with di- and monochlorotriazines are expected. In this work, novel non-polar reactive dyes with a monofluorotriazine reactive group are synthesised and applied to cotton. Prior to dyeing, the cotton is presoaked in a solution of methanol to swell the fibres. The methanol replaces the water in the cotton and will

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attach to the cotton H-bonds. The hydrophobic part of the methanol will make diffusion of the hydrophobic non-polar reactive dyes into the cotton possible. This pretreatment[24] in combination with a cosolvent, applied during dyeing, is essential to facilitate the transport and diffusion of the dye across the fibre to reach the reactive sites of the cotton.

First, a kinetic study of the novel non-polar reactive dyes was done to determine their behaviour and the reaction mechanism with –OH groups in $scCO_2$. Therefore, reactions with methanol, as model for cotton, were carried out at different conditions. Secondly, cotton was dyed in supercritical carbon dioxide using the fluorotriazine dyes. Most of the dyeing experiments were done at 120 °C, 300 bar and over 4 h. The effect of adding acids to the reaction or dyeing medium on the kinetics and dyeing performance on cotton were investigated and are discussed.

Experimental

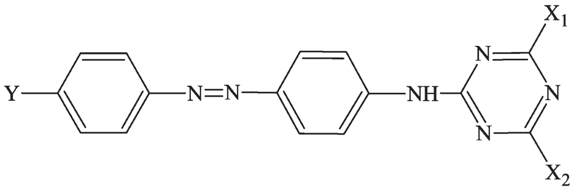
Materials

Mercerised cotton (128 g m^{-2}) was supplied by Stork N.V., The Netherlands. Methanol and acetonitrile (HPLC grade) were obtained from Fischer and Rathburn respectively. Isopropanol also HPLC grade was from Baker. The carbon dioxide supplied by Hoek Loos had a purity of 99.97%. The phosphoric acid (H_3PO_4) was from Baker and the acetic acid (CH_3COOH or HAc) was from Fluka. The non-polar reactive dyes involved in this study were synthesised in our laboratory. Their structures are given in Table 1. A complete description of the dye synthesis is given in the next section.

Dye synthesis

a. Synthesis of dye 1. 4-Phenylazoaniline (7.89 g, 40 mmol) was dissolved in a mixture of dioxane (400 ml) and water (200 ml). The solution was cooled to 0 °C. Cyanuric fluoride (3.41 ml, 40 mmol) was added dropwise over 20 min keeping the temperature at 0 °C and the pH of the reaction mixture at 4–4.5 with sodium carbonate (2 M). The resulting crystal slurry was stirred for 20 min at 0 °C followed by 1 hour stirring at 20 °C. The precipitate was filtered, washed with water (100 ml) and dried under vacuum over phosphorus pentoxide. Yield, 8.7 g (70%), yellow powder; TLC analysis showed one product spot ($R_f = 0.53$; acetone : hexane = 1 : 2, Polygram® Sil G/UV_{254} as adsorbent phase), MS m/z 312 (M^+).

Table 1 Structures of the reactive disperse dyes



Structure	X_1	X_2	Y	Name in the text
1	–F	–F	–H	$S1F_2$
2	–F	$–OCH_3$	–H	$S1FOCH_3$
3	–F	$–NH_2$	–H	$S1FNH_2$
4	–Cl	$–NH_2$	–H	$S1ClNH_2$

b. Synthesis of dye 2. Dye 1 (500 mg, 1.6 mmol) was suspended in a mixture of methanol (50 ml) and anhydrous sodium carbonate (150 mg, 1.4 mmol). After 1 hour stirring at room temperature, TLC analysis showed the reaction to be complete. Over 5 min, water (100 ml) was added. The resulting product slurry was stirred for an additional 5 min. The precipitate was filtered off, washed with water and dried under vacuum over phosphorus pentoxide. Yield, 450 mg (87%), yellow powder; TLC analysis showed one product spot (R_f = 0.4; acetone : hexane = 1 : 3, Polygram® Sil G/UV_{254} as adsorbent phase), MS m/z 324 (M^+).

c. Synthesis of dye 3. Dye 1 (1 g, 3.2 mmol) was dissolved in dioxane (70 ml). Ammonia (2.5%, 10 ml) was added, resulting in immediate precipitation of the product. After 5 min stirring at room temperature, TLC analysis showed the reaction to be complete. Over 10 min, water (140 ml) was added. The resulting product slurry was stirred for an additional 5 min. The precipitate was filtered off, washed with water and dried under vacuum over phosphorus pentoxide. Yield, 0.9 g (91%), yellow powder; TLC analysis showed one product spot (R_f = 0.55; acetone : hexane = 2 : 3, Polygram® Sil G/UV_{254} as adsorbent phase), MS m/z 309 (M^+).

d. Synthesis of dye 4. 4-Phenylazoaniline (7.89 g, 40 mmol) was dissolved in a mixture of dioxane (480 ml) and water (160 ml). The solution was cooled to 0 °C. A solution of cyanuric chloride (7.52 g, 40 mmol) in dioxane (40 ml) was added dropwise over 1 hour, while keeping the temperature at 0 °C and the pH of the reaction mixture at 6–7 with sodium carbonate (2 M, 12.5 ml). TLC analysis of the reaction mixture indicated that the reaction was completed. Over 1 hour a mixture of dioxane (560 ml) and water (800 ml) was added to the reaction mixture at 0 °C. The resulting crystal slurry was stirred for 1 hour at 20 °C. The precipitate was filtered, washed with water (100 ml) and dried under vacuum over phosphorus pentoxide. Yield, 13 g (93%), yellow powder; TLC analysis showed one product spot ($R_f = 0.53$; acetone : hexane = 1 : 2, Polygram® Sil G/UV_{254} as adsorbent phase), MS m/z 344 (M^+). The product obtained (1 g, 2.9 mmol) was dissolved in dioxane (25 ml). Ammonia (25%, 5 ml) was added. After 15 min stirring at room temperature, TLC analysis showed the reaction to be completed. Over 20 min, water (70 ml) was added. The resulting product slurry was stirred for an additional 15 min. The precipitate was filtered off, washed with water and dried under vacuum over phosphorus pentoxide. Yield, 0.9 g (95%), yellow powder; TLC analysis showed one product spot (R_f = 0.5; acetone : hexane = 2 : 3, Polygram® Sil G/UV_{254} as adsorbent phase), MS m/z 325 (M^+).

Experimental set-up

High pressure batch reactors were used for the kinetic and the dyeing experiments. The reactors consist of a sample vessel of 150 mL attached to a pressure manometer and to a needle valve. The designed pressure of the reactors was 350 bar.

Experimental procedure

Kinetic experimental procedure. To carry out the kinetic experiments, first a stock solution of 0.2 g l^{-1} of the dyes in acetonitrile was made. This solution was subsequently, diluted to a concentration of 0.02 g l^{-1} with methanol and immediately used for the reactions. When supercritical carbon dioxide ($scCO_2$) was the reaction medium, 1 ml of the dye solution in methanol was introduced to the reactor. Once the reactor was sealed, 90 g of liquid carbon dioxide was introduced from the CO_2 bottle to the reactor *via* the needle valve. The reactor was subsequently placed in the thermostatic bath settled at a temperature of 120 °C. Within 10 min the pressure in the reactor reached 300 bar. Conversely, when the kinetic experiments were done with methanol as reactant and as a solvent medium, 25 ml of the dye solution in methanol was poured into the reactor. The reactor was sealed and placed in the thermostatic bath at 120 °C. For both procedures, when the reaction time was completed, the reactor was removed from the thermostatic bath and the reaction was stopped by cooling. Afterwards, the reaction mixture was carefully collected in a sample flask *via* the needle valve. The composition of the sample was immediately determined by HPLC analysis.

Kinetic experimental procedure with addition of acid. The experimental procedure described for the reactions in $scCO_2$ was followed here with the exception of the addition of a known amount of H_3PO_4 together with the dye solution. The acid concentration was 0.01 g acid (g MeOH)$^{-1}$. The pressure and temperature of the reactions were 300 bar and 120 °C.

Dyeing experimental procedure. Before the dyeing procedure started, a simple pretreatment was done to the cotton to improve its dyeability in supercritical carbon dioxide. In a sample flask a piece of 0.25 g of cotton was immersed in a fluid medium consisting of 20 g of methanol. The pretreatment was carried out at 40 °C and 1 bar by gently shaking the sample flask for 12 h. The pre-treated piece of cotton was removed from the methanol and transferred to the reactor for the dyeing procedure. The pre-treated cotton contained 60% methanol by weight.

The cotton, the dye, the cosolvent and the acid were placed in the high pressure batch reactor. The amount of dye was 10% owf (on weight of the fibre) and the cosolvent was used at a concentration of 2% by weight of carbon dioxide. The acids used in this study were H_3PO_4 in concentrations of 0.1, 0.3 and 0.7% owf and CH_3COOH (HAc) in concentrations of 30, 80 and 170% owf. The reactor was sealed and 90 g of liquid carbon dioxide was introduced from the CO_2 bottle *via* the needle valve. Subsequently, the reactor was placed in a thermostatic bath settled at 120 °C. The initial pressure in the reactor was 60 bar, within 10 min a pressure of 300 bar was reached. After 4 h dyeing, the reactor was removed from the thermostatic bath and cooled down under running water to reduce the pressure. When the pressure was 60 bar the reactor was completely depressurised by opening the needle valve. The reactor was opened and the piece of cotton was removed from the sample vessel.

HPLC analyses

The chromatographic analyses were performed in a Chrompack liquid chromatograph equipped with a Varian ProStart 310 UV/VIS detector. The chromatographic column was an (250 × 4.6 mm) Inertsil 5 ODS-2 column and the mobile phase was a mixture (60 : 40 v/v) of acetonitrile and water at a flow rate of 1 ml min^{-1}. A Marathon autosampler was used to inject dye samples of 50 µl while the chromatographic column was maintained at 25 °C. The dye peaks were detected at a wavelength of 474 nm.

Determination of colour strength

The colour strength (K/S) in the piece of cotton was determined by the Kubelka–Munk equation (eqn. (1)). In this equation, R_{min} is the minimum value of the reflectance curve, which is determined by measuring the cotton with a colour spectrophotometer.[25]

$$\frac{K}{S} = \frac{(1 - R_{min})^2}{2 \cdot R_{min}} \tag{1}$$

Determination of dye fixation

To determine the dye fixation, a half piece of the dyed cotton was extracted in a Soxhlet extractor for 1 hour in a 30 : 70 (v/v) mixture of water and acetone at 85 °C.

The dye fixation was calculated based on the degree of adsorbed dye on the cotton (eqn. (2)) after dyeing and after being extracted. The total dye fixed could not be determined due to the complexity of measuring the dyebath exhaustion at high-pressures in $scCO_2$.

$$F = \frac{(K/S)_{extracted}}{(K/S)_{dyed}} \cdot 100\% \tag{2}$$

Results and discussion

Kinetic study

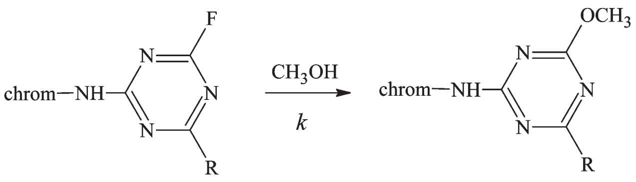
Methanol was suggested as a model for cotton by Bentley *et al.*,[26] because the reactive site of the cotton is also a primary alcohol. Based on previous research[22] on chlorotriazines, monofluorotriazines ($S1FOCH_3$ and $S1FNH_2$) were chosen as promising candidates for this investigation.

1,3,5-triazine systems react with nucleophiles *via* concerted nucleophilic aromatic substitution[27] that strongly depends on the reaction medium. A general scheme of the model reaction of monofluorotriazines is shown in Scheme 1.

In our previous study[22] it was demonstrated that the reaction of triazines with methanol followed a pseudo-first order reaction mechanism. The reaction rate law for first order kinetic reaction is defined in eqn. (3).

$$\ln\,[\text{Dye}]_t = \ln\,[\text{Dye}]_0 - kt \tag{3}$$

Both monofluorotriazine dyes were reacted with methanol in different reaction media. When ln ($[\text{Dye}]_0/[\text{Dye}]_t$) was represented as a function of time (t), the straight line obtained for all experimental conditions confirmed the pseudo-first



R : -OCH_3, -NH_2

Chromophore (Chrom) = $C_6H_5N_2C_6H_4$-

Scheme 1 Model reaction of monofluorotriazines with methanol.

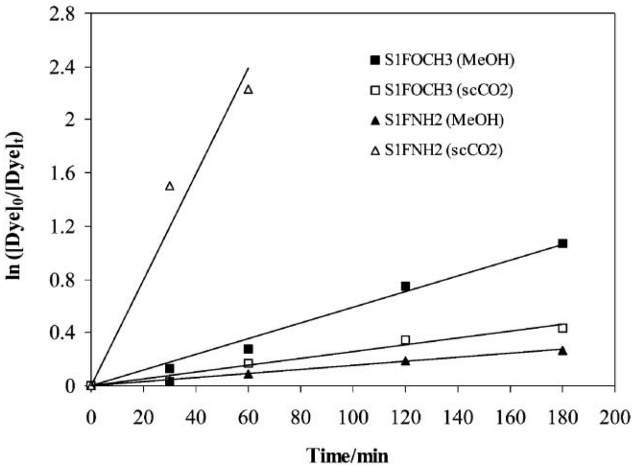


Fig. 1 ln ($[Dye]_0/[Dye]_t$) as a function of time for reaction of the monofluorotriazines with methanol in supercritical carbon dioxide ($scCO_2$) and methanol.

order kinetics (Fig. 1). From the slope the rate constants (*k*) were calculated and are shown in Table 2.

The values obtained for the rate constants are in accordance with the study of Horrobin[28] on the hydrolysis of 1,3,5-triazines. The reactivity depends on the reaction medium, which is closely related to the dye structure. In a neutral reaction medium, like methanol, dyes with an alkoxide group attached to the triazinyl ring are more reactive than those with an amine group.[23,29] Under these conditions, the reaction mechanism of triazines with methanol is comparable to that observed in a basic medium, where an electron donor group will deactivate the electrophilic position by the mesomeric effect. In our experiments, methanol is a neutral reaction medium and the reactivity behaviour of the monofluorotriazine dyes corresponds to that discussed for the hydrolysis of triazines.[28] $S1FOCH_3$ has a larger *k* value of 10.3 × 10^{-5} s^{-1} compared to $S1FNH_2$ with a *k* value of 2.5 × 10^{-5} s^{-1}. However in $scCO_2$ an inversion of the reactivity pattern has been observed. A *k* value of 74.0 × 10^{-5} s^{-1} was measured for $S1FNH_2$ whereas $S1FOCH_3$ showed a *k* of 4.3 × 10^{-5} s^{-1}. It is remarkable that the *k* of $S1FNH_2$ increased by a factor of 30 in $scCO_2$ compared to methanol. It has to be noted that the reaction enhancement in $scCO_2$ might in reality be even higher, since the dye and methanol are diluted in CO_2 reducing the probability of molecular collisions, which might lead to a lower observed reaction rate.

Table 2 Rate constant (*k*) for the methanolysis reaction of the dyes in methanol (MeOH), supercritical carbon dioxide ($scCO_2$) and acidified (0.004 mol% H_3PO_4) supercritical carbon dioxide ($scCO_2$ + acid) at 120 °C

	10^5 × k/s^{-1}		
Dye	MeOH	$scCO_2$	$scCO_2$ + acid
$S1FOCH_3$	10.3	4.3	378
$S1FNH_2$	2.5	74.0	270
$S1ClNH_2$	4.8	31.6	300

The reaction mechanism of triazines in an acid medium explains this reactivity; and $scCO_2$ can be considered as a moderately acid medium. In such a medium the nucleophilic attack of the methanol can be acid-catalysed by a previous protonation of the triazinyl ring. While in a neutral medium the presence of an electron donor group had a negative effect on the reactivity, in an acid medium this type of group will improve the reaction. The electron donor groups provide negative charge to the ring, which favours the protonation in an acid medium, and stabilises the proton by the mesomeric effect. As a result, the nucleophilic attack of the methanol to the electrophilic position is highly facilitated. Amines are stronger electron donating groups than alkoxide, so the reaction with methanol should occur more rapidly. This is reflected in the *k* values. Despite the fact that $scCO_2$ can be considered as an acid medium, protons as such are not likely to be present. Consequently, the nucleophilic attack cannot be acid-catalysed.

Since a moderately acidic medium showed such a significant increase in the *k* value of $S1FNH_2$, acid (0.01 g H_3PO_4 (g MeOH)$^{-1}$) was added to the reaction medium and reactions were carried out to determine whether this acidification would lead to a higher reactivity (Table 2). The increase in the *k* values was exceptional for both dyes. Values of 378 × 10^{-5} s^{-1} for $S1FOCH_3$ and 270 × 10^{-5} s^{-1} for $S1FNH_2$ were measured. In this more strongly acidic medium, the basicity of the substituents on the triazine ring influences the reactivity. The more basic the group attached to the ring, the lower the reactivity due to a decrease in the basicity of the ring. Amines are more basic than alkoxides and, as expected, a smaller *k* value was measured for $S1FNH_2$ in agreement with the study of Horrobin.[29]

The reactivity of the monofluorotriazine ($S1FNH_2$) reactive group was compared to that of a monochlorotriazine ($S1ClNH_2$) (Table 2). Fluoride is more electron-withdrawing than chloride; consequently, it can more strongly attract the negative charge from an electron donor group, resulting in a partial negative charge around the electrophilic position. In a neutral medium, such as methanol, the nucleophilic attack is then restricted, which explains the lower *k* values of monofluorotriazine compared to monochlorotriazine. Conversely, in an acidic medium this electronegative character of fluoride is very beneficial, because the protonation of the ring can occur easily, and as a result of this, a rapidly nucleophilic attack will take place, as observed in the *k* values.

The importance of the dye structure and the reaction medium is clearly demonstrated in this kinetic study. The *k* values observed with monofluorotriazines when acid was added to the reaction medium suggest that it might be possible to achieve good dye fixation for cotton.

Dyeing results and discussion

The first dyeing experiments were done using the same H_3PO_4 concentration as that from the kinetic experiments. However, this concentration seriously damaged the cotton. To avoid cotton damage a reduction by a factor of 32 was made. The initial amount of acid for the dyeing experiments was now of 0.1% owf. Moreover, it was decided also to test acetic acid, which is already used in the textile industry and it is less aggressive towards the cotton fibres. Acetic acid is a weaker acid than H_3PO_4, so higher concentrations may be required to achieve the same effect on the cotton that is dyed. The experimental amount of acetic acid (HAc) was 30% owf.

The dyeing results from the monofluorotriazine dyes, represented by the colour strength (*K*/*S*) and degree of fixation, can be observed in Fig. 2 and Fig. 3 for $S1FOCH_3$ and $S1FNH_2$, respectively.

An improvement in coloration and fixation was obtained in the cotton dyed with $S1FOCH_3$ using acids. It should be noted that these values are higher than the *K*/*S* values from cotton dyed without acids, even after a dyeing time of 7 h.

The highest dye fixation of 77% was obtained when cotton was dyed with H_3PO_4, which also showed excellent *K*/*S* values, of 26.5 after dyeing and the highest value of 20 after extraction. The largest *K*/*S* value after dyeing was observed when HAc was applied, showing a value of 30. As occurred with $S1FOCH_3$, dyeing cotton with $S1FNH_2$ in the presence of HAc provided the largest *K*/*S* after dyeing with a value of 25.6, but this high value was coupled to a very low fixation of 35%. With regard to fixation, the cotton dyed in the presence of H_3PO_4 has the highest fixation of the series (77%). However, when cotton was dyed in the absence of any acid the best *K*/*S* value obtained after extraction was 14.7. All pieces of cotton were found to display an evenly distributed yellow colour. It is noticeable that no damage to the cotton, after a visual and tactile inspection, was observed after being dyed in the presence of acids. However, stress–strain measurements of the dyed cotton according to common test methods should be performed for future commercialization. Furthermore, it is significant that these dyeing results are in accordance with the kinetic study. In supercritical carbon dioxide the largest *k* value was obtained for $S1FNH_2$. Upon addition of acids, $S1FOCH_3$ showed the largest *k* value. Concerning the cotton coloration after dyeing, $S1FNH_2$ provided the best *K*/*S* value when cotton was dyed in $scCO_2$ without acids, whereas $S1FOCH_3$ required acid addition to reach the largest *K*/*S* value.

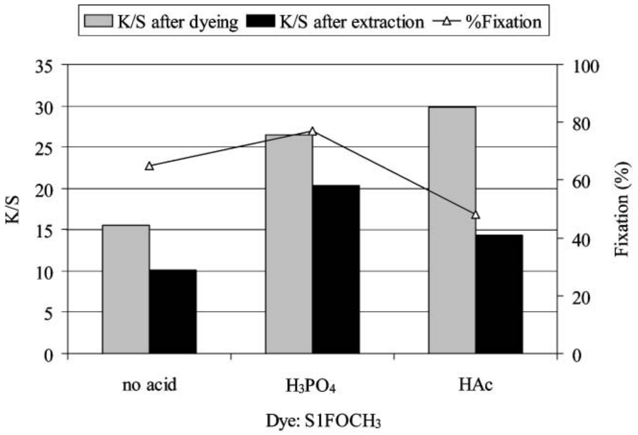


Fig. 2 Effect of acids on the colour strength *K*/*S* and dye fixation on cotton dyed with $S1FOCH_3$. Dyeing conditions: H_3PO_4 (0.1% owf); HAc (30% owf); MeOH as cosolvent and dyeing time 4 h (except for "no acid" experiment (7 h)).

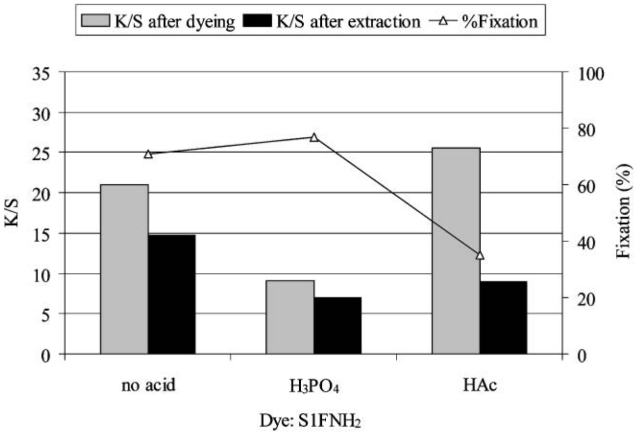


Fig. 3 Effect of acids on the colour strength *K*/*S* and dye fixation on cotton dyed with $S1FNH_2$. Dyeing conditions: H_3PO_4 (0.1% owf); HAc (30% owf); MeOH as cosolvent and dyeing time 4 h (except for "no acid" experiment (7 h)).

The difference in the dyeing performance of the dyes might be related to the cosolvent applied during the dyeing process. Cosolvents are necessary as dye carriers and to ensure the swelling of the cotton fibres. In the previous experiments methanol was the cosolvent of choice. As observed in the kinetic experiments, methanol and $S1FNH_2$ easily react in an acidic medium, so methanol will compete with cotton for the dye. It seems that the reaction of $S1FNH_2$ with methanol is favoured in an acid medium. To avoid these competitive reactions the secondary, and therefore less reactive, alcohol isopropanol was applied as cosolvent. The experiments with isopropanol were carried out for both dyes in the presence of H_3PO_4 in a concentration of 0.1% owf. The results are given in Fig. 4.

The dyeing results clearly improved with isopropanol for $S1FNH_2$. A remarkable increase in the *K*/*S* values after dyeing and after extraction was measured. The *K*/*S* after dyeing increased from 9.1 to 24 and after extraction from 7 to 17.4. Conversely, $S1FOCH_3$ showed an increase in the *K*/*S* value after dyeing from 26.5 to 31.9. From these results it can be observed that the choice of the optimal cosolvent should be based on the dye structure.

To prevent cotton damage, the acid concentration was considerably reduced compared to the kinetic study. Nevertheless, it should be possible to increase this concentration, under the cotton damage boundary, so the reaction of the cotton with the dye might be improved. The acid concentrations applied in this series of experiments were 0.1, 0.3 and

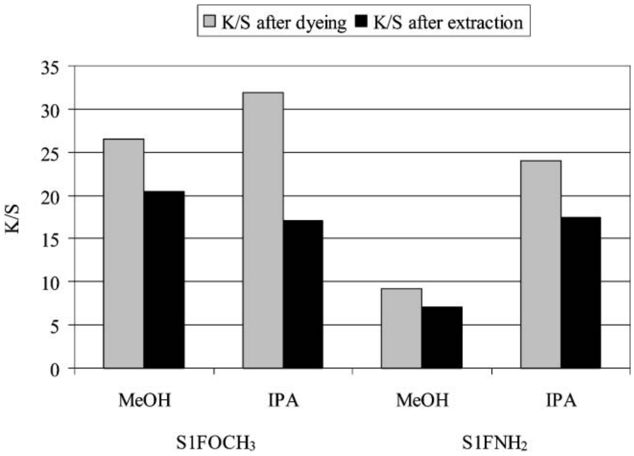


Fig. 4 Comparison of the effect of methanol and isopropanol (IPA), as cosolvents, on the dyeing of cotton with $S1FOCH_3$ and $S1FNH_2$ in the presence of H_3PO_4 0.1% owf. Dyeing time 4 h.

0.7% owf for H_3PO_4 and 80 and 170% owf for HAc. Moreover, isopropanol was used as cosolvent. Fig. 5 and 6 show the results for cotton dyed with $S1FNH_2$ in the presence of H_3PO_4 and HAc respectively. The results for $S1FOCH_3$ are given in Fig. 7 for H_3PO_4 and Fig. 8 for HAc. From the figures, it can be observed that independently of the dye structure or type of acid used, an increase in the acid concentration did not necessarily lead to an increase in the coloration of dyed cotton and in dye fixation.

An outstanding dye fixation of 99% on cotton dyed with $S1FNH_2$ was achieved either with H_3PO_4 (0.7% owf) or HAc (80% owf). This value is superior to the value reported in the literature[17] for a monofluorotriazine reactive dye. This 99% fixation indicates that a rinse-step to remove unfixed dye from the textile can be completely eliminated. Besides the excellent fixation values, the colour strength (*K*/*S*) was also very good. A larger *K*/*S* value after extraction was observed with HAc (17.3) than with H_3PO_4 (*K*/*S* of 11.3).

Considering the results from $S1FOCH_3$ dye the best fixation with a value of 82% was obtained at a H_3PO_4 concentration of 0.3% owf. In spite of a slight decrease in the *K*/*S* value after dyeing with increasing acid concentrations, the fixation was clearly improved. When HAc was used, the best fixation and *K*/*S* values were measured at a concentration of 80% owf.

Dyeing experiments with acids were also done using difluorotriazine ($S1F_2$). In the batch reactor cotton was dyed

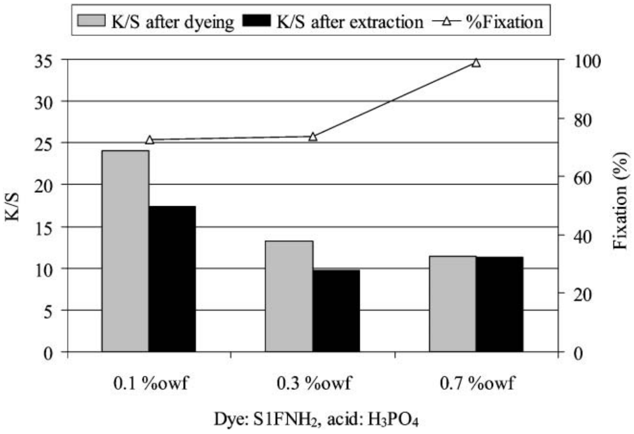


Fig. 5 Effect of H_3PO_4 concentration on the *K*/*S* of dyed cotton and on the dye fixation using $S1FNH_2$ dye.

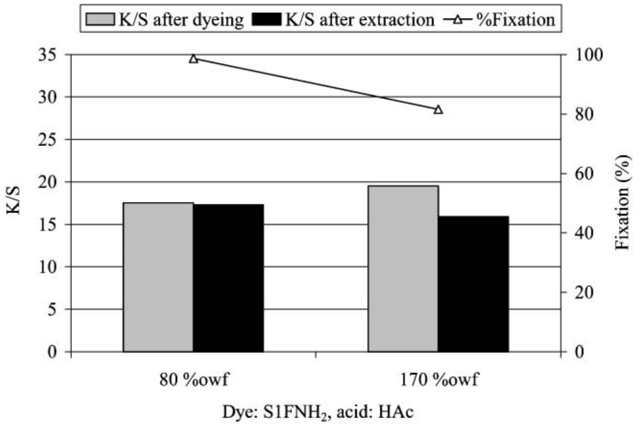


Fig. 6 Effect of HAc concentration on the *K*/*S* of dyed cotton and on the dye fixation using $S1FNH_2$ dye.

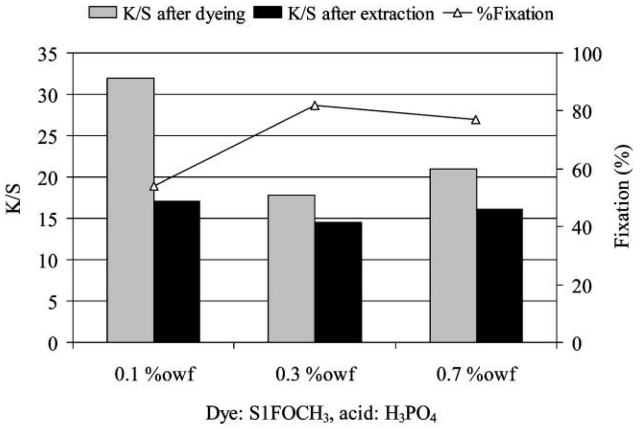


Fig. 7 Effect of H_3PO_4 concentration on the *K*/*S* of dyed cotton and on the dye fixation using $S1FOCH_3$ dye.

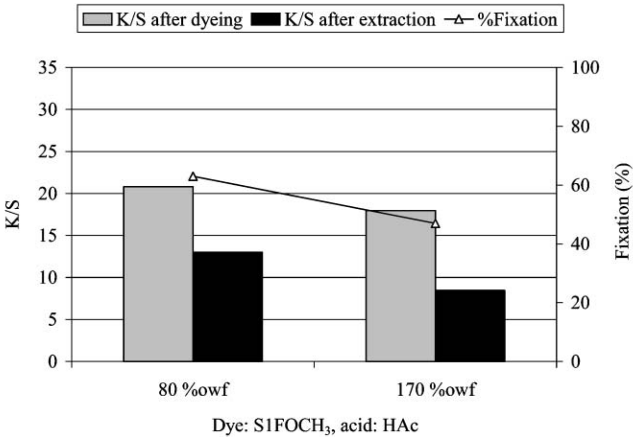


Fig. 8 Effect of HAc concentration on the *K*/*S* of dyed cotton and on the dye fixation using $S1FOCH_3$ dye.

using 10% owf of the dye and 0.7% owf H_3PO_4. The *K*/*S* values were slightly lower than those observed with the monofluorotriazines and the dye fixation was 83%. However, the dye fixation increased up to 100% when the process was scaled-up (Fig. 9). This experiment was done in a 4 l dyeing machine and $scCO_2$ was circulated through the vessel during the dyeing process. A detailed description of the dyeing machine is given in a previous publication.[24] Basically the dyeing procedure was similar to the one explained in the experimental section for the 150 ml reactor, with the exception of an important reduction in the pretreatment solvent. In this experiment a piece of cotton of 7 g was pretreated in 70 g methanol. After the pretreatment the cotton was dyed using isopropanol as cosolvent at a concentration 2% by weight of CO_2; 5% owf of $S1F_2$ and H_3PO_4 at a concentration of 0.3% owf. The cotton was evenly dyed and the *K*/*S* values after dyeing and after extraction showed a value of 11. To achieve a fixation of 100%, less dye and less acid were needed than in the small reactor due to the CO_2 circulation through the system. This means that excellent dyeing results can be also expected on further scale-up of the process.

Owing to the 100% fixation there is no need of a rinse step after dyeing the cotton to remove any unfixed dye, as a result of which no waste is generated. All the dye that reached the cotton has reacted. The dye dissolved in the CO_2 can be easily separated at the end of the dyeing process, and the CO_2 can be reused, making the supercritical dyeing of cotton economically and ecologically attractive.

From the kinetic study it follows that monochlorotriazine ($S1ClNH_2$) can react with cotton as well. Therefore, pieces of cotton were dyed with monochlorotriazine ($S1ClNH_2$) in the presence and absence of acids. The results are given in Table 3 and are compared to cotton dyed with monofluorotriazine ($S1FNH_2$).

Monofluorotriazine is certainly superior to monochlorotriazine for dyeing cotton, as reflected in the larger *K*/*S* values and fixation. These results confirm the ability and outstanding reactivity of monofluorotriazines to dye cotton in supercritical carbon dioxide.

Table 3 *K*/*S* values and dye fixation for the monochlorotriazine ($S1ClNH_2$) and monofluorotriazine ($S1FNH_2$) in different dyeing media

	$S1ClNH_2$			$S1FNH_2$		
	No acid[a]	H_3PO_4[b]	HAc[b]	No acid[a]	H_3PO_4[b]	HAc[b]
K/*S* after dyeing	11.1	5.7	9.1	20.9	13.2	17.5
K/*S* after extraction	5.2	4.2	4.2	14.7	9.8	17.3
Fixation (%)	47	74	46	71	74	99

[a] When acid was not added, the dyeing time was 7 h and methanol was the cosolvent. [b] Acid concentration: H_3PO_4 (0.3% owf) and HAc (80% owf).

The excellent results of fluorotriazine dyes with cotton under acidic conditions suggest that it might be possible to eliminate the pretreatment of cotton prior to dyeing, and maybe even the addition of a cosolvent during dyeing. Hence, by reproducing the experimental conditions used for one of the best results with $S1FNH_2$ and 80% owf of HAc, dyeing experiments were performed with untreated cotton, with and without cosolvent (Fig. 10).

The pretreatment of cotton before dyeing and the use of cosolvent during the dyeing process cannot be eliminated. Pretreatment of the cotton and cosolvent are required for making cotton more accessible to the dye and favouring dye transport and diffusion across the fibre. By measuring the *K*/*S* value after dyeing it is possible to determine if dyeing limitation steps, such as dye transport, have been overcome. Indeed, our *K*/*S* values after dyeing were on average 20 compared to values of 1.5 from the literature,[19,20] indicating the success of dye transport and diffusion in our experiments.

Despite the requirement of a pretreatment step before dyeing, it might be possible to pretreat and dye the cotton substrate in the same dyeing vessel, so the whole process can be done in one batch. Such a pretreatment is environmentally safe, and compared to other pretreatment methods for cotton[15–17,19] our method shows several advantages. The amount of methanol used in the pretreatment is 80 g (g cotton)$^{-1}$; however, this amount can be reduced by a factor of 8 as observed during the experiment in the 4 l dyeing machine.

The pretreatment does not involve any chemical reactions with the cotton, methanol only interacts physically with the cotton, creating new H-bonds within adjacent cellulose chains.

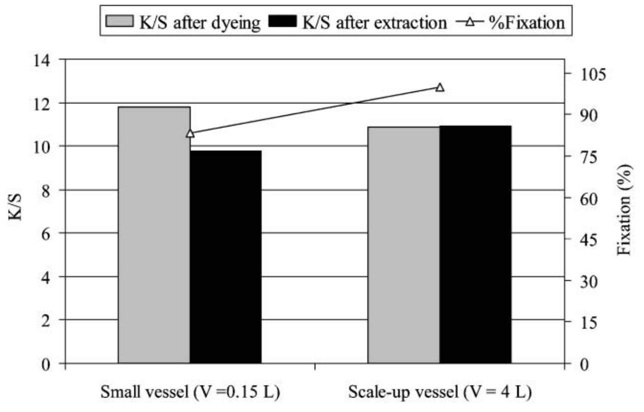


Fig. 9 Scale-up of the dyeing process with a difluorotriazine. Dyeing conditions: small vessel: 10% owf of $S1F_2$ and 0.7% owf H_3PO_4; scale-up vessel: 5% owf of $S1F_2$ and 0.3% owf H_3PO_4.

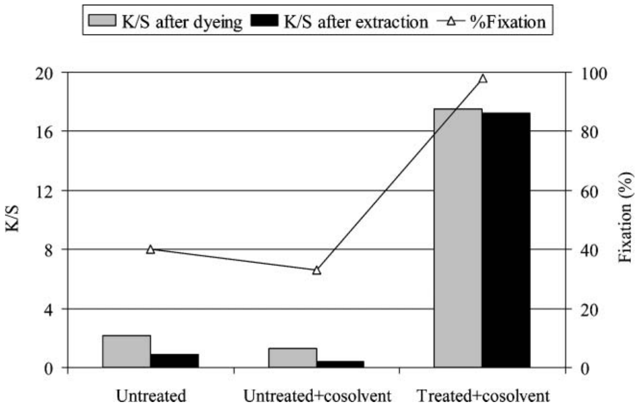


Fig. 10 Effect of the pretreatment and cosolvent on cotton dyed with $S1FNH_2$ and HAc at a concentration of 80% owf.

As a result of this, the structure of cotton remains unchanged and the methanol can be easily reused for several batches. Moreover, the pretreated cotton can be used without drying it, as was done in the method of Maeda *et al.*[21] where the cotton had to be dried at 100 °C with the resulting energy consumption. Besides, no traces of pretreatment solvent after dyeing were found. Consequently, it is not necessary to rinse the cotton before or after dyeing, so there is no consumption of water during the whole process of dyeing cotton in $scCO_2$. A limitation of the pretreatment method is related to the use of methanol as a swelling agent. Methanol and cotton competed for the dye as confirmed in the HPLC analyses of some unfixed dye, where methanolised dye was observed. However the excellent coloration of the cotton observed after extraction suggested that the dye reacted with the cotton to a major extent, so the dyeing performance was not altered.

This study presents fluorotriazines as the best dyes to achieve remarkable dye fixation and coloration on cotton dyed in supercritical carbon dioxide. The addition of acids during the dyeing process is responsible for this high fixation. An important step towards the commercialization of an industrial process for dyeing cotton in supercritical carbon dioxide has been made, namely elimination of water consumption and of waste production.

Conclusions

An outstanding dye fixation of 99% on cotton dyed in supercritical carbon dioxide was achieved using monofluorotriazine reactive dyes and by adding small quantities of acids. The pieces of cotton dyed displayed an even distribution of the dye and cotton damage was not observed within the acid range used.

The results were reproduced at larger scale with a significant reduction of the amount of dye and acid used. A fixation of 100% was observed in a piece of cotton of 7 g dyed with a difluorotriazine dye and with 0.3% owf of H_3PO_4.

The superior reactivity of fluorotriazines as reactive groups compared to chlorotriazines was also confirmed. The colour strength (K/S) of monochlorotriazines after extraction was 4.2 while values of 9.8 and 17.3 were measured with monofluorotriazines.

Several advantages of dyeing cotton with $scCO_2$ compared to water have been settled with this study. Since it is possible to achieve dye fixation of 100%, a rinse step of the cotton after dyeing is not necessary to remove unfixed dye. Consequently, there is no consumption of water and production of wastewater; and the energy needed for drying the textile can now be saved. Finally, the dye and cosolvent can be easily separated from the CO_2 at the end of the process and the CO_2 can be reused.

Acknowledgements

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Selective rhodium catalysed synthesis of *trans*-1,4-hexadiene in polyethylene glycol 1000–water solvent systems

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trans-1,4-Hexadiene is of great importance in the production of functionalizable polymers and is employed in preparing ethylene-propylene-diene-monomer (EPDM) terpolymers. Synthesis of *trans*-1,4-hexadiene by the codimerization of 1,3-butadiene and ethylene has been studied since the 1960s and many transition metals were used as catalysts, *e.g.* rhodium, nickel, cobalt or ruthenium. Among them, only rhodium catalysed reactions gave the desired *trans*-1,4-hexadiene, however, only with low reaction rates. In this paper, a new combination of a rhodium catalyst with the polyethylene glycol 1000 (PEG1000)–water solvent system was studied and a high amount of *trans*-1,4-hexadiene was attained together with a 58% total conversion of ethylene and a 71% selectivity of 1,4-hexadiene.

1. Introduction

trans-1,4-Hexadiene is very useful in the production of functionalizable polymers and is employed in preparing EPDM terpolymers (Ethylene-Propylene-Diene-Monomer).[1] *cis*-1,4-Hexadiene, however, has a deleterious effect on polymerization catalysts and moreover, is difficult to separate from the *trans*-isomer.[2] Therefore a catalyst system in favor of producing *trans*-, but not *cis*-1,4-hexadiene, is desired. Many Ziegler-type catalysts based on nickel, cobalt and iron salts are very effective for the codimerization of 1,3-butadiene and ethylene, but only rhodium catalysts selectively give the desired *trans*-1,4-hexadiene. This reaction was studied by Alderson *et al.* in 1965.[3] Su and Colette reported the influence of weak and strong donor ligands on the rhodium catalysed codimerization of 1,3-butadiene and ethylene to produce *trans*-1,4-hexadiene. They found that weak oxygen donors with a pK_a of -5 to -2, such as ethers, ketones and esters, increased the reaction rate, but had no effect on the *trans* : *cis* ratio of 1,4-hexadiene. Stronger donors with a pK_a of -2 to 0, such as alcohols, water, DMF and phosphorus oxides also increased the reaction rate but in addition steered the stereo-selectivity towards the formation of *trans*-1,4-hexadiene. However, all these strong donors inhibited the catalyst activity at high donor : Rh ratios.[4]

As described above, the coordinating ability of the solvent has a large influence on the reaction of 1,3-butadiene and ethylene. Both kinds of solvents have independent advantages: weakly coordinating solvents accelerate the reaction rate whereas strong coordinating solvents enhance the selectivity for *trans*-1,4-hexadiene. We were interested in studying the effect of the combination of both kinds of solvents, because we assumed that in the presence of both strongly and weakly coordinating solvents a high ratio of *trans*-1,4-hexadiene could be achieved concomitantly with a high conversion of the substrates.

In this paper, we studied the solvent combinations of polyethylene glycol 1000 (PEG1000) and water. PEG1000 was here taken as a weak coordinating solvent because of its tangled and bulky form in highly concentrated solutions. Its low cost, low volatility and its environmentally benign nature can also be taken as advantages. Therefore, the rhodium catalysed codimerization of 1,3-butadiene and ethylene was carried out in a PEG1000–water system and dodecane was used as an *in situ* extractant for the hexadienes formed.

2. Experimental

2.1 Chemicals

1,3-Butadiene (grade 1.3) and ethylene (grade 2.7) were purchased from Messer-Griesheim. $RhCl_3 \cdot 3H_2O$ was used as received from Umicore AG & Co. Polyethylene glycol 1000 was received from Acros and used without any further treatment. Dodecane was obtained from Acros. Hexadiene isomers used as GC standards were purchased from Aldrich and ABCR.

2.2 Rhodium catalysed codimerization

Given amounts of the catalyst $RhCl_3 \cdot 3H_2O$ and the solvents were weighed into a Schlenk flask. The mixture of catalyst and solvents was transferred into a 300 ml Parr stainless steel autoclave, which was pre-vacuumed and rinsed with argon. The desired amount of 1,3-butadiene was condensed into the autoclave at -30 °C and a calculated amount of ethylene was pressured into the autoclave. Then the autoclave was heated up to the reaction temperature in 10 minutes. The reaction was considered to start when isothermal conditions were reached. All reactions and handling of reagents were carried out under argon by using the standard Schlenk technique.

2.3 Analysis and product characterization

Routine gas chromatographic analysis was carried out on a HP 6890 instrument (Hewlett-Packard GmbH, Waldbronn,

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Germany) equipped with a FID and a HP-5 capillary column (30 m, coating 5% diphenyl- and 95% dimethyl-polysiloxane, diameter 0.25 mm, film thickness 0.25 μm), connected to an auto-sampler. Standard hexadiene samples were used for the identification of the products. Octane was employed as an external standard for quantification. In most of the reactions, 1,3-butadiene was in surplus and all calculated reaction conversions were based on the molar amount of ethylene.

3. Results and discussion

3.1 Codimerization of 1,3-butadiene and ethylene

As shown in Scheme 1, by using PEG1000–water as solvent, rhodium catalysed codimerization of 1,3-butadiene and ethylene yielded mainly *trans*-1,4-hexadiene. However, isomerizations of 1,4-hexadienes into 2,4-hexadienes were observed in a certain amount, since 2,4-hexadienes are thermodynamically more stable than 1,4-hexadienes[5] (see Table 1). By-products like 3-methyl-1,4-heptadiene and its isomers were observed only in minor amounts.

3.2 Water as co-solvent

Since the early studies on codimerization of 1,3-butadiene and ethylene, the important effect of water as co-solvent has been noted.[3,6] The presence of the right amount of water promoted both the reaction rate and the selectivity for *trans*-1,4-hexadiene.

With the addition of small amounts of water to the Rh–PEG1000 catalyst system, the selectivity for the 1,4-hexadienes, the amount of *trans*-isomer and the conversion of the substrates increase. An optimum conversion can be reached by the addition of exiguous amounts of water (see run 2 and 3 in Table 2); however, the addition of higher amounts of water strongly inhibits the codimerization reaction.

3.3 Influence of the butadiene : ethylene ratio

Even in the early literature[3] some results indicated that the reaction rate and the selectivity for 1,4-hexadiene were dependent on the molar ratio of 1,3-butadiene and ethylene. In our investigations, shown in Fig. 1 the molar ratio of ethylene to butadiene proved to have a large influence both on the reaction conversion and on the selectivity for the *trans*-1,4-hexadiene. If the ethylene : butadiene ratio amounts to 0.8 : 1, the conversion of ethylene reaches 48% and the selectivity for 1,4-hexadiene is 69% (98.2% of which is found to be the *trans*-isomer). If the molar ratio of ethylene and butadiene is raised, the reaction conversion decreases. For example only about 5% of ethylene was converted at an ethylene : butadiene molar ratio of 2 : 1.

Table 1 Free enthalpy (ΔG) of hexadiene isomers

	1,4-Hexadiene	*trans*-2-*trans*-4-Hexadiene	*cis*-2-*trans*-4-Hexadiene
ΔG/kJ mol^{-1}	164.7	141.7	145.9

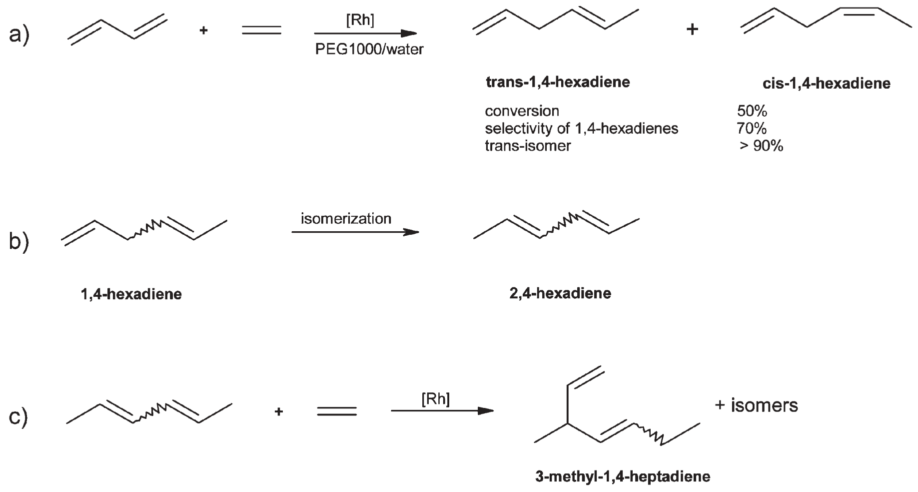
Table 2 Influence of the water amount

Run	Water[a] (wt%)	Conversion of ethylene (%)	Selectivity for 1,4-hexadiene (%)	*trans*-1,4-Hexadiene (%)
1	0	40	53	95.2
2	0.7	48	71	97.9
3	1.3	48	69	98.2
4	3.2	21	68	97.9
5	6.2	12	64	98.4

[a] Reaction conditions: $RhCl_3{\cdot}3H_2O$, 0.235 mmol; PEG1000, 30 g; 1,3-butadiene, 20 g (0.37 mol); ethylene, 8.5 g (0.30 mol); 70 °C; 2 hours.

3.4 Influence of the reaction temperature

The following study (see Fig. 2) shows the influence of the temperature on the total conversion and the selectivity of 1,4-hexadiene. The results indicate that the conversions of the codimerization of butadiene and ethylene increase with increasing reaction temperature. However at a reaction temperature higher than 70 °C, the selectivity of 1,4-hexadiene decreases due to the isomerization of the 1,4-hexadienes to the conjugated 2,4-hexadienes. It is reasonable that the amount of *trans*-1,4-hexadiene decreases with rising reaction temperature



Scheme 1 Codimerization of 1,3-butadiene and ethylene.

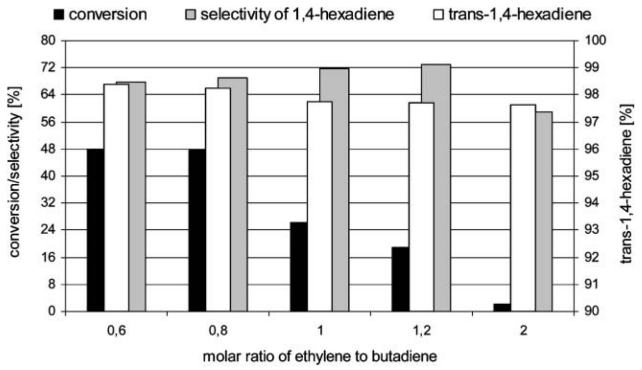


Fig. 1 Influence of the ethylene : butadiene ratio.

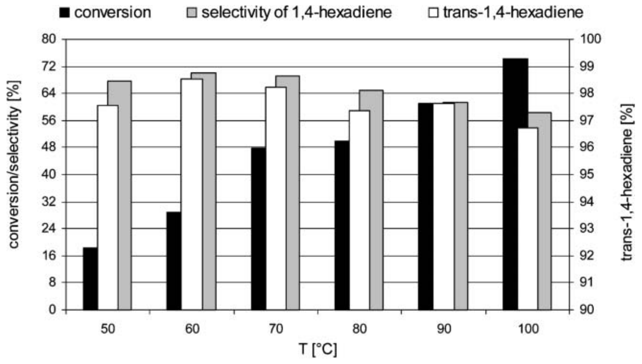


Fig. 2 Influence of the reaction temperature.

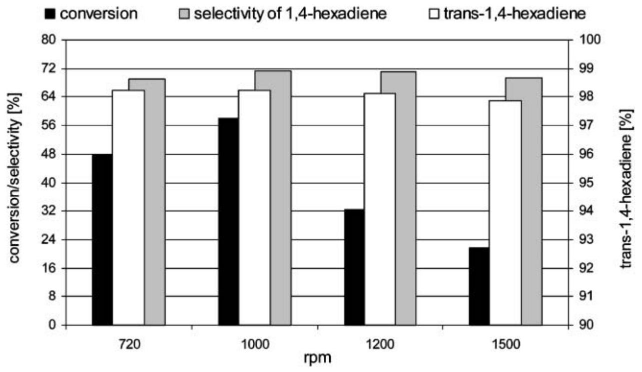


Fig. 3 Influence of the stirring rate.

because the *trans*-1,4-hexadiene is more active in isomerization than its *cis*-isomer. The detailed study of the isomerization of 1,4-hexadienes to conjugated 2,4-hexadienes is given in ref. 7.

3.5 Influence of the stirring rate

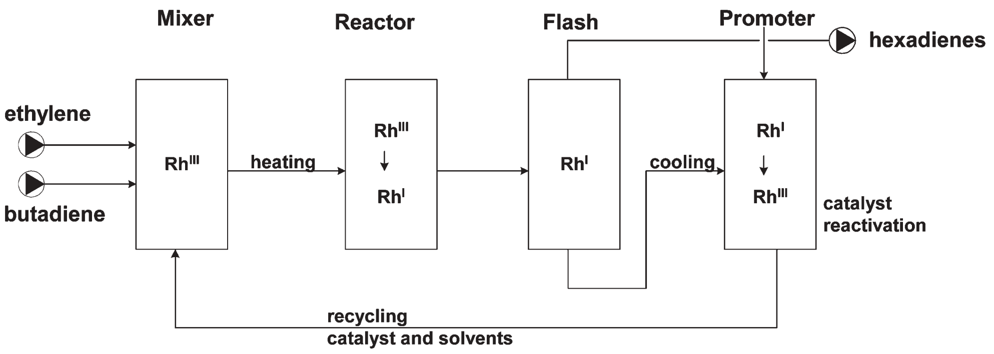
Because aliphatic hydrocarbons have only an extremely low solubility in polyethylene glycols,[8] the reaction system in this study can be regarded as a gas–liquid–liquid system. So a further study of the influence of the stirring rate was necessary since the mixing plays an important role in the mass transfer between both the gas and the liquid phases.

As shown in Fig. 3, the highest conversion and selectivity of *trans*-1,4-hexadiene are obtained when the stirring rate amounts to 1000 rpm, while higher stirring rates resulted in lower conversions and selectivity for *trans*-1,4-hexadiene. This can be explained by the fact that stirring rates higher than 1000 rpm induce a flooding of the reaction system in the autoclave. This flooding behaviour[9,10] means that the stirrer is completely enveloped by gas and is incapable of dispersing the gas into the fluid phase. Thus the interface for the mass transport between the gas and the liquid phases decreases dramatically, so that the mass transfer is greatly weakened.

3.6 Catalyst recycling

For economical reasons it is of great importance to also study the catalyst recycling. In the codimerization of butadiene and ethylene, one problem in catalyst recycling is the catalyst deactivation. The active Rh^{III} can be deactivated to Rh^{I} by the coordination of olefins onto the rhodium catalyst.[11] Thus, the rhodium catalyst has to be reactivated before it is recycled to the next reaction batch. As described in the literature, some organic chlorides can be used for the reactivation of the rhodium catalyst.[12] Our studies[13,14] showed that cinnamyl chloride was one of the most effective promoters to convert Rh^{I} back to Rh^{III}. Therefore, in the following recycling study, the rhodium catalyst was reactivated by using cinnamyl chloride each time before it was recycled to the next run.

Scheme 2 shows the general flow diagram for the recycling runs. The hexadienes can easily be separated from the catalyst phase by distillation since they have low boiling points between 60 °C and 82 °C. Directly after the separation of the products, the catalyst is reactivated by the promoter and recycled into the next run.



Scheme 2 Flow diagram for the recycling runs.

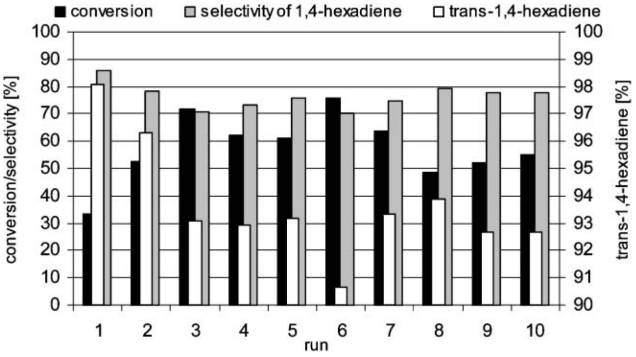


Fig. 4 Catalyst recycling by using cinnamyl chloride as promoter.

In the first recycling runs (see Fig. 4), the promoter cinnamyl chloride enhances the conversion to about 50%, whereas the selectivity for the 1,4-hexadienes decreases to about 75%. Also the amount of *trans*-1,4-hexadiene is reduced from 98% to 96%. This reduction in the selectivity for the *trans*-isomer can be explained by the following correlation: on the one hand the promoter accelerates the formation of both *trans*- and *cis*-1,4-hexadiene. On the other hand the active catalyst also promotes the isomerization of the two 1,4-hexadienes to the conjugated hexadienes, and the *trans*-form isomerizes faster than the *cis*-form.[7] However, in all recycling runs using the promoter cinnamyl chloride, the *trans*-isomer always makes up more than 90% of the 1,4-hexadiene.

4. Conclusion

The novel solvent combination of polyethylene glycol 1000 and water was successfully applied in the rhodium catalysed codimerization of 1,3-butadiene and ethylene. In the presence of PEG1000 and exiguous amounts of water, a conversion of 58% and a selectivity for 1,4-hexadiene of 71% (98% of which is *trans*-1,4-hexadiene) were achieved. These results were obtained at very mild reaction conditions, in particular at a reaction temperature of 70 °C, a reaction pressure of 15–20 bar, a reaction time of 2 hours and a stirring rate of 1000 rpm. This new reaction system seems to be a promising alternative for the industrial production of *trans*-1,4-hexadiene.

Because of catalyst decay, a reactivation of the catalyst is indispensable in the recycling runs. By using cinnamyl chloride as promoter, the rhodium catalyst could be recycled for 9 runs with slight fluctuations in the conversion and the selectivity for 1,4-hexadiene. Though slight decreases in the selectivity for *trans*-1,4-hexadiene were observed in the recycling runs, the amount of *trans*-1,4-hexadiene proved to be always higher than 90% of the total 1,4-hexadiene produced.

Acknowledgements

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