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p-cymene as solvent for olefin metathesis: matching efficiency and sustainability

Artur V. Granato,[a] Alexandra G. Santos,[a] and Eduardo N. dos Santos*[a]

The underexploited, biorenewable, *p*-cymene is employed as a solvent for the metathesis of various substrates. *p*-cymene is a nontoxic compound that can be obtained in large amounts from side product of cellulose and citrus industry. For the cross-metathesis of estragole with methyl acrylate, this solvent prevents the consecutive double-bond isomerization of the product and gives the best yield of all solvents tested. Undesired consecutive isomerization is a major problem for many substrates in olefin metathesis, including pharmaceutical precursors, and the use of *p*-cymene as solvent may be a way to prevent it. This solvent presented a better performance for metathesis than toluene for three substrates tested in this work, matching its performance for other two substrates.

Introduction

Olefin metathesis has become a major tool in modern organic chemistry. It is widely employed in petrochemistry,[1] and since the development of well-defined Schrock and Grubbs catalysts, it has also been used in fine chemicals and pharmaceutical industry.[2,3] The commercial availability of various robust pre-catalysts as exemplified in Figure 1 helped to disseminate the use of this methodology in academia and in industry. An outstanding application of metathesis is in bio-refineries, in which triglycerides from plants are transformed into olefins and unsaturated esters that find applications both as “drop in” and new chemicals.[4]

Although in some cases it is possible to run this reaction in neat substrates,[5-7] for most applications the use of a solvent is mandatory. In line with the global tendency of the chemical industry to use solvents that cause less environmental impact;[8] various potentially greener solvents have been employed for C-C double bond metathesis, e.g. water,[9] ionic liquids,[10] methyl-THF,[11] organic carbonates,[12] among others. A tentative green solvent guide specifically for metathesis has been recently published.[13] The chlorinated solvents, very efficient and once ubiquitous in C-C double bond metathesis, are now classified as hazardous or very hazardous in a recent rank.[14] Toluene has been used as an alternative, because it is considerably less problematic than the chlorinated ones, while still efficient. However, toluene is produced from fossil sources, compromising its sustainable utilization.

Perhaps surprising is the fact that *p*-cymene has not yet been reported as an alternative solvent for Ru-catalyzed C-C double bond metathesis, since it acts as a ligand in various ruthenium(II) complexes, including some metathesis pre-catalysts.[15-17] Therefore, a stabilizing effect for such kind of catalyst could be forecasted. *p*-cymene is a naturally occurring compound present in significant amounts in various essential oils, notably in those from *Thymus* gender, and is considered to be nontoxic.[18] Its acute oral LD_{50} in rats is 4.75 g/Kg (for comparison, the acute oral LD_{50} in rats of toluene ranges from 2.6 to 7.5 g/Kg).[19] Nowadays, the large-scale production of *p*-cymene relies on petrochemicals, but Clark et al.[20,21] have recently acknowledged its potential as a renewable solvent, once it can be readily obtained from renewable sources also available in large scale.[22,23] The aromatization of d-limonene obtained from citrus industry produces *p*-cymene in high yields[22] and the potential for this route may reach 500,000 ton/year.[24]

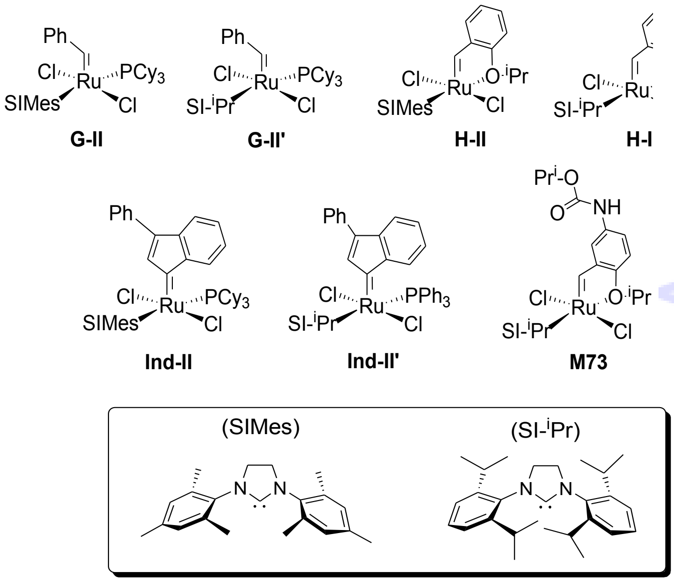

Figure 1. Selection of commercial ruthenium catalysts.

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An even more promising renewable starting material for this solvent is a mixture known as industrial dipentene, a cheap co-product of the Kraft cellulose process generated worldwide in million ton scale.[23] Industrial dipentene has racemic limonene as the major constituent, along with other *p*-menthenic monoterpenes. These components can be readily converted to *p*-cymene by aromatization with the additional bonus of green hydrogen co-production.[25] Thus, *p*-cymene has an enormous potential to be a sustainable alternative to aromatic solvents such as benzene or toluene and its production employing bio-renewable starting materials is expected to increase**.** Pursuing greener routes for fine chemicals synthesis,[26] we have been interested in aggregating the complexity generated by nature in direct catalytic routes to chemicals used by the cosmetic industry.

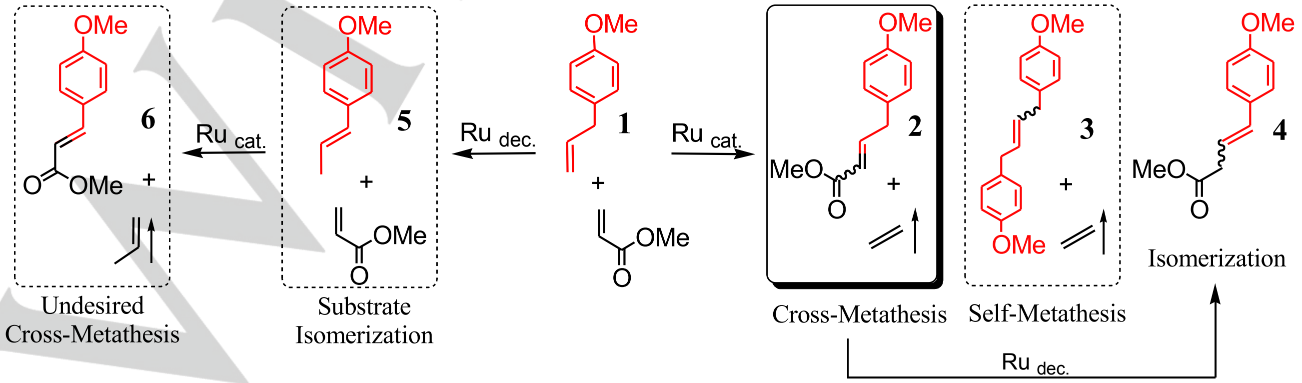
In a recent example, we have developed a one-step synthesis of the commercial fragrance Canthoxal® by the hydroformylation of the naturally occurring estragole, employing water as a solvent in a recyclable biphasic system.[27] We have also established a route to produce octyl methoxycinnamate, a major UV-A filter used in sunscreen lotions, by the ruthenium-catalyzed cross-metathesis of the naturally occurring anethole with the commodity chemical 2-ethylhexyl acrylate.[28] More generally, the cross-metathesis of natural products with acrylates is an excellent approach to the synthesis of monomers, polymers[29,30] or fine chemicals.[12,28,31-33]

In this work we compared the performance of traditional solvents, as well as other solvents regarded as greener alternatives, with *p*-cymene in the challenging cross-metathesis of naturally occurring propenylbenzenes with acrylates.

Results and Discussion

The cross-metathesis of methyl acrylate with estragole (**1**), a naturally occurring allylbenzene that can be obtained as a co-product in the Kraft cellulose process, was chosen as a test reaction. This is a particularly challenging reaction because the cross-metathesis may be followed by the C-C double-bond isomerization, a process that is detrimental to good yields of the primarily formed cross-metathesis products (Scheme 1). For example, Bruneau et al.[12] described the analogous cross-metathesis of eugenol with methyl acrylate employing various Ru-ylidene catalysts. In toluene with 2 mol% of **H-II** (Figure 1) at 80 °C, the isomerization products reached 54%. In dimethylcarbonate (DMC), the isomerization products reached 43% even at room temperature. The addition of 1,4-benzoquinone (5 mol% related to catalyst) resulted in considerable reduction in isomerization activity (9%) and allowed up to 78% of isolated yield of the cross-metathesis product. Broadly speaking, isomerization is a major problem for several substrates used in metathesis processes.[31-33] Remarkable examples are reported in the pharmaceutical development for the ring closing metathesis (RCM) of terminal dienes to produce antiviral macrocycles.[2] Besides the selectivity loss, in some cases the isomerization products result in Fischer-type carbenes that inhibit the metathesis activity.[37]

In order to choose the initial conditions for this work, some reaction employing 1,2-dichloroethane as solvent were examined. Considering that **1** is prone to give self-metathesis and that for acrylates this tendency is much smaller,[38] the latter was used in a four-fold molar excess to maximize the cross-metathesis of **1**. The increase in catalyst concentration seems to accelerate its decomposition process, with the consequent increase in the rate of isomerization (Table 1, entries 1-9). The best compromise among yields and selectivity was chosen: a solvent volume of 4 mL and a catalyst amount of $2.5x10^{-3}$ mmol (0.5 mol % relative to **1**). The presence of ethene is detrimental to the lifetime of the catalysts due to the formation of unstable Ru-methylidene species.[39] The use of argon flow during the reaction helps to eliminate light olefins and leads to better yields (Table 1, entry 7 *vs.* 10) and was adopted as standard in this work. Lower temperatures reduce the consecutive isomerization, but at the expense of the reaction rate (Table 1, entry 12 vs. 10 and 11). The best yield was obtained at 70 °C, which was the temperature adopted to carry out the subsequent studies.



Scheme 1. Cross-metathesis of estragole (**1**) with methyl acrylate.

Table 1. Cross-metathesis of estragole (**1**) with methyl acrylate using **H-II**.[a]

Entry	$V_{Solvent}$ [mL]	**H-II** [mmol]	Conv.[b] [%]	Product distribution [%][b]				Yield **2** [%][b]
				2	**3**	**4**	**6**	
1	none	$5.0x10^{-3}$	26	78	16	6	0	20
2	2		57	70	14	12	4	40
3	4		80	80	8	10	2	64
4	10		75	84	8	8	0	63
5	4	$6.2x10^{-4}$	12	94	2	4	0	11
6		$1.2x10^{-3}$	38	88	2	7	3	33
7		$2.5x10^{-3}$	78	85	1	12	2	66
8		$5.0x10^{-3}$	80	80	8	10	2	64
9		$1.0x10^{-2}$	91	65	9	19	7	59
10[c]	4	$2.5x10^{-3}$	86	91	2	6	1	78
11[c,d]			58	96	3	1	0	56
12[c,e]			90	88	1	10	1	79

[a] estragole (**1**) (78 µL, 0.50 mmol); methyl acrylate (181 µL, 2.0 mmol); **H-II**; dichloroethane; 50°C; 4 h.
[b] determined by gas chromatography, based on **1**
[c] argon swept system
[d] 30°C
[e] 70°C

For a greener process, not only should the solvent be safe from the operational, health, and environmental viewpoint,[14] but also should be obtained from renewable sources[26] and should allow good yields for the product in a specific process.[13] In Table 2, a comparison among various solvents under the previously selected reaction conditions is shown. If the reaction is carried in neat substrates (entry 1), the conversion is low and the selectivity for the cross-metathesis product **2** is poor. Not only is the primary product **2** consecutively isomerized to **4**, but also the substrate is isomerized to **5**, leading to the formation of the cross-metathesis product **6**. Employing the usually efficient, but hazardous[14] 1,2-dichoroethane (DCE) as solvent, entry 2, the conversion increases considerably, but c.a. 10% of **2** is consecutively isomerized to **4**. The use of the less hazardous toluene (TOL), entry 3, leads to similar results. In entry 4, employing methyl THF (Me-THF) obtained from bio-renewable sources, the selectivity for **2** raises to 90%, but the conversion is considerably reduced. Employing the renewable[14] dimethylcarbonate (DMC), entry 5, the consecutive isomerization reaches 20%, which impacts negatively the yield. Diethylcarbonate (DEC), entry 6, gives slightly better results, in agreement with the previous work employing the analogous eugenol as substrate.[12] The best results were obtained employing *p*-cymene (*p*-CYM) as solvent (entry 7): the conversion reached 95% and the consecutive isomerization was practically suppressed. This finding suggests that *p*-cymene is a very promising solvent for C-C double-bond metathesis because it reduces the undesired isomerization.

Table 2. Cross-metathesis of estragole (**1**) with methyl acrylate: solvent variation.[a]

Entry	Solvent [b]	Conv. [%]	Product distribution [%]				Yield **2** [%][c]
			2	**3**	**4**	**6**	
1	none	37	68	2	25	5	25
2	DCE	90	88	1	10	1	79
3	TOL	88	92	0	8	0	81
4	Me-THF	81	90	2	6	2	73
5	DMC	86	77	1	20	2	66
6	DEC	90	84	1	14	1	76
7	*p*-CYM	95	98	1	1	0	93

[a] estragole (**1**) (78 µL, 0.50 mmol); methyl acrylate (181 µL, 2.0 mmol); **H-II** (1.56 mg, $2.5x10^{-3}$ mmol); solvent (if any, 4.0 mL); 70 °C; 4 h.
[b] DCE: 1,2-dichloroethane; TOL: toluene; Me-THF: 2-methyltetra hydrofurane; DMC: dimethylcarbonate; DEC: diethylcarbonate; *p*-CYM: *p*-cymene;
[c] determined by gas chromatography, based on **1**

It is also noteworthy that, among the solvents examined, *p*-cymene (99%, Sigma-Aldrich) has the lowest specification level or was submitted to the simplest pre-treatment. Me-THF, THF, and 1,2-dichloroethane were anhydrous, packed under inert atmosphere by the supplier (Aldrich Sure-seal solvents). Diethyl carbonate and dimethyl carbonate were distilled and stored over 4Å molecular sieves under argon, while *p*-cymene was only distilled under vacuum and stored under argon. We also compared the performance of the distilled *p*-cymene against *p*-cymene, from a recently opened bottle, only bubbled with argon for 10 min, without distillation or any further treatment, for the cross-metathesis of **1** with methyl-acrylate. The results were very similar, suggesting that even vacuum distillation is unnecessary. The GC analysis (see Figure S19 in the supporting information) of *p*-cymene as received indicates that it is quite pure (99,97% based on GC-FID area integration). Typically deleterious impurities such as water, acids, bases or even peroxides, if present, do not prevent it to perform better than alternative solvents of higher specification levels.

In order to verify the generality of the beneficial effects of *p*-cymene, the commercial catalysts shown in Figure 1 were tested in the cross-metathesis of **1** with methyl acrylate in this solvent and the results are presented in Table 3. It is noteworthy that in *p*-cymene the consecutive isomerization is almost suppressed for all catalysts tested. It is also worthwhile mentioning that the cheaper versions of second-generation catalysts **Ind-II** and **G-II** give good yields even at low loading (0.5%) of catalyst for this challenging reaction. The system employing **G-II** as pre-catalyst (entry 2, Table 3) presented a higher isomerization activity, which suggests its faster decomposition. This effect could be forecasted considering the deleterious effect of the leaving PCy_3 in the cross-metathesis with acrylates demonstrated by Fogg[40]. Thus, it is surprising that **Ind-II** matches the output of **H-II** for this reaction, and this suggests that the ylidene ligand installed in the pre-catalyst may play a role in the pathways of decomposition promoted by PCy_3. As expected, the influence of modifying ligand (NHC) is more significant than the leaving ligands (PCy_3, PPh_3, Isopropyl ether moiety) or the reactive ylidene ligands (benzylidene, indenylidene, isopropoxybenzylidene). The catalysts bearing the bulkier SI-^{i}Pr (c.f. **Ind-II'**, **G-II'**, **M73**) are more prone to give self-metathesis product **3** than the ones

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Table 3. Cross-metathesis of estragole (**1**) with methyl acrylate: catalyst variation in *p*-cymene.[a]

Entry	Catalyst[b]	Conv. [%]	Product distribution [%]				Yield **2** [%][c]
			2	**3**	**4**	**6**	
1	**H-II**	95	98	1	1	0	93
2	**G-II**	92	91	1	8	0	84
3	**Ind-II**	95	97	1	2	0	92
4	**Ind-II’**	70	69	30	1	0	48
5	**G-II’**	78	92	6	2	0	72
6	**M73**	76	75	22	2	0	57
7	**H-II’**	85	84	13	3	0	71

[a] estragole (**1**) (78 µL, 0.50 mmol); methyl acrylate (181 µL, 2.0 mmol); catalyst (1.56 mg, 2.5×10^{-3} mmol); *p*-cymene (4.0 mL); 70°C; 4 h.
[b] for structures, see Fig. 1
[c] determined by gas chromatography, based on **1**

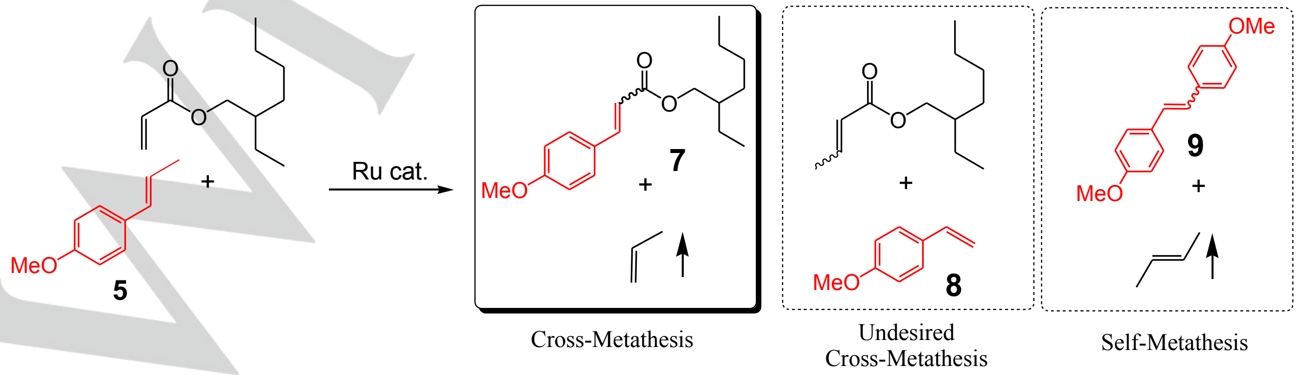
bearing the SIMes as ligand (**H-II**, **G-II**, **Ind-II**). For the catalysts containing the bulkier SI-^{i}Pr ligand, the homo coupling of two allyl fragments of **1** result in less steric hindrance than the hetero coupling of the allyl fragment of **1** and the vinyl fragment of the acrylate. As a consequence, the contribution of the self-metathesis is higher than for the catalysts bearing the SIMes ligand.

It is well accepted in literature that isomerization during metathesis is due to ruthenium species that arises from decomposition of the metathesis catalyst, although there are some questions about the nature of these species.

Fogg et al.[35] demonstrated that RuCl(CO)(H)(PCy_3)(SIMes)], which was once considered to be responsible for parallel isomerization, is not kinetically competent to account for the isomerization during the self-metathesis of estragole. Nelson and Percy [36] suggest that lack in isomerization activity of this species is due to the low lability of the PCy_3 ligand, but the 14e [RuCl(CO)(H)(SIMes)] species is very active for isomerization and can be formed directly from ruthenium-methylidene species present in the metathesis catalytic cycles of terminal C-C double-bond. The authors also demonstrated that there is a clear solvent effect on the rate of isomerization, which increases in the order toluene < chloroform ~ benzene < dichloromethane. It is, therefore, outstanding the capacity of *p*-cymene to reduce the isomerization process, which is superior to the best solvent reported (toluene). One can speculate that *p*-cymene can trap unsaturated ruthenium species responsible for isomerization to form saturated η^6-*p*-cymene bounded ruthenium species. Other reasons such as Ru-hydride trapping by diene impurities of *p*-cymene cannot be ruled out. Regardless the accuracy of the explanation, *p*-cymene has proved to be a useful solvent in C-C double-bond metathesis.

In a previous work[28] we established a route to the synthesis of cinnamate derivatives through the cross-metathesis of propenylbenzenes obtained from renewable sources and commodity acrylates. Some of the products are known for their anti-inflammatory activity, and the cross-metathesis of *trans*-anethole (**5**) with 2-ethylhexyl acrylate (Scheme 2) leads in one step to octyl methoxycinnamate (**7**), a UV-A filter largely used in sunscreen lotions. *trans*-anethole is a representative example of a naturally occurring propenylbenzene and is largely employed in chemical industry.

The former studies were carried employing the 1,2-dichloroethane as solvent, which is now classified as hazardous.[14] In this work, a set of solvents considered more benign was tested for the same reaction, and the results are presented in Table 4. In entry 1 the results in DCE are presented under similar conditions to the previous work. In entry 2 a further excess of 2-ethylhexyl acrylate was employed to make up the reaction volume and avoid the use of additional solvents. The conversion and yield were lower than in DCE, indicating that the use of a solvent is beneficial and therefore a set of less hazardous solvents was then examined. When toluene is employed, entry 3, the results are better than in neat acrylate and the yield for **7** reaches 93%. Employing the more polar and renewable methyl-THF, entry 4, conversion is good, but a significant amount of self-metathesis product **9** is observed. The use of DMC or DEC seems to be inappropriate for this particular reaction, since neither the conversion nor the yields are good. The fact that **8** is not transformed into **7** or **9** under these reaction conditions suggests a fast catalyst deactivation. The results employing *p*-cymene as solvent are presented in entry 7. Although slightly inferior than toluene (c.f. entry 3 vs. 7), the yield is still in the range



Scheme 2. Cross-metathesis of anethole (**5**) with 2-ethylhexyl acrylate.

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Table 4. Cross-metathesis of anethole (**5**) with 2-ethylhexyl acrylate.[a]

Entry	Solvent[b]	Conv. [%]	Product distribution [%]			Yield **7** [%][c]
			7	**8**	**9**	
1	DCE	100	97	1	1	97
2	Neat[d]	87	91	4	5	79
3	TOL	99	94	1	5	93
4	Me-THF	99	81	1	18	80
5	DMC	69	55	19	26	38
6	DEC	76	54	22	24	41
7	*p*-CYM	99	91	2	7	90

[a] anethole (**5**) (75 µL, 0.5 mmol); 2-ethyhexyl acrylate (416 µL, 2.0 mmol); **H-II** (1.56 mg, 2.5x10^{-3} mmol); solvent (if any, 2.5 mL); 70°C, 4 h.
[b] DCE: 1,2-dichloroethane; TOL: toluene; Me-THF: 2-methyltetrahydrofurane; DMC: dimethyl carbonate; DEC: diethyl carbonate; *p*-CYM: *p*-cymene;
[c] determined by gas chromatography, based on **5**
[d] extra 2-ethyhexyl acrylate (2.5 mL)

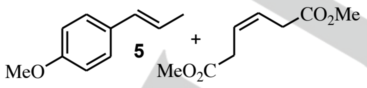
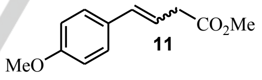
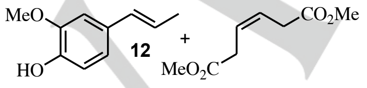
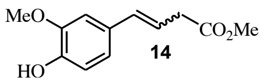
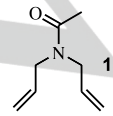
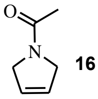
considered acceptable for a green process.[13] Due to its potential to be obtained from renewable sources, *p*-cymene seems to be the most sustainable solvent alternative among the examined solvents for this transformation.

In order to verify the generality of the utility of *p*-cymene as a solvent for metathesis, we tested this solvent with other substrates. Toluene is a suitable solvent to use as a benchmark, because it is presently among the most employed solvents for this reaction. We tested the cross metathesis of *trans*-anethole (**5**) and isoeugenol (**12**) with a different class of counter-part, namely *cis*-1,4-diacetoxy-2-butene, as well as the ring-closing metathesis (RCM) of N,N-diallyacetamide (**15**), and the results are presented in Table 5. The relative improvement in yield for *p*-cymene in the cross-metathesis of **5** with *cis*-1,4-diacetoxy-2-butene was 12% (Table 5, entry 1). For the cross-metathesis of **12**, which contains a unprotected phenol group, with *cis*- *cis*-1,4-diacetoxy-2-butene the relative improvement in yield was 36% (Table 5, entry 2). For the RCM of **15**, the yield was essentially the same in both solvents. Thus, *p*-cymene presented a better performance as a solvent for metathesis for three out of five substrates tested in this work, and matches the performance of toluene for remaining two substrates.

Conclusions

We demonstrated that *p*-cymene is an excellent alternative solvent for the cross-metathesis of estragole with methyl acrylate. It is outstanding that this solvent prevents the consecutive double-bond isomerization of the cross-metathesis product. Taking into account that isomerization is a major problem in olefin metathesis, *p*-cymene has an enormous potential to replace the hazardous 1,2-dichloroethane or the non-renewable toluene in olefin metathesis. Although a careful global analysis must be carried out for each application taking into account, *e.g.*, the costs for solvent recycling, *p*-cymene seems to be a promising candidate to replace toluene as a greener alternative in metathesis since it is apparently less toxic, it can be obtained from renewable sources and it matches or surpasses the performance of toluene for the substrates studied in this article.

Table 5. Comparative study of cross-metathesis and RCM in toluene or *p*-cymene.

Entry	Reactants	Main Product	Catalyst [mol%]	Yield [%][d]	
				toluene	*p*-cymene
1[a]	 **5**	 **11**	**Ind-II** (1.0 mol%)	55	67
2[b]	 **12**	 **14**	**Ind-II** (1.0 mol%)	64	87
3[c]	 **15**	 **16**	**GII** (0.25 mol%)	92	94

[a] anethole (**5**) (75 µL, 0.50 mmol); cis-1,4-diacetoxy-2-butene (336 µL, 2.0 mmol); **Ind-II** (4.75 mg, 5.0x10^{-3} mmol); solvent (2.5 mL); 70 °C; 4 h.
[b] isoeugenol (**12**) (76 µL, 0.50 mmol); cis-1,4-diacetoxy-2-butene (336 µL, 2.0 mmol); **Ind-II** (4.75 mg, 5.0x10^{-3} mmol); solvent (2.5 mL); 70 °C; 4 h.
[c] N-N-diallylacetamide (**15**) (78 µL, 0.50 mmol); **G-II** (1.1 mg, 1.25x10^{-3} mmol); solvent (4.0 mL); 40 °C, 30 min.
[d] determined by gas chromatography, based on substrate.

Experimental Section

General procedures

Except otherwise specified, all reactions were carried out in an argon-filled glovebox (MBraun) and all chemicals were purchased from Sigma-Aldrich. Anhydrous Sure-seal solvents, dichloroethane, methyl-THF and THF were used as received. Diethyl carbonate and dimethyl carbonate were distilled under argon and stored over 4A molecular sieves. *p*-cymene was distilled in a Kugelrohr distillation apparatus at 50 °C and 10^{-1} mbar, collected under argon and stored in the glove box. Estragole (98%) and *trans*-anethole (99%) were passed through a neutral alumina column and bubbled with argon for 10 minutes before use. Methyl acrylate (99%) and 2-ethylhexyl acrylate (98%) were degassed by three freeze-pump-thaw cycles, and stored under argon at -19 °C. The catalysts **G-II** (CAS 246047-72-3), **G-II'** (CAS 373640-75-6), **H-II** (CAS 301224-40-8), **H-II'** (CAS 635679-24-2) were purchased from Sigma-Aldrich and the catalysts **Ind-II** (CAS 536724-67-1), **Ind-II'** (1307233-23-3), and **M73** (1025728-57-7) were kindly donated by UMICORE.

Protocols for metathesis reactions

The reactions were carried out in a HEL7 reactor, which allow seven tests in parallel. Each well has a 20 mL glass insert, a PTFE-coated magnetic stirring bar and an individual condenser tip with a customized PTFE gasket to prevent cross-contamination. The reactor was degased and introduced in the glove box. Each glass insert was loaded with estragole (76 mg, 0.50 mmol), *p*-xylene (54 mg, 0.50 mmol), methyl acrylate (173 mg, 2.0 mmol), solvent (4.0 mL) and catalyst (2.5x10^{-3} mol, 0.5 mol%). The reactor was sealed, taken out of the glove box, introduced in a pre-heated aluminum block that reached 1/3 of its length and temperature of the block was kept at 70°C by a PID controller. The overhead of the reactor was cooled by a circulating mixture of water/ethyleneglycol at 5 °C, and swept with a steady argon flow. Under these conditions, no cross-contamination was observed. After 4 hours the reactor was opened to air and a 0.50 mL sample was taken of each vial, diluted with 1.0 mL of untreated dichloroethane and analyzed by gas chromatography (GC). For the cross-metathesis of *trans*-anethole with 2-ethylhexyl acrylate, each glass insert was loaded with anethole (74 mg, 0.50 mmol), 2-ethylhexyl acrylate (368 mg, 2.0 mmol), solvent (2.5 mL) and catalyst (2.5x10^{-3} mol, 0.5 mol%). After 4 hours the reactor was opened to air and *p*-xylene (54 mg, 0.50 mmol) was added in each vial. For GC analysis, 0.10 mL sample was taken of each vial and diluted with 1.0 mL untreated dichloroethane.

Product analysis

The quantification of the products was made by gas chromatography (GC) employing *p*-xylene as internal standard on Shimadzu GC2010 Plus apparatus with an auto-sampler, using an inlet split ratio of 50:1, an inlet temperature of 310°C, and H$_2$ (UHP grade) as carrier gas, a nonpolar Rtx-5M column (30 m length, 250 µm internal diameter) and a flame ionization detector (FID) at 320 °C. For the quantification of the products of the cross-metathesis of estragole with methyl acrylate the temperature program was: 50 °C for 5.0 min, heating at 15 °C/min to 280 °C and isotherm for 5.0 min. For the cross metathesis of *trans*-anethole with 2-ethylhexyl acrylate the temperature program was: 50 °C for 3 min, heating at 10 °C/min to 310 °C and isotherm for 5 min. For the cross-metathesis reactions with cis-1,4-diacetoxy-2-butene the temperature program was: 50 °C for 2 min, heating at 10 °C/min to 310 °C and isotherm for 5 min (see Supporting Information S13). For the ring-closing metathesis reaction of N,N-diallylacetamide the products quantification was made by gas chromatography (GC) employing *p*-xylene as the internal standard on Shimadzu GC2010 Plus apparatus with an auto-sampler, using an inlet split ratio of 50:1, an inlet temperature of 230 °C, and H$_2$ (UHP grade) as carrier gas, a polar Rtx®-Wax column (30 m length, 250 µm internal diameter) and a flame ionization detector (FID) at 230 °C. The temperature program was: 50 °C for 3 min, heating at 20 °C/min to 230 °C and isotherm for 5 min (see Supporting Information S17). The qualitative analysis of the products was made by mass spectrometry on a Shimadzu GC2010/QP2010-GC/MS apparatus employing an electron impact detector at 70 eV (see Supporting Information). The GC conditions were identical to GC/FID, except for the carrier gas (helium). The major products were also separated by preparative thin layer chromatography in silica using hexane/ethyl acetate as eluent and identified by ^{1}H-Nuclear Magnetic Resonance (^{1}H-NMR) and ^{13}C-Nuclear Magnetic Resonance (^{13}C-NMR) on a Brucker 400 MHz NanoBay spectrometer at 298K, and referenced to the residual proton signals of the deuterated solvent. Signals are reported in ppm, relative to TMS (^{1}H) at 0 ppm (see Supporting Information).

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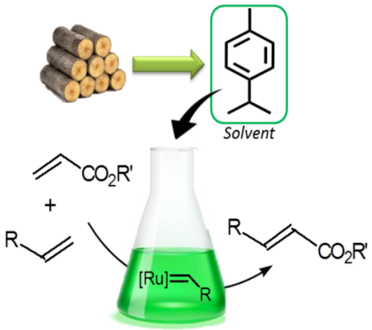
FULL PAPER

p-cymene, which can be produced from rejects of cellulose and citrus industry, is an excellent solvent for Ru-catalysed metathesis of various substrates. It prevents the undesired consecutive double-bond isomerization and delivers better yields as compared to other bio-renewable solvents.



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p-cymene as solvent for olefin metathesis: matching efficiency and sustainability