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MeSesamol, a bio-based and versatile polar aprotic solvent for organic synthesis and depolymerization

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ABSTRACT

Applications of polar aprotic solvents are inevitable in the chemical industry, but few nonhazardous alternatives are available. Herein, we propose methyl sesamol (MeSesamol) as a promising new bio-based alternative for polar aprotic solvents and demonstrate its versatile applications. MeSesamol was derived from natural resources using environmentally friendly and facile procedures, such as methylation using dimethyl carbonate. MeSesamol has a distinctive smell and demonstrates excellent properties as a green solvent candidate: high boiling and open-cup flash points, immiscibility with water but miscibility with common organic solvents, high stability and resistance to several acids and bases. MeSesamol was an effective solvent in nine C–C coupling reactions, including the Suzuki and Sonogashira reactions and asymmetric Michael addition. MeSesamol lies close to dichloromethane (DCM) in Hansen space and achieves a similar or higher yield and enantiomeric excess (up to 97% and 99%, respectively) in the asymmetric Michael reactions compared to DCM. MeSesamol proved to be an excellent recyclable solvent in the depolymerizations of bisphenol-A polycarbonate (BPA–PC) and polyethylene terephthalate (PET). MeSesamol was recycled in five reaction cycles with excellent efficiency (92%–100%) and outstanding cumulative monomer yields (92% bisphenol-A from BPA–PC and 92% terephthalic acid from PET). To properly compare the depolymerization reactions, we propose two green metrics, namely, the corrected energy-economy factor (ϵ_{corr}) and the corrected environmental energy impact (ξ_{corr}).

1. Introduction

The continued extraction of limited fossil fuels and the resulting environmental problems have driven the search for renewable materials and energy sources. In fact, the search for renewables is among the largest challenges of humankind. The same endeavor is devoted to solvents, which comprise a large proportion of waste from chemical industries [1].

In 2015, the United Nations announced 17 major Sustainable Development Goals, including reduction of environmental impacts by the chemical sector [2]. In the same year, the ACS Green Chemistry Institute Pharmaceutical Roundtable encouraged the replacement of polar aprotic and halogenated solvents with new green solvents [3].

Most of the green solvents are less toxic, contain no halogen atoms, and have a low vapor pressure, thereby reducing occupational exposure and environmental releases to the atmosphere. A green solvent should also be thermally stable and easily available from natural and renewable sources. It is important to highlight that green solvents are not the sole requirements of sustainable chemistry; low energy demand and reduced waste generation are also essential for promoting green chemistry [4].

To meet the increasingly stringent environmental regulations, pharmaceutical companies such as GSK [5], Pfizer [6], AstraZeneca [7], and Sanofi [8] have published their own solvent-sustainability guides to aid comparisons of different solvents [9]. These guidelines and recent reviews stress the need for finding greener solvents. Polar aprotic solvents (PASs) and chlorinated solvents are especially difficult to replace

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with greener alternatives [10,11].

Among the widely used PASS in organic synthesis are *N,N*-dimethylformamide (DMF), dimethyl sulfoxide (DMSO), *N,N*-dimethylacetamide (DMAc), and *N*-methyl-2-pyrrolidone (NMP), which are noted for their remarkable solubilization power. PASS are the favored solvents in S_N2 reactions because they effectively solvate the cations while leaving the anions free as nucleophiles. PASS are also commonly employed in cross-coupling reactions [12], solid-phase peptide synthesis [13], and fabrication of polymer membranes [14]. The polymer industry heavily relies on PASS because most polymers are poorly solubilized in non-PASS. Approximately 400 million tons of plastic are produced globally each year, although polymer recycling remains problematic and faces many challenges [15]. For instance, BPA-PC must be collected and recycled because its monomer (bisphenol-A) is a possible xenoestrogen and poses a major health concern. Furthermore, BPA-PC is used in a wide variety of consumer and industrial products, such as electronic components, storage devices (CDs and DVDs), automobiles, and safety equipment. Unless recycled, the resulting BPA-PC waste accumulates rapidly. Although several methods for the chemical recycling of BPA-PC have been developed over the past few decades, most of these methods require elevated temperatures [16]. Similarly, PET has been chemolytically depolymerized using recyclable heterogeneous organocatalysts [17] and KOH in alcohols (e.g., MeOH, EtOH) [18–20]. Thielemans and co-workers simultaneously depolymerized a mixed stream of PET and BPA-PC within 2 min via KOH-in-MeOH hydrolysis (KMH) under microwave-assisted heating to 130 °C [21].

PASS are usually derived from fossil-based sources and most of them are hazardous to human health and the environment. Therefore, they should be substituted with greener solvents. Green alternatives are preferably derived from renewable sources and should be safer to handle, less toxic, and exhibit similar to or better solubilization power than fossil-based derivatives. Recently, bio-based solvents derived from biomass resources have promised to halt the depletion of fossil energy [22,23]. Among the promising bio-based solvents are γ -valerolactone (GVL) [24], *p*-cymene [25], dimethyl isosorbide (DMI) [26], dihydrolevoglucosenone (cyrene) [27,28], diformylxylose [29], and methyl 5-(dimethylamino)-2-methyl-5-oxopentanoate (sold under the brand name Rhodiasolv PolarClean) [30,31]. Cyrene has been already used in several industrially relevant applications: as a replacement solvent in the production of a revolutionary graphene ink [32], in drug discovery as solvent in amide bond formation [33], as a mediator of carbon-carbon coupling reactions [34], and as the drug-delivery medium in antibacterial susceptibility testing [35].

The 1,3-benzodioxole scaffold of sesamol is ubiquitous in biomasses and natural compounds (such as piperine and bicuculline). Sesamol is a white crystalline solid with a melting point of 62–65 °C. We converted sesamol to its methyl ether using an inexpensive, non-toxic methylating agent, dimethyl carbonate, resulting in MeSesamol, which is a colorless liquid and a green solvent candidate. Moreover, we hypothesized that methylation improves the stability of sesamol by inhibiting its oxidation. Therefore, starting from sesamol, we attempted a green synthesis of MeSesamol and investigated the potential applicability of MeSesamol as a greener alternative for traditional PASS (Fig. 1).

2. Materials and methods

2.1. General information

The starting materials and reagents were purchased from commercially available sources (Merck, TCI Europe, and VWR). The depolymerization reactions were performed using Makrolon® 2658 BPA-PC granules and PET flakes from HUKU Ltd. (Hungary). Infrared (IR) spectra were recorded on a Bruker Alpha-T Fourier-transform IR (FTIR) spectrometer. Optical rotations were measured on a PerkinElmer 241 polarimeter calibrated by measuring the optical rotations of both enantiomers of menthol. Thin-layer chromatography (TLC) was performed using silica gel 60 F₂₅₄ (Merck) plates. The reactions were monitored by TLC and high-performance liquid chromatography–mass spectrometry (HPLC–MS). The solvent ratios in the eluents are given in volume units (mL mL⁻¹). Nuclear magnetic resonance (NMR) spectra were recorded on a Bruker DRX-500 Avance spectrometer (at 500 and 126 MHz for the ¹H and ¹³C spectra, respectively) or on a Bruker 300 Avance spectrometer (at 300 and 75.5 MHz for the ¹H and ¹³C spectra, respectively) at specified temperatures. High-resolution MS was measured on a Bruker MicroTOF II instrument using positive electrospray ionization. The measured values are reported to four decimal places. HPLC–MS was performed on an HPLC system using a Shimadzu LCMS-2020 (Shimadzu Corp., Japan) device equipped with a Reprospher (Altmann Analytik Corp., Germany) 100 Å C18 (5 µm; 100 × 3 mm) column and a positive/negative double ion source with a quadrupole MS analyzer in the range 50–1000 *m/z*. The flash point was measured using Marcusson's open-cup method. Thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC) analysis were carried out on a TGA 209 F1 analyzer (Netzsch) under an N₂ atmosphere over the temperature range 30–900 °C. Low-temperature DSC measurements were performed on a DSC 250 (TA instruments) over the temperature range –90–170 °C. The

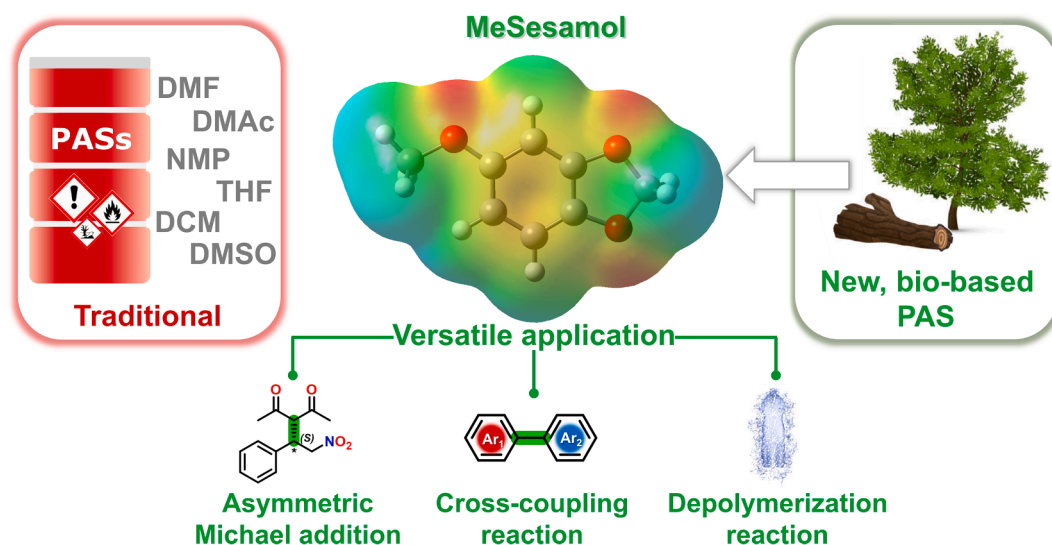


Fig. 1. MeSesamol as a promising alternative for traditional PASS.

Hansen solubility parameters were determined using HSPiP Software (5th Edition version 5.4.06). Further details are available in the [Supplementary Material](#).

2.2. Experimental

2.2.1. MeSesamol synthesis

Synthesis of MeSesamol using methyl iodide based on a modified literature procedure [36]: Sesamol (10 g, 72.5 mmol) was dissolved in acetone (160 mL), and K_2CO_3 (35 g, 254 mmol). After adding methyl iodide (9 mL, 20.5 g, 145 mmol), the reaction mixture was stirred overnight at room temperature under argon atmosphere. Once the reaction was complete (based on TLC with SiO_2 , heptane:EtOAc = 2:1), the K_2CO_3 was filtered and washed with acetone (30 mL). The volatile components were removed under reduced pressure. Water (40 mL) was added and the product was extracted with dichloromethane (3×40 mL). The combined organic phase was sequentially washed with hydrochloric acid (30 mL, 1 M) and aqueous NaOH (20 mL, 0.5 M), then dried over $MgSO_4$, filtered, and concentrated *in vacuo*. The crude product was purified by vacuum distillation (bp 102 °C at 2.2 mmHg). The resulting colorless liquid was characterized as follows: R_f : 0.70 (SiO_2 TLC, heptane:EtOAc = 4:1) HRMS m/z : $[M + H]^+$ calculated for $[C_8H_9O_3]^+$: expected 153.0552; found 153.0515. δ_H (500 MHz, $CDCl_3$, 27 °C): 3.75 (s, 3H); 5.91 (s, 2H); 6.32 (dd, $J = 8.5$ Hz, 2.5 Hz 1H); 6.49 (d, $J = 2.5$ Hz, 1H); 6.71 (d, $J = 8.5$ Hz, 1H) ppm. δ_C (126 MHz, $CDCl_3$, 27 °C): 56.1; 97.6; 101.2; 104.8; 108.0; 141.7; 148.4; 155.3 ppm.

Synthesis of MeSesamol using DMC without MeOH removal: Sesamol (10 g, 72.5 mmol) was dissolved in dimethyl carbonate (DMC) (50 mL, 0.594 mol). After adding K_2CO_3 (11 g, 79.6 mmol) and an appropriate catalyst—1,8-diazabicyclo[5.4.0]undec-7-ene (DBU) (2.17 mL, 14.5 mmol), 1,5-diazabicyclo[4.3.0]non-5-ene (DBN) (1.79 mL, 14.5 mmol), or cetyltrimethylammonium bromide (CTAB) (10.6 g, 29.1 mmol)—the reaction mixture was refluxed in an oil bath. Once the reaction was complete (based on TLC with SiO_2 , heptane:EtOAc = 2:1), the solid was filtered and washed with EtOAc. The volatile components were removed *in vacuo* and the crude product was purified by vacuum distillation, similarly to the above-mentioned process.

Synthesis of MeSesamol using DMC with MeOH removal and DMC replenishment: Sesamol (10 g, 72.5 mmol) was dissolved in DMC (50 mL, 0.594 mol). After adding DBU (16.2 mL, 0.109 mol), the reaction mixture was refluxed in an oil bath. The methanol produced during the reaction was removed by distillation and the DMC was replenished to its original volume at half hour intervals. Based on a TLC analysis (SiO_2 , heptane:EtOAc = 2:1), the reaction was completed at 2 h. The volatile components were removed *in vacuo* and EtOAc (30 mL) was added to the remaining mixture. The organic phase was extracted with mixed cc. HCl (10 mL) and water (20 mL). The HCl addition induced considerable gas evolution. The organic phase was washed with water (20 mL), dried over $MgSO_4$, filtered, and concentrated *in vacuo*. The crude product was purified by vacuum distillation as described above.

Synthesis of MeSesamol using DMC with MeOH removal and no DMC replenishment: Sesamol (10 g, 72.5 mmol) was dissolved in DMC (30 mL, 0.356 mol). After adding DBU (16.2 mL, 0.109 mol), the reaction mixture was refluxed in an oil bath. During the reaction, the formed methanol was removed by distillation using a Vigreux column, avoiding the need for DMC replenishment (see [Fig. S1](#) in the [Supplementary Material](#)). The reflux temperature was maintained steadily between 94 and 98 °C, which marked the endpoint of the reaction. Based on a TLC analysis (SiO_2 , heptane:EtOAc = 2:1), the reaction was completed at 3 h. The volatile components were removed *in vacuo* and EtOAc (30 mL) was added to the residue. The organic phase was extracted with a mixture of cc. HCl (10 mL) and water (20 mL). Again, the HCl addition induced considerable gas evolution. The organic phase was washed with water (20 mL), dried over $MgSO_4$, filtered, and concentrated *in vacuo*. The crude product was purified by vacuum distillation as described above. This synthesis was up-scaled threefold under the same reaction

conditions (see Section 2.3 in the [Supplementary Material](#)).

2.2.2. General procedure of thiourea organocatalysts synthesis

A solution of an appropriate isothiocyanate (0.1 mmol) in MeSesamol (200 μ L) was added to a solution of cinchona amine (32.3 mg, 0.1 mmol) in MeSesamol (300 μ L), and the reaction mixture was stirred for 2.5 h at room temperature. The crude product was purified by preparative TLC on silica gel (EtOAc:EtOH: NH_3 (aq) = 10:1:0.1) to obtain the corresponding organocatalyst. The spectral data were fully consistent with those reported in the literature [37,38].

2.2.3. General procedure for Michael addition of pentane-2,4-dione to *trans*- β -nitrostyrene

trans- β -Nitrostyrene (11.7 mg, 0.0785 mmol) and the corresponding organocatalyst were dissolved in MeSesamol or DCM (500 μ L) in a small vial. Subsequently, pentane-2,4-dione (20 μ L, 0.196 mmol) was added to this solution and the resulting reaction mixture was stirred at room temperature for 24 h. The crude product was purified by preparative TLC on silica gel (heptane:EtOAc = 2:1) to obtain a Michael adduct. The spectroscopic data of the product were consistent with the reported data (the absolute configuration was determined from optical rotation of the products) [39]. Enantiomeric excess values were determined by chiral HPLC on a Shimadzu LC-20 instrument (Shimadzu Corp., Japan) using a Phenomenex Lux Cellulose-3 column (3 μ m, 250 \times 4.6 mm) and an acetonitrile–water (40:60) eluent with a flow rate of 0.6 mL min^{-1} . The column temperature was 30 °C and the UV detection wavelength was 222 nm. $t_{R(S)}$ = 12.3 min and $t_{R(R)}$ = 14.6 min.

2.2.4. General procedure of the Suzuki reaction

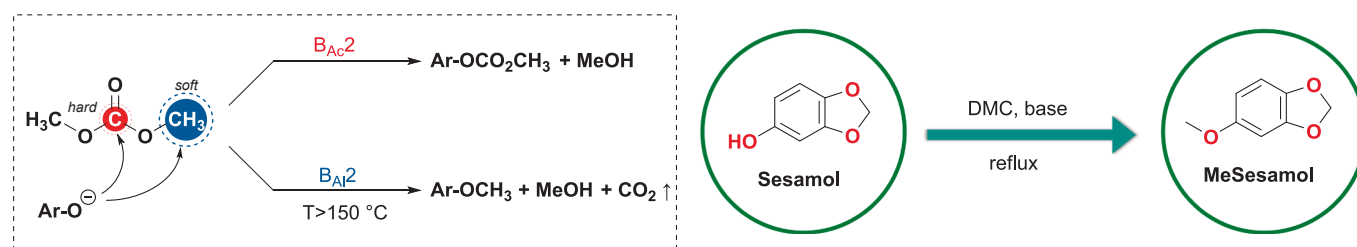
The [1,1'-bis(diphenylphosphino)ferrocene]dichloropalladium(II) ($Pd(dppf)Cl_2$) catalyst (8 mg, 0.0109 mmol, 4 mol%), the corresponding boronic acid derivative (0.287 mmol), and Cs_2CO_3 (178 mg, 0.547 mmol) were placed into a glass vial. The vial was capped and purged with nitrogen gas before adding a solution of aromatic halides (0.274 mmol) in MeSesamol (500 μ L). The reaction mixture was stirred at 80 °C for 5 h. The mixture was diluted with EtOAc (5 mL) and washed with water (5 mL). The organic phase was separated and the aqueous phase was extracted with EtOAc (3×3 mL). The volatile components were evaporated *in vacuo*. The preparative yields of entries 1 and 2 in [Table 4](#) were determined after precipitation in heptane. The yields of all other entries were determined by quantitative NMR using ethylene carbonate as an internal standard.

2.2.5. Procedure of the Sonogashira reaction

The [1,1'-bis(diphenylphosphino)ferrocene]dichloropalladium(II) ($Pd(PPh_3)_2Cl_2$) (3.5 mg, 2 mol%) and CuI (1.9 mg, 4 mol%) catalysts were charged into a glass vial. The vial was capped and purged with nitrogen gas before adding a solution of iodobenzene (28 μ L, 51.0 mg, 0.25 mmol), phenylacetylene (29 μ L, 26.9 mg, 0.263 mmol), and triethylamine (38 μ L, 27.8 mg, 0.275 mmol) in MeSesamol (500 μ L). The reaction mixture was stirred at room temperature for 1 h, and purified by preparative TLC on silica gel (heptane:EtOAc = 100:1). The product was obtained as pale-yellow crystals (36.6 mg, 82%).

2.2.6. General procedure of BPA-PC depolymerization

The BPA-PC granules (approximately 0.5 g), KOH-in-MeOH solution (1.25 M, 10 mL), and MeSesamol (10 mL) were charged into a round-bottom flask. The purity of the applied potassium hydroxide flakes was 89.6% (Lach-ner Ltd., Czech Republic). The resulting heterogeneous mixture was stirred magnetically at 500 rpm for 1 h at room temperature. Next, distilled water (10 mL) was added and the mixture was stirred until the white precipitate had completely dissolved (5 min). The resulting two phases were separated and MeSesamol was reused in the following reaction cycle. The aqueous phase was adjusted to an acidic pH with concentrated hydrochloric acid (1.5 mL). The volatile components of the obtained homogeneous solution were removed *in vacuo*. As



Scheme 1. Dual reactivity of dimethyl carbonate [26,40–43] and MeSesamol syntheses using dimethyl carbonate as the methylating agent.

Table 1
Synthesis of MeSesamol using DMC as the methylating agent.

Entry	Catalyst	Base	DMC	MeOH removal	Reaction time [h]	Yield[%]
1	0.2 eq DBU	1.1 eq K ₂ CO ₃	8.2 eq	×	30	74
2	0.2 eq DBN	1.1 eq K ₂ CO ₃	8.2 eq	×	26	63
3	0.4 eq CTAB	1.1 eq K ₂ CO ₃	8.2 eq	×	22	62
4	1.5 eq DBU		8.2 eq ^a	✓	2	91
5	1.5 eq DBU		4.9 eq ^b	✓	3	89–92

^a DMC was replenished to its initial volume every half hour; ^b DMC loss was prevented using a Vigreux column.

the volatile components evaporated, BPA precipitated from the water. The flask was stored in a refrigerator for 1 h to allow the complete crystallization of BPA. The crystallized BPA was filtered, washed with distilled water (2 × 25 mL), heptane (2 × 25 mL), and dried under vacuum to afford white crystals of BPA.

2.2.7. General procedure of PET depolymerization

The PET flakes (approximately 0.5 g), KOH-in-MeOH or KOH-in-EtOH solution (1.25 M, 10 mL), and MeSesamol (10 mL) were charged into a round-bottom flask. The procedure was identical to that of BPA–PC depolymerization (subsection 2.2.6) except for the temperature of magnetic stirring (50 °C). The pH of the resulting aqueous phase was adjusted to 2 with concentrated hydrochloric acid. After pH adjustment, the white precipitate was filtered, washed with distilled water (2 × 25 mL), MeOH or EtOH (2 × 25 mL), and dried under a vacuum to obtain white–pale-yellow crystals of TPA.

3. Results and discussion

3.1. Synthesis of MeSesamol

Sesamol can be synthesized in large quantities using safrole as the precursor (see Scheme S1 in the Supplementary material). Meanwhile, MeSesamol can be prepared using well-established methylating agents such as dimethyl sulfate or methyl halides. Methyl iodide with potassium carbonate in acetone afforded MeSesamol in quantitative yields [36]. As methyl iodide is toxic and expensive, we hypothesized that MeSesamol synthesis can be made via a green process using DMC as the methylating agent. DMC is more environmentally friendly than methyl iodide and plays the dual role of a solvent and an electrophilic reagent. DMC can undergo two types of electrophilic reactions, namely, carboxymethylation and methylation (Scheme 1) [26,40–43]. High temperatures (above 150 °C) promote the methylation reaction (via the BA12 mechanism), which has a higher activation barrier than

carboxymethylation. As the boiling point of DMC is 90 °C, the temperature-dependent methylation reaction is usually performed under pressure. Methylation at lower temperatures under atmospheric pressure can proceed in the presence of quaternary ammonium salts [44,45], ionic liquid [46], a strong cyclic amidine base [47,48], such as DBU, and 1,4-diazabicyclo[2.2.2]octane, or microwave heating [48].

For the first time, we applied eco-friendly DMC at lower temperatures, instead of hazardous methyl iodide or dimethyl sulfate in the methylation of sesamol. For this purpose, the utilization of different basic catalysts was investigated. A DBU catalyst with K₂CO₃ base afforded MeSesamol in 74% yield but the reaction time was excessively long (30 h; see entry 1 of Table 1). After replacing DBU with a DBN or CTAB catalyst, the reaction time was marginally shortened but the yields were slightly lower (entries 2–3 in Table 1). Replacing the K₂CO₃ base with DBU allowed a homogeneous reaction with a greatly enhanced reaction rate (entries 4–5 in Table 1). The methanol produced during this reaction lowered the reflux temperature but could be continuously removed to promote methylation. The loss of DMC was successfully prevented by enhancing the plate number of the distillation unit. The use of a Vigreux column (see Fig. S1 in the Supplementary material for the reaction apparatus) removed the need for continuous DMC replenishment (entry 5 of Table 1). Overall, this efficient and green method can methylate sesamol under atmospheric pressure, obtaining MeSesamol with 89–92% yield in 3 h.

3.2. Properties of MeSesamol

For the first time, we studied the physical properties of MeSesamol: atmospheric boiling point, melting point, density, viscosity, flash point that are summarized in Table 2. MeSesamol is a colorless-to-pale-yellow liquid with a pleasant smell that can potentially assist the detection of solvent spills and leaks during industrial processes. MeSesamol has a relatively high boiling point (229–230 °C) and consequently a low vapor pressure and low exposure risk to humans. However, as the removal of

Table 2
Physical properties of MeSesamol and common bio-based solvents.

Solvent	Boiling point [°C]	Melting point [°C]	Density [g mL ⁻¹]	Viscosity [mPas]	Flash point [°C]
GVL	207–208	–31	1.05	1.86	96 ^a
<i>p</i> -Cymene	177	–68	0.86	3.40	52 ^b
Cyrene	226	–20	1.25	14.5	108 ^b
MeSesamol	229–230	–18	1.21	4.14	123 ^a

^a open-cup flash point; ^b closed-cup flash point.

MeSesamol from the product solution by distillation is energy-intensive, it should be replaced by crystallization or extraction from MeSesamol. From DSC measurements, the melting point of MeSesamol was determined as $-18\text{ }^{\circ}\text{C}$ (see Figure S23B in the Supplementary Material). MeSesamol showed a higher density at $23\text{ }^{\circ}\text{C}$ (1.21 g mL^{-1}) than conventional PASs (DMF: 0.95 g mL^{-1} , DMSO: 1.10 g mL^{-1} , NMP: 1.03 g mL^{-1}) and medium viscosity (4.14 mPas). The flash point can provide valuable information on the potential safety risks of solvents, which are flammable. The higher open-cup flash point of MeSesamol ($123\text{ }^{\circ}\text{C}$) than those of DMSO ($95\text{ }^{\circ}\text{C}$), DMF ($58\text{ }^{\circ}\text{C}$), DMAc ($70\text{ }^{\circ}\text{C}$), and NMP ($86\text{ }^{\circ}\text{C}$) implies that MeSesamol is safer than conventional solvents. In addition, refractive index measurement was performed for sodium D-line ($n_D^{23} = 1.5420$).

The stability of MeSesamol was tested under different conditions: in a closed transparent vial, under air exposure, under sparging with argon gas, and in the presence of 2,6-di-*tert*-butyl-4-methylphenol (BHT). BHT is widely used to prevent oxidation of ethereal solvents (e.g., tetrahydrofuran [THF]) and consequent formation of free radical-mediated peroxide. Using peroxide strips, we confirmed that no peroxide formed in MeSesamol after two-months of storage. During the eight-week period, the samples were also investigated weekly by ^1H NMR. Under all tested conditions, new signals appeared in the ^1H NMR spectra after one week (Fig. 2a). The new signals close to the NMR signals of MeSesamol were assigned to dimerization of MeSesamol [49,50]. The ratio of the dimer was approx. 10% over the two-months period. To check this assignment, the dimer was synthesized and its structure was confirmed by two-dimensional NMR (Figs. S19–22). Comparing the NMR spectra obtained during the stability study with that of the synthesized dimer, we concluded that MeSesamol was dimerized during storage (Fig. 2b).

The thermal stability of MeSesamol was assessed over five days at $100\text{ }^{\circ}\text{C}$. Although a yellow discoloration was observed over time, the HPLC and NMR results showed no detectable changes (refer to Section 7 in the Supplementary Material). MeSesamol also remained stable over five days in the presence of common acids and bases. The selected acids [hydrochloric acid (1 M), acetic acid, and trifluoroacetic acid] and bases [sodium hydroxide solution (1 M), triethylamine, and pyridine] are commonly used in organic chemical reactions. Again, slight discoloration was observed in several cases, but the HPLC and NMR results remained unchanged (refer to Fig. S17 in the Supplementary Material).

Miscibility tests were performed in 19 organic solvents and water (Section 9 in the Supplementary material). All organic solvents were fully miscible with MeSesamol within the tested range of solvent ratios

(4:1 to 1:4) but no apparent miscibility was observed with water. We thus determined the exact solubility of water using HPLC. The water solubility of MeSesamol was 1.15 g L^{-1} at room temperature. In comparison, cyrene and GVL are fully miscible with water, 2-MeTHF is highly soluble in water (solubility = 140 g L^{-1}), and *p*-cymene is partially soluble in water (solubility = 20 mg L^{-1}). Furthermore, water is a key factor in many reactions, thus we determined the water content of MeSesamol, which was up to 3278 ppm (see Section 10 in the Supplementary Material). The nonmiscibility of MeSesamol with water is advantageous for extractions as it facilitates the reaction work-up.

The miscibilities of the solvents and compatibilities of MeSesamol with polymers were determined using the Hansen solubility parameter (HSP) model. HSPs are useful for evaluating polymer synthesis, polymer materials, and polymer degradation. The HSPs of MeSesamol were determined using HSPiP software and compared with those of some commonly used organic and bio-based solvents (Fig. 3, Table S1). If two solvents locate closely in Hansen space, that is, their Hansen distance (R_d) is small, they probably have similar solubility characteristics and dissolve the same types of solutes. The R_d values suggest that MeSesamol is a greener alternative to DCM, THF, and NMP (Table 3).

The products of organic syntheses often contain impurities of trace solvents. Therefore, to assist the identification of MeSesamol as a residual solvent, we measured the NMR spectra of MeSesamol in dimethylsulfoxide- d_6 , CDCl_3 , CD_3OD , CD_3CN , acetone- d_6 , THF- d_8 , and toluene- d_8 (subsection 2.4.1. in the Supplementary Material) and submitted them to the recently established and searchable NMR-impurity database [51].

3.3. Application of MeSesamol as a reaction media

The Suzuki–Miyaura cross-coupling reaction is widely used as a Pd-catalyzed C–C bond-forming reaction in chemical industries. The original Suzuki–Miyaura reaction was performed in THF, EtOH, and benzene solvents [52] but has since been achieved in environmentally friendly media such as water, biomass-derived solvents, deep eutectic solvents, and supercritical carbon dioxide [53]. Here we reacted iodo- (2a) or bromophenol (2b) and 4-methoxyphenylboronic acid (1a) using Pd(dppf) Cl_2 catalyst and MeSesamol solvent (entries 1–2 in Table 4). The scope of the reaction was further expanded to electron-rich and electron-deficient boronic acids and aryl halides (entries 3–11 of Table 4). As substitutes of the boronic acid derivative (1a–1b), electron-donating groups gave higher yields (72–87%; see entries 1–8 in Table 4) than the electron-withdrawing methoxycarbonyl groups (1c, 48–78%; see

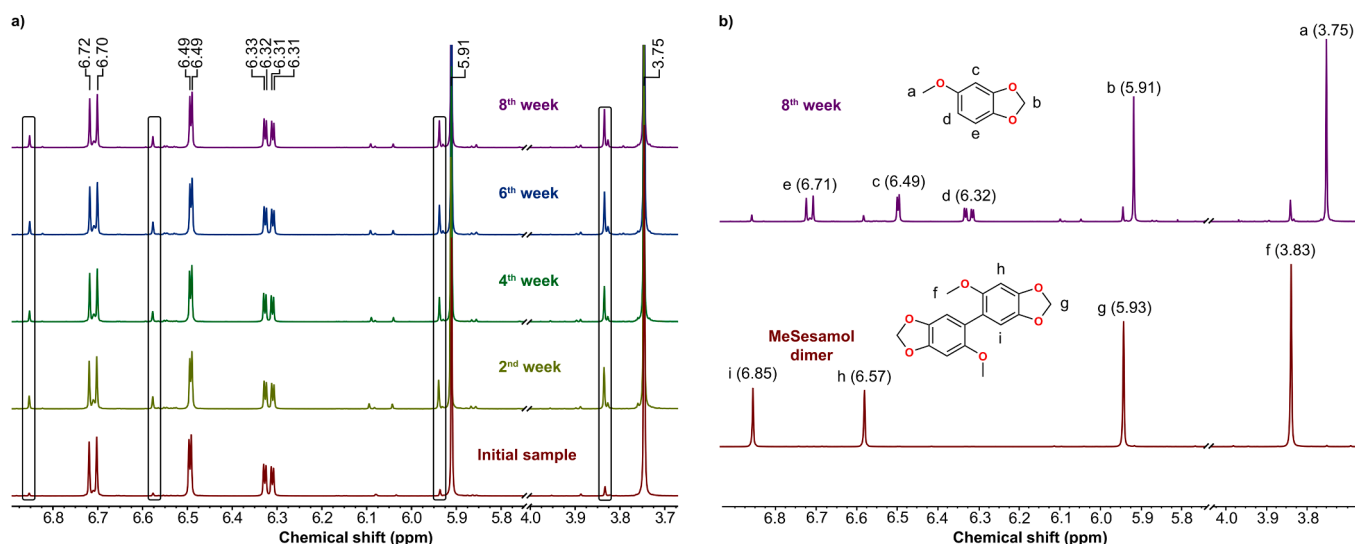


Fig. 2. Comparison of ^1H NMR spectra of MeSesamol obtained weekly (a) and the MeSesamol dimer (b).

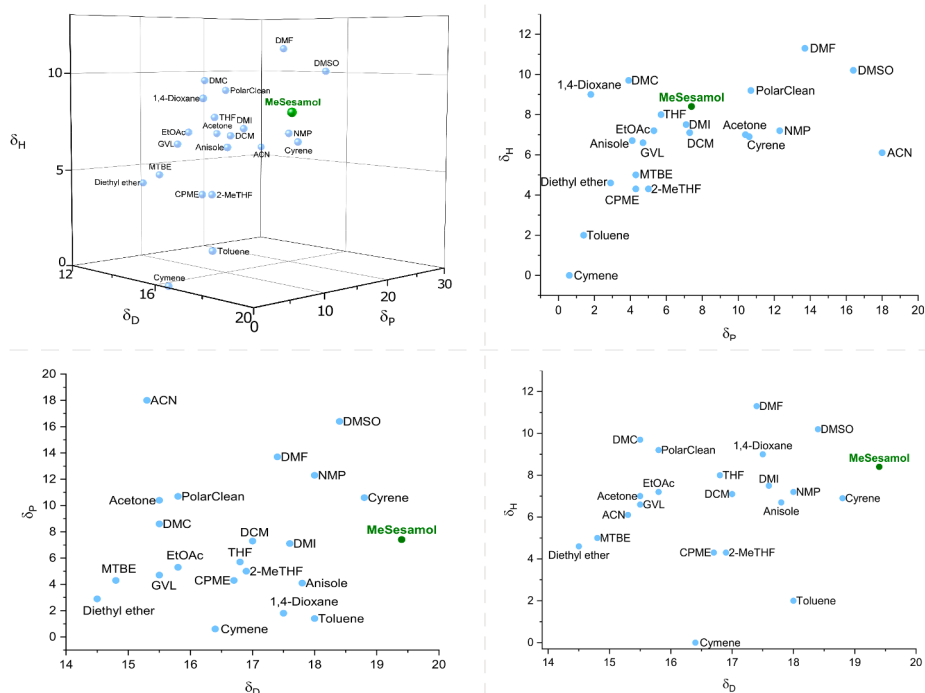


Fig. 3. Locations of MeSesamol and common organic solvents visualized in 3D Hansen space (upper left) and in 2D projected planes.

Table 3

Calculated Hansen solubility parameters of MeSesamol and the solvents closest to MeSesamol in Hansen space, where δ_D , δ_P , and δ_H denote the dispersion, polar intermolecular, and hydrogen bonding forces, respectively.

Class	Solvent	δ_D	δ_P	δ_H	Hildebrand values	R_a
Alternative solvents	MeSesamol	19.4	7.4	8.4	22.4	–
	DMI ^a	17.6	7.1	7.5	20.4	3.72
	Cyrene	18.8	10.6	6.9	22.7	3.73
	Anisole	17.8	4.1	6.7	19.5	4.90
Undesired solvents	DCM	17	7.3	7.1	19.8	4.97
	THF	16.8	5.7	8	19.5	5.49
	NMP	18	12.3	7.2	23.0	5.77

^a dimethyl isosorbide.

entries 9–11 of Table 4).

MeSesamol was also applied as the solvent in sp^2 – sp carbon–carbon bond formation via the Sonogashira reaction. When iodobenzene (**4**) was coupled with phenylacetylene (**5**) using $\text{Pd}(\text{PPh}_3)_2\text{Cl}_2$, copper iodide co-catalysts and triethylamine base, the product (**6**) was obtained in high isolated yield (82%) at room temperature (Scheme 2a).

Recently, interest in organocatalysis has increased since David MacMillan and Benjamin List were awarded the 2021 Nobel Prize for their groundbreaking work in asymmetric organocatalysis [54].

Table 4

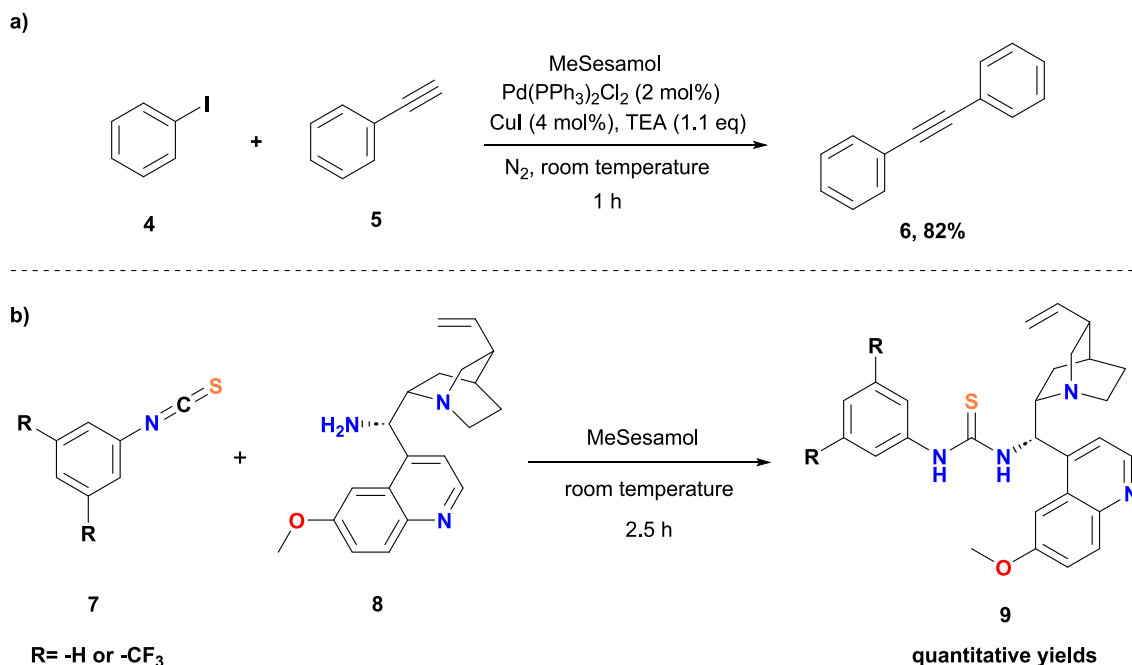
Use of MeSesamol solvent in Suzuki–Miyaura cross-coupling reactions.

Entry	R_1	R_2	X	Yield ^a [%]
1	–OMe (1a)	–OH (2a)	–I	72 (74) ^b
2	–OMe (1a)	–OH (2b)	–Br	74 (80) ^b
3	–Me (1b)	–H (2c)	–I	84
4	–Me (1b)	–H (2d)	–Br	80
5	–Me (1b)	–OMe (2e)	–Br	79
6	–OMe (1a)	–H (2c)	–I	83
7	–OMe (1a)	–H (2d)	–Br	87
8	–OMe (1a)	–OMe (2e)	–Br	77
9	–COOMe (1c)	–H (2c)	–I	54
10	–COOMe (1c)	–H (2d)	–Br	78
11	–COOMe (1c)	–OMe (2e)	–Br	48

^a NMR yield with ethylene carbonate as the internal standard; ^b isolated yield, dppf: 1,1'-bis(diphenylphosphino)ferrocene.

Thioureas—a class of hydrogen-bond organocatalysts—are among the most widely used organocatalysts owing to their excellent catalytic activity in various organic transformations. The thiourea moiety combined with a chiral backbone (such as a cinchona alkaloid) can be used in enantioselective reactions such as asymmetric Michael addition [55]. For example, Hayashi [55] reported a key role for asymmetric Michael addition (a conjugate addition reaction) in the enantioselective formation of carbon–carbon bonds in chiral active pharmaceutical ingredients (e.g., oseltamivir, prostaglandin E1, and baclofen) [56].

Here we synthesized two cinchona alkaloid-derived thiourea organocatalysts (**8**) starting from the corresponding isothiocyanate (**7**) applying MeSesamol as the solvent. The nucleophilic addition of cinchona amine (**8**) to isothiocyanate (**7**) gave the thiourea organocatalyst (**9**) in quantitative yield (Scheme 2b). The synthesized thiourea organocatalysts were applied to the asymmetric Michael addition of acetylacetone (**10**) and *trans*- β -nitrostyrene (**11**). To further expand the application possibilities of MeSesamol as solvent, we additionally synthesized four squaramide organocatalysts. Like thioureas, squaramides act as double-hydrogen-bond donors in organocatalytic reactions. To prove the similar solubility characteristics of MeSesamol and DCM (as implied by the HSPs in Table 3), all reactions were also carried out in DCM (Fig. 4). In all cases, the yields and enantiomeric excess values in MeSesamol were similar to or better than those obtained in DCM. Our findings demonstrate that MeSesamol is a greener alternative to DCM with competitive performance.



Scheme 2. MeSesamol as a solvent in (a) the Sonogashira cross-coupling reaction and (b) thiourea synthesis.

3.4. Application of MeSesamol in polymer science

Another essential property of solvents is high solubilization power. To reduce environmental impacts, polymer science is increasingly adopting green solvents in processes ranging from polymer fabrication to polymer degradation [57–61]. From an industrial perspective, expanding the palette of green alternatives that can replace traditional polar aprotic solvents (e.g., NMP, DMF, DMAc) poses a major challenge [60,62]. The HSP values place MeSesamol within the polar aprotic region of Hansen space, suggesting that MeSesamol is a good solvent choice for several polymers. The solubility performance of MeSesamol was evaluated through solubility trials on conventional and emerging polymers (see Section 12 in the [Supplementary Material](#)). The solubility properties of the most common polymers are shown in [Fig. 5](#).

BPA-PC was found to be soluble in MeSesamol at room temperature, opening opportunities for BPA-PC depolymerization in the highly efficient KMH system. Depolymerization was completed within a remarkably short time (within 1 h) at room temperature. After adding water to the reaction mixture, the reactants were readily separated from the valuable monomers. This method also allowed the straightforward recovery and reuse of MeSesamol. As shown in [Fig. 6](#), MeSesamol was recycled through four additional reactions with no significant change in monomer yields. To isolate BPA, the pH was adjusted with aqueous HCl solution. This process induced the formation of potassium chloride, a valuable by-product with wide-ranging applications from fertilizers to medicine and food processing. Moreover, the other by-product, namely dimethyl carbonate, can be used for the preparation of MeSesamol. Throughout the five reaction cycles, MeSesamol was recycled with high efficiency (96–100%) and achieved high BPA yields (up to 97%; see [Fig. 6](#)).

PET can be chemically recycled under basic conditions. Full conversion during PET hydrolysis usually requires high temperatures (above 100 °C) and takes several hours [63]. Although PET is insoluble in MeSesamol at room temperature ([Fig. 5](#)), considerable swelling of the polymer was observed in MeSesamol. Similarly to BPA-PC depolymerization, we thus implemented the depolymerization reaction in the KOH-in-alcohol system at 50 °C ([Fig. 6](#) and [S34](#)). To improve the environmental friendliness of the depolymerization process, MeOH was replaced with EtOH, a less toxic, mass-produced green solvent from

renewable sources. MeSesamol was also recycled after water addition and reused in additional reaction cycles. Over five reaction cycles in the KOH-in-MeOH system, the MeSesamol recovery was high (92–96%) and the TPA yields were excellent (82–92%) ([Fig. S34](#)). The TPA yields (88–95%) in the KOH-in-EtOH system were slightly higher than in KOH-in-MeOH system over the five reaction cycles. Therefore, the KOH-in-EtOH process is favorable in terms of HSE and yield.

MeSesamol played an essential role in the depolymerization reactions. Under the same conditions but without MeSesamol, the depolymerization conversion rates of BPA-PC and PET were only 5% and 28%, respectively. As efficient, low-temperature depolymerization methods for BPA-PC and PET are scarce in the literature, the exploitation of MeSesamol and optimization of its reaction conditions are recommended as future work.

3.5. Sustainability assessment

Recently, Thielemans and co-workers proposed a new green metric for comparing PET and BPA-PC depolymerization methods [18,21,63]. This metric, called the environmental energy impact [ξ , Eq. (1)], is calculated as the ratio of the environmental factor (E_{factor}) to the energy-economy factor (ϵ). The latter is a function of the yield Y , the reaction temperature T , and the reaction time [t , Eq. (2)]. The authors also suggested modifying E_{factor} as Eq. (3), because an estimated 90% of the solvent can be recycled through industrial processes [63]. Although the energy-economy factor can be usefully compared among different techniques at elevated temperatures, it ignores an important fact: reactions at ambient temperatures have no extra energy demand. Therefore, we propose an energy-economy factor that also makes reactions at standard ambient temperature (25 °C) comparable [Eq. (4.1)]. To avoid division by zero, we let ϵ_{corr} equal the reaction yield at 25 °C [Eq. (4.2)]. This adjustment allows better comparisons of the energy impacts among reactions, even those conducted at ambient temperatures, because lowering the reaction temperature lowers the energy demand, thus increasing the ϵ_{corr} ([Table 6](#); see [Supplementary Material](#) for details). Moreover, the energy demands of ambient temperature reactions decisively depend on the reaction time, as the ϵ_{corr} values of such reactions are almost identical. Eqs. (1)–(4) are given as

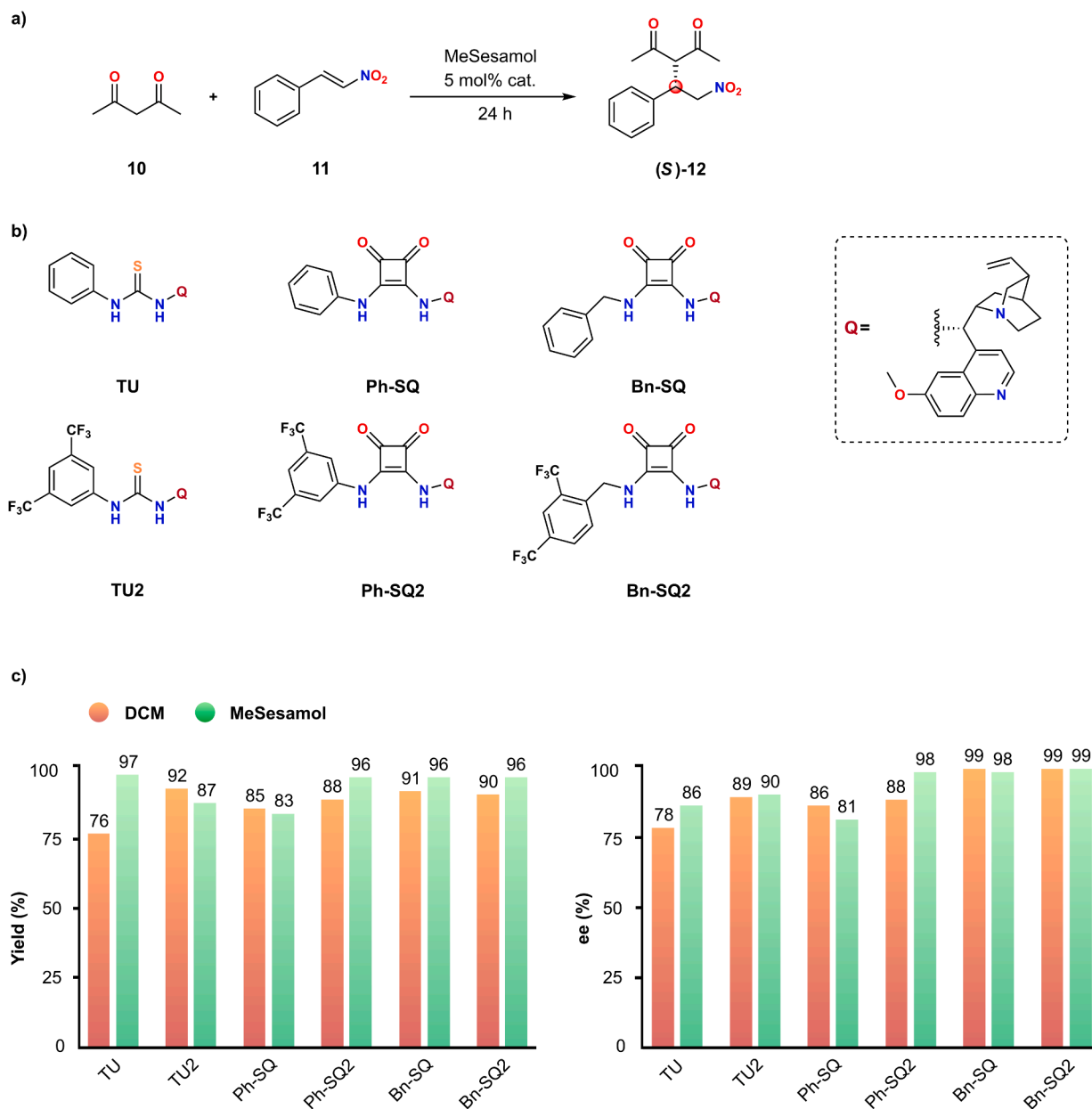


Fig. 4. Application of MeSesamol in an asymmetric Michael addition model reaction (a), the structure of organocatalysts used in this reaction scope (b), reaction yields and enantiomeric excess values using DCM and MeSesamol as solvents in the model reactions (c).

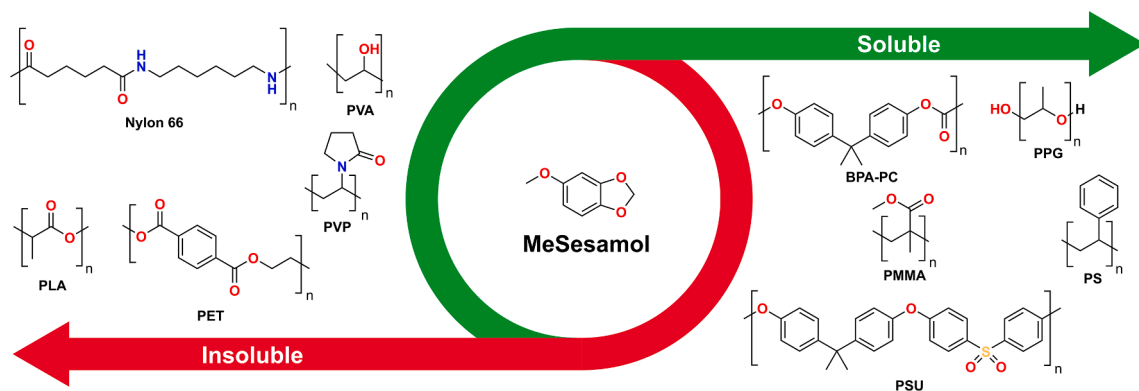


Fig. 5. Solubilizability of polymers with MeSesamol (all polymers are listed in Table S3).

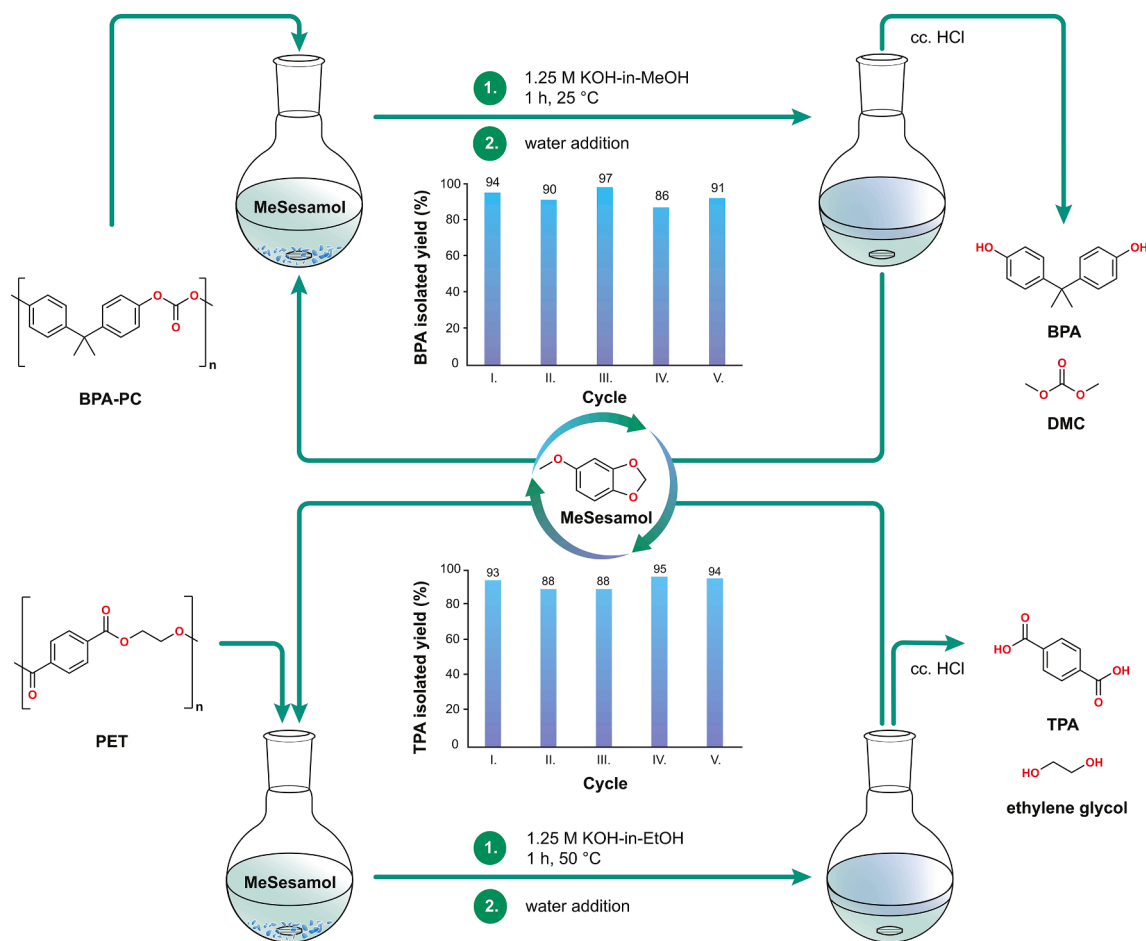


Fig. 6. MeSesamol as a recyclable solvent in the depolymerization of BPA-PC and PET. Upon completion of the reaction, water was added, the product was isolated from the aqueous phase, while MeSesamol was reused in another reaction cycle.

$$\xi = \frac{E_{factor}}{\epsilon}$$

$$\epsilon = \frac{Y}{T \bullet t}$$

(1)

(2)

Supplementary Material for details), our method is one of the lowest-temperature alkaline-hydrolysis methods for the conversion of waste PET, although the ϵ_{corr} is an order of magnitude larger in microwave-assisted depolymerizations than in the conventional heating used in our method. Microwave heating offers an extremely short reaction time, thus, it has great ϵ_{corr} value; however, microwave-heated methods are potentially difficult to scale-up. Overall, BPA-PC and PET chemolytic

$$E_{factor} =$$

$$\left[0.1 \bullet \left(\frac{\text{solvent}}{\text{polymer}} \text{massratio} \right) + \frac{\text{catalyst}}{\text{polymer}} \text{massratio} + \frac{\text{othersubstances}}{\text{polymer}} \text{massratio} \right] \bullet m_{polymer} + \frac{Y \bullet \frac{MM_{product}}{MM_{polymer}} \bullet m_{polymer}}{Y \bullet \frac{MM_{product}}{MM_{polymer}} \bullet m_{polymer}} \quad (3)$$

$$\epsilon_{corr} = \frac{Y}{(T - 25^{\circ}C) \bullet t} \quad (4.1)$$

$$\epsilon_{corr} = Y \quad \text{if } T = 25^{\circ}C \quad (4.2)$$

As shown in Table 5, our method has a slightly higher energy-economy factor than some of the most prominent BPA-PC depolymerization methods reported in the literature (see Supplementary Material for details). Comparing the green chemistry metrics between our method and other PET depolymerization processes (Table 6, see

depolymerization in MeSesamol solvent achieves outstanding performance and MeSesamol can be recycled through several reactions, reducing waste generation.

4. Conclusion

We have demonstrated the green synthesis and multiple applications of MeSesamol as a new bio-based solvent. Methylation with DMC afforded MeSesamol in excellent yield (up to 91%) after only 3 h. We determined the main physical properties and stability of MeSesamol under practically relevant conditions. MeSesamol is advantaged by a

Table 5

Green chemistry metrics of our method and the most prominently reported BPA-PC depolymerization methods, calculated using the corrected energy-economy coefficient.

Ref	T [°C]	Reaction time [min]	Catalyst	Solvent	Reaction condition	ϵ [°C ⁻¹ min ⁻¹]	ξ [°C min]	ϵ_{corr} [°C ⁻¹ min ⁻¹]	ξ_{corr} [°C min]
[64]	67	10	NaOH	THF + H ₂ O	MW	1.2×10^{-3}	495	1.9×10^{-3}	310
[64]	67	10	KOH	THF + H ₂ O	MW	1.2×10^{-3}	493	1.9×10^{-3}	309
[65]	40	10	NaOH	NMP + MeOH	conventional heating	1.9×10^{-3}	236	4.9×10^{-3}	88
[65]	40	35	NaOH	THF + MeOH	conventional heating	6.8×10^{-4}	553	1.8×10^{-3}	207
[66]	30	15	NaOH	THF + MeOH	ultrasound	2.1×10^{-3}	225	1.3×10^{-3}	38
<i>This work</i>	25	60	KOH	MeSesamol + MeOH	conventional heating	6.1×10^{-4}	7973	9.2×10^{-1}	5

Table 6

Green chemistry metrics of PET depolymerization ordered by decreasing temperature, calculated using the corrected energy-economy factor.

Ref	T [°C]	Reaction time [min]	Catalyst	Solvent	Reaction condition	ϵ_{corr} [°C ⁻¹ min ⁻¹]	ξ_{corr} [°C min]
[67]	220	2	NaOH (aq)	H ₂ O	MW	2.5×10^{-3}	266
[18]	120	1	KOH	MeOH	MW	9.9×10^{-3}	198
[68]	110	30	NaOH (aq)	EtOH + H ₂ O	conventional heating	3.5×10^{-4}	18,618
[69]	90	45	NaOH (aq), TBAI	H ₂ O	ultrasound	3.4×10^{-4}	11,610
[20]	80	60	KOH	EtOH + H ₂ O	conventional heating	3.0×10^{-4}	8,049
<i>This work</i>	50	60	KOH	MeSesamol + EtOH	conventional heating	6.1×10^{-4}	8,267

high boiling point (which reduces environmental emissions and human exposure), a high open-cup flash point, water immiscibility, and a pleasant distinctive smell. We demonstrated that undesired PASs and DCM can be potentially replaced with MeSesamol in several reactions, including the cross-coupling Suzuki and Sonogashira reactions, thiourea syntheses, and asymmetric Michael additions. To facilitate the uptake of MeSesamol in polymer science, we measured the solubilities of 44 polymers in MeSesamol. BPA-PC and PET were fully depolymerized in MeSesamol with high monomer yields (up to 97%). As MeSesamol is immiscible with water, it was efficiently recycled after depolymerization via simple phase separation. Meanwhile, owing to the excellent solubilization power of MeSesamol, the proposed method degraded the polymers at much lower temperatures than previously described methods while delivering comparable or superior energy-economy impact. Energy-economy is of paramount importance for solving the modern energy crisis. Overall, MeSesamol is a promising greener alternative solvent, however, further investigations of properties such as biodegradability, corrosivity, and carcinogenicity are required.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.cej.2023.144365>.

References

- [1] E.A. Aboagye, J.D. Chea, K.M. Yenkie, Systems level roadmap for solvent recovery and reuse in industries, *IScience*. 24 (10) (2021) 103114, <https://doi.org/10.1016/j.isci.2021.103114>.
- [2] SDGs-Chemistry, (n.d.). <https://www.acs.org/sustainability/chemistry-sustainable-development-goals.html>.
- [3] M.C. Bryan, P.J. Dunn, D. Entwistle, F. Gallou, S.G. Koenig, J.D. Hayler, M. R. Hickey, S. Hughes, M.E. Kopach, G. Moine, P. Richardson, F. Roschangar, A. Steven, F.J. Weiberth, Key Green Chemistry research areas from a pharmaceutical manufacturers' perspective revisited, *Green Chem.* 20 (2018) 5082–5103, <https://doi.org/10.1039/C8GC01276H>.
- [4] C.J. Clarke, W.C. Tu, O. Levers, A. Bröhl, J.P. Hallett, Green and Sustainable Solvents in Chemical Processes, *Chem. Rev.* 118 (2018) 747–800, <https://doi.org/10.1021/acs.chemrev.7b00571>.
- [5] C.M. Alder, J.D. Hayler, R.K. Henderson, A.M. Redman, L. Shukla, L.E. Shuster, H. F. Sneddon, Updating and further expanding GSK's solvent sustainability guide, *Green Chem.* 18 (2016) 3879–3890, <https://doi.org/10.1039/C6GC00611F>.
- [6] K. Alfonsi, J. Colberg, P.J. Dunn, T. Fevig, S. Jennings, T.A. Johnson, H.P. Kleine, C. Knight, M.A. Nagy, D.A. Perry, M. Stefaniak, Green chemistry tools to influence a medicinal chemistry and research chemistry based organisation, *Green Chem.* 10 (2008) 31–36, <https://doi.org/10.1039/B711717E>.
- [7] L.J. Diorazio, D.R.J. Hose, N.K. Adlington, Toward a More Holistic Framework for Solvent Selection, *Org. Process Res. Dev.* 20 (2016) 760–773, <https://doi.org/10.1021/acs.oprd.6b00015>.
- [8] D. Prat, O. Pardigon, H.W. Flemming, S. Letestu, V. Ducandas, P. Isnard, E. Guntrum, T. Senac, S. Ruisseau, P. Cruciani, P. Hosek, Sanofi's Solvent Selection Guide: A Step Toward More Sustainable Processes, *Org. Process Res. Dev.* 17 (2013) 1517–1525, <https://doi.org/10.1021/op4002565>.
- [9] F.P. Byrne, S. Jin, G. Paggiola, T.H.M. Petchey, J.H. Clark, T.J. Farmer, A.J. Hunt, C. Robert McElroy, J. Sherwood, Tools and techniques for solvent selection: green solvent selection guides, *Sustain. Chem. Process.* 4 (2016) 1–24, <https://doi.org/10.1186/s40508-016-0051-Z>.
- [10] A. Jordan, P. Stoy, H.F. Sneddon, Chlorinated Solvents: Their Advantages, Disadvantages, and Alternatives in Organic and Medicinal Chemistry, *Chem. Rev.* 121 (2021) 1582–1622, https://doi.org/10.1021/ACS.CHEMREV.0C00709/SUPPL_FILE/CROC00709_SI_001.PDF.
- [11] A. Jordan, C.G.J. Hall, L.R. Thorp, H.F. Sneddon, Replacement of Less-Preferred Dipolar Aprotic and Ethereal Solvents in Synthetic Organic Chemistry with More Sustainable Alternatives, *Chem. Rev.* 122 (2022) 6749–6794, https://doi.org/10.1021/ACS.CHEMREV.1C00672/ASSET/IMAGES/LARGE/CR1C00672_0046.JPEG.
- [12] J. Sherwood, J.H. Clark, I.J.S. Fairlamb, J.M. Slattery, Solvent effects in palladium catalysed cross-coupling reactions, *Green Chem.* 21 (2019) 2164–2213, <https://doi.org/10.1039/C9GC00617F>.
- [13] K. Wegner, D. Barnes, K. Manzor, A. Jardine, D. Moran, Evaluation of greener solvents for solid-phase peptide synthesis, *Green Chem. Lett. Rev.* 14 (2021) 152–164, <https://doi.org/10.1080/17518253.2021.1877363>.

- [14] Y.H. See Toh, F.W. Lim, A.G. Livingston, Polymeric membranes for nanofiltration in polar aprotic solvents, *J. Memb. Sci.* 301 (2007) 3–10, <https://doi.org/10.1016/J.MEMSCI.2007.06.034>.
- [15] R. Geyer, J.R. Jambeck, K.L. Law, Production, use, and fate of all plastics ever made, *Sci. Adv.* 3 (2017), <https://doi.org/10.1126/SCIADV.1700782>.
- [16] J.G. Kim, Chemical recycling of poly(bisphenol A carbonate), *Polym. Chem.* 11 (2020) 4830–4849, <https://doi.org/10.1039/C9PY01927H>.
- [17] Z. Fehér, J. Kiss, P. Kisszékelyi, J. Molnár, P. Huszthy, L. Kárpáti, J. Kupai, Optimisation of PET glycolysis by applying recyclable heterogeneous organocatalysts, *Green Chem.* 24 (2022) 8447–8459, <https://doi.org/10.1039/D2GC02860C>.
- [18] J.J. Rubio Arias, W. Thielemans, Instantaneous hydrolysis of PET bottles: an efficient pathway for the chemical recycling of condensation polymers, *Green Chem.* 23 (2021) 9945–9956, <https://doi.org/10.1039/D1GC02896K>.
- [19] L.C. Hu, A. Oku, E. Yamada, K. Tomari, Alkali-Decomposition of Poly(ethylene terephthalate) in Mixed Media of Nonaqueous Alcohol and Ether. Study on Recycling of Poly(ethylene terephthalate), *Polym. J.* 29 (1997) 708–712, <https://doi.org/10.1295/polymj.29.708>.
- [20] X.-L. Wang, W.-L. An, R. Du, F. Tian, Y. Yang, X.u. Zhao, S. Xu, Y.-Z. Wang, Rapid hydrolysis of PET in high-concentration alcohol aqueous solution by pore formation and spontaneous separation of terephthalate, *J. Environ. Chem. Eng.* 11 (2) (2023) 109434, <https://doi.org/10.1016/J.JECE.2023.109434>.
- [21] J.J. Rubio Arias, E. Barnard, W. Thielemans, Ultrafast Simultaneous and Selective Depolymerization of Heterogeneous Streams of Polyethylene Terephthalate and Polycarbonate: Towards Industrially Feasible Chemical Recycling, *ChemSusChem.* 15 (2022) e202200625, <https://doi.org/10.1002/CSSC.202200625>.
- [22] Y. Gu, F. Jérôme, Bio-based solvents: an emerging generation of fluids for the design of eco-efficient processes in catalysis and organic chemistry, *Chem. Soc. Rev.* 42 (2013) 9550–9570, <https://doi.org/10.1039/C3CS60241A>.
- [23] J.H. Clark, T.J. Farmer, A.J. Hunt, J. Sherwood, Opportunities for Bio-Based Solvents Created as Petrochemical and Fuel Products Transition towards Renewable Resources, *Int. J. Mol. Sci.* 16 (2015) 17101–17159, <https://doi.org/10.3390/IJMS160817101>.
- [24] I.T. Horváth, H. Mehdi, V. Fábos, L. Boda, L.T. Mika, γ -Valerolactone—a sustainable liquid for energy and carbon-based chemicals, *Green Chem.* 10 (2008) 238–242, <https://doi.org/10.1039/B712863K>.
- [25] J.H. Clark, D.J. Macquarrie, J. Sherwood, A quantitative comparison between conventional and bio-derived solvents from citrus waste in esterification and amidation kinetic studies, *Green Chem.* 14 (2012) 90–93, <https://doi.org/10.1039/C1GC16299C>.
- [26] P. Tundo, F. Aricó, G. Gauthier, L. Rossi, A.E. Rosamilia, H.S. Bevinakatti, R. L. Sievert, C.P. Newman, Green Synthesis of Dimethyl Isosorbide, *ChemSusChem.* 3 (2010) 566–570, <https://doi.org/10.1002/CSSC.201000011>.
- [27] J. Sherwood, M. De Bruyn, A. Constantinou, L. Moity, C.R. McElroy, T.J. Farmer, T. Duncan, W. Raverty, A.J. Hunt, J.H. Clark, Dihydrolevoglucosenone (Cyrene) as a bio-based alternative for dipolar aprotic solvents, *Chem. Commun.* 50 (68) (2014) 9650–9652, <https://doi.org/10.1039/C4CC04133J>.
- [28] J.E. Camp, Bio-available Solvent Cyrene: Synthesis, Derivatization, and Applications, *ChemSusChem.* 11 (2018) 3048–3055, <https://doi.org/10.1002/CSSC.201801420>.
- [29] A.O. Komarova, G.R. Dick, J.S. Luterbacher, Diformylxylose as a new polar aprotic solvent produced from renewable biomass, *Green Chem.* 23 (2021) 4790–4799, <https://doi.org/10.1039/D1GC00641J>.
- [30] A. Randová, L. Bartovská, P. Morávek, P. Matějka, M. Novotná, S. Matějková, E. Drioli, A. Figoli, M. Lanč, K. Friess, A fundamental study of the physicochemical properties of Rhodiasolv®PolarClean: A promising alternative to common and hazardous solvents, *J. Mol. Liq.* 224 (2016) 1163–1171, <https://doi.org/10.1016/J.MOLLIQ.2016.10.085>.
- [31] L. Cseri, G. Szekeley, Towards cleaner PolarClean: efficient synthesis and extended applications of the polar aprotic solvent methyl 5-(dimethylamino)-2-methyl-5-oxopentanoate, *Green Chem.* 21 (2019) 4178–4188, <https://doi.org/10.1039/C9GC01958H>.
- [32] K. Pan, Y. Fan, T. Leng, J. Li, Z. Xin, J. Zhang, L. Hao, J. Gallop, K.S. Novoselov, Z. Hu, Sustainable production of highly conductive multilayer graphene ink for wireless connectivity and IoT applications, *Nat. Commun.* 2018 91. 9 (2018) 1–10, <https://doi.org/10.1038/s41467-018-07632-w>.
- [33] K.L. Wilson, J. Murray, C. Jamieson, A.J.B. Watson, Cyrene as a bio-based solvent for HATU mediated amide coupling, *Org. Biomol. Chem.* 16 (2018) 2851–2854, <https://doi.org/10.1039/C8OB00653A>.
- [34] K. Wilson, J. Murray, C. Jamieson, A. Watson, Cyrene as a Bio-Based Solvent for the Suzuki-Miyaura Cross-Coupling, *Synlett.* 29 (05) (2018) 650–654, <https://doi.org/10.1055/s-0036-1589143>.
- [35] J.E. Camp, S.B. Nyamini, F.J. Scott, Cyrene™ is a green alternative to DMSO as a solvent for antibacterial drug discovery against ESKAPE pathogens, *RSC Med. Chem.* 11 (2020) 111–117, <https://doi.org/10.1039/C9MD00341J>.
- [36] P.F. Schuda, W.A. Price, Total Synthesis of Isoflavones: Jamaicin, Calopogonium Isoflavone-B, Pseudobaptigenin, and Maxima Substance-B. Friedel-Crafts Acylation Reactions with Acid-Sensitive Substrates, *J. Org. Chem.* 52 (1987) 1972–1979, <https://doi.org/10.1021/JO00386A014>.
- [37] B. Vakulya, S. Varga, A. Csámpai, T. Soós, Highly enantioselective conjugate addition of nitromethane to aldehydes using bifunctional cinchona organocatalysts, *Org. Lett.* 7 (2005) 1967–1969, <https://doi.org/10.1021/ol050431s>.
- [38] G. Zhang, C. Zhu, D. Liu, J. Pan, J. Zhang, D. Hu, B. Song, Solvent-free enantioselective conjugate addition and bioactivities of nitromethane to Chalcone containing pyridine, *Tetrahedron.* 73 (2017) 129–136, <https://doi.org/10.1016/J.TET.2016.11.063>.
- [39] C. Didaskalou, J. Kupai, L. Cseri, J. Barabas, E. Vass, T. Holtz, G. Szekeley, Membrane-Grafted Asymmetric Organocatalyst for an Integrated Synthesis-Separation Platform, *ACS Catal.* 8 (2018) 7430–7438, <https://doi.org/10.1021/acscatal.8b01706>.
- [40] G. Fiorani, A. Perosa, M. Selva, Dimethyl carbonate: a versatile reagent for a sustainable valorization of renewables, *Green Chem.* 20 (2018) 288–322, <https://doi.org/10.1039/C7GC02118F>.
- [41] Y. Ono, Catalysis in the production and reactions of dimethyl carbonate, an environmentally benign building block, *Appl. Catal. A Gen.* 155 (1997) 133–166, [https://doi.org/10.1016/S0926-860X\(96\)00402-4](https://doi.org/10.1016/S0926-860X(96)00402-4).
- [42] P. Tundo, M. Selva, The Chemistry of Dimethyl Carbonate, *Acc. Chem. Res.* 35 (2002) 706–716, <https://doi.org/10.1021/AR010076F>.
- [43] P.H. Vendramini, L.A. Zeoly, R.A. Cormanich, M. Buehl, M.N. Eberlin, B.R. V. Ferreira, Unveiling the mechanism of N-methylation of indole with dimethylcarbonate using either DABCO or DBU as catalyst, *J. Mass Spectrom.* 56 (2021) e4707, <https://doi.org/10.1002/JMS.4707>.
- [44] A. Ben Taleb, G. Jenner, Scope of the N-alkylation of amides and the C-alkylation of malonates by methyl formate and dimethyl carbonate, *J. Mol. Catal.* 84 (1993) L131–L136, [https://doi.org/10.1016/0304-5102\(93\)85044-T](https://doi.org/10.1016/0304-5102(93)85044-T).
- [45] S. Ouk, S. Thiebaud, E. Borredon, P. Legars, L. Lecomte, O-Methylation of phenolic compounds with dimethyl carbonate under solid/liquid phase transfer system, *Tetrahedron Lett.* 43 (2002) 2661–2663, [https://doi.org/10.1016/S0040-4039\(02\)00201-0](https://doi.org/10.1016/S0040-4039(02)00201-0).
- [46] L.S. Zhen, Z.J. Xuan, M.M. Wei, X.H. Bao, N. Sun, Catalytic O-methylation of phenols with dimethyl carbonate to aryl methyl ethers using [BMIm]Cl, *Green Chem.* 7 (2005) 97–99, <https://doi.org/10.1039/B411201F>.
- [47] W.C. Shieh, M. Lozanov, M. Loo, O. Repić, T.J. Blacklock, DABCO- and DBU-accelerated green chemistry for N-, O-, and S-benzylation with dibenzyl carbonate, *Tetrahedron Lett.* 44 (2003) 4563–4565, [https://doi.org/10.1016/S0040-4039\(03\)00992-4](https://doi.org/10.1016/S0040-4039(03)00992-4).
- [48] W.C. Shieh, S. Dell, O. Repić, 1,8-Diazabicyclo[5.4.0]undec-7-ene (DBU) and microwave-accelerated green chemistry in methylation of phenols, indoles, and benzimidazoles with dimethyl carbonate, *Org. Lett.* 3 (2001) 4279–4281, <https://doi.org/10.1021/OL016949N>.
- [49] Y. Makino, S. Uchiyama, K.I. Ohno, H. Arakawa, Low-cost fluorimetric determination of radicals based on fluorogenic dimerization of the natural phenol sesamol, *Anal. Chem.* 82 (2010) 1213–1220, <https://doi.org/10.1021/AC9029778>.
- [50] K. Kikugawa, M. Arai, T. Kurechi, Participation of sesamol in stability of sesame oil, *J. Am. Oil Chem. Soc.* 60 (1983) 1528–1533, <https://doi.org/10.1007/BF02666577>.
- [51] L. Cseri, S. Kumar, P. Palchuber, G. Szekeley, NMR Chemical Shifts of Emerging Green Solvents, Acids, and Bases for Facile Trace Impurity Analysis, *ACS Sustainable Chem. Eng.* 11 (14) (2023) 5696–5725, <https://doi.org/10.1021/acscuschemeng.3c00244>.
- [52] N. Miyaura, K. Yamada, A. Suzuki, A new stereospecific cross-coupling by the palladium-catalyzed reaction of 1-alkenylboranes with 1-alkenyl or 1-alkynyl halides, *Tetrahedron Lett.* 20 (1979) 3437–3440, [https://doi.org/10.1016/S0040-4039\(01\)95429-2](https://doi.org/10.1016/S0040-4039(01)95429-2).
- [53] S.E. Hooshmand, B. Heidari, R. Sedghi, R.S. Varma, Recent advances in the Suzuki-Miyaura cross-coupling reaction using efficient catalysts in eco-friendly media, *Green Chem.* 21 (2019) 381–405, <https://doi.org/10.1039/C8GC02860E>.
- [54] D. Castelvécchi, E. Stoye, ‘Elegant’ catalysts that tell left from right scoop chemistry Nobel, *Nature.* 598 (2021) 247–248, <https://doi.org/10.1038/D41586-021-02704-2>.
- [55] S.J. Connon, Asymmetric catalysis with bifunctional cinchona alkaloid-based urea and thiourea organocatalysts, *Chem. Commun.* (2008) 2499–2510, <https://doi.org/10.1039/B719249E>.
- [56] Y. Hayashi, Pot economy and one-pot synthesis, *Chem. Sci.* 7 (2016) 866–880, <https://doi.org/10.1039/c5sc02913a>.
- [57] T. Erdmenger, C. Guerrero-Sanchez, J. Vitz, R. Hoogenboom, U.S. Schubert, Recent developments in the utilization of green solvents in polymer chemistry, *Chem. Soc. Rev.* 39 (2010) 3317–3333, <https://doi.org/10.1039/B909964F>.
- [58] T. Marino, F. Galiano, A. Molino, A. Figoli, New frontiers in sustainable membrane preparation: Cyrene™ as green bioderived solvent, *J. Memb. Sci.* 580 (2019) 224–234, <https://doi.org/10.1016/J.MEMSCI.2019.03.034>.
- [59] V.A. Pereira, P.V. Mendonca, J.F.J. Coelho, A.C. Serra, Liquid salts as eco-friendly solvents for atom transfer radical polymerization: a review, *Polym. Chem.* 10 (2019) 4904–4913, <https://doi.org/10.1039/C9PY00865A>.
- [60] S. Fadlallah, A.A.M. Peru, L. Longé, F. Allais, Chemo-enzymatic synthesis of a levoglucosenone-derived bi-functional monomer and its ring-opening metathesis polymerization in the green solvent Cyrene™, *Polym. Chem.* 11 (2020) 7471–7475, <https://doi.org/10.1039/D0PY01471K>.
- [61] M. Ramírez-Martínez, S.L. Aristizábal, G. Szekeley, S.P. Nunes, Bio-based solvents for polyolefin dissolution and membrane fabrication: from plastic waste to value-added materials, *Green Chem.* 25 (3) (2023) 966–977, <https://doi.org/10.1039/D2GC03181G>.
- [62] D. Kim, S.P. Nunes, Green solvents for membrane manufacture: Recent trends and perspectives, *Curr. Opin. Green Sustain. Chem.* 28 (2021), 100427, <https://doi.org/10.1016/J.COCS.2020.100427>.
- [63] E. Barnard, J.J. Rubio Arias, W. Thielemans, Chemolytic depolymerisation of PET: a review, *Green Chem.* 23 (2021) 3765–3789, <https://doi.org/10.1039/D1GC00887K>.
- [64] L. Rosi, M. Bartoli, A. Undri, M. Frediani, P. Frediani, Synthesis of dianols or BPA through catalytic hydrolysis/glycolysis of waste polycarbonates using a

- microwave heating, *J. Mol. Catal. A Chem.* 408 (2015) 278–286, <https://doi.org/10.1016/J.MOLCATA.2015.07.027>.
- [65] F.S. Liu, Z. Li, S.T. Yu, X. Cui, C.X. Xie, X.P. Ge, Methanolysis and hydrolysis of polycarbonate under moderate conditions, *J. Polym. Environ.* 17 (2009) 208–211, <https://doi.org/10.1007/s10924-009-0140-0>.
- [66] C.S. Bhogle, A.B. Pandit, Ultrasound assisted methanolysis of polycarbonate at room temperature, *Ultrason. Sonochem.* 58 (2019), 104667, <https://doi.org/10.1016/J.ULTSONCH.2019.104667>.
- [67] A. Căta, M.N. Ștefănuț, I.M.C. Ienașcu, C. Tănăsie, M. Miclău, ALKALINE HYDROLYSIS OF POLYETHYLENE TEREPHTHALATE UNDER MICROWAVE IRRADIATION, accessed February 19, 2023, *Rev. Roum. Chim.* 62 (2017) 531–538, <http://web.icf.ro/rrch/>.
- [68] M. Yamashita, H. Mukai, Alkaline Hydrolysis of Polyethylene Terephthalate at Lower Reaction Temperature, *Sci. Eng. Rev. Doshisha Univ.* 52 (2011) 143–148.
- [69] N.R. Paliwal, A.K. Mungray, Ultrasound assisted alkaline hydrolysis of poly (ethylene terephthalate) in presence of phase transfer catalyst, *Polym. Degrad. Stab.* 98 (2013) 2094–2101, <https://doi.org/10.1016/J.POLYMDEGRADSTAB.2013.06.030>.