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Dedicated to Professor Vittorio Mortarini on the occasion of his 70th Birthday

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Abstract

The massive increase in glycerol production from the transesterification of vegetable oils has stimulated a large effort to find novel uses for this compound. Hence, the use of glycerol as a solvent for organic synthesis has drawn particular interest. Drawbacks of this green and renewable solvent are a low solubility of highly hydrophobic molecules and a high viscosity, which often requires the use of a fluidifying co-solvent. These limitations can be easily overcome by performing reactions under high-intensity ultrasound and microwaves in a standalone or combined manner. These non-conventional techniques facilitate and widen the use of glycerol as a solvent in organic synthesis. Glycerol allows excellent acoustic cavitation even at high temperatures (70-100 °C), which is otherwise negligible in water. Herein, we describe three different types of applications: 1) the catalytic transfer hydrogenation of benzaldehyde to benzyl alcohol in which glycerol plays the dual role of the solvent and hydrogen donor ; 2) the palladium-catalyzed Suzuki cross-coupling; and (3) the Barbier reaction. In all cases glycerol proved to be a greener, less expensive, and safer alter- native to the classic volatile organic solvents.

Introduction

The need for clean processes, in which energy and waste are minimized and costs are reduced, is of general concern. To reach this goal in organic synthesis, the use of sustainable re- action media, for example, an environmentally friendly solvent with suitable chemico-physical and biological properties that allows for reactants and catalysts to be dissolved, reactions to be worked-up, and catalysts to be recycled easily, is a crucial feature.[1–3]

Glycerol is a non-toxic, non-hazardous, non-volatile, biodegradable, and recyclable liquid that is produced as a byproduct of the transesterification of oil from renewable sources. It has recently gained increased attention as an alternative sustainable solvent for catalytic and non-catalytic organic transformations.[4–9] Although its use as a solvent goes back to the middle of the last century,[10] it has only recently been found that glycerol can dissolve many organic and inorganic compounds, including transition-metal complexes. It also allows products to be easily separated by extraction with glycerol-immiscible solvents, such as ethers, esters,[4–8] and supercritical carbon dioxide.[9] Moreover, employing glycerol as a solvent has often resulted in improved product yields and selectivity.[7, 8] Glycerol can also be reused and enables transition-metal complexes to be recycled in a simple way.[4, 5] In the catalytic transfer hydrogenation of various unsaturated organic compounds[11] and in the transesterification of alcohols[12], glycerol was simultaneously used as a solvent and reactant. Owing to its very low toxicity, glycerol can also be a suitable solvent in the synthesis of active pharmaceutical ingredients, in which the level of solvent residue is strictly controlled.

Although glycerol exhibits promising features as a sustainable solvent for liquid-phase catalytic and non-catalytic organic syntheses, its use has several drawbacks, including a high viscosity and a low solubility of highly hydrophobic compounds and gases, such as hydrogen and oxygen. These factors limit its mass transport capabilities. These limitations can be overcome by using high-intensity ultrasound (US)[13, 14] and microwaves (MW) in a stand-alone[15] or combined manner,[16, 17] to enhance momentum, heat, and mass transfer and hence to accelerate reaction rates. In recent years both techniques have emerged as new and irreplaceable tools in organic synthesis.[18, 19] Although dielectric heating and sonication save energy, they strongly accelerate chemical transformations and often improve selectivity and strongly reduce the amount of catalyst required.[20] Preliminary results from the MW-promoted Wolff–Kishner reduction of

benzaldehyde to toluene[21] and C C coupling reactions (Heck and Suzuki) in glycerol[5] were reported.

So far, we have not been able to find comprehensive studies of organic reactions in glycerol under US and/or MW in literature. In the present work, both US and MW irradiation, standalone or combined techniques, were employed for the first time for organic transformations in glycerol. Three representative reactions have been investigated, including selective transfer hydrogenation and metal-catalyzed C C couplings.

Results and Discussion

The aim of this work was to demonstrate that glycerol can be successfully used as a solvent of choice in several types of organic reactions and that the use of non-conventional techniques, such as US and MW, may solve problems of solubility and high viscosity by enhancing heat and mass transfer.

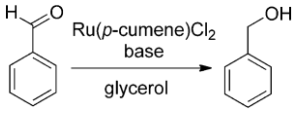
An important application of glycerol is in the transfer hydrogenation reaction, a reaction that is usually performed by using a hydrogen donor, which can also fulfill the role of the solvent.[22–25] The most commonly used hydrogen sources are simple alcohols, such as 2-propanol.[26, 27] As mentioned above, glycerol can be used both as a solvent and a hydrogen donor in the catalytic transfer hydrogenation of various unsaturated organic molecules.[11, 28] Various catalysts, such as Raney-Ni or Ru and Rh complexes, have been tested,[29, 30] and a few MW-assisted reactions have been reported.[31] In this study, we exploited the dual effect of glycerol in the MW- and US-promoted transfer hydrogenation of benzaldehyde, which was catalyzed by using a Ru(p-cumene)Cl_2 dimer under varying reaction temperatures, base concentrations, and irradiation power values.

We also focused our attention on metal-catalyzed C C coupling reactions in which glycerol also proved itself to be a suitable solvent. Suzuki couplings have long been the subject of intensive work in the area of transition-metal synthesis (reaction conditions, media, and techniques). These transformations have been performed in several green media such as water, ethanol, polyethylene glycol, supercritical carbon dioxide, ionic liquids, and in the absence of a solvent.[32] Few promising results have been obtained in glycerol.[5] Several papers have reported on the palladium-catalyzed Suzuki couplings carried out under MW and US irradiation,[33] even in a combined fashion,[34] with several advantages. Glycerol dissolved organic substrates, inorganic bases, and palladium complexes as a polar organic solvent, and allowed for the reaction product

to be easily isolated through a simple extraction process using glycerol-immiscible solvents, such as diethyl ether, and also permitted catalyst recycling.

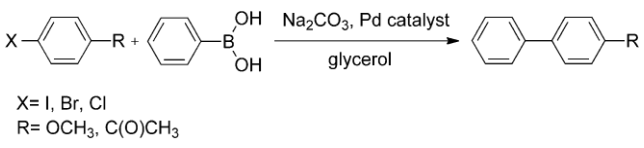
Barbier-type reactions, historically performed in anhydrous solvents, have been widely studied in aqueous media using tin, zinc, indium, and other metals.[35] On the basis of our previous experience with sonochemical Barbier reactions,[36, 37] we tested this reaction in glycerol. Experiments were carried out in triplicate and in duplicate for a few cases (conventional conditions). As with the transfer hydrogenation of benzaldehyde (Scheme 1, Table 1), a first set of experiments was performed in an oil bath (OB). Surprisingly, yields were negligible if only KOH or NaOH were used (entries 1 and 2) and could be improved by combining the two bases (entry 3). Under sonochemical conditions, base dispersion in glycerol was optimal (entries 4-7) resulting in a shorter reaction time.

The crucial role of sonication was shown in the transfer hydrogenation of benzaldehyde, in which short pre-sonication yielded similar benzyl alcohol yields in half the reaction time (entry 4) as compared to the conventional method. Even the combined US/MW irradiation by means of a pyrex horn (entry 7) could not compete with the US irradiation (titanium horn) in a thermostated oil bath (US/OB) with 100 % yield after 3 h (entry 6 c).



Scheme 1. Benzaldehyde transfer hydrogenation reaction

We studied a series of metal-catalyzed C C couplings in glycerol, including the Suzuki reaction (Scheme 2). We compared conductive heating in an oil bath (OB), MW irradiation (MW), US horn irradiation combined with conductive heating in a thermostated oil bath (US/OB), and simultaneous US/MW irradiation (US/MW) (Table 2).The coupling between 4-iodoanisole and phenylboronic acid using ligand-free palladium salts or palladium on charcoal was used as a model reaction.



Scheme 2. Suzuki cross-coupling reaction in glycerol.

Preliminary sonochemical trials performed at room temperature using a probe system with a titanium horn gave poor yields. For this reason, all the reactions were performed at 80 °C. This is one of the great advantages of glycerol; it allows excellent acoustic cavitation even at high temperatures. We observed that in all cases palladium chloride and palladium acetate were more efficient than palladium on charcoal (Table 2). US/OB, MW, and simultaneous US/MW irradiation strongly improved the reaction rate. The latter (entry 5) and the US/OB method (entry 2) gave the best results due to enhanced heat and mass transfer.

The conditions and yields of reactions using bromo- and chloroarenes in glycerol and ligand-free catalysts are reported in Table 3. In addition to classical palladium salts, we used a palladium-loaded cross-linked chitosan,[38] which gave the best results using both 3-bromoanisole and 4-Cl-acetophenone (entries 15 and 20, respectively). This polymeric catalyst was also used during conventional heating (OB) in the case of 3-bro- moanisole ; however, the reaction yield was close to 80 % after 12 h stirring at 80 °C. The weight content of Pd^{II} in cross-linked chitosan, analyzed by using inductively coupled plasma mass spectrometry (ICP-MS), was 0.39 %. No advantages were observed at higher MW power and temperature values in closed vessels under pressure (entry 9). Lower yields were observed with 4-chloroacetophenone (entries 16–20), although US, MW- UP, and US/MW irradiation markedly increased the yield.

Table 3. Suzuki cross-coupling using different substrates

Entry	Substrate	Catalyst	Method[a]	t[min]	T[°C]	Yield [%]
1	4-Br-anisole	$PdCl_2$	OB[b]	60	80	36
2	4-Br-anisole	$PdCl_2$	US/OB	60	80	75
3	4-Br-anisole	$PdCl_2$	MW	30	80	70
4	4-Br-anisole	$PdCl_2$	US/MW	30	80	73
5	4-Br-anisole	$Pd(OAc)_2$	OB	60	80	71
6	4-Br-anisole	$Pd(OAc)_2$	US/OB	60	80	89
7	4-Br-anisole	$Pd(OAc)_2$	MW	30	90	78
8	4-Br-anisole	$Pd(OAc)_2$	US/MW	60	90	83
9	4-Br-anisole	$Pd(OAc)_2$	MW/UP[c]	30	140	79
10	3-Br-anisole	$PdCl_2$	OB	60	80	62
11	3-Br-anisole	$PdCl_2$	US/OB	60	80	77
12	3-Br-anisole	$PdCl_2$	MW	30	80	69
13	3-Br-anisole	$Pd(OAc)_2$	MW	30	80	78
14	3-Br-anisole	Pd/C	US/MW	30	80	64
15	3-Br-anisole	Supp-Pd[d]	US/MW	60	80	86
16	4-Cl-acet.[e]	$Pd(OAc)_2$	OB	60	90	10
17	4-Cl-acet.	$Pd(OAc)_2$	US/OB	60	90	38

18	4-Cl-acet.	$Pd(OAc)_2$	MW/UP	60	140	41
19	4-Cl-acet.	$Pd(OAc)_2$	US/MW	60	90	48
20	4-Cl-acet.	Supp-Pd[d]	US/MW	60	90	61

[a] Reaction conditions: see Table 2. [b] OB=oil bath. [c] MW/UP=MW under pressure (closed vessel). [d] Supp-Pd=palladium-cross-linked chitosan. [e] 4-Cl-acet.=4-Cl-acetophenone.

Another striking example of a reaction in glycerol is the Barbier reaction, which was first studied by using benzaldehyde as a substrate (Scheme 3). We compared the classical solvent system THF/NH_4Cl with glycerol/NH_4Cl (Table 4). The effect of a US cleaning bath on the reaction rate was negligible, whereas using a US horn at room temperature yielded 80 % alcohol in only 15 min, and 100 % conversion after 1 hour without byproduct formation (entries 4–6).

Scheme 3. Barbier reaction in Glycerol

Table 4. Barbier reaction using benzaldehyde and propargyl bromide.[a]

Entry	Solvent	Method	T [°C]	t [min]	Yield [%]	Byproduct [%]
1	THF/NH_4Cl	st.	RT	90	81	3
2	THF/NH_4Cl	st.	40	90	72	10
3	Glyc/NH_4Cl	st.	RT	90	80	12
4	Glyc/NH_4Cl	US[b]	RT	15	80	–
5	Glyc/NH_4Cl	US[b]	RT	30	89	–
6	Glyc/NH_4Cl	US[b]	RT	60	100	–

[a] Reaction conditions : benzaldehyde (1 mmol), propargyl bromide (2 mmol), zinc powder (2 mmol). [b] Titanium US horn

A set of different aldehydes and halides was also tested in glycerol/NH_4Cl at room temperature under magnetic stirring in US using a cleaning bath or a US horn at 40 °C (Table 5). No re- action occurred with 5-chloropent-1-yne, whereas 3-bromopropene reacted very quickly with benzaldehyde (entries 1 and 2, respectively).

Table 5. Barbier reaction using different substrates.[a]

Entry	Method	Aldehyde	Halide	Yield [%]
1[b]	OB	benzaldehyde	5-chloropentyne	–
2[b]	OB	benzaldehyde	3-bromopropene	70
3[b]	OB	(E)-3-(4-(Me_2-phenyl)acrylaldehyde	3-bromopropene	5

4[b]	OB	ethyl vanillin	3-bromopropene	77
5[b]	OB	4-methoxybenzaldehyde	3-bromopropene	99
6[c]	US/OB	4-methoxybenzaldehyde	3-bromopropene	99
7[c]	US/OB	4-methoxybenzaldehyde	propargyl bromide	19
8[c]	US/OB	2,4-dimethoxybenzaldehyde	3-bromopropene	91
9[c]	US/OB	benzaldehyde	3-bromopropene	99

[a] Reaction conditions : aldehyde (1 mmol), halide (2 mmol), zinc powder (2 mmol), 40 8C. [b] Time reaction :90 min. [c] Time reaction : 30 min

Thus, 3-bromopropene was also reacted with a series of dif- ferent aldehydes, giving high yields in all reactions (entries 3–6). The reaction with propargyl bromide generated a byprod- uct (entry 7). Byproducts were also detected when 3-bromo-propene was employed together with 2,4-dimethoxybenzaldehyde (entry 8). It was demonstrated that the Barbier reaction in glycerol under high-intensity US (horn) is extremely efficient and fast.

Conclusions

Glycerol proved to be a very attractive, non-volatile, polar sol- vent for several organic reactions under heterogeneous catalysis. We have observed a mutual advantage working under MW- or US-irradiation. Glycerol was successfully employed both as a solvent and as a hydrogen donor in the transfer hy- drogenation of benzaldehyde, and US dramatically increased the reaction yields. Improved dispersion of a base in glycerol was obtained with efficient presonication, reducing reaction times even when the reaction was performed in an oil bath or MW oven Enhanced reaction rates were detected for the palladium- catalyzed Suzuki cross-coupling reactions in glycerol in the order MW/US > US > MW. Both US- and MW-irradiation greatly improved the reaction of halobenzenes, such as chloroaceto- phenone, which are poorly reactive toward C C coupling. Out- standing catalytic activity was achieved using a solid ligand-free catalyst, a palladium-loaded cross-linked chitosan. Good yields were also obtained in the Barbier reaction, proving that the use of glycerol as a solvent maintains the conversion yield in the same range as other organic solvents, while enabling a greener procedure and easier work up of the products through a simple extraction process using ethyl acetate.

We believe that using glycerol as a solvent for organic trans- formations not only improves reaction performance in terms of yields and costs, but also offers an attractive way to conduct

green and sustainable processes. Applications of glycerol in other organic reactions are ongoing in our laboratory

Experimental Section

Materials

All reagents were obtained from commercial sources and used without further purification. Reactions were monitored by using thin layer chromatography (TLC) carried out on precoated, glass- backed plates (thickness 0.25 mm, Merck 60 F254), which were vi- sualized by UV inspection and/or by heating after being sprayed with H_2SO_4 (5 %) in ethanol. Gas chromatography–mass spectroscopy (GC–MS) analyses were carried out by using an Agilent 6890 gas chromatograph (Agilent Technologies-USA) fitted with an Agilent Network 5973 mass detector. Sonochemical reactions were performed in commercially available probe systems equipped either with an immersion horn or a cavitating tube, both made from titanium (Danacamerini, Italy). The working frequency was 19.5–19.6 kHz and the power 30–45 W. MW-promoted reactions were carried out in a professional oven (Microsynth-Milestone, Italy); this oven was also used for combined MW/US irradiation after a probe equipped with a pyrex horn was inserted. The palladium content in solution was determined by using inductively coupled plasma mass spectroscopy (ICP-MS) performed by using a Quadrupole-ICP-MS X Series II (Thermo Fisher Scientific) after digestion in HNO_3.

Methods

Benzaldehyde transfer hydrogenation: In a typical procedure, benzaldehyde (1 mmol), a base (0.01–0.02 mmol), and Ru(*p*-cumene)Cl_2 dimer (0.01 mmol) were added to glycerol (21 mmol, 2 g). In some procedures (Table 1), the mixture was pre-sonicated by using a US cup-horn (100 W; 19.0 kHz) for 15 min. For reactions under conventional heating, the mixture was placed in a preheated oil bath at 70 °C and magnetically stirred for 24 h. For MW-assisted reactions, the mixture was irradiated at a fixed temperature (70 °C) in a MW oven (maximum power 40–45 W) for 2 h. For US-assisted reactions, the mixture was heated to 60 °C in an oil bath and sonicated by using a titanium horn (30 W) for up to 4 h. The reaction mixture was then cooled down to room temperature, the product was extracted by using ethyl acetate and dried under vacuum. Product conversions were determined by using GC–MS.

Suzuki cross-coupling reaction: In a typical procedure, 4-iodoanisole (1 mmol), phenylboronic acid (1.2 mmol), Na_2CO_3 (1.2 mmol), and either the palladium salt (0.02 mmol) or the corresponding amount of solid catalysts (5 % Pd/C or palladium-cross-linked chitosan)

were added to a flask with glycerol (21 mmol, 2 g). For reactions under conventional heating, the mixture was placed in a pre- heated oil bath at 80 °C and magnetically stirred for 60 min under N2. For MW-assisted reactions, the mixture was irradiated at a fixed temperature (80 °C) in a MW-reactor (max power 40–45 W) under a nitrogen atmosphere. For US-assisted reactions, the mixture was heated to 80 °C in an oil bath and sonicated under nitrogen by using a titanium horn (30 W) for 60 min. The simultaneous US/MW irradiation experiments were performed in glycerol (109 mmol,10 g), irradiated in a MW oven, and sonicated by using a pyrex horn under N2 at a fixed temperature (80 °C) for 60 min. The reac- tion mixture was then cooled down to room temperature, the product was extracted with diethyl ether, filtered on a Hirsh funnel (paper filter) and dried under vacuum. Product conversions were determined by using GC–MS.

Barbier reaction: In a typical procedure, aldehyde (1 mmol), allyl (or propargyl) halide (2 mmol), and zinc powder (2 mmol) were added to a mixture of a saturated aqueous ammonium chloride solution which was added to an equal amount of glycerol or alternatively THF. The mixture was stirred for 90 min at room temperature or stirred in an oil bath at 40 °C. For US-assisted reactions the mixture was sonicated in a US bath for 90 min or sonicated by using a titanium horn (60 W) for 30 min. The reaction mixture was then cooled down to room temperature and the product was extracted by using ethyl acetate and dried under vacuum. Product conversions were determined by using GC–MS.

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