# Transfer hydrogenation of a carbonyl compound in glycerol-based solvent mixtures

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**Abstract:** Three representative carbonyl compounds were efficiently hydrogenated in a glycerol-triacetin or glycerol-tributyrin mixture. The addition of triacetin to glycerol favorably altered the polarity of the reaction mixture, thereby increasing the solubility of reactants and, in turn, reactant conversion rates. Maximum conversion was detected in a glycerol-triacetin mixture (80:20) in the presence of a Ru(p-cymene)Cl$_2$-dimer catalyst.

## 1. Introduction

Most organic transformations are performed in a solvent that aids in bringing the reactants and catalysts together by dissolving them in solution and that delivers the heat and momentum needed for the reaction to proceed. The nature of the solvent and its characteristics determine the reaction performance in terms of conversion and selectivity and the efficiency of the overall process, e.g., final product yield after reaction work-up.[1,2] Hence, the solvent has to be tailored with respect to each reaction requirement. In addition, the use of a solvent also increases the E-factor of the process, which is defined as the mass ratio of waste to desired product.[3] Yet the use of a solvent may also have unwanted environmental effects, as it can be emitted to the air or it can contaminate the ground and/or water sources.

The goal in recent years to obtain maximum reaction efficiency while minimizing the effects of the reaction on the natural and social environments has driven a considerable increase in the use of green solvents that, by definition, have negligible to no influences on the environment.[4-6] The main characteristics of green solvents that contribute to their environmental friendliness are thus their low toxicity, low vapor pressure and high boiling point together with the fact that they are readily removable and recyclable. With these properties in mind, several groups of solvents are accepted as green solvents, including water[7,8], supercritical fluids (especially supercritical CO$_2$)[9,10], ionic liquids[11,12] and flourous solvents.[13] However, besides their direct environmental impact, the solvents used in reactions can also have indirect environmental effects associated with the materials and energy that were consumed and discharged during solvent preparation. From this perspective, bio-degradable solvents produced from renewable sources are preferred. Several other properties of the solvent must also be considered in the quest for maximum reaction efficiency. For example, the choice of reaction solvent also dictates not only whether non-conventional and more efficient heating techniques such as microwave heating can be employed, but also the product separation technique and procedure. In

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addition, solvent choice may also facilitate the catalyst recycling process. Finally, the price of the solvent and its availability are also important considerations. In summary, a solvent that meets all of the above-mentioned requirements is not only a green solvent, it is also termed a sustainable solvent[6].

Recently, we proposed the use of glycerol (Figure 1a) and its derivatives – e.g., propandiols and glycerol triacetate (triacetin, Figure 1b) or glycerol tributyrate (tributyrin, Figure 1c) – as sustainable solvents, and we employed them successfully in a variety of catalytic and non-catalytic organic transformations.[14-16] Although glycerol itself is highly polar and viscous, these disadvantages are overcome, while maintaining the sustainable nature of the solvent, when using glycerol derivatives. Since our pioneering work, many other groups have used glycerol derivatives as solvents and have extolled the advantages of using these solvents over other petroleum-based or green solvents.[17,18] In addition, besides their beneficial physicochemical properties, their reusability, and their ability to tolerate non-conventional heating and mixing techniques[19], glycerol-based solvents are also cheap and readily available because glycerol is produced as a by-product in the production of fatty acid derivatives for fuels, i.e., biodiesel, and for pharmaceuticals and cosmetics. In follow up to our initial work with glycerol and its derivatives, we recently showed that performing organic reactions in various glycerol-triacetin mixtures to tune the polarity of the reaction mixture resulted in increased reactant solubility that, in turn, enhanced product yields.[20]
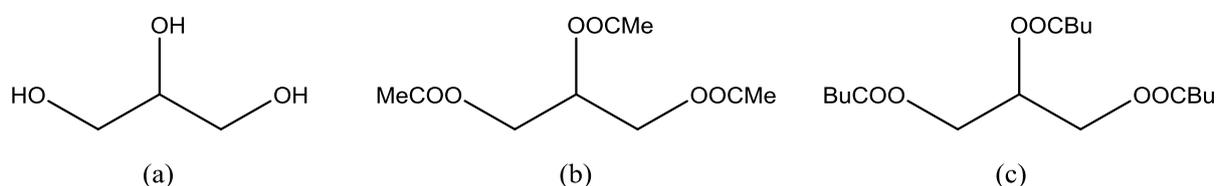


(a)                                         (b)                                         (c)

**Figure 1**. Solvents employed in the study: (a) glycerol, (b) glycerol triacetate-triacetin, (c) glycerol tributyrate-tributyrin

Lastly, it was also shown that besides being a solvent, glycerol can also act simultaneously as the hydrogen donor in the transfer-hydrogenation of unsaturated organic compounds[21-24], yielding dihydroxyacetone, a valuable compound, as a product.[24] In this case, glycerol cannot be replaced by another green solvent that cannot donate hydrogen. Thus, to tailor the properties of the reaction medium and increase catalytic performance, the reaction can be performed in a mixture of glycerol and other glycerol derivatives. Indeed, the maximum yield of octane was obtained by performing the transfer-hydrogenation of 1-octene in a glycerol-triacetin mixture of 70 wt.% glycerol-30 wt.% triacetin.[20]

In the current study, representative carbonyl compounds underwent transfer-hydrogenation (Figure 2) in mixtures of glycerol and triacetin or tributyrin, and the effect on catalytic performance of glycerol content in the reaction mixture was studied.
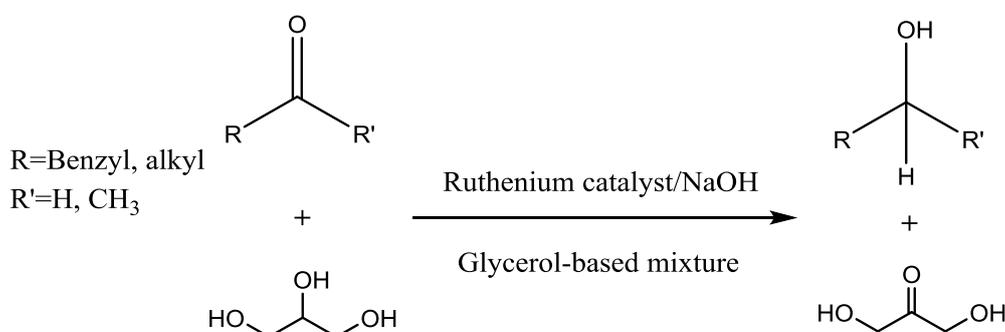


**Figure 2**. Transfer-hydrogenation of carbonyl compounds in glycerol-based mixtures

## 2. Results and discussion

The previously reported catalytic route, in which glycerol is used in the catalytic transfer-hydrogenation of unsaturated organic compounds including carbonyls[21-24], does not require large amounts of metal hydride or special equipment or any of the precautions that are typically taken when molecular hydrogen is used in hydrogenation reactions. It also does not generate large amounts of waste, as the oxidation of glycerol during the reaction yields dihydroxyacetone, a valuable intermediate in the production of many chemicals. However, the use in this reaction of glycerol, whose viscosity and polarity are relatively high, results in a relatively low product yield. It was therefore suggested that the addition of a less polar and less viscous glycerol derivative like triacetin to glycerol will result in better dissolution of the substrate in the reaction mixture and a subsequently higher product yield.[20]

To examine this hypothesis, the transfer-hydrogenation of benzaldehyde as a representative aldehyde (Figure 2) was analyzed in various glycerol-triacetin mixtures. The investigation began by running the reaction with three different ruthenium catalysts: $RuCl_3$, Dichlorotris(triphenylphosphine)ruthenium ($RuCl_3(TPP)_2$) and [Ru(p-cymene)$Cl_2$]$_2$ (ruthenium dimer). The results are presented in Figure 3.

As illustrated in Figure 3, regardless of which ruthenium catalyst was used, the addition of triacetin (Figure 1b) to glycerol indeed affected reaction performance. Also, the ruthenium catalyst used did not affect the maximum conversion to benzyl alcohol, which was obtained using an 80:20 (wt.%) glycerol-triacetin mixture and was double that of the conversion performed in pure glycerol. A possible explanation of the maximum benzaldehyde conversion found for the glycerol-triacetin mixture may be a reduction in the polarity and viscosity of the reaction mixture conferred by the use of triacetin with the glycerol. The putative effects of triacetin on this reaction mixture would, in turn, lead to greater dissolution of the benzaldehyde and better mass, heat and momentum transfer, which together will promote higher rates of conversion. A comparison of the conversions obtained with each of the three catalysts showed a minor effect on reaction performance, such that the conversion of benzaldehyde decreased slightly among the catalysts in the order ruthenium dimer > $RuCl_3(TPP)_2$ > $RuCl_3$. This finding is probably attributed to the addition of ligands to the ruthenium center, which stabilized the catalyst, thereby facilitating its higher activity.
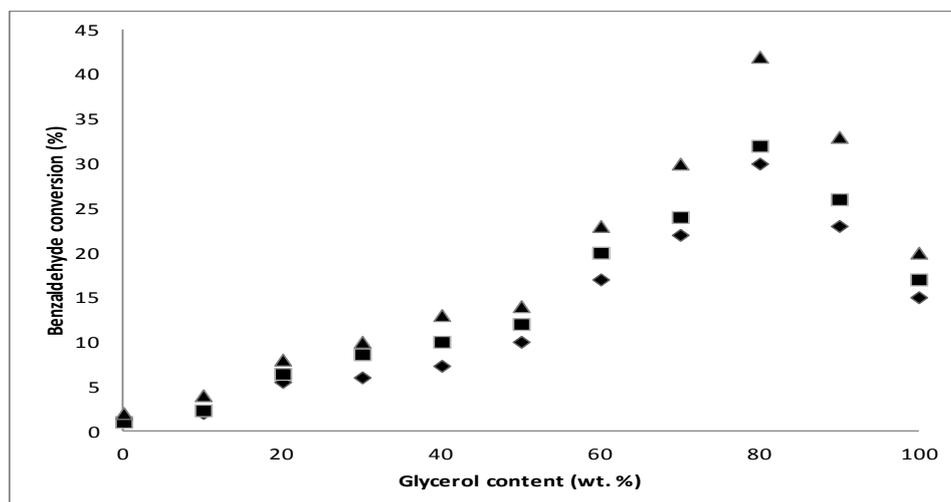


**Figure 3**. Transfer-hydrogenation of benzaldehyde in glycerol-triacetin mixtures. Reaction conditions: 1.88 mmol of benzaldehyde, 0.25 mmol NaOH, 0.188 mmol of ruthenium catalyst, 4.0 g of reaction mixture, 70°C, 5 h. (♦) $RuCl_3$, (■) $RuCl_3(TPP)_2$ and (▲) Ruthenium dimer

In the second stage of the investigation, benzaldehyde was replaced by octanal, as a representative aliphatic aldehyde and 2-octanone as a representative ketone, and the transfer-hydrogenation reactions were performed in glycerol-triacetin mixtures with a ruthenium dimer catalyst

(Figure 4). Maximum conversion was not affected by the type of substrate and was obtained using the 80:20 (wt.%) glycerol-triacetin mixture. As expected, under these conditions, the conversion of benzaldehyde, as an activated aromatic aldehyde, was highest, followed by that of octanal while 2-octanone exhibited the lowest conversion rate.
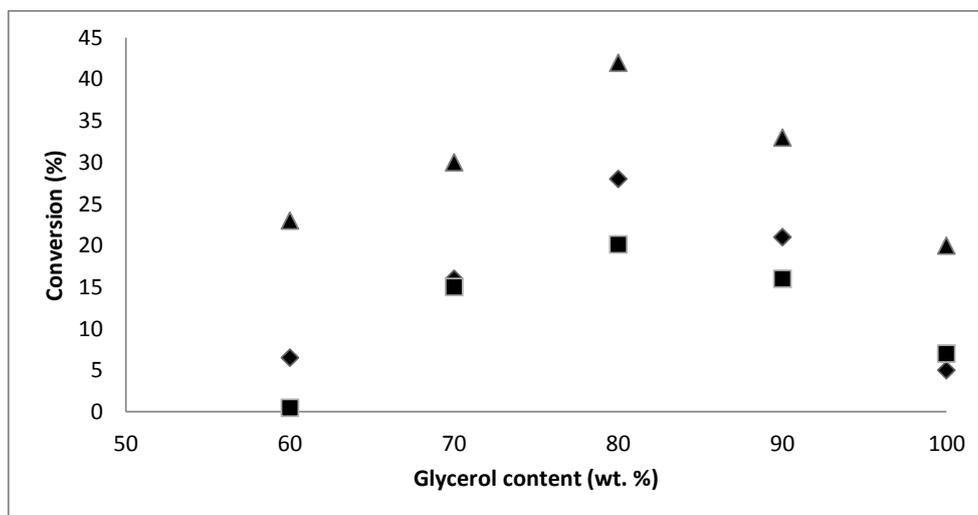


**Figure 4**. Transfer-hydrogenation of representative carbonyl compounds in glycerol-triacetin mixtures. Reaction conditions: 1.88 mmol of carbonyl compound, 0.25 mmol NaOH, 0.188 mmol of ruthenium catalyst, 4.0 g of reaction mixture, 70°C, 5 h. (♦) octanal, (■) 2-octanone and (▲) benzaldehyde
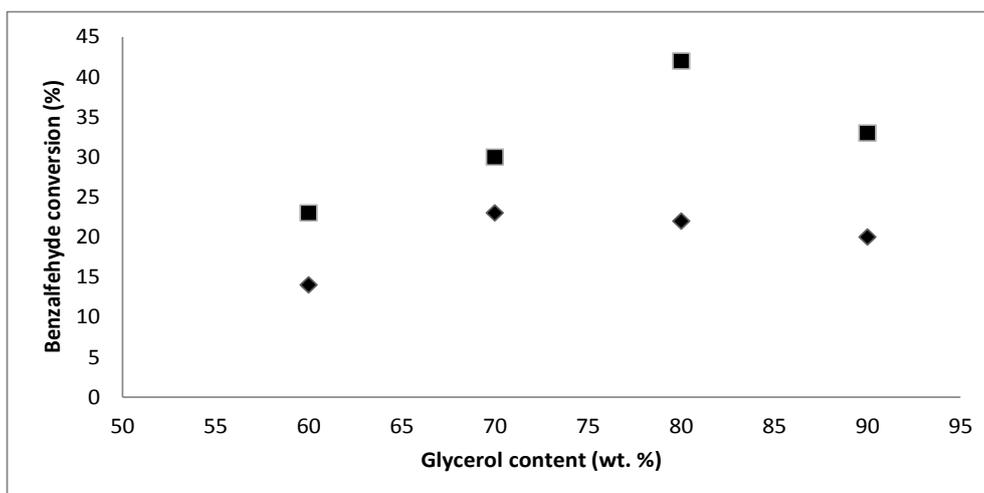


**Figure 5**. Transfer-hydrogenation of benzaldehyde in glycerol-triacetin/tributyrin mixtures. Reaction conditions: 1.88 mmol of benzaldehyde, 0.25 mmol NaOH, 0.188 mmol of ruthenium catalyst, 4.0 g of reaction mixture, 70°C, 5 h. (■) glycerol-triacetin and (♦) glycerol-tributyrin

Finally, the effect of the nature of the added glycerol derivative on benzaldehyde conversion was studied by replacing triacetin (Figure 1b) with tributyrin (Figure 1c) and using the ruthenium dimer as the catalyst (Figure 5). The results show that the addition of tributyrin to glycerol yielded lower conversions compared to the addition of triacetin to glycerol. In addition, the maximum conversion with tributyrin was obtained with the 70:30 (wt.%) glycerol-tributyrin mixture, and it was less sharp than that for triacetin, which was obtained using the 80:20 (wt.%) glycerol-triacetin mixture. The observed shift in the relative amounts of glycerol and glycerol derivative used in the reaction mixture with the highest conversion rate for each glycerol derivative may be attributed to the lower

polarity of tributyrin compared to that of triacetin[25]. In addition, the lower overall conversion obtained with tributyrin compared to that with triacetin may be due to the lower solubility of benzaldehyde in the tributyrin reaction mixture.

## 3. Experimental Section

All chemicals were purchased from Aldrich.

### 3.1. General procedure for the transfer hydrogenation reaction:

In a typical procedure, 1.88 mmol of carbonyl compound, 0.25 mmol (0.01 g) NaOH and 0.188 mmol (10%) ruthenium catalyst were added to a vial with 4.0 g of reaction mixture. The solution was placed in a preheated oil bath and heated to 70°C, after which it was magnetically stirred for 5 h. At the end of the reaction, the reaction mixture was cooled and extracted with 3 x 3 mL of petroleum ether (60-80). Finally, the ether phase was reduced under vacuum, and the mixture was analyzed by GC analysis using an HP-5 column (30 m × 0.25 mm, 0.25 μm thick) with chlorobenzene as an internal standard to determine the reaction conversion rate.

## 4. Conclusions

In conclusion, mixtures of glycerol with its two representative derivatives, triacetin and tributyrin, were employed as green reaction mediums in the transfer-hydrogenation of selected carbonyl compounds. The addition of triacetin to glycerol favorably altered the solvent polarity and, in turn, reactant solubility, thereby leading to higher conversions. The maximum conversion rates were detected in an 80:20 (wt.%) glycerol-triacetin mixture.

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