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Aqueous biphasic hydrogenations catalyzed by rhodium and iridium complexes modified with human serum albumin

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ABSTRACT

Water soluble complexes derived from the interaction between $Rh(CO)_2(acac)$ and $[Ir(COD)Cl]_2$, respectively, with human serum albumin (HSA), were employed in the aqueous biphasic hydrogenation of α,β-unsaturated compounds as 2-cyclohexen-1-one (**I**), 2-butenal (**V**), 3-phenyl-2-propenal (**IX**) and 3-aryl-2-methyl-2-propenals (**XIII** and **XVII**).

Both catalytic systems Rh/HSA and Ir/HSA showed to be very active in the hydrogenation of ketone **I** even at low temperature and hydrogen pressure; in particular, the rhodium based catalyst showed to be very selective affording exclusively cyclohexanone (**II**). The α,β-unsaturated aldehydes investigated required higher temperature (up to 60 °C) and pressure (5 MPa) to obtain good conversions. In this case Rh/HSA resulted to be more active than Ir based catalyst. In all cases both Rh/HSA and Ir/HSA were easily recycled without significant loss of activity.

1. Introduction

Homogeneous catalysis is a powerful tool in a wide range of organic syntheses. One of the major drawbacks of homogeneous catalytic processes is the difficulty to separate and reuse the catalyst. For this reason and for the consideration of the environmental aspects of chemical production, liquid–liquid two-phase systems have been developed in these last years, with the catalyst confined in one of the two phases and the product in the other phase [1]. In particular, aqueous/organic biphasic reactions are increasingly attractive using water soluble catalyst [1–3]. The most common catalysts are complexes modified with hydrophilic phosphanes, principally sulfonated phosphines as TPPTS (triphenylphosphine-3,3′,3″-trisulfonic acid trisodium salt), employed in the famous Ruhrchemie/Rhône-Poulenc biphasic process for the hydroformylation of propene [4–7].

Besides hydroformylation, aqueous biphasic hydrogenation has been extensively explored; in particular, the hydrogenation of α,β-unsaturated carbonyl compounds has attracted the interest of the researchers. The selective hydrogenation of α,β-unsaturated aldehydes is a challenging problem and it strongly depends on the nature of the active metal catalyst and on the hydrogenation reaction conditions (pH, catalyst concentration, ligand amount, etc.) [8–12]. Generally, by analogy with Ru/PPh_3 systems, the water soluble Ru/TPPTS complex selectively hydrogenates the C=O bond; likewise, the analogous Ir/TPPTS complex is capable to reduce the carbonyl moiety, even if with a lower activity than the ruthenium derivatives. The Rh(I)/TPPTS complex hydrogenates α,β-unsaturated aldehydes into the corresponding saturated aldehydes, without decarbonylation, as in the case of 3-phenyl-2-propenal that can be selectively reduced to 3-phenylpropanal [8,13,14].

The research for active and selective water soluble catalysts, not containing phosphines, led to the design of new ligands and/or surfactants having different hydrophilic groups such as –COOH, NR_3, –OH. [1–3]. In this context, a class of ligands, based on macromolecular substances, such as proteins, attracted the interest and a few metal complex–protein composites were patented and used by Japanese researchers for catalytic hydrogenation and oxidation reactions [15,16]. Potential advantages of using these ligands/surfactants are either easy availability or the possibility to increase the solubility of the reagents in water so enhancing the reaction rate. Then, their peculiar complex structure could induce regio-, chemo- and enantio-selective reactions, too. Water soluble complexes derived from the interaction between $Rh(CO)_2(acac)$ and human serum albumin (HSA) were also used by us in a highly efficient and chemoselective hydroformylation reaction [17–20]. On the basis of the interesting results obtained in the oxo-experiments, we decided to extend our research work to the aqueous biphasic hydrogenation of some α,β-unsaturated

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carbonyl compounds in the presence of $Rh(CO)_2(acac)$/HSA (Rh/HSA) and of the complex obtained by the interaction of $[Ir(COD)Cl]_2$ with HSA (Ir/HSA).

2. Experimental

2.1. General remarks

HSA was purchased from Aldrich. $Rh(CO)_2(acac)$ and $[Ir(COD)Cl]_2$ were obtained by Strem. 2-Cyclohexen-1-one, 2-butenal, 3-phenyl-2-propenal and 3-phenyl-2-methyl-2-propenal were Aldrich products. 3-(1,3-Benzodioxol-5-yil)-2-methyl-propenal was synthesized as described in the literature [21]. Flash chromatographies were carried out on silica gel Merck 60, 230–400 mesh. ^1H NMR and ^{13}C NMR spectra were recorded on a Bruker Avance 300, using $CDCl_3$ or D_2O as solvent. GC analyses were carried out on an Agilent 6850A gaschromatograph, using an HP1 column (30 m × 0.32 mm × 0.25 μm). GC–MS analyses were performed by using an Agilent MS Network 5937 using an HP-5MS column (30 m × 0.25 mm × 0.25 μm). IR spectra were recorded on an FTIR Nicolet Magna 750 instrument. Solvents were purified as described in the literature [22].

2.2. General procedure for the aqueous biphasic hydrogenation experiments

In a Schlenk tube the transition metal complex and HSA were stirred under nitrogen in 5 mL of disareated H_2O until complete dissolution of the complex. A solution of the substrate in organic solvent (2 mL) was then added to the aqueous phase. The Schlenk tube was transferred into a 150 mL stainless steel autoclave under nitrogen, pressurized with H_2 and heated at 20–80 °C for the due time (see tables). The reactor was then cooled to room temperature and the residual gases released. The organic phase was separated, dried on Na_2SO_4 and analyzed by GC and GC–MS. The water phase was recycled for further experiments.

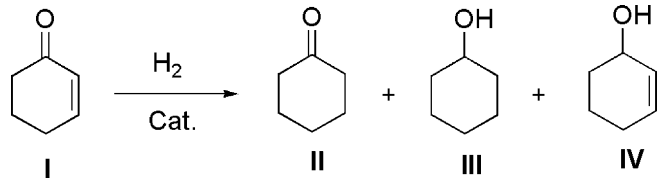
3. Results and discussion

3.1. α,β-Unsaturated ketones

2-Cyclohexen-1-one (**I**) was chosen as model substrate to investigate the selectivity of our catalytic systems towards the hydrogenation of the carbon–carbon and carbon–oxygen double bond, respectively, in α,β-unsaturated ketones (Scheme 1).

Both the catalytic systems Rh/HSA and Ir/HSA were very active in the hydrogenation of **I** working at 40 °C under 5 MPa of H_2, showing a quantitative conversion after 4 h. The rhodium catalyst exclusively afforded cyclohexanone (**II**), while the iridium catalyst gave a mixture of cyclohexanone (**II**) and cyclohexanol (**III**) (see Table 1). Both catalysts were used in some recycle experiments without any loss of activity and selectivity.

We decided to evaluate the influence of the hydrogen pressure, maintaining constant the other reaction parameters; thus we performed experiments at 2, 0.5 and 0.1 MPa of H_2, respectively. At both 2 and 0.5 MPa, Rh/HSA always gave cyclohexanone (**II**) in quantitative yield (see Table 2).



Scheme 1. Aqueous biphasic hydrogenation of 2-cyclohexen-1-one (**I**).

Table 1
Aqueous biphasic hydrogenation of 2-cyclohexen-1-one (**I**) catalyzed by Rh/HSA and Ir/HSA.

Run	Catalytic system	Conv. (%)	**II** selectivity (%)	**III** selectivity (%)
1	Rh/HSA	100	100	–
2–5[a]	Rh/HSA	100	100	–
6	Ir/HSA	100	35	65
7[a]	Ir/HSA	100	36	64
8[a]	Ir/HSA	100	33	67
9[a]	Ir/HSA	100	35	65

Substrate = 5.2 mmol; $Rh(CO)_2acac$ = 0.0104 mmol; $[Ir(COD)Cl]_2$ = 0.0052 mmol; HSA = 12.2 mg; H_2O = 5 mL; toluene = 2 mL; $p(H_2)$ = 5 MPa; T = 40 °C; t = 4 h. Substrate/metal (molar ratio) = 500/1.
[a] Reaction carried out by using the aqueous phase recovered from the previous run.

Table 2
Aqueous biphasic hydrogenation of 2-cyclohexen-1-one (**I**) catalyzed by Rh/HSA at different H_2 pressures.

Run	$p(H_2)$ (MPa)	Conv. (%)	**II** selectivity (%)
1	2	100	100
2–3[a]	2	100	100
4	0.5	100	100
5–6[a]	0.5	100	100

Substrate = 5.2 mmol; $Rh(CO)_2acac$ = 0.0104 mmol; HSA = 12.2 mg; H_2O = 5 mL; toluene = 2 mL; T = 40 °C; t = 4 h. Substrate/metal (molar ratio) = 500/1.
[a] Reaction carried out by using the aqueous phase recovered from the previous run.

Table 3
Aqueous biphasic hydrogenation of 2-cyclohexen-1-one (**I**) catalyzed by Rh/HSA at 0.1 MPa and different temperatures.

Run	Temp. (°C)	Conv. (%)	**II** selectivity (%)
1	40	52	100
2[a]	40	93	100
3[a]	40	64	100
4	20	57	100
5[a]	20	69	100
6[a]	20	55	100
7[a]	20	32	100

Substrate = 5.2 mmol; $Rh(CO)_2acac$ = 0.0104 mmol; HSA = 12.2 mg; H_2O = 5 mL; toluene = 2 mL; $p(H_2)$ = 0.1 MPa; t = 4 h. Substrate/metal (molar ratio) = 500/1.
[a] Reaction carried out by using the aqueous phase recovered from the previous run.

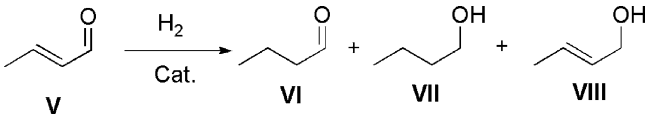
When the reaction was performed at 0.1 MPa of H_2, at 40 or 20 °C, in the presence of the Rh catalyst, after 4 h, conversion was partial but selectivity remained unchanged (see Table 3). It is to underline that after the first recycle the catalyst system reached a maximum of activity.

By decreasing the H_2 pressure, the iridium catalyst showed a lower activity and a change in the selectivity in comparison with

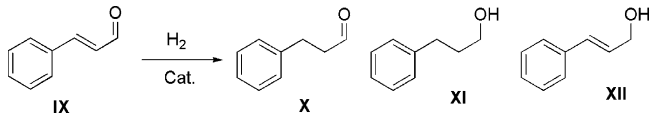
Table 4
Aqueous biphasic hydrogenation of 2-cyclohexen-1-one (**I**) catalyzed by Ir/HSA at different H_2 pressures.

Run	$p(H_2)$ (MPa)	Conv. (%)	**II** selectivity (%)	**III** selectivity (%)
1	2	76	89	11
2[a]	2	82	89	11
3[a]	2	65	88	11
4	0.5	54	88	12
5[a]	0.5	37	89	11
6[a]	0.5	29	88	12

Substrate = 5.2 mmol; $[Ir(COD)Cl]_2$ = 0.0052 mmol; HSA = 12.2 mg; H_2O = 5 mL; toluene = 2 mL; T = 40 °C; t = 4 h. Substrate/metal (molar ratio) = 500/1.
[a] Reaction carried out by using the aqueous phase recovered from the previous run.



Scheme 2. Aqueous biphasic hydrogenation of 2-butenal (**V**).



Scheme 3. Aqueous biphasic hydrogenation of 3-phenyl-2-propenal (**IX**).

the experiments carried out at 5 MPa, being now compound **II** formed in higher amount (see Table 4) [23]

3.2. α,β-*Unsaturated aldehydes*

The regioselective hydrogenation of α,β-unsaturated aldehydes to the corresponding saturated aldehydes or to unsaturated alcohols is a very relevant reaction for the synthesis of valuable fine chemicals. In this context we investigated the activity of our catalytic systems in the hydrogenation of some α,β-unsaturated aldehydes, such as (E)-2-butenal (**V**), (E)-3-phenyl-2-propenal (**IX**), (E)-2-methyl-3-phenyl-2-propenal (**XIII**) and (E)-3-(1,3-benzodioxol-5-yl)-2-methylpropenal (**XVII**), having different electronic and steric characteristics.

Preliminary experiments were carried out on (E)-2-butenal (**V**), at 60 °C and 5 MPa of H_2 for 22 h (Scheme 2).

As in the case of the 2-cyclohexen-1-one, Rh/HSA showed a good catalytic activity leading to a complete substrate conversion. Butanal (**VI**) was the prevailing reaction product, obtained in more than 90% selectivity; the saturated alcohol **VII** was obtained in a little amount, less than 10%. The catalytic system did not show any loss of activity in two recycle experiments (see Table 5).

Ir/HSA was much less active than Rh/HSA, giving at the best 48% of substrate conversion: in this case, the selectivity of the reaction, both in the first experiment and in the recycle ones, was slightly shifted towards the formation of butanol (**VII**), once more showing the pronounced capability of the iridium catalyst to hydrogenate the carbonyl moiety. In all cases, both in the presence of the rhodium catalyst and of the iridium based catalytic system, the unsaturated alcohol 2-buten-1-ol (**VIII**) was never found in the reaction mixtures. Among the α,β-unsaturated aldehydes, (E)-3-phenyl-2-propenal (**IX**) was particularly attractive to be subjected to hydrogenation as the corresponding saturated aldehyde **X** is an important intermediate for the synthesis of anti-HIV drugs [13]; moreover it has been recently used as additive for food flavours [13]. Also the unsaturated alcohol **XII** is a valuable building block for fragrances [13]. Therefore, we performed some hydrogenation experiments on compound **IX** to evaluate the chemical activity and selectivity of both Rh/HSA and Ir/HSA. As preliminary experiments showed that the iridium catalyst was scarcely active in the reduction of this substrate, all the reactions were carried out in the presence of the rhodium based catalytic system (Scheme 3).

The reactions were carried out by using toluene or 2-MeTHF as the solvent of the organic phase or without any organic solvent. As reported in the plot, the catalytic system Rh/HSA always showed a good activity and a fairly good stability, as demonstrated by the recycle experiments. In the presence of 2-MeTHF initially the substrate conversion was very high but we could observe a gradual conversion decrease of about 10–15% starting from the second recycle experiment. In the absence of organic solvent there was a strong enhancement of the catalytic activity after the first experiment followed by an adjustment around about 60% of substrate conversion. When the reactions were carried out in the biphasic system water/toluene the substrate conversions were slightly lower than those in 2-MeTHF or in neat, but always more than satisfactory, with 70% conversion after three recycle experiments (see Fig. 1) [24]. Though the selectivity towards the saturated aldehyde **X** was always high (80–90%), the saturated alcohol **XI** was formed in not negligible amount (up to 17%), while the unsaturated alcohol **XII** was produced only in traces. It is noteworthy that the presence of the aromatic ring strongly decreases the activity of the catalytic system Rh/HSA, as we can observe by comparing the data obtained in the hydrogenation of 2-butenal (**V**) with respect to 3-phenyl-2-propenal (**IX**) hydrogenation. It is possible, however, that the difference in reactivity between the two aldehydes is due also to a lower solubility of the latter substrate in the interphase where the reaction occurs.

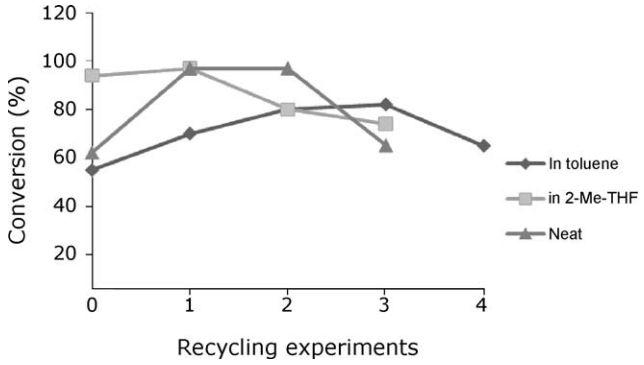


Fig. 1. Aqueous biphasic hydrogenation of (E)-3-phenyl-2-propenal (**IX**) catalyzed by Rh/HSA. *Note*: Substrate = 5.2 mmol; $Rh(CO)_2acac$ = 0.0104 mmol; HSA = 12.2 mg; H_2O = 5 mL; solvent = 2 mL; $p(H_2)$ = 5 MPa; T = 60 °C; t = 22 h. Substrate/metal (molar ratio) = 500/1.

Table 5
Aqueous biphasic hydrogenation of 2-butenal (**V**) catalyzed by Rh/HSA and Ir/HSA.

Run	Cat.	Conv. (%)	**VI** selectivity (%)	**VII** selectivity (%)
1	Rh/HSA	100	91	9
2[a]	Rh/HSA	100	93	7
3[a]	Rh/HSA	100	94	6
4	Ir/HSA	48	39	61
5[a]	Ir/HSA	30	45	55
6[a]	Ir/HSA	23	44	56

Substrate = 5.2 mmol; $Rh(CO)_2acac$ = 0.0104 mmol; $[Ir(COD)Cl]_2$ = 0.0052 mmol; HSA = 12.2 mg; H_2O = 5 mL; toluene = 2 mL; $p(H_2)$ = 5 MPa; T = 60 °C; t = 22 h. Substrate/metal (molar ratio) = 500/1.

[a] Reaction carried out by using the aqueous phase recovered from the previous run.

Table 6
Aqueous biphasic hydrogenation of 3-phenyl-2-propenal (**IX**) catalyzed by Rh/HSA and Rh/TPPTS.

Run	Cat.	Conv. (%)	**X** selectivity (%)	**XI** selectivity (%)	**XII** selectivity (%)
1	Rh/HSA	54	84	13	3
2[a]	Rh/HSA	73	85	12	3
3[a]	Rh/HSA	82	90	9	1
4[a]	Rh/HSA	82	92	7	1
5[a]	Rh/HSA	70	94	5	1
6	Rh/TPPTS	98	77	20	<1
7[a]	Rh/TPPTS	99	78	20	<1
8[a]	Rh/TPPTS	99	77	21	<1
9[a]	Rh/TPPTS	99	78	20	<1

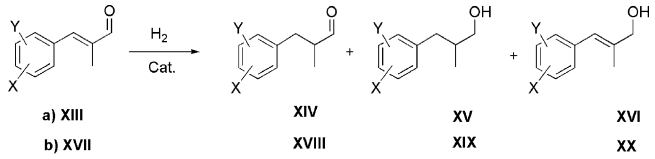
Substrate = 5.2 mmol; $Rh(CO)_2acac$ = 0.0104 mmol; HSA = 12.2 mg; $Rh(CO)_2acac$/TPPTS (molar ratio) = 1/3; H_2O = 5 mL; toluene = 2 mL; $p(H_2)$ = 5 MPa; T = 60 °C; t = 22 h. Substrate/metal (molar ratio) = 500/1. TPPTS = (triphenylphosphine-3,3′,3″-trisulfonic acid trisodium salt).

[a] Reaction carried out by using the aqueous phase recovered from the previous run.

Table 7
Aqueous biphasic hydrogenation of 3-phenyl-2-propenal (**IX**) catalyzed by Rh/HSA and Rh/TPPTS for 1 h.

Run	Cat.	Conv. (%)	**X** selectivity (%)	**XI** selectivity (%)	**XII** selectivity (%)
1	Rh/HSA	12.5	100	–	–
2[a]	Rh/HSA	13.3	100	–	–
3[a]	Rh/HSA	11.6	100	–	–
4[a]	Rh/HSA	11.3	100	–	–
5	Rh/TPPTS	76.9	87	13	–
6[a]	Rh/TPPTS	54.0	88	12	–
7[a]	Rh/TPPTS	53.3	90	10	–
8[a]	Rh/TPPTS	48.0	93	7	–

Substrate = 5.2 mmol; $Rh(CO)_2acac$ = 0.0104 mmol; HSA = 12.2 mg; $Rh(CO)_2acac$/TPPTS (molar ratio) = 1/3; H_2O = 5 mL; toluene = 2 mL; $p(H_2)$ = 5 MPa; T = 60 °C; t = 1 h. Substrate/metal (molar ratio) = 500/1. TPPTS = (triphenylphosphine-3,3′,3″-trisulfonic acid trisodium salt).
[a] Reaction carried out by using the aqueous phase recovered from the previous run.



a) X = Y = H;
b) X, Y = 3,4-(O-CH_2-O)

Scheme 4. Aqueous biphasic hydrogenation of 3-aryl-2-methyl-2-propenals (**XIII** and **XVII**).

Table 8
Aqueous biphasic hydrogenation of 3-aryl-2-methyl-2-propenals (**XIII** and **XVII**) catalyzed by Rh/HSA.

Run	Substrate	Conv. (%)	**XIV** (or **XVIII**) selectivity (%)	**XV** (or **XIX**) selectivity (%)	**XVI** (or **XX**) selectivity (%)
1	**XIII**[b]	47	92	3	5
2[a]	**XIII**[b]	42	94	2	4
3[a]	**XIII**[b]	45	91	3	6
4	**XVII**[c]	24	86	14	–
5[a]	**XVII**[c]	31	90	10	–
6[a]	**XVII**[c]	32	89	11	–
7[a]	**XVII**[c]	48	88	12	–
8[a]	**XVII**[c]	36	89	11	–

Substrate = 5.2 mmol; $Rh(CO)_2acac$ = 0.0104 mmol; HSA = 12.2 mg; H_2O = 5 mL; $p(H_2)$ = 5 MPa; T = 60 °C; t = 22 h. Substrate/Rh (molar ratio) = 500/1.
[a] Reaction carried out by using the aqueous phase recovered from the previous run.
[b] Solvent was 2-MeTHF (2 mL).
[c] Solvent was toluene (2 mL).

Although data on the hydrogenation of substrate **IX** catalyzed by some water soluble rhodium based catalysts were already reported in the literature [8–12,14,25], we decided to perform some experiments by using the catalytic system $Rh(CO)_2acac$/TPPTS in the same reaction conditions adopted for Rh/HSA to have a better comparison: Rh/HSA resulted to be less active than Rh/TPPTS but more selective towards the C=C hydrogenation (Table 6).

In order to better compare the selectivity of these catalytic precursors, we carried out some experiments under the same reaction conditions but only for 1 h to obtain lower conversions: Rh/HSA afforded exclusively the saturated aldehyde **X** while Rh/TPPTS produced also alcohol **XI**, even if in small amounts (see Table 7). This different chemo- and regioselectivity of Rh/HSA with respect to Rh/TPPTS had been already noted also in the hydroformylation of safrole and isosafrole, respectively, to produce the fragrance Helional® [19]. It is noteworthy to observe that, even for a short reaction time and at low substrate conversions, Rh/HSA maintains its activity practically unchanged in three recycle experiments, while Rh/TPPTS begins to degrade after the first recycle experiment.

Finally we tested the hydrogenation of two 3-aryl-2-methyl-2-propenals, aryl being phenyl (compound **XIII**) and 1,3-benzodioxol-5-yl (compound **XVII**) (Scheme 4), at 60 °C and 5 MPa of H_2 for 22 h in the biphasic system H_2O/2-MeTHF and H_2O/toluene, respectively. Hydrogenation products are intermediate and active ingredients of drugs and fragrances [26–30]. In this case, Rh/HSA is less active with respect to 3-phenyl-2-propenal (**IX**) hydrogenation, either for steric hindrance of the methyl group on the carbon–carbon double bond or perhaps for solubility reasons too. Despite a decrease of activity, the selectivity towards the saturated aldehydes **XIV** and **XVIII** was very high (86–92%) (Table 8).

The aldehydes **XIV** and **XVIII** present a stereogenic center, therefore, after purification by flash-chromatography, they were subjected to a polarimetric measurement but, disappointingly, both compounds resulted to be nearly racemate.

This result was not quite surprising, as a similar outcome was also found in styrene hydroformylation [18]. In order to explain this phenomenon, we previously tried to get information on the structure of the catalytic system Rh/HSA [18,31]. MALDI-TOFMS measurements showed that the Rh/HSA complex is constituted by 4 molecules of HSA and 89 rhodium atoms; furthermore, the presence of protein tetramers was revealed. We supposed that Rh coordinates the sulfur atoms of the protein: this hypothesis was supported by CD spectra and by SEM analysis that showed a superficial distribution of rhodium very similar to that of sulfur. Moreover, CD spectra suggest a different stereochemistry of the HSA bound Rh(I) compound, most probably due to a different conformation of the protein. Two limiting conformations are actually reported, the N and the B, the N being the prevailing one for pH values up to 7, and the B being more stable for pH $\geq$8 [32,33]. At physiological pH the HSA is expected to assume both conformations [34]; therefore, at pH 7.4, the protein can assume both the conformations, the prevailing one depending on the structure of the ligand and the conformational equilibrium between the N and B conformations must be taken into account.

4. Conclusive remarks

The catalytic systems Rh/HSA and Ir/HSA showed to be active in the hydrogenation of representatives substrates that present in their molecules both C=C and C=O double bonds. In particular, the rhodium based catalyst resulted to be interesting as far as conversion and selectivity are concerned. Analogously to the above mentioned rhodium complexes modified with water soluble phosphanes [8–14], also our catalytic system Rh/HSA preferentially reduce the olefinic double bond of α,β-unsaturated carbonyl compounds, even at high hydrogen pressure (5 MPa); in particular, 2-cyclohex-1-one, was exclusively hydrogenated to cyclohexanone, in all the experimental conditions employed. On the contrary, but quite along with the data reported in the literature for water soluble iridium complexes [8,12], the catalytic system Ir/HSA is less selective towards the reduction of the olefinic double bond and, under 5 MPa of H_2, the hydrogenation of the carbonyl moiety is the prevailing reaction. Very interestingly, by lowering the hydrogen pressure, this catalytic system tends to promote the reduction of the carbon–carbon double bond, as highlighted in the hydrogenation of 2-cyclohex-1-one.

The catalytic system Rh/HSA showed to be very chemo- and regioselective but, disappointingly, it was not able to induce any enantioselection. At the moment we have not any experimental evidence to explain this fact but we suppose that this lack of

enantioselectivity can be due to the complex chiral structure of the protein in which the metal ions could find in environments endowed with opposite chirality, so resulting in a substantial balance of the enantioselectivity.

It is noteworthy that both Rh/HSA and Ir/HSA can be easily recycled without significant loss of activity.

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[23] $[Ir(COD)Cl]_2$, without any external ligand, was employed to hydrogenate 2-cyclohexen-1-one (**I**) in toluene at 40 °C and 2 MPa: after 1 h, ketone **I** was completely converted to cyclohexanone (**II**) but the Ir complex was completely reduced to metallic iridium.
[24] $Rh(CO)_2acac$, without any external ligand, was used as catalyst in the hydrogenation of 3-phenyl-2-propenal (**IX**) in toluene at 60 °C and 5 MPa H_2: after 1 h, conversion was complete with formation of 80% of saturated aldehyde **X** and 20% of the corresponding alcohol **XI**. By prolonging the reaction time to 22 h we obtained the same result. It is noteworthy that at the end of the reaction the solution was clear and colourless as the rhodium complex was totally transformed into black metallic rhodium.
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