

On the acylation reactions of anisole using α,β -unsaturated organic acids as acylating agents and solid acids as catalysts: a mechanistic overview

C. Castro, A. Corma, J. Primo*

Instituto de Tecnología Química, UPV-CSIC, Universidad Politécnica de Valencia, Avda. de los Naranjos s/n, 46022 Valencia, Spain

Received 22 May 2001; accepted 11 June 2001

Abstract

The mechanism of the acylation of anisole with α,β -unsaturated acids, i.e. acrylic, crotonic and methacrylic acid, has been investigated using phosphotungstic acid ($\text{H}_3\text{PW}_{12}\text{O}_{40}$), as pure form, supported on SiO_2 and in the form of cesium salts as catalysts. Since α,β -unsaturated acid can either alkylate and/or acylate the aromatic compound, the influence of the catalyst on the selectivity for these two competing reactions was studied. Analysis of products obtained on the acylation of aromatic compounds with α,β -unsaturated acids shows that all the catalysts are more active for acylation than alkylation. Secondary products coming from intermolecular reactions of the acylated product with anisole as well as tertiary products coming from its further decomposition and recombination with another anisole molecule were observed. Heteropolyacids supported on silica were found to be more active and selective towards acylation reactions than zeolites HY and H β , even when the activity per acid site was considered. Zeolites and cesium salts from heteropolyacids favor acid polymerization reaction rather than the acylation of the aromatic compound. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Acylation anisole; Acylation with organic acids; Heteropolyacids acylation catalysts

1. Introduction

Acylation of aromatic compounds is a widely used reaction for the production of fine chemicals [1]. When α,β -unsaturated acids are used as acylating agents, the possibilities of further reactions of the resultant phenylketone is increased due to the introduction of the double bond in the side chain.

The classic methodology for acylation is the Friedel–Crafts methodology, implies the use of more than stoichiometric amounts of Lewis acids such as metal halides but some Brønsted acids such as

polyphosphoric and sulfuric acid can also be used as catalysts [2]. Moreover, the reaction is carried out in homogeneous phase and the catalysts must be destroyed to obtain the final products, generating a great amount of corrosive and toxic waste products.

Due to all these environmental limitations, many efforts are being made to find solid acid catalysts, which can successfully carry out acylation reactions with anhydrides and acids as acylating agents, with a more environmental-friendly technology. It has been shown that zeolites and in general, solid catalysts containing Brønsted acid sites are adequate agents for carrying out the acylation of activated aromatic rings with carboxylic acids [3–6]. It has also been proposed, that a rare earth exchanged zeolite can catalyze the acylation of toluene with carboxylic acid [7]. It is then of

* Corresponding author. Tel.: +34-96-3877807;

fax: +34-96-3877809.

E-mail address: jprimo@qim.upv.es (J. Primo).

interest to study the influence of the acid strength of the Brønsted acid sites on the catalysts activity when acylating aromatic hydrocarbons with different activation degrees, using carboxylic acids as acylating agents. Previous studies have shown that Phosphotungstic acid (HPW) supported on silica at 60% as well as in the form of cesium salts were active in the acylation reaction of aromatic compounds with acid chlorides as well as with α,β -unsaturated acids [8,9]. Owing to these results, the study of anisole, which has a highly activated aromatic ring, seemed to be even more suitable for testing acylation reactions than xylenes and toluene.

In this work, we have used crotonic, acrylic and methylcrotonic acids as acylating agents of anisole. Crotonic acid was taken as the standard product for further comparisons. The results previously obtained in the acylation of xylenes and toluene [8], and the results obtained with compounds containing different double bond functions (acrylic and methylcrotonic acids), were compared and the influence of the catalyst acidity has been elucidated by using two large pore zeolites (HY and H β) and phosphotungstic acid (H₃PW₁₂O₄₀), pure supported on silica and in the form of cesium salts.

2. Experimental

2.1. Materials

The silica source was obtained from BASF chemicals and characterized as having a BET surface area of 137 m²/g. This material was calcined at 800 °C before being used.

Crotonic acid, acrylic acid and methylcrotonic acid, with a nominal purity of 99% were supplied by Aldrich and used without further purification.

Phosphotungstic acid was also supplied by Aldrich and aromatic compounds with nominal purity of $\geq 98\%$ were supplied by Fluka and used without further purification.

Supported HPW (HPW6 where the weight percent of HPW on silica was of 60%) was prepared as indicated before [8]. Cesium salts from heteropolyacids were prepared as described by Okuhara et al. [9].

Table 1 resumes the textural properties of the catalysts used.

Results are presented as yields percentage of the acylated products and were calculated as the molar percentage of products formed in relation to the initial molar amount of acid. The turnover number (TNO) was calculated as the molar amount of acid converted to acylated product per mol of proton present on the catalyst.

2.2. Reaction procedure

The reactions were carried out in a batch reactor, with controlled temperature and magnetic stirring. Prior to its use, the heteropolyacids were activated, when required, in situ by heating it at 300 °C under a vacuum of 1 Torr for 2 h. Zeolites were calcined at 500 °C for 3 h. Thereafter, the preheated reactants were transferred to the reactor and the resulting suspension was stirred at the reaction temperature. The reaction temperature was taken as the reflux temperature of anisole (154 °C). The reactant proportions used were the same as used in 8, i.e. 10:1 mol% aromatic compound: acylating agent; 10:1 mol% acylating agent:

Table 1

Micropore volume ($V_{\mu\text{pore}}$), micropore area ($S_{\mu\text{pore}}$), total pore volume (V_{total}), average pore size (ϕ) and BET surface area (S_{BET}) of catalysts used measured with adsorption/desorption of nitrogen

Catalyst	S_{BET} (m ² /g)	$V_{\mu\text{pore}}$ (cm ³ /g)	$S_{\mu\text{pore}}$ (m ² /g)	V_{total} (cm ³ /g)	ϕ (Å)
Cs ₁ HPWs	14	0.0006	1.3	0.009	24
Cs ₂ HPWs	74	0.0319	64	0.039	15
Cs _{2.5} HPWs	118	0.0257	53	0.077	26
HPW6s	54	0.0049	11	0.150	110
HPWps	7	0.0006	1.22	0.016	86
H β	560	0.19	383	0.49	25
HY-100	654	0.30	606	0.39	17

catalyst. Samples were taken periodically from the reactor with a filtering syringe and analyzed by GC (Varian 3000) in order to follow the reaction kinetics. GC–MS (Varian-3300/SATURN II) and ^1H , ^{13}C NMR (300 MHz VXR-400S) were used in order to identify the products formed. At the end of the reaction, the catalyst was filtered and washed with dichloromethane, the filtrate was then weighed and analyzed by GC–MS, the catalyst was extracted with dichloromethane using a Soxhlet apparatus and the mass balance was calculated taking into account the extracted fraction.

3. Results and discussion

Fig. 1 shows the possible reactions for an α,β -unsaturated acid in the presence of an acid catalyst. It can be observed that due to the conjugated system of the α,β -unsaturated acid, two cationic species coexist in the reaction media. Both species can react further either with an anisole molecule, to form the acylated (product **1a**) or the alkylated product (product **2a**). After that, both alkylated and acylated products are able to react either with another anisole molecule to form a biphenylpropanone (product **3a**) or intramolecularly to form the corresponding indanone (product **4a**).

3.1. Acylation with crotonic acid

The reaction was first carried out with 0.086 mmol of catalyst (10 mol% of the acylating agent). Crotonic acid was used as acylating agent and the heteropolyacid supported on silica at 60% w/w (HPW6s) was

used as catalyst. Under these conditions, the reaction is very fast and 100% conversion is achieved after 25 min of reaction time (see Fig. 2). Nevertheless, the major compounds detected in this reaction did not correspond to the expected products (**1–4**) shown in Fig. 1, with only a small quantity of product **3a** present.

The mass spectra of the major compounds obtained showed a molecular peak at $m/z = 242$, with a base peak at $m/z = 227$, probably due to a loss of a methyl group. The presence of another intense peak of $m/z = 121$, indicates the loss of a fragment of $m/z = 106$, which could correspond to a loss of a methoxyphenyl group. The products were then isolated by liquid chromatography and analyzed by ^1H NMR. Their structures were unambiguously assigned to products **5–8**. These products were found to come from the decomposition of product **3** according to the mechanism proposed in Fig. 3. A closer look to Fig. 2, reveals that this mechanism is feasible, and it can be interpreted as if product **1a** is being formed and rapidly reacts to give product **3a**, which can decompose into products **5a–8a**. This decomposition takes place due to the protonation of the ketone in an acidic media, which leads to the rupture of a carbon–carbon bond generating a benzyl or benzoyl carbocation specie. Both species are very stable owing to the effect of the methoxy group at the *para*-position of the aromatic ring. Further reaction of these species with an anisole molecule led to the formation of the products **5–8**, depicted in Fig. 3. The mechanism proposed is very interesting from the organic chemistry point of view, since it implies the formation of a carbocation specie from a compound which seemed to be already very stable. Also, from the point of view of the catalyst, the formation of a

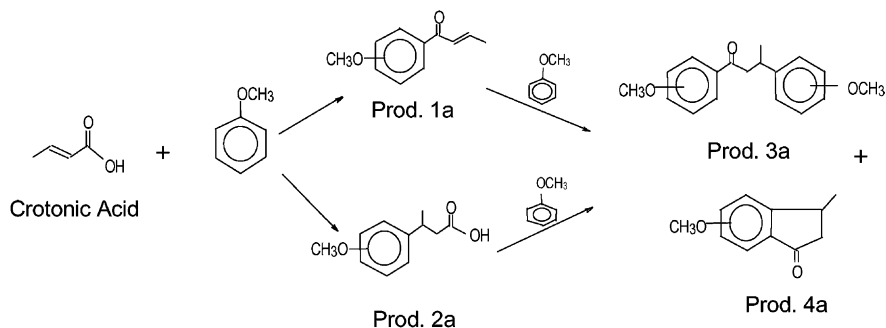


Fig. 1. Expected reactions involved in the acylation of anisole with crotonic acid.

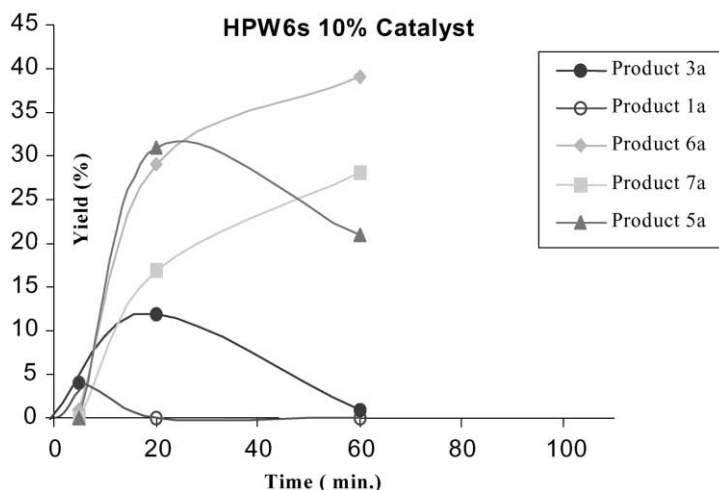


Fig. 2. Graphic showing the kinetic behavior of the acylation reaction of anisole with crotonic acid using 10 mol% of HPW6s as acid catalyst.

carbocation is very important in order to know the acid strength of the acid sites.

The rapid formation of the tertiary products (**5a–8a**) did not allow the study of the first acylation reactions. Because of this, and in order to diminish the rate of conversion and better observe the formation of the acylated products **1a** and **3a**, the amount of heteropolyacids and its salts were reduced to one tenth of the amount used in the previous reaction (0.0086 mmol). In these conditions, HPW6s produces mainly the acylated products **1a** and **3a** and only a small amount of product coming from the decomposition of **3a** is observed (see Fig. 4). These results show, that the acylated product of anisole, contrary to what was found

for xylenes and toluene, reacts faster by intermolecular reaction than by intramolecular reaction [8]. This is probably due to the difference in the reactivity of the aromatic ring of anisole and of the alkylaromatics.

3.2. Influence of the catalyst

Table 2 presents the results obtained with different catalysts for the acylation reaction of anisole with crotonic acid. It can be observed there, that the other heteropolycompounds used behave similarly to HPW6s. Thus, the major products detected were the acylated product **1a** and the product coming from the further intermolecular alkylation of another anisole molecule

Table 2

Conversion and yields (mol%) of the products obtained in the acylation reaction of anisole with crotonic acid at 154 °C

Catalysts	Yields						Conversion
	1a	3a	5a	6a	7a	8a	
HPW6s	28	31	6	7	0	0	72
HPW6a	10	20	10	9	0	0	49
HPWps	8	19	9	8	0	0	99
CS ₁ HPWs	12	18	4	4	1	1	57
CS ₂ HPWs	11	1	1	1	1	1	47
CS _{2.5} HPWs	19	4	1	1	1	1	42
HY ^a	2	1	0	0	0	0	39
Hβ ^a	12	13	4	2	0	0	95

^a Ratio of catalyst to acylating agent used: 10% mol/mol.

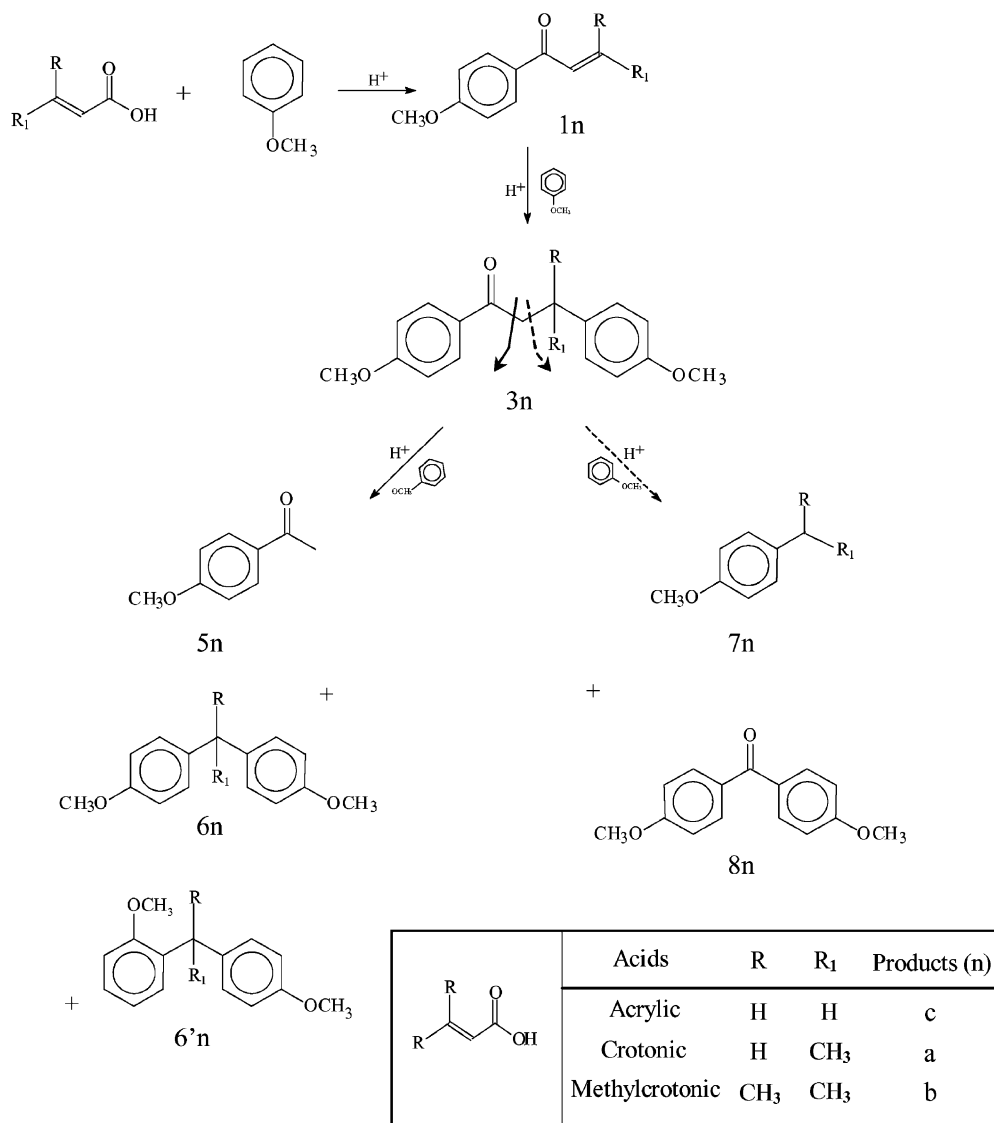


Fig. 3. Scheme of the reaction route of the acylation reaction of anisole with an α,β -unsaturated acid: formation of products 5–8 and structure of acids used in this work.

(3a), with only a small amount of products coming from its decomposition.

It can also be observed that, when HPW6s is used as catalyst, the highest yields of acylated products were obtained. The thermally treated sample (HPW6a) showed a decrease of the catalytic activity. This fact indicates the importance of water of crystallization on the activity of this catalyst for acylation reactions

using free carboxylic acids. Some authors have also observed the importance of water of crystallization on the catalytic activity of HPW [10].

The activity of tungstophosphoric acid (HPW) was increased by supporting it on silica, in order to increase the number of acids sites accessible to organic molecules. The samples supported on silica gave higher yields of acylated products than unsupported

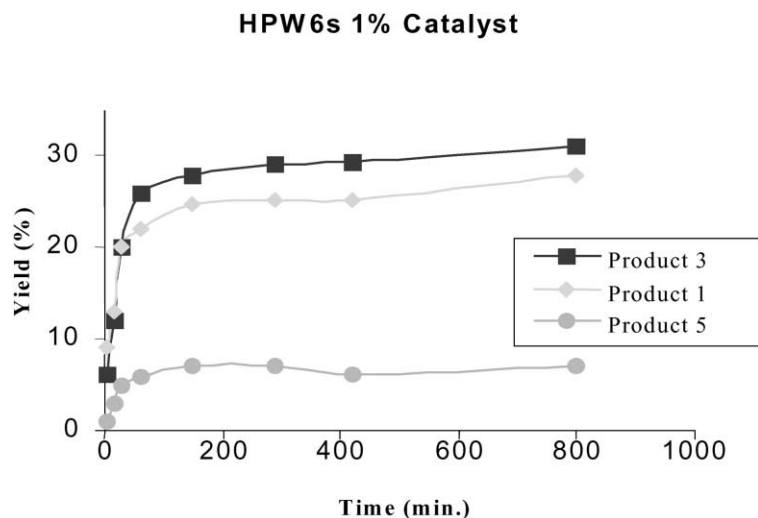


Fig. 4. Graphic showing the kinetic behavior of the acylation reaction of anisole with crotonic acid using 1 mol% of HPW6s as acid catalyst.

HPW, which favors polymerization rather than acylation. The high conversion values obtained for the HPWp can be attributed to the pseudo-liquid effect of the catalyst, which would favor the adsorption of crotonic acid. Further polymerization of crotonic acid should be then attributed to the acid adsorption rather than anisole on the acid centers of HPWp.

When cesium salts of the heteropolyacid are used as catalysts, a significant amount of polymerization reaction takes place (see Table 2). The change of the hydrophilic properties of the salt could be one of the causes for this behavior. Thus, crotonic acid would react by the double bond owing to the hydrophobic characteristics of the salt, favoring the adsorption of the alkenyl group rather than the carboxylic group. This adsorption favors the formation of the protonated specie by the alkenyl group, which is responsible for the formation of polymers. It should also be taken into account that the presence of Cs cations may direct the interaction of the carboxylic group with the alkali cation, leaving the alkenyl group free to be attacked by the acid site of the heteropolyacid. Nevertheless, when the TON are calculated for each catalyst (Table 3), one observes that the TON for the heteropolysalts are higher than for the heteropolyacid supported on silica. This is mainly due to the great accessibility of the acid sites in the former, caused by the enhancement of HPW surface in the Cs salt

Table 3

Turnover number calculated for the reaction of anisole with crotonic acid and stated as the conversion to acylated products per mol of proton of the catalyst used

Catalyst	TON
HPW6s	32
HPW6a	21
HPWps	20
Cs ₁ HPWs	27
Cs ₂ HPWs	21
Cs _{2.5} HPWs	72
HY ^a	0.03
Hβ ^a	1.2

^a Ratio of catalyst to acylating agent used: 10% mol/mol.

due to the very small crystallites formed [11]. In this way, the losses of acid sites are compensated by the increase of the accessibility of the protons left. The salt containing 2.5 mol of cesium cations per mol of heteropolyacid possesses the highest surface area and gave the highest conversion as well as the highest TON towards the acylated compound **1a**. Cs₁HPW presented a TON comparable to that of HPW6s, but the selectivity towards acylated compounds is higher for the heteropolyacid supported on silica. In the case of Cs₂HPW, a decrease in total conversion and in the yields of acylated products can occur, which results in a decrease of the TON.

Table 4
Yields (%) of products obtained in the reaction of anisole with methylcrotonic and acrylic acid at 154 °C for HPW6s and Cs_{2.5}HPWs

Catalyst	Acids	Yields (%)					Conversion
		1	3	5	6	6'	
HPW6s	Methylcrotonic	10	5	15	34	28	100
Cs _{2.5} HPWs	Methylcrotonic	17	2	2	1	1	100
HPW6s	Acrylic	1	16	0	0	0	62
Cs _{2.5} HPWs	Acrylic	0	0	0	0	0	49

It has been presented so far, that in the case of these acid-catalyzed acylation reactions, the adsorption properties of the catalyst can be almost as important as the acid strength of the sites [12]. In the case of heteropolyacids, not only the acidity, but also the adsorption properties of the heteropolycompounds can be modified by synthesizing different salts. In our case, the Cs salts are more hydrophobic than the acid form, and this should have a beneficial effect for the adsorption of the less polar molecules [13]. On top of that, the soft basicity of the heteropolyanion, which can be changed by the presence of Cs⁺, gives to the system a special acid–base bifunctionality, which enhances the catalytic activity of the heteropolysalt.

The zeolites tested in this work were the less active catalysts for the acylation reactions at the conditions used. The yields of acylated products obtained for a 10% mol/mol of catalyst was comparable to those obtained with 1% of heteropolyacids. Moreover, these catalysts seemed to favor polymerization of the crotonic acid rather than the acylation reaction itself.

3.3. Acylation with acrylic acid and methylcrotonic acid

Having in mind, the results obtained for crotonic acid and attempting to determine the influence of the substituting groups on the double bond of α,β -unsaturated acids, the acylation reaction of anisole was also carried out with acrylic and methylcrotonic acids. The catalysts used for these reactions were the HPW supported on silica at 60% (HPW6s), and the cesium salt containing 2.5 cesium cations per molecule of HPW (Cs_{2.5}HPWs). The amount of catalyst used was 0.0086 mmol/mmol of crotonic acid. Acylated products obtained with these reactants are shown in Table 4.

Both acrylic and methylcrotonic acids showed similar behavior to crotonic acid in the acylation of anisole. Firstly, the acylation of anisole occurs, followed by further reaction of this acylated compound with another anisole molecule to produce the acylated/alkylated product **3**. In the case of methylcrotonic acid, the presence of two methyl groups as substitutes in the double bond favors the rupture of the carbon–carbon bond in the α position to the carbonyl group. This rupture forms a stable tertiary carbocation, which can react further with another molecule of anisole in order to generate products **5b**, **6b**, and **6'b**. These decomposition products were not observed in the reaction of acrylic acid, because in this case, the hydrogen atoms that substitute the methyl groups of the double bond do not favor the rupture of the carbon–carbon bond and consequently, the reaction stops when product **3c** is formed.

When Cs_{2.5}HPWs is used as catalyst, the rate of the acid polymerization increases respect to that observed for HPW6s. Again this can be related to changes in the environment of the acid sites of the heteropolyacid when cesium is incorporated to its secondary structure. The maximum effect is observed for the reaction with acrylic acid, that is fully converted to polymers and no acylation occurs.

4. Conclusions

The experiments carried out in this work showed that phosphotungstic acid supported on silica as well as its cesium acid salts are active catalysts for the acylation reaction of anisole with α,β -unsaturated carboxylic acids as acylating agents. Intermolecular

reactions are favored when activated aromatic compounds such as anisole are used, contrary to what was observed in the case of xylenes and toluene. Moreover, the product coming from a first acylation reaction suffers a further alkylation reaction (product **3**) and then undergoes a bond rupture and further recombination with another solvent molecule if the benzyl carbocation to be formed is stabilized. The crystallization water content of the heteropolyacid is an important parameter that controls activity of silica supported HPW. When using α,β -unsaturated carboxylic acids as acylating agents, polymerization of the acid can occur, and its extension depends on the adsorption characteristics of the catalysts.

Acknowledgements

This work was supported by Spanish CICYT (Project MAT2000-1392). Consellería de Educació i Ciència of the Generalitat Valenciana is also acknowledged for funding Mr. Castro's Ph.D. fellowship.

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