Applied Catalysis A: General 486 (2014) 94–104

Contents lists available at ScienceDirect

Applied Catalysis A: General

journal homepage: www.elsevier.com/locate/apcata

Synthesis of α,β-unsaturated aldehydes and nitriles via cross-metathesis reactions using Grubbs' catalysts

Sandra M. Rountree [a], Sarah F.R. Taylor [a], Christopher Hardacre [a,**], M. Cristina Lagunas [a,*], Paul N. Davey [b]

[a] QUILL Research Centre, School of Chemistry and Chemical Engineering, Queen's University, Belfast BT9 5AG, Northern Ireland, UK
[b] Givaudan Schweiz AG, Ueberlandstrasse 138, CH-8600 Duebendorf, Switzerland

ARTICLE INFO

Article history:
Received 22 May 2014
Received in revised form 18 August 2014
Accepted 25 August 2014
Available online 2 September 2014

Keywords:
Cross-metathesis
Grubbs' catalysts
Acrolein
Fragrances

ABSTRACT

A series of α,β-unsaturated aldehydes and nitriles of significant interest in the fragrance industry have been prepared using Grubbs' catalysts in cross-metathesis reactions of electron-deficient olefins (i.e., acrolein, crotonaldehyde, methacrolein, and acrylonitrile) with various 1-alkenes, including 1-decene, 1-octene, 1-hexene and 2-allyloxy-6-methylheptane. The latter is of particular interest, as it has not previously being used as a substrate in cross-metathesis reactions and allows access to valuable intermediates for the synthesis of new fragrances. Most reactions gave good selectivity of the desired CM product (≥90%). Detailed optimisation and mechanistic studies have been performed on the cross-metathesis of acrolein with 1-decene. Recycling of the catalyst has been attempted using ionic liquids.

1. Introduction

α,β-Unsaturated aldehydes and nitriles are of significant interest in the fragrance and flavour industries, either by themselves or as key intermediates in the preparation of other synthetic scents [1]. They are also important intermediates in numerous organic processes, such as Diels Alder reactions [2], Michael additions [3] or aldol condensations [4], to name a few. Wittig-type reactions are commonly used to prepare α,β-unsaturated aldehydes and nitriles [5], but a variety of other methods have also been reported, including, for example, catalytic oxidation of allylic alcohols [6], Ru-catalysed isomerisation of propargylic alcohols [7], or synthesis via Grignard reagents [8]. In addition, cross-metathesis (CM) reactions have been applied to prepare α,β-unsaturated aldehydes and nitriles, but this route is still relatively unexplored, in particular with substrates containing electron deficient double bonds such as acrolein and related α-carbonyl compounds [9]. It should be noted that synthetic routes involving cross-metathesis have been shown to be advantageous over more conventional methods. For example, they allow direct access to chiral pharmaceutical intermediates without the need for a chiral resolution step [9c].

It has been established that α,β-unsaturated aldehydes and nitriles do not react with Grubbs' first generation catalyst (**1**, Chart 1) [10], but are able to react in cross-metathesis reactions using ruthenium catalysts with NHC ligands (e.g., **2**–**3** in Chart 1). This is attributed to the greater electron donating ability of the NHC ligand compared to tricyclohexylphosphine (PCy_3) [10a]. Thus, good yields of CM products using NHC-Ru catalysts have been reported, for example, in reactions involving acrolein, methacrolein, acrylic acid, crotonaldehyde or acrylates [9b–e, 9g, 11]. Cross-metathesis reactions using acrylonitrile as substrate are more common and include processes using Schrock's molybdenum catalyst [12], as well as a variety of NHC-ruthenium catalysts [9g,13]. As in the case of acrolein, acrylonitrile shows poor reactivity with catalyst **1** [10c,13e]. Some of these reactions have been reported to work in neat conditions [11].

Selective formation of the cross-metathesis product can be achieved by combining an olefin that shows slow or no self-metathesis (classified as Type II/III olefins) with an olefin able of fast self-metathesis or Type I (e.g., 1-alkenes; see Scheme 1) [14]. In these reactions, the Type I homo-dimer may form initially [Scheme 1(b)], but undergoes secondary metathesis with the Type II/III olefin to produce the desired CM product [Scheme 1(c)]. Although the classification of a particular olefin depends on the catalyst, acrolein and related compounds, including acrylonitrile, are generally classified as Type II or Type III olefins [14].

Ruthenium-catalysed cross-coupling reactions with terminal olefins almost always occur with a high degree of *E*-selectivity [15],

---

* Corresponding author. Tel.: +44 028 90974436; fax: +44 028 90976524.
** Corresponding author. Tel.: +44 028 90974592; fax: +44 028 90976524.
E-mail addresses: c.hardacre@qub.ac.uk (C. Hardacre), c.lagunas@qub.ac.uk (M.C. Lagunas).

http://dx.doi.org/10.1016/j.apcata.2014.08.032
0926-860X/© 2014 Elsevier B.V. All rights reserved.

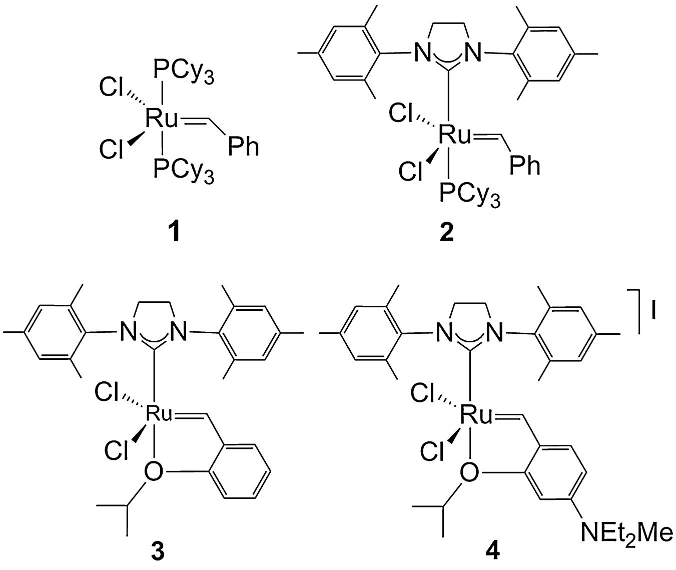
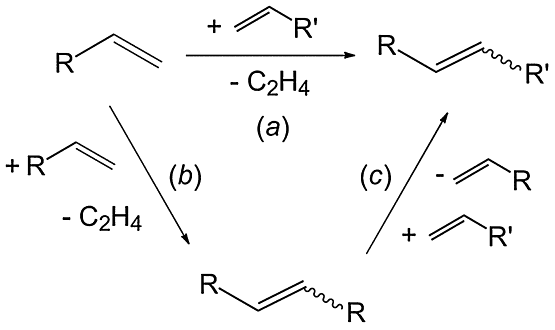


Chart 1. Grubbs' first (**1**) and second (**2**) generation catalysts, and Hoveyda-Grubbs' catalysts (**3**, **4**).

although strategies to favour *Z*-selectivity have been developed [16]. Acrylonitrile, however, generally produces cross-metathesis products where the *Z* isomer is predominant, and it has been proposed that this *Z*-stereoselectivity must be kinetically controlled and most likely related to the small size and/or electron-withdrawing properties of the cyano group [12,13b,13e,17]. A few examples in which cross-metathesis reactions of acrylonitrile have produced the *E*-isomer as the major component have also been reported [18].

In order to improve recyclability of Grubbs' catalysts, ionic liquids (ILs) have been used as reaction media or for the immobilisation of the catalyst onto silica (e.g., using the 'supported ionic liquid phase' or SILP concept) [19]. For example, Grubbs' second generation catalyst **2** has shown enhanced activity in CM reactions in ionic liquids, compared to dichloromethane [20], and Hoveyda-Grubbs' type catalysts immobilised onto silica gave excellent yields in RCM metathesis reactions [19a]. In both cases, the catalysts could be easily recycled up to four times. In addition to conventional Grubbs' catalysts, ionic analogues have been developed (e.g., complex **4** in Chart 1) with the aim of increasing the catalyst's retention time in the ionic liquid, thus improving its recyclability and reducing leaching into the organic phase [21].

In this paper, a series of α,β-unsaturated aldehydes and nitriles of significant interest in the fragrance industry have been prepared using Grubbs' catalysts in cross-metathesis reactions of electron-deficient olefins (i.e., acrolein, crotonaldehyde, methacrolein, and acrylonitrile) with various 1-alkenes. Detailed kinetic and mechanistic studies have been performed on the cross-metathesis of acrolein with 1-decene and attempts to recycle the catalyst by using ILs are also reported. Of particular interest are the reactions using 2-allyloxy-6-methylheptane, as this substrate has not previously being used in cross-metathesis. The product from its reaction with acrolein, 6,10-dimethyl-5-oxoundec-2-enal, is of use in the synthesis of a novel fragrance material [22].



Scheme 1. Reactions involved in the cross-metathesis of olefins of Type I (RC=CH$_2$) and Type II/III (R′C=CH$_2$).

2. Experimental

2.1. Catalyst preparation

Catalysts **1**–**3** were obtained from Aldrich and used as received. Ionic catalyst **4** was synthesised following a literature procedure [21e]. The ionic liquids were prepared as described elsewhere [23]. Catalysts and ionic liquids were handled and stored in a glovebox.

2.1.1. Preparation of supported catalyst 3

Buffered silica was first prepared by stirring 5 g of the corresponding Davicat silica 1 or 2 (see Table 4) in distilled water (100 mL) with a BHD buffer capsule (pH 7) for 2 h at 25 °C. The silica was then filtered, washed with distilled water (3 mL × 20 mL) and dried in an oven (85 °C) on a watch-glass overnight. Catalyst **3** (6.7 mg, 0.01 mmol) was weighed into a Schlenk flask, under nitrogen. To this was added dichloromethane (5 mL), [C$_4$mim][NTf$_2$] (0.1 mL) and pre-dried silica (0.2 g, either untreated or buffered). This mixture was stirred for 10–15 min and the dichloromethane then removed under vacuum. Further drying under vacuum (4–5 h) produced the supported catalyst as a green powder.

2.2. Catalyst characterisation

Catalyst **4** was characterised by NMR spectroscopy. Its ^{1}H and ^{13}C NMR spectra were in good agreement with literature data [24]. NMR spectra were performed on either a Bruker Avance DRX (300 MHz) or DPX (500 MHz) spectrometer.

ICP analyses were performed at the ASEP unit in Queen's University Belfast. Samples to determine the amount of catalyst dissolved in various solvents were prepared by adding 9 mg (0.014 mmol) of catalyst **3** and 10 mL of solvent (dichloromethane, 1,2-dichloroethane, ethyl acetate, methanol, tetrahydrofuran, 2-propanol or pentane) into a Schlenk flask, under nitrogen. The mixtures were stirred for 10 min and then passed through a sintered glass funnel. Any undissolved catalyst remaining on the funnel was washed with dichloromethane (5 mL) into a crucible. The dichloromethane was allowed to evaporate and the remaining residue in the crucible was submitted for ICP-MS analysis. A sample was also analysed containing the same amount of catalyst (9 mg, 0.014 mmol) and 10 mL of dichloromethane but no filtration was undertaken, giving a value of 250 ppm of Ru. Compared with this standard the % of undissolved Ru in each solvent was calculated: dichloromethane (2%), 1,2-dichloroethane (8%), ethyl acetate (14%), methanol (17%), tetrahydrofuran (49%), 2-propanol (50%) and pentane (88%).

2.3. Catalytic tests

2.3.1. General

The reagents 1-decene, 1-octene, 1-hexene, 2-allyloxy-6-methylheptane, acrolein, methacrolein, crotonaldehyde, acrylonitrile and decane (all obtained from Aldrich), and solvents (dichloromethane, 1,2-dichloroethane, ethyl acetate, 2-propanol and pentane) were dried over activated molecular sieves (85 °C) and degassed with nitrogen for 1–2 h prior to use. Methanol and tetrahydrofuran were collected from a MBRAUN manual solvent purification system, under nitrogen, and dried over molecular sieves (85 °C). All other reagents were obtained from Aldrich and used as received. GC-FID samples were analysed using a Hewlett Packard 6890 GC fitted with an RTX-5 column (30 m, 0.25 μm diameter). GC–MS (Perkin Elmer Turbo Mass) was performed using a PE5MS column (length, 30 m; thickness, 0.25 μm; IDO, 0.32 mm). Decane was used as internal standard for GC analysis.

2.3.2. Reaction of acrolein and 1-decene in organic solvents

2.3.2.1. General procedure. Unless otherwise stated, this procedure was applied to all the reactions described below. The catalyst was weighed into a Schlenk flask, in a glovebox. The flask was then taken out of the glovebox and opened to a Schlenk line, under nitrogen. To this, the corresponding solvent was added, followed by decane (internal standard) and the substrates required in each case (see below). The reaction mixture was stirred under nitrogen, at *r.t.*, for 24 h. During this time, the Schlenk flask was kept opened to the nitrogen line to allow volatile by-products (ethene or propene) to escape. Samples (0.5 mL) for GC analysis were taken approximately every 10 min for 1 h, and then every hour for 8 h. A final sample was taken after 24 h. Each sample was quenched with tert-butylhydroperoxide (TBHP, 1 drop), diluted with diethyl ether (1.6 mL) and filtered through a silica plug prior to being submitted for GC analysis. An example of a GC trace obtained in these reactions is shown in Appendix A (Fig. A1).

2.3.2.2. Variation of catalyst. To the corresponding catalyst **1**–**4** (0.1 mmol, 10 mol%), the following were added: dichloromethane (20 mL), decane (0.2 mL, 1 mmol), 1-decene (0.2 mL, 1 mmol) and acrolein (0.07 mL, 1 mmol).

*2.3.2.3. Variation of catalyst (**3**) loading.* To the corresponding amount of catalyst **3** [2.2 mg (0.35 mol%), 6.7 mg (1.0 mol%), 9.0 mg (1.4 mol%), 21.2 mg (3.5 mol%), 42.5 mg (7 mol%), or 85 mg (14 mol%)] was added dichloromethane (20 mL), decane (0.2 mL, 1 mmol), 1-decene (0.2 mL, 1 mmol) and acrolein (0.07 mL, 1 mmol).

2.3.2.4. Variation of solvent. The same amount of catalyst **3** (21.2 mg, 3.5 mol%) was added into six Schlenk flasks. To each flask were added 20 mL of the corresponding solvent (1,2-dichloroethane, ethyl acetate, pentane, tetrahydrofuran, methanol or 2-propanol) followed by decane (0.2 mL, 1 mmol), 1-decene (0.2 mL, 1 mmol) and acrolein (0.07 mL, 1 mmol).

2.3.2.5. Variation of 1-decene:acrolein ratio. To a Schlenk flask loaded with catalyst **3** (21.2 mg, 3.5 mol%) were added dichloromethane (20 mL), decane (0.2 mL, 1 mmol), 1-decene (0.2 mL, 1 mmol) and acrolein [0.14 mL (2 mmol) or 0.35 mL (5 mmol)].

2.3.2.6. Variation of [1-decene]. The same amount of catalyst **3** (9 mg, 1.4 mol%) was added into three Schlenk flasks. To each flask was added dichloromethane (40 mL, 5 mL or 2 mL), decane (0.2 mL, 1 mmol), 1-decene (0.2 mL, 1 mmol) and acrolein (0.07 mL, 1 mmol).

2.3.2.7. Varying the catalyst loading in ethyl acetate. To a Schlenk flask loaded with catalyst **3** [6.7 mg (1.0 mol%), 9.0 mg (1.4 mol%), 21.2 mg (3.5 mol%), 42.5 mg (7 mol%)] were added ethyl acetate (20 mL), decane (0.2 mL, 1 mmol), 1-decene (0.2 mL, 1 mmol) and acrolein (0.07 mL, 1 mmol).

2.3.2.8. Isolation of undec-2-enal. To a Schlenk flask loaded with catalyst **3** (21.2 mg, 0.034 mmol; 3.5 mol%) dichloromethane (20 mL) was added, along with 1-decene (0.2 mL, 1 mmol) and acrolein (0.07 mL, 1 mmol), and the reaction mixture was stirred, under nitrogen, for 24 h. Most of the solvent was removed under vacuum and the remaining mixture was then passed through a silica column (5 cm × 2.5 cm) prepared with hexane. Hexane (20 mL) was flushed through the column followed by a 20:80 mixture of diethyl ether:hexane (ca. 100 mL). Fractions containing the desired product were identified by TLC, when eluting with the diethyl ether:hexane mixture. These fractions were combined, and the solvent removed under vacuum. The remaining residue was then dried under vacuum overnight, yielding 132 mg (0.78 mmol; 78%) of undec-2-enal (NMR data included in Appendix A).

2.3.3. Mechanistic studies

Unless otherwise indicated, samples for GC analysis were taken and treated as described above (Section 2.3.2.1).

2.3.3.1. Reactions with added products. To a Schlenk flask containing catalyst **3** (9 mg, 1.4 mol%), under nitrogen, were added dichloromethane (20 mL), decane (0.2 mL, 1 mmol), 1-decene (0.2 mL, 1 mmol) and acrolein (0.07 mL, 1 mmol), and the resulting mixture was stirred. To this, a solution of undec-2-enal (0.2 mL, 1 mmol) or octadec-9-ene (269.6 mg, 1 mmol) in dichloromethane (5 mL), under nitrogen, was added slowly over 1 h (ca. 1 mL every 10 min).

2.3.3.2. Slow addition of catalyst. A solution of catalyst **3** (10.6 mg, 1.7 mol %) in dichloromethane (6 mL) was prepared in a Schlenk flask. This was added slowly, either over 3 h (i.e., 1 mL every 30 min) or over 4.5 h (ca. 0.7 mL every 30 min), to a Schlenk flask containing dichloromethane (20 mL), decane (0.2 mL, 1 mmol), 1-decene (0.2 mL, 1 mmol) and acrolein (0.07 mL, 1 mmol). Samples (0.5 mL) for GC analysis were taken every 30 min during addition of catalyst and every hour after for 8 h; a final sample was taken after 24 h.

2.3.3.3. Addition of fresh catalyst. To a Schlenk flask containing catalyst **3** (4.5 mg, 0.007 mmol), under nitrogen, were added dichloromethane (20 mL), decane (0.2 mL, 1 mmol), 1-decene (0.2 mL, 1 mmol) and acrolein (0.07 mL, 1 mmol). The resulting mixture was stirred for 4 h, after which, more catalyst **3** (4.5 mg, 0.007 mmol) was added.

2.3.3.4. Delayed addition of 1-decene. The same amount of catalyst **3** (9 mg, 1.4 mol%) was added into two Schlenk flasks together with dichloromethane (20 mL), decane (0.2 mL, 1 mmol) and acrolein (0.07 mL, 1 mmol). The resulting mixtures were stirred and 1-decene (0.2 mL, 1 mmol) was added after 1 h to one of the flasks, and after 2 h to the other.

2.3.4. Reactions with various substrates

To a Schlenk flask loaded with catalyst **3** (13.4 mg, 2 mol%) were added dichloromethane (40 mL), decane (0.2 mL, 1 mmol) and either 1-decene, 1-octene, 1-hexene or 2-allyloxy-6-methylheptane (1 mmol) along with acrolein, crotonaldehyde, methacrolein or acrylonitrile (1 mmol). The reaction mixtures were stirred, under nitrogen, for 24 h. Samples for GC analysis were taken as described above (Section 2.3.2.1). In order to isolate the cross-metathesis products the reactions were carried out in the same way, in dichloromethane, but samples were not taken for GC analysis. In each case, most of the solvent was removed under vacuum after 24 h, and the remaining mixture passed through a silica column (5 cm × 2.5 cm) prepared with hexane. Hexane (20 mL) was flushed through the column followed by diethyl ether:hexane (20:80; ca. 100 mL). Fractions containing the desired product were identified by TLC, when eluting with the diethyl ether:hexane mixture. These fractions were combined, and the solvents removed under vacuum. The remaining

Table 1
Reaction data for the reaction between acrolein and 1-decene.[a]

Entry	Variant		Conversion of 1-decene (%)	Yield of undec-2-enal (%)	Selectivity	
					Undec-2-enal (CM)	Octadec-9-ene (SM)
1a	Catalyst (10 mol%)[b]	1	30	3	15	85
1b		2	54	48	98	2
1c		3	88	70	95	5
1d		4	60	59	94	6
1e	Catalyst 3 loading (dichloro-methane)[b]	14 mol%	88	80	95	5
1f		7.0 mol%	87	71	92	8
1g		3.5 mol%	88	69	95	5
1h		1.4 mol%	79	68	98	2
1i		1.0 mol%	74	63	98	2
1j		0.35 mol%	45	39	98	2
1k	Solvent[b,c]	1,2-Dichloroethane	87	67	92	8
1l		Ethyl acetate	74	56	93	7
1m		Pentane	69	40	91	9
1n		Tetrahydrofuran	52	37	96	4
1o		Methanol	37	5	66	34
1p		2-Propanol	16	12	94	6
1q	1-Decene: acrolein[d]	1:2	89	72	97	3
1r		1:5	89	74	96	4
1s	[1-Decene][e]	0.025 M	87	81	99	1
1t		0.2 M	77	69	98	2
1u		0.5 M	64	67	99	1
1v	Catalyst 3 loading (ethyl acetate)[b]	7.0 mol%	80	60	96	4
1x		1.4 mol%	45	49	97	3
1y		1.0 mol%	35	42	97	3

[a] All reactions performed at r.t. in dichloromethane (20 mL), unless stated otherwise. All data obtained by GC analysis after 8 h. The estimated error for the GC yields is ±2%.

[b] 1-Decene:acrolein = 1:1 (1.0 mmol).

[c] Reactions in 20 mL of solvent and 3.5 mol% catalyst **3**.

[d] 1.0 mmol of 1-decene, 3.5 mol% catalyst **3**.

[e] 1-Decene:acrolein = 1:1 (1.0 mmol); 1.4 mol% catalyst **3** in 40 mL (*1s*), 5 mL (*1t*) or 2 mL (*1u*) of dichloromethane.

residue was then dried under vacuum overnight, yielding the corresponding cross-metathesis product (see Table 3 for isolated yields and Appendix A for NMR data of the products derived from 2-allyloxy-6-methylheptane).

2.3.5. Reactions using ionic liquids

2.3.5.1. Cross-metathesis reactions in ionic liquids (ILs). To a Schlenk flask containing catalyst **3** (3.4 mg, 2 mol%), under nitrogen, were added 10 mL of the corresponding ionic liquid ([1-butyl-3-methylimidazolium][X], X = NTf_2 (Tf = CF_3SO_2), PF_6, OTf; or [A][NTf_2], A = 1-butyl-2,3-dimethylimidazolium, 1-butyl-1-methyl-pyrrolidinium, methyl(trioctyl)ammonium, tetradecyl(trihexyl)phosphonium) followed by decane (0.05 mL, 0.25 mmol), 1-decene (0.05 mL, 0.25 mmol) and acrolein (0.02 mL, 0.28 mmol), and the resulting mixture was stirred at r.t. for 24 h. After this, the IL layer was extracted with pentane (3 mL × 10 mL). All the pentane extracts were combined and the solvent removed under vacuum. The residue was analysed by ^{1}H NMR spectroscopy. To begin a new reaction fresh substrates were added to the IL.

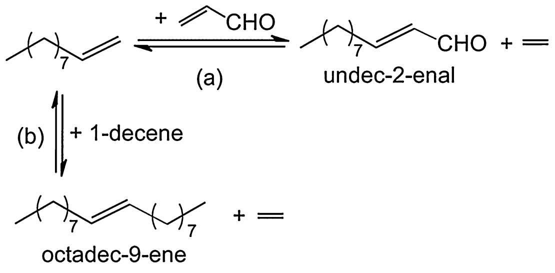
2.3.5.2. Cross-metathesis reactions in IL:DCM (1:1). To a Schlenk flask containing catalyst **3** (3.4 mg, 1.4 mol%) or **4** (6.5 mg, 3 mol%) under nitrogen, were added 5 mL of [C_4mim][NTf_2] and 5 mL of dichloromethane, followed by decane (0.05 mL, 0.25 mmol), 1-decene (0.05 mL, 0.25 mmol) and acrolein (0.02 mL, 0.28 mmol). The resulting mixture was stirred at r.t. for 24 h. After this, the dichloromethane was removed under vacuum and the IL layer was extracted with pentane (3 mL × 10 mL). All the pentane extracts combined and the solvent removed under vacuum. The residue was analysed by ^{1}H NMR spectroscopy. To begin a new reaction fresh dichloromethane and substrates were added to the IL.

*2.3.5.3. Reactions using supported catalyst **3** in pentane.* Catalyst **3** (6.7 mg, 2 mol%) was supported on Silica 1 or 2 (untreated or buffered) using the method described above. To this was added pentane (20 mL), decane (0.1 mL, 0.5 mmol), 1-decene (0.1 mL, 0.5 mmol) and acrolein (0.035 mL, 0.5 mmol). The reaction mixture was stirred, at r.t., for 6 h, under nitrogen. After this, the pentane layer was separated with a syringe and the supported catalyst was washed with pentane (3 mL × 20 mL). The solvent from the combined pentane extracts was removed under vacuum and the residue analysed by GC. For this, samples were quenched with tert-butylhydroperoxide (TBHP, 1 drop), diluted with diethyl ether (1.6 mL) and filtered through a silica plug prior to being submitted for GC analysis. The supported catalyst was recovered by drying under vacuum. To begin a new reaction, fresh pentane and substrates were then added to the silica-supported catalyst. This process was repeated twice for a total of three runs.

3. Results and discussion

3.1. Cross-metathesis between acrolein and 1-decene

The cross-metathesis reaction of acrolein and 1-decene was studied in the first instance (Scheme 2). The effect of varying the catalyst, solvent, concentration of 1-decene and ratio of starting materials was analysed. The results are summarised in Table 1. In all cases, the reactions yielded the cross-metathesis (CM) product, undec-2-enal (normally as the major product), together with the self-metathesis (SM) product of 1-decene (octadec-9-ene). As expected, self-metathesis of acrolein was not detected in any of the reactions [14]. The reactions took place with high *E*-selectivity and



Scheme 2. (a) Cross-metathesis (CM) and (b) self-metathesis (SM) products formed in the reaction between acrolein and 1-decene.

only this isomeric form of undec-2-enal was isolated, as indicated by ^{1}H NMR spectroscopy.

3.1.1. *Variation of catalyst*

The reaction between acrolein and 1-decene was carried out in the presence of ruthenium catalysts **1**–**4** (Chart 1, Fig. 1). All the reactions were performed, in the first instance, in dichloromethane at *r.t.* (8 h) and 10 mol% of catalyst (Table 1, entries *1a–1d*). Conversions between 30% (**1**) and 88% (**3**) were obtained, whereas the best yields of CM product, undec-2-enal, were achieved with Hoveyda-Grubbs' catalysts **3** (70%) and **4** (59%). Catalysts **2**–**4** all gave a high ratio of CM:SM product (with >94% selectivity of CM product), whereas the opposite was found for **1** (85% selectivity of SM product, octadec-9-ene). Given the above results, catalyst **3** was used in the optimisation studies (see below).

The mechanism for Grubbs' catalysed metathesis reactions involves coordination of the olefins to the metal and exchange of alkylidene groups through a 'ruthenacyclobutane' intermediate [10a,25]. In the case of Grubbs first (**1**) and second (**2**) generation catalysts, the initiation step involves the reversible dissociation of phosphine to form a catalytically active 14-electron complex, which will subsequently coordinate an olefinic substrate. Recoordination of free phosphine regenerates the initial 16-electron complex resulting in loss of activity. Although phosphine dissociation in catalyst **2** has been shown to be slower than for **1**, once dissociated, coordination of the olefin is more favourable than reattachment of the phosphine in the case of catalyst **2**. This often results in **2** being more active than **1** in metathesis reactions [25a]. The higher conversion of 1-decene obtained with catalyst **2** compared to **1** (Table 1, entries *1a,b*) agrees with the above mechanism. In addition, the better σ-donating ability of the NHC ligand in **2** compared to PCy_3 in catalyst **1** favours the *trans*-coordination of acrolein (an electron-poor olefin), allowing the cross-metathesis process to occur, whereas mainly self-metathesis of 1-decene is observed with catalyst **1** (unreactive towards acrolein). Similar variations in reactivity for catalysts **1** and **2** with electron-poor olefins have been reported before [9c,10, 26].

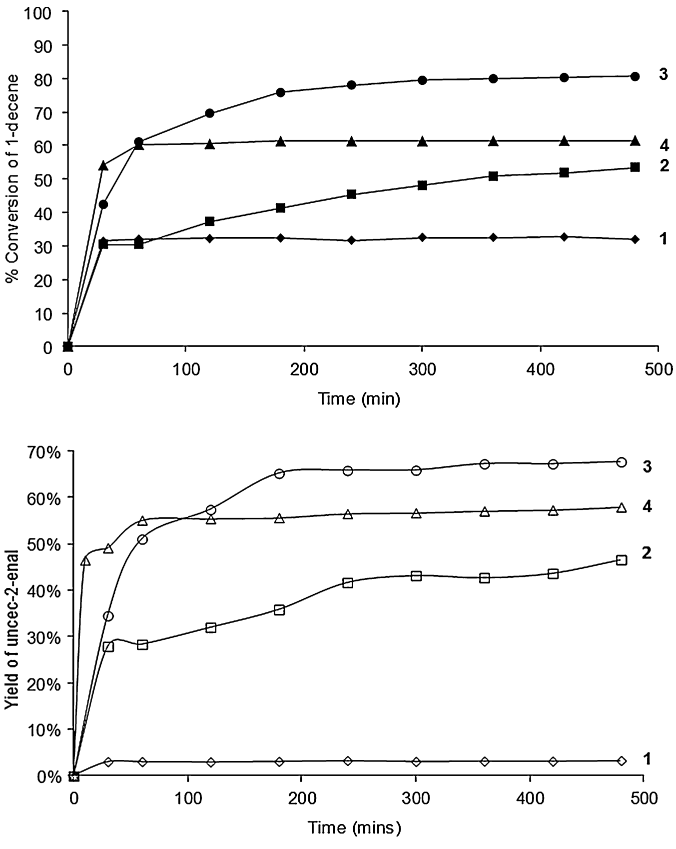


Fig. 1. Conversion of 1-decene (top) and formation of cross-metathesis product (bottom) in the reaction between acrolein and 1-decene in the presence of catalysts **1**–**4** in dichloromethane using 10 mol% of catalyst.

The phosphine-free Hoveyda-Grubbs' catalysts (such as **3** and **4**) are activated through de-coordination of the chelating oxo group of the styrenyl ligand, which can readily detach from the metal centre thus allowing the release of the styrene and attachment of an olefinic substrate [27]. Compared to phosphine, the styrenyl ligand is less effective at re-binding to the metal and, therefore, does not compete as efficiently with olefin substrates [27b]. Accordingly, catalyst **3** has been shown to be more active with electron-deficient olefins than second and first generation Grubbs' catalysts [27b,28]. The higher conversion of 1-decene obtained with catalyst **3** and **4** agrees with this (Table 1, entries *1c,d*). The inclusion of an electron-withdrawing group (EWG) in the benzylidene fragment (as in catalyst **4**) often increases the catalyst's activity, as the EWG weakens the O—Ru bond and favours the initiation of the catalytic reaction [17b,21e]. For example, catalyst **4** has shown higher activity than **3** in ring-closing metathesis reactions in dichloromethane as well as in more polar solvents [21e]. In the reaction of 1-decene with acrolein, however, conversion of 1-decene was lower with catalyst **4** than **3**. This may be related to poorer solubility of **4** in dichloromethane at the conditions used, although this was not investigated in detail.

3.1.2. *Catalyst loading*

A series of reactions were carried out with catalyst **3**, varying the catalyst loading in the range 0.35–14 mol% (Table 1, entries *1e–1j*). As expected, increasing the catalyst loading resulted in a gradual increase in conversion of 1-decene, which ranged between ca. 45% (using 0.35 mol% catalyst) and ca. 88% (using 14 mol%), as well as an increase in the yield of CM product (ranging from 39% to 80%). In all cases, the ratio of CM:SM product was high (>92% selectivity of CM product). However, the differences in conversion and yield in the reactions performed with catalyst loadings between 1.4 and 14 mol% are too small to justify the use of high amounts of catalyst. Therefore, catalyst loadings between 1.4 and 3.5 mol% were used in all subsequent experiments, as they provided the best balance of activity and yield of CM product per mole of catalyst.

3.1.3. *Variation of solvent*

Grubbs' catalysts are known to be affected by the nature of the solvent; for example, high coordinating ability of the solvent and the presence of protic functionalities are known to hinder metathesis reactions, whereas polar solvents often result in higher initiation rates [25a,29]. In order to study how these various factors affect the reaction of acrolein and 1-decene, the reaction was examined using 3.5 mol% catalyst **3** in 1,2-dichloroethane, ethyl acetate, pentane, tetrahydrofuran, methanol and 2-propanol (Table 1, *1k–1p*), and compared with the results obtained, at the same conditions, in dichloromethane (entry *1g*). The effect of catalyst solubility was also considered.

The reactions in methanol and 2-propanol produced the lowest conversions of 1-decene ($\leq$37%) and yields of undec-2-enal ($\leq$12%). The reaction in methanol also resulted in the lowest ratio (66:34) between the CM and SM products, with all the other solvents giving a high selectivity, >90%, of undec-2-enal. The best conversions of 1-decene (87–88%) and yields (67–69%) were obtained in dichloromethane or 1,2-dichloroethane, followed by ethyl acetate (74% conversion of 1-decene, 56% yield of unde-2-enal).

During the reactions, it was clearly observed that catalyst **3** did not fully dissolve in some of the solvents. In order to analyse the catalyst solubility in more detail, ICP studies were undertaken following catalyst dissolution in all solvents. These showed that ca. 88% of Ru remained undissolved in pentane, whereas 2-propanol and tetrahydrofuran dissolved ca. 50%. Better catalyst solubility was found in methanol and ethyl acetate (14–17% of Ru remained undissolved); with 1,2-dichloroethane and dichloromethane giving the highest solubility (8% and 2% of Ru undissolved, respectively). The same trend, with comparable amounts of undissolved Ru remaining, was also found in the case of catalyst **1** during studies on the dimerisation reaction of cyclooctene [23]. The insoluble rest of the catalyst may play a role in the catalytic process (e.g., via a heterogeneous reaction and/or as an additional source of catalytic species during the reaction). However, other factors should also be considered.

In addition to low catalyst solubility, the poor activity observed in protic solvents methanol and 2-propanol might be attributed to their ability to degrade the catalyst [30]. In agreement with previous work, polar solvents dichloromethane, 1,2-dichloroethane and ethyl acetate gave the best results [23,25a]. However, the lower conversion and yield in tetrahydrofuran, compared with the other polar solvents, may be related to the lower catalyst solubility in tetrahydrofuran. The coordinating nature of the solvent does not appear to be a determining factor, since both strongly and weakly coordinating solvents (e.g., ethyl acetate and dichloromethane, respectively) gave good results. It should be noted, however, that pentane showed relatively good activity despite having the lowest catalyst solubility. This may be related to its non-coordinating nature.

The high ratio of self-metathesis product obtained in methanol compared with all the other solvents tested, may be due to the coordinating ability of methanol, although a similar effect is not seen in ethyl acetate, tetrahydrofuran or 2-propanol, also able to bind to the ruthenium centre through their oxygen atoms. The smaller size of methanol may favour its coordination to the metal, thus hindering coordination of acrolein and/or octadec-9-ene to the catalyst to form the CM product.

Overall, the good results obtained in dichloromethane and 1,2-dichloroethane for the cross-metathesis reaction may be attributed to a combination of polarity, good catalyst solubility, and weakly-coordinating properties. However, the lower toxicity of ethyl acetate, compared with the chlorinated solvents, makes it particularly interesting for industrial applications. Herein, further work was carried out mainly using dichloromethane, although the effect of catalyst loading in ethyl acetate was also analysed.

3.1.4. *Influence of concentration of substrate and ratio of starting materials*

In order to assess if the formation of cross-metathesis vs. self-metathesis product was dependant of the ratio of the starting materials and/or the concentration of substrate, the reaction was monitored at various 1-decene:acrolein ratios, and as a function of substrate concentration, using catalyst **3** in dichloromethane.

CM reactions often need an excess of one of the reagents to shift the equilibrium and give good CM product yields [14]. Thus, in an attempt to improve the yield of undec-2-enal, reactions with an excess of acrolein (i.e., 2 and 5 equiv.) and 3.5 mol% of catalyst **3** were carried out in dichloromethane (Table 1, entries *1q–1r*). There were no significant differences in the results between the 1:2 and 1:5 reactions, as both processes resulted in good conversions of 1-decene (89%) and yield of undec-2-enal (72–74%, 96–97% selectivity). Interestingly, these results are also comparable with those of the 1:1 reaction under the same conditions (88% conversion, 69% yield; 95% selectivity; entry *1g*). Therefore, the ratio of the reactants does not appear to significantly affect the results and there are not significant benefits in using excess acrolein, which is toxic and a lachrymator. This is in contrast with previous reports on CM reactions involving acrolein, where excess of the olefin is required [9b,9e].

The 1:1 reaction between acrolein and 1-decene was carried out in varying volumes of dichloromethane, while maintaining constant the catalyst loading (1.4 mol%). The results are summarised in Table 1 as a function of the concentration of 1-decene (entries *1s–1u*; see entry 1 h for [1-decene] = 0.05 M). Increasing the concentration of 1-decene resulted in a gradual decrease in conversion of 1-decene from 87% to 64%. The best yield of CM product (81%) is also obtained at the lowest concentration of 1-decene (0.03 M), whereas the reactions at higher concentrations of substrate all gave similar yields (67–69%). The selectivity towards undec-2-enal, however, remained unaffected and was high (98–99%) in all cases. Loss of activity with increased substrate concentration has been previously shown for Ru catalysts in cross-metathesis reactions. This could be related to poisoning of the catalyst [13e].

3.1.5. *Effect of catalyst loading in ethyl acetate*

As indicated in Section 3.1.3, the best non-chlorinated solvent for the reaction was ethyl acetate and would, therefore, be more suitable for industrial use. In order to optimise the results in this solvent, the 1:1 reaction between acrolein and 1-decene was studied at various catalyst loadings ranging from 1 to 7 mol%, using catalyst **3** (Table 1, see entries *1v–1y* and *1l*). The trends observed were similar to those seen in dichloromethane, discussed above. All the reactions gave good selectivity to undec-2-enal (ca. 97%) and the conversion and yield of undec-2-enal increased with catalyst loading, as expected (i.e., conversion of 1-decene increased from 35% to 80% and yield of CM product from 42% to 60%). The best overall results per mol of catalyst were obtained at a loading of 3.5 mol% (74% conversion, 56% yield, entry *1l*); with highest catalyst loading (7 mol%, entry *1v*) leading to only a small improvement in conversion (80%) and yield (60%).

3.1.6. *Isolation of undec-2-enal*

Based on the above studies and in order to isolate the CM product, undec-2-enal, in good yield, the 1:1 reaction between 1-decene and acrolein was carried out using 3.5 mol% of catalyst **3**, in dichloromethane (20 mL) for 24 h. Purification of the crude product by column chromatography gave undec-2-enal with an isolated yield of ca. 78%. The ^{1}H NMR spectrum of the isolated product agreed well with that reported for *E*-undec-2-enal [31].

3.1.7. *Mechanistic studies*

None of the reactions discussed above resulted in complete conversion of 1-decene, with the highest conversion achieved being 89% (Table 1). A series of studies were carried out to determine the cause of these incomplete conversions, as well as to shed light on the mechanism of the reaction. In particular, the potential poisoning of the catalyst with products undec-2-enal and octadec-9-ene was analysed, as well as the effect of a delayed addition of 1-decene or of the gradual addition of catalyst to the reaction.

Reactions between 1-decene and acrolein (1:1), with added undec-2-enal or octadec-9-ene (i.e., 1 equiv. added over 1 h), were

Table 2

Summary of the results for the reactions between acrolein and 1-decene with added products (entries *2a–2b*), varying the catalyst addition method (entries *2c–2e*), and with delayed addition of 1-decene (entries *2f–2g*).[a] To facilitate comparison, data taken from Table 1 for a 'standard' reaction performed at the same conditions are also included (entry 2 h).[a]

Entry	Reaction	Conversion of 1-decene (%)	Yield of undec-2-enal (%)	Selectivity	
				Undec-2-enal (CM)	Octadec-9-ene (SM)
2a	Added undec-2-enal[b]	53	57	98	2
2b	Added octadec-9-ene[b]	72	39	56	44
2c	Catalyst added gradually over 3 h	88	81	99	1
2d	Catalyst added gradually over 4.5 h	84	76	99	1
2e	Fresh catalyst added after 4 h	85	80	99	1
2f	1-Decene added after 1 h	86	82	99	1
2g	1-Decene added after 2 h	71	75	98	2
2h	Standard reaction[c]	79	68	98	2

[a] All reactions performed at r.t. for 8 h, in dichloromethane (20 mL), using 1.4–1.7 mol% catalyst **3**, 1-decene:acrolein = 1:1 (1 mmol). All data obtained by GC analysis. The estimated error for the GC yields is ±2%.

[b] Values show actual amount of products formed during the reaction, as the amount of products added have been subtracted from the results.

[c] As in entry *1h* in Table 1.

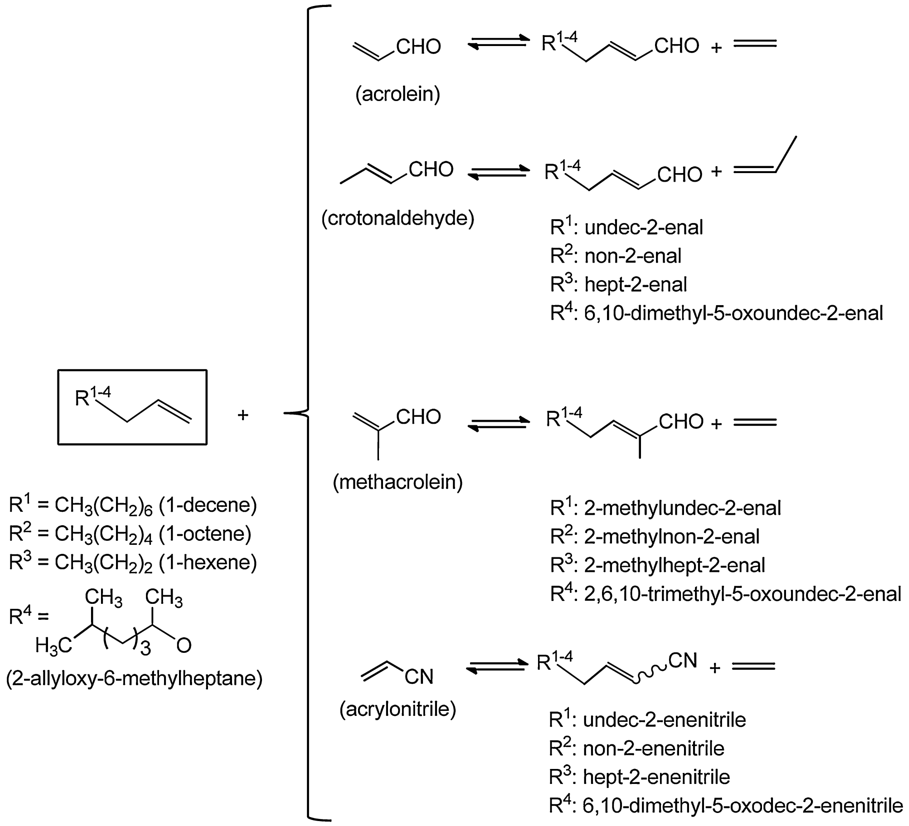
carried out in dichloromethane, using 1.4 mol% catalyst **3** (Table 2, entries *2a–b*). Compared with the same reaction without added products (entry *2h*), the addition of undec-2-enal significantly reduced the conversion of 1-decene (from 79% to 53%) and the yield of undec-2-enal (from 68% to 57%), while maintaining high selectivity towards the cross-metathesis product (98%). It appears, therefore, that undec-2-enal is able to deactivate the catalyst, thus decreasing conversion and yield of CM product. In contrast, the addition of octadec-9-ene had little effect on the conversion of 1-decene (72%), indicating that the catalyst is not deactivated by the SM product. The reaction, however, resulted in formation of significantly less undec-2-enal (39%) and more octadec-9-ene (i.e., CM:SM = 56:44). It appears that octadec-9-ene added to the reaction disfavours pathways (a) and/or (c) (Scheme 1) and leads to the formation of less cross-metathesis product and more homo-dimer. Although the mechanism of this process is currently unknown, it may involve attachment to the catalyst of octadec-9-ene when present at high enough concentration. It should be noted that the self-metathesis of 1-decene in analogous conditions (i.e., 1.4 mol% of catalyst **3** in dichloromethane) resulted in only 5% conversion of 1-decene. Relatively low conversions of 1-decene have previously been reported using the Hoveyda-Grubbs' catalyst (i.e., 57% conversion obtained in toluene at 80 °C, Ru/1-decene = 1:100), attributed to gradual catalyst deactivation [32].

In order to improve conversion by reducing the possibility of catalyst deactivation by undec-2-enal, two reactions between 1-decene and acrolein in dichloromethane were then performed wherein catalyst **3** (1.4 mol%) was added gradually over 3 h or 4.5 h (Table 2, entries *2c* and *2d*). In a separate experiment, 0.7 mol% of **3** was added at the beginning of the reaction with a further 0.7 mol% being added after 4 h (Table 2, entry *2e*). In all three reactions, comparable conversions of 1-decene (85–88%), yields of undec-2-enal (76–81%), and selectivity (99%) were obtained. Overall, these results are slightly better than the standard procedure, where all the catalyst is added at the start (entry *2h*), indicating that some catalyst decomposition takes place during the reaction.

Finally, the effect of adding the acrolein to the catalyst first, for either 1 h or 2 h, before addition of 1-decene (Table 2, entries *2f* and *2g*, respectively), was investigated, and results compared with a standard reaction in the same conditions (entry *2h*). After 1 h, acrolein does not appear to have degraded the catalyst, as it gives the best conversion of 1-decene (86%) and yield of undec-2-enal (82%), compared with 79% conversion and 68% yield, when both starting materials are added together at the start. Delaying the addition of 1-decene for another hour, however, did not improve the conversion (71%) and also led to a decrease in the yield of undec-2-enal to 75%. The selectivity towards the CM product remains high in all cases (98–99%); and none of the reactions showed self-metathesis of acrolein. The improved performance of catalyst **3** following mixing with acrolein for 1 h suggests that acrolein activates the catalyst by adding onto it. A longer catalyst-acrolein reaction time results in some deactivation, probably due to decomposition of the catalyst. It has been shown that propagating species of the type [Ru]═CH(CO)R only form in a small percentage and rapidly decompose [9b], or are not detected at all during the process [9d]. On this basis, [Ru]═CH(CO)R intermediates are not considered responsible for the bulk of product formation in metathesis reactions [9b,9d]. Interestingly, our results indicate that formation of an analogous catalyst-acrolein species of the type [Ru]═CH(CO)H, although short-lived, has a significant effect on the performance of the catalyst.

3.2. *Cross-metathesis reactions with various substrates*

The cross-metathesis of acrolein with three other alkenes, 1-hexene, 1-octene, and 2-allyloxy-6-methylheptane was investigated using catalyst **3**. In addition, other type II/III olefins [14], including crotonaldehyde, methacrolein and acrylonitrile, were used instead of acrolein as starting materials (Scheme 3). All the reactions produced the expected cross-metathesis products, although the yields varied in a wide range, from 1% to 71% (Table 3). As observed in the acrolein:1-decene reactions discussed above, no self-metathesis product of the α,β-unsaturated aldehyde/nitrile was detected in any of the reactions, whereas formation of the alkenes' self-metathesis products was seen in all cases, with the exception of 1-hexene. The fact that the self-metathesis product of 1-hexene is not observed is surprising, in particular in the reaction with methacrolein which appears to favour the self-metathesis of the other olefins. The reasons for this behaviour are currently unclear. The homo-dimer of 1-hexene may well form in the reactions, but the smaller size of this alkene may favour a rapid secondary metathesis reaction to form the CM product, according to Scheme 1c. A series of cross-metathesis reactions between 1-hexene and methyl vinyl ketone using various Ru-NHC catalysts have been reported to produce only traces of the self-metathesis product of methyl vinyl ketone together with the cross-metathesis product. The self-metathesis of 1-hexene was only observed in a few cases where conversion was incomplete [33]. It should be also noted that in other CM reactions reported in the literature, the homo-dimer of 1-hexene has been observed. For example, the 2:1 reaction between acrylonitrile and 1-hexene using the pyridine-containing catalyst [RuCl(═CHPh){1,3-*bis*(2,6-dimethylphenyl)-4,5-dihydroimidazol-2-ylidene}$(py)_2$] (in dichloromethane at 45 °C), results in 5–7% yield of self-metathesis product. In addition, the CM product, hept-2-enenitrile, was obtained at 37% and 51% yield using 2 mol%



Scheme 3. Cross-metathesis (CM) of 1-hexene, 1-octene, 1-decene, and 2-allyloxy-6-methylheptane with various α,β-unsaturated aldehydes and acrylonitrile. Note that the reactions with acrolein and crotonaldehyde produce the same CM products but ethene or propene is formed as by-product, respectively.

and 10 mol% of catalyst, respectively [17a]. These results are comparable to that found herein (i.e., 42% yield, using 2 mol% of catalyst **3**; see below).

All the cross-metathesis products were isolated using a similar method to that described above for undec-2-enal (Section 3.1.6), and characterised by ^{1}H and ^{13}C NMR spectroscopy. In all cases, the isolated yields were comparable with those determined by GC (Table 3). With the exception of the derivatives of 2-allyloxy-6-methylheptane (Scheme 3, R^4), all the products had previously been reported, and their ^{1}H and ^{13}C NMR spectra were consistent with the published data [8,17a, 34]. As expected, only the *E* isomer of the CM products was observed in the reactions with the α, β-unsaturated aldehydes, whereas the reactions with acrylonitrile produced in all cases a mixture of the *Z* and *E* isomers of the corresponding α,β-unsaturated nitrile. This predominance of the *Z* isomer in cross-metathesis reactions involving

Table 3
Reaction data for the reactions 1-decene, 1-octene, 1-hexene and 2-allyloxy-6-methylheptane with various substrates.[a]

Entry	Reaction		Conversion (%)[b]	Yield of CM product [isolated yield] (%)	Selectivity[c]	
					CM product	SM product
3a	1-Decene	Crotonaldehyde	80	65 [71]	91	9
3b		Acrylonitrile	60	70 [80]	99	1
3c		Methacrolein	42	24 [30]	59	41
3d	1-Octene	Acrolein	77	71 [75]	99	1
3e		Crotonaldehyde	80	47 [51]	90	10
3f		Acrylonitrile	62	56 [65]	99	1
3g		Methacrolein	43	28 [35]	63	37
3h	1-Hexene	Acrolein	74	52 [60]	100	0
3i		Crotonaldehyde	71	49 [55]	100	0
3j		Acrylonitrile	55	42 [48]	100	0
3k		Methacrolein	30	16 [25]	100	0
3l	2-Allyloxy-6-methylheptane	Acrolein	76	33 [33]	92	8
3m		Crotonaldehyde	43	12 [15]	83	17
3n		Acrylonitrile	19	3 [5]	85	15
3o		Methacrolein	20	1 [4]	18	82

[a] All reactions performed at r.t. for 8 h, in dichloromethane (40 mL), using ca. 2 mol% of catalyst **3**; 1-decene:acrolein = 1:1 (1 mmol). All data obtained by GC analysis, with the exception of the isolated yields. The estimated error for the GC yields is ±2%.

[b] Conversion of 1-alkene (entries *3a*–*3k*) or 2-allyloxy-6-methylheptane (entries *3l*–*3o*).

[c] See Scheme 3 for cross-metathesis (CM) and self-metathesis (SM) products of all reactions.

acrylonitrile has previously been reported [12,13b, 13e, 17]. According to NMR data of the isolated products, the CM products of acrylonitrile with 1-decene, 1-octene or 1-hexene were all obtained with a Z/E ratio of 3; whereas the product with 2-allyloxy-6-methylheptane (6,10-dimethyl-5-oxodec-2-enenitrile) resulted in $Z/E = 2$.

In the reactions with the three linear 1-alkenes (Table 3, entries *3a–3k*), similar trends were observed for each 1-alkene. Thus, the best conversions (71–80%) were achieved when either acrolein or crotonaldehyde were used as starting materials; whereas lower values were obtained with acrylonitrile (55–62%), followed by methacrolein (30–43%). The best yields of CM product were consistently obtained with acrolein (52–71%), followed by acrylonitrile and crotonaldehyde which gave comparable yields for each 1-alkene (i.e., ranging between 42% and 70%). All the reactions with methacrolein gave significantly lower yields (16–28%). Methacrolein also gave the lowest selectivities of CM product with 1-decene (59%) and 1-octene (63%), compared with the three other substrates (90–99%). The presence of a bulky Me substituent next to the aldehyde functionality in methacrolein appears to hinder its reaction with catalyst **3**, resulting in low conversions and yields of CM product. Sterically demanding substrates often have a deactivating effect in Grubbs' catalysed metathesis reactions. For example, poor reactivity of methacrolein (i.e., compared to crotonaldehyde) has been reported in cross-metathesis with 1,5-cyclooctediene using catalyst **1** [35]. However, our results contrast with those of Chatterjee et al. where good reactivity of second generation Grubbs' catalysts was found with geminal disubstituted olefins [9b,36]. In particular, a better yield was reported for the cross-metathesis of 6-acetoxyhex-1-ene with methacrolein (92%), compared to acrolein (62%), using catalyst $[RuCl_2({=}CHCHCMe_2)$(1,3-dimesityl-4,5-dihydroimidazol-2-ylidene)$(PCy_3)]$ (Cy = cyclohexyl) [9b]. Therein, it was observed that the *trans* orientation was favoured in the presence of the Me group close to the metal centre [i.e., E:Z = 1.1:1 (acrolein), >20:1 (methacrolein)]. As discussed above, in the reactions with acrolein and methacrolein described, herein, the E isomer is always favoured.

The lower conversions and CM yields obtained with acrylonitrile compared with acrolein, may be related to the higher electron-withdrawing ability of the CN group (i.e., stronger $-I$ effect), thus disfavouring its addition to the catalyst. In addition, the strongest coordinating ability of the CN group may deactivate the catalyst by binding to the metal through the N atom [17a]. It should be noted that the cross-metathesis of acrylonitrile with 1-octene and 1-decene has been reported using 5 mol% of Schrock's catalyst in dichloromethane [12]. The yields of the corresponding CM products were of 56% and 72% respectively, which is consistent with the values obtained, herein, for catalyst **3**. The authors report higher overall yields in diethyl ether, where the reactions were slower, and relatively high Z/E ratios (8.5–9). The self-metathesis products were obtained at 4% yield. The cross-metathesis of acrylonitrile and 1-decene has also been reported using ruthenium catalyst **2** (Chart 1) in dichloromethane (20 h, 2 mol% catalyst) [13a]. Although this study did not include details on yields or selectivity, it was noted that the purity of the acrylonitrile used in the reactions is of utmost importance in achieving high yields and reproducibility.

The synthesis of undec-2-enenitrile has also been previously reported by reaction of cyanoacetic acid with butanal, using pyridine containing a few drops of piperidine as solvent and catalyst [37]. In this case, the β,γ-unsaturated isomers ($Z/E = 1.5$) form in addition to α,β-unsaturated nitriles ($Z/E = 1.7$). No isomerisation was observed during the CM reactions described, herein. The odour character of the α,β-unsaturated nitrile obtained by us, was compared with that of a sample containing a mixture of the α,β- and β,γ-unsaturated isomers at the same Z/E ratios. Interestingly, two perfumers at Givaudan agreed that the samples were different in character although they were divided in their preference.

The reactions with 2-allyloxy-6-methylheptane (Table 3, entries *3l–3o*) resulted in poorer yields of CM product (1–33%) and, generally, gave lower conversions (20–76%) and selectivities (18–92%) than those of the linear 1-alkenes. These results may be related to the presence of the bulkier substituent in 2-allyloxy-6-methylheptane. Similarly to that observed with the other alkenes, the reaction with acrolein gave the best overall results; whereas those with acrylonitrile and methacrolein gave the worst values. The observed preference for the self-metathesis product is probably due to poor secondary metathesis of the sterically demanding 2-allyloxy-6-methylheptane homo-dimer [Scheme 1c]. This effect increases with the deactivating nature of the α,β-unsaturated substrate (i.e., with increasing bulkiness or electron withdrawing ability). In addition, the lower reactivity of 2-allyloxy-6-methylheptane compared to the other alkenes tested could be related to the formation of a vinyl ether by-product during the process (i.e., via a Ru-catalysed double-bond migration [38]), as vinyl ethers are known to attach irreversibly to Ru catalysts, thus deactivating them [25a,39]. Whereas vinyl ether species have not been detected during the experiments described herein, formation of unreactive Ru-carbenes resulting from the reaction of the catalyst and vinyl ethers cannot be ruled out.

3.3. Reactions using ionic liquids

The possibility of recycling the catalyst was examined by performing the cross-metathesis between acrolein and 1-decene in ionic liquids. Reactions using catalyst **3** were carried out in a series of ionic liquids with a common cation ($[C_4mim]$[anion]; C_4mim = 1-butyl-3-methylimidazolium; anion = NTf_2 ($Tf = CF_3SO_2$), $EtSO_4$, PF_6, OTf) or anion ([cation]$[NTf_2]$; cation = 1-ethyl-3-methylimidazolium, 1-hexyl-3-methylimidazolium, 1-butyl-2,3-dimethylimidazolium, 1-butyl-1-methyl-pyrrolidinium, methyl(trioctyl)ammonium, tetradecyl(trihexyl)phosphonium). Only partial extraction of the products from the ILs was achieved using pentane or diethyl ether, but preliminary analysis of the reaction mixtures using NMR spectroscopy showed that $[C_4mim][NTf_2]$ produced the best yield of CM product, albeit very low (<5%). In order to improve the yield, reactions were attempted in a 1:1 $[C_4mim][NTf_2]$/dichloromethane homogeneous mixture, using catalyst **3** as well as ionic catalyst **4** (Chart 1). However, the yields of CM product still remained low (≤5%) and no reaction was observed upon recycling of the catalysts.

Reactions were then attempted with catalyst **3** supported on silica using $[C_4mim][NTf_2]$, according to the 'supported ionic liquid phase' (SILP) methodology. Catalyst **3** was immobilised using $[C_4mim][NTf_2]$ and two types of Davicat silica with varying surface area and pore diameter (Table 4). The silica was used either untreated (pH 4) or buffered [pH 10 (*silica 1*) or 7 (*silica 2*)]. The activity of the supported catalyst was then examined for the reaction between 1-decene and acrolein (2 mol% catalyst in pentane, 6 h). The cross-metathesis product, undec-2-enal, was obtained in moderate to good yields (60–72%) in all cases (Table 4). Formation of self-metathesis product (ca. 2% selectivity) was also observed in all the reactions. However, attempts to recycle the catalysts were unsuccessful, with only 1–2% yield obtained on the first recycle and no product observed on the second recycle. This indicates that the catalyst deactivated after the first run and/or leached into the organic phase during the recycling process.

Examining the results after the first run, the best yield of undec-2-enal (72%) was obtained using buffered *silica 1*, which had the most alkaline pH, whereas the lowest yields were at pH 4 (60–65% yield), although the differences are small. The surface area and pore

Table 4
Yield of undec-2-enal obtained from the reactions of 1-decene and acrolein with catalyst **3** supported on silica using [C_4mim][NTf_2]. All reactions performed at r.t. in pentane, using 2 mol% of catalyst **3** (6 h per run).

	Silica	Run	Yield of CM product (%)
Silica 1[a]	Untreated (pH 4)	1	60
		2	1
		3	0
	Buffered (pH 10)	1	72
		2	2
		3	0
Silica 2[b]	Untreated (pH 4)	1	65
		2	1
		3	0
	Buffered (pH 7)	1	67
		2	2
		3	0

[a] Surface area: 40 $m^2 g^{-1}$; pore diameter: 1000 Å.
[b] Surface area: 273 $m^2 g^{-1}$; pore diameter: 140 Å.

diameter of the silica, however, did not appear to have any significant influence on the yield of cross-metathesis product. Although the supported catalyst was not recyclable, it gave much better yields of undec-2-enal than the IL homogeneous systems (≤5%, see above). It also gave better results than the analogous reaction in pentane, which produced 40% yield of CM product using 3.5 mol% of catalyst **3** (Table 1, entry *1m*).

4. Conclusions

The Ru-catalysed cross-metathesis reaction of acrolein and 1-decene has been studied in detail. Overall, the best results (81% yield of undec-2-enal, 99% selectivity, 88% conversion of 1-decene) have been obtained in dichloromethane using catalyst **3** at relatively low loading (1.4 mol%) and added gradually over a period of 3 h (see Table 2, entry *2c*). It is interesting to note that, in contrast with previous studies, using excess of acrolein in the reactions did not significantly affect the outcome. Incomplete conversion of 1-decene is partly attributed to deactivation of the catalyst by the product undece-2-enal; hence the conversion and yield of CM product improves by adding fresh catalyst throughout the reaction. Good results (82% yield of undec-2-enal, 99% selectivity, 86% conversion of 1-decene) were also obtained by delaying the addition of 1-decene to the catalyst-acrolein mixture (see Table 2, entry *2f*), suggesting that catalyst-acrolein species may help to initiate the process. In addition to dichloromethane, 1,2-dichloroethane and the non-chlorinated solvent ethyl acetate also proved to be convenient solvents for the reaction.

Based on the optimised conditions for the acrolein:1-decene reaction, a series of α,β-unsaturated aldehydes and nitriles of interest to the fragrance industry have been prepared via cross-metathesis of acrolein, crotonaldehyde, methacrolein, or acrylonitrile with 1-decene, 1-octene, 1-hexene and 2-allyloxy-6-methylheptane. Most reactions gave good selectivity of the desired CM product (≥90%), although yields varied broadly with the nature of the substrate. The reactions with acrolein gave the best results overall. In general, the conversion of alkene and yield of CM product decreased with the presence of bulky substituents in the substrates (i.e., reactions involving methacrolein and/or 2-allyloxy-6-methylheptane gave the worst results). It is interesting to note that isomerisation has not been observed in any of the reactions and only the α,β-unsaturated products have been detected. In the case of the undec-2-enenitrile, the smell of the α,β-isomer prepared herein has shown to be different in character to that of the mixture of α,β- and β,γ-unsaturated isomers obtained by other methods.

Acknowledgments

The authors acknowledge support from QUILL. S.M.R. acknowledges support from the Department of Education and Learning in Northern Ireland and Givaudan SA. The authors thank Dominique Lelievre and Alain Alchenberger (Givaudan SA) for odour assessments.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.apcata.2014.08.032.

References

[1] (a) P. Kraft, J.A. Bajgrowicz, C. Denis, G. Fráter, Angew. Chem. Int. Ed. 39 (2000) 2980–3010;
(b) C.S. Sell, The Chemistry of Fragrances: From Perfumer to Consumer, second ed., The Royal Society of Chemistry, Cambridge, 2006;
(c) P.G.N. Mertens, F. Cuypers, P. Vandezande, X. Ye, F. Verpoort, I.F.J. Vankelecom, D.E. de Vos, Appl. Catal. A: Gen. 325 (2007) 130–139;
(d) A. Stolle, T. Gallert, C. Schmoger, B. Ondruschka, RSC Adv. 3 (2013) 2112–2153.

[2] (a) H.B. Kagan, O. Riant, Chem. Rev. 92 (1992) 1007–1019;
(b) K.C. Nicolaou, S.A. Snyder, T. Montagnon, G. Vassilikogiannakis, Angew. Chem. Int. Ed. 41 (2002) 1668–1698;
(c) Y. Hayashi, S. Samanta, H. Gotoh, H. Ishikawa, Angew. Chem. Int. Ed. 47 (2008) 6634–6637;
(d) E. Taarning, R. Madsen, Chem. Eur. J. 14 (2008) 5638–5644.

[3] (a) C. Gimbert, M. Lumbierres, C. Marchi, M. Moreno-Mañas, R.M. Sebastián, A. Vallribera, Tetrahedron 61 (2005) 8598–8605;
(b) M. Bell, K. Frisch, K.A. Jørgensen, J. Org. Chem. 71 (2006) 5407–5410;
(c) X. Luo, Z. Zhou, X. Li, X. Liang, J. Ye, RSC Adv. 1 (2011) 698–705;
(d) C.F. Nising, S. Brase, Chem. Soc. Rev. 41 (2012) 988–999;
(e) X. Xin, Q. Zhang, Y. Liang, R. Zhang, D. Dong, Org. Biomol. Chem. 12 (2014) 2427–2435.

[4] (a) Z. Wang, Comprehensive Organic Name Reactions and Reagents: Aldol Reaction and Aldol Condensation, vol. 1, John Wiley & Sons, Hoboken, 2009;
(b) S.I. Lee, J.H. Jang, G.-S. Hwang, D.H. Ryu, J. Org. Chem. 78 (2012) 770–775.

[5] (a) J.-M. Nuzillard, A. Boumendjel, G. Massiot, Tetrahedron Lett. 30 (1989) 3779–3780;
(b) M. Kajjout, M. Smietana, J. Leroy, C. Rolando, Tetrahedron Lett. 54 (2013) 1658–1660.

[6] (a) A. Abad, C. Almela, A. Corma, H. Garcia, Chem. Commun. (2006) 3178–3180;
(b) J. Liu, S. Ma, Org. Lett. 15 (2013) 5150–5153.

[7] V. Cadierno, S.E. García-Garrido, J. Gimeno, Adv. Synth. Catal. 348 (2006) 101–110.

[8] H. Ren, A. Krasovskiy, P. Knochel, Org. Lett. 6 (2004) 4215–4217.

[9] (a) R.H.A. Bosma, G.C.N. Vandenaardweg, J.C. Mol, J. Organomet. Chem. 280 (1985) 115–122;
(b) A.K. Chatterjee, J.P. Morgan, M. Scholl, R.H. Grubbs, J. Am. Chem. Soc. 122 (2000) 3783–3784;
(c) R.L. Pederson, I.M. Fellows, T.A. Ung, H. Ishihara, S.P. Hajela, Adv. Synth. Catal. 344 (2002) 728–735;
(d) G.S. Forman, R.P. Tooze, J. Organomet. Chem. 690 (2005) 5863–5866;
(e) X. Miao, C. Fischmeister, C. Bruneau, P.H. Dixneuf, ChemSusChem 2 (2009) 542–545;
(f) S.P. Nolan, H. Clavier, Chem. Soc. Rev. 39 (2010) 3305–3316;
(g) X. Miao, C. Fischmeister, C. Bruneau, P.H. Dixneuf, J.-L. Dubois, J.-L. Couturier, ChemSusChem 5 (2012) 1410–1414.

[10] (a) R.H. Grubbs, Tetrahedron 60 (2004) 7117–7140;
(b) D.J. O'Leary, H.E. Blackwell, R.A. Washenfelder, K. Miura, R.H. Grubbs, Tetrahedron Lett. 40 (1999) 1091–1094;
(c) H.E. Blackwell, D.J. O'Leary, A.K. Chatterjee, R.A. Washenfelder, D.A. Bussmann, R.H. Grubbs, J. Am. Chem. Soc. 122 (1999) 58–71.

[11] (a) A. Rybak, M.A.R. Meier, Green Chem. 9 (2007) 1356–1361;
(b) A. Rybak, M.A.R. Meier, Green Chem. 10 (2008) 1099–1104;
(c) G.B. Djigoué, M.A.R. Meier, Appl. Catal. A: Gen. 368 (2009) 158–162;
(d) H. Bilel, N. Hamdi, F. Zagrouba, C. Fischmeister, C. Bruneau, RSC Adv. 2 (2012) 9584–9589.

[12] W.E. Crowe, D.R. Goldberg, J. Am. Chem. Soc. 117 (1995) 5162–5163.

[13] (a) T.M. Cameron, A.S. Gamble, K.A. Abboud, J.M. Boncella, Chem. Commun. (2002) 1148–1149;
(b) J.A. Love, J.P. Morgan, T.M. Trnka, R.H. Grubbs, Angew. Chem. Int. Ed. 41 (2002) 4035–4037;
(c) M. Rivard, S. Blechert, Eur. J. Org. Chem. (2003) 2225–2228;
(d) N. Vinokurov, J.R. Garabatos-Perera, Z. Zhao-Karger, M. Wiebcke, H. Butenschoen, Organometallics 27 (2008) 1878–1886;
(e) X. Miao, P.H. Dixneuf, C. Fischmeister, C. Bruneau, Green Chem. 13 (2011) 2258–2271;

(f) X. Miao, R. Malacea, C. Fischmeister, C. Bruneau, P.H. Dixneuf, Green Chem. 13 (2011) 2911–2919;
(g) G.-L. Wu, S.-L. Cao, J. Chen, Z. Chen, Eur. J. Org. Chem. 2012 (2012) 6777–6784;
(h) X. Miao, C. Fischmeister, P.H. Dixneuf, C. Bruneau, J.L. Dubois, J.L. Couturier, Green Chem. 14 (2012) 2179–2183;
(i) C. Bruneau, C. Fischmeister, X. Miao, R. Malacea, P.H. Dixneuf, Eur. J. Lipid Sci. Technol. 112 (2010) 3–9.

[14] A.K. Chatterjee, T.-L. Choi, D.P. Sanders, R.H. Grubbs, J. Am. Chem. Soc. 125 (2003) 11360–11370.

[15] (a) D. Lee, Nature 471 (2011) 452–453;
(b) S.J. Connon, S. Blechert, Angew. Chem. Int. Ed. 42 (2003) 1900–1923.

[16] (a) B.L. Quigley, R.H. Grubbs, Chem. Sci. 5 (2014) 501–506;
(b) K. Endo, R.H. Grubbs, J. Am. Chem. Soc. 133 (2011) 8525–8527;
(c) B.K. Keitz, K. Endo, P.R. Patel, M.B. Herbert, R.H. Grubbs, J. Am. Chem. Soc. 134 (2012) 693–699;
(d) R.K.M. Khan, S. Torker, A.H. Hoveyda, J. Am. Chem. Soc. 135 (2013) 10258–10261;
(e) G. Occhipinti, F.R. Hansen, K.W. Tornroos, V.R. Jensen, J. Am. Chem. Soc. 135 (2013) 3331–3334;
(f) L.E. Rosebrugh, M.B. Herbert, V.M. Marx, B.K. Keitz, R.H. Grubbs, J. Am. Chem. Soc. 135 (2013) 1276–1279;
(g) S. Shahane, C. Bruneau, C. Fischmeister, ChemCatChem 5 (2013) 3436–3459.

[17] (a) C.-X. Bai, W.-Z. Zhang, R. He, X.-B. Lu, Z.-Q. Zhang, Tetrahedron Lett. 46 (2005) 7225–7228;
(b) A. Michrowska, R. Bujok, S. Harutyunyan, V. Sashuk, G. Dolgonos, K. Grela, J. Am. Chem. Soc. 126 (2004) 9318–9325.

[18] (a) N. Ledoux, A. Linden, B. Allaert, H.V. Mierde, F. Verpoort, Adv. Synth. Catal. 349 (2007) 1692–1700;
(b) K. Vehlow, S. Maechling, S. Blechert, Organometallics 25 (2005) 25–28;
(c) E.L. Rosen, D.H. Sung, Z. Chen, V.M. Lynch, C.W. Bielawski, Organometallics 29 (2009) 250–256.

[19] (a) D. Fischer, S. Blechert, Adv. Synth. Catal. 347 (2005) 1329–1332;
(b) T.S. Halbach, S. Mix, D. Fischer, S. Maechling, J.O. Krause, C. Sievers, S. Blechert, O. Nuyken, M.R. Buchmeiser, J. Org. Chem. 70 (2005) 4687–4694;
(c) S. Doherty, P. Goodrich, C. Hardacre, V. Parvulescu, C. Paun, Adv. Synth. Catal. 350 (2008) 295–302;
(d) B. Autenrieth, W. Frey, M.R. Buchmeiser, Chem. Eur. J. 18 (2012) 14069–14078.

[20] X. Ding, X. Lv, B. Hui, Z. Chen, M. Xiao, B. Guo, W. Tang, Tetrahedron Lett. 47 (2006) 2921–2924.

[21] (a) S. Csihony, C. Fischmeister, C. Bruneau, I.T. Horvath, P.H. Dixneuf, New J. Chem. 26 (2002) 1667–1670;
(b) H. Clavier, N. Audic, M. Mauduit, J.C. Guillemin, Chem. Commun. (2004) 2282–2283;
(c) H. Clavier, N. Audic, J.C. Guillemin, M. Mauduit, J. Organomet. Chem. 690 (2005) 3585–3599;
(d) H. Clavier, S.P. Nolan, M. Mauduit, Organometallics 27 (2008) 2287–2292;
(e) A. Michrowska, L. Gulajski, Z. Kaczmarska, K. Mennecke, A. Kirschning, K. Grela, Green Chem. 8 (2006) 685–688;
(f) S.R. Dubberley, P.E. Romero, W.E. Piers, R. McDonald, M. Parvez, Inorg. Chim. Acta 359 (2006) 2658–2664;
(g) C.P. Ferraz, B. Autenrieth, W. Frey, M.R. Buchmeiser, ChemCatChem 6 (2014) 191–198.

[22] H.-S. Dang, S. Ellwood, A.-D. Fortineau, C. Furniss, Fragrance compositions and compounds, Quest International Services B.V., Neth.; Givaudan Nederland Services B.V., Patent No. WO2008092678A2 (2008).

[23] S.M. Rountree, M.C. Lagunas, C. Hardacre, P.N. Davey, Appl. Catal. A: Gen. 408 (2011) 54–62.

[24] L. Gulajski, A. Michrowska, J. Naroznik, Z. Kaczmarska, L. Rupnicki, K. Grela, ChemSusChem 1 (2008) 103–109.

[25] (a) M.S. Sanford, J.A. Love, R.H. Grubbs, J. Am. Chem. Soc. 123 (2001) 6543–6554;
(b) T. Vorfalt, K.-J. Wannowius, H. Plenio, Angew. Chem. Int. Ed. 49 (2010) 5533–5536.

[26] J. Patel, S. Mujcinovic, W.R. Jackson, A.J. Robinson, A.K. Serelis, C. Such, Green Chem. 8 (2006) 450–454.

[27] (a) S.B. Garber, J.S. Kingsbury, B.L. Gray, A.H. Hoveyda, J. Am. Chem. Soc. 122 (2000) 8168–8179;
(b) A.H. Hoveyda, D.G. Gillingham, J.J. Van Veldhuizen, O. Kataoka, S.B. Garber, J.S. Kingsbury, J.P.A. Harrity, Org. Biomol. Chem. 2 (2004) 8–23;
(c) J.S. Kingsbury, J.P.A. Harrity, P.J. Bonitatebus, A.H. Hoveyda, J. Am. Chem. Soc. 121 (1999) 791–799.

[28] (a) S. Randl, S. Gessler, H. Wakamatsu, S. Blechert, Synlett (2001) 430–432;
(b) S. Imhof, S. Randl, S. Blechert, Chem. Commun. (2001) 1692–1693;
(c) S. Gessler, S. Randl, S. Blechert, Tetrahedron Lett. 41 (2000) 9973–9976.

[29] C.S. Adjiman, A.J. Clarke, G. Cooper, P.C. Taylor, Chem. Commun. (2008) 2806–2808.

[30] (a) D. Banti, J.C. Mol, J. Organomet. Chem. 689 (2004) 3113–3116;
(b) M.B. Dinger, J.C. Mol, Eur. J. Inorg. Chem. (2003) 2827–2833;
(c) M.B. Dinger, J.C. Mol, Organometallics 22 (2003) 1089–1095.

[31] S.-M. Seo, J. Kim, E. Kim, H.-M. Park, Y.-J. Kim, I.-K. Park, J. Agric. Food Chem. 58 (2010) 1823–1827.

[32] J. Pastva, J. Čejka, N. Žilková, O. Mestek, M. Rangus, H. Balcar, J. Mol. Catal. A: Chem. 378 (2013) 184–192.

[33] (a) A. Leitgeb, M. Abbas, R.C. Fischer, A. Poater, L. Cavallo, C. Slugovc, Catal. Sci. Technol. 2 (2012) 1640–1643;
(b) M. Abbas, A. Leitgeb, C. Slugovc, Synlett 24 (2013) 1193–1196.

[34] (a) R. Naef, A. Jaquier, Flavour Fragr. J. 21 (2006) 768–771;
(b) W.-Z. Zhang, R. He, R. Zhang, Eur. J. Inorg. Chem. 2007 (2007) 5345–5352.

[35] J.P. Morgan, C. Morrill, R.H. Grubbs, Org. Lett. 4 (2001) 67–70.

[36] A.K. Chatterjee, R.H. Grubbs, Org. Lett. 1 (1999) 1751–1753.

[37] C.K. Lee, J.Y. Shim, Org. Prep. Proc. Int. 22 (1990) 94–96.

[38] N. Kuznik, S. Krompiec, Coord. Chem. Rev. 251 (2007) 222–233.

[39] R.H. Grubbs, S. Chang, Tetrahedron 54 (1998) 4413–4450.