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# Recent advances in allylindium reagents in organic synthesis

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## 1. Introduction

In the late 1980s, Araki and co-workers reported the first Barbier-type allylation of carbonyl compounds using indium metal in an anhydrous organic solvent.[1] Later, Li and Chan successfully carried out the indium-mediated, Barbier-type allylation in

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aqueous media in 1990.[2] After the findings of Li and Chan, indium- and/or indium salt-mediated allylation reactions in aqueous media have attracted much attention in organic synthesis, because the reactions proceed smoothly at room temperature without any additive, while other metals usually require anhydrous organic solvents.[3] Although allylindium reagents are sensitive to oxygen and strong proton donors, such as, HCl, as Araki and co-workers have reported,[4] most of the reactions could be carried out very conveniently without special precautions under an air atmosphere and in water as the solvent.

Allylindium sesquihalides have hitherto been developed as mild nucleophilic reagents in organic synthesis. Addition to carbonyl compounds and imines is a typical reaction of allylindium reagents, giving the corresponding homoallylic alcohols and amines, respectively.[3] The reactions of allylindium reagents with aldehydes, ketones, *N*-acylimines, *N*-tosylimines, and related reactive electrophiles have already been compiled in many reviews including their regio-, enantio-, and diastereo-selectivities.[3] Thus, we have excluded the reactions of allylindium reagents with substrates having a carbon–oxygen double bond (C=O) and a carbon–nitrogen double bond (C=N) in this review. Recently, however, the chemistry of allylindium reagents has been rapidly growing, and widening their applicability in organic synthesis. A more in-depth understanding of the structure and reactivity of allylindium reagents has been established,[5] and various reactions of allylindium reagents have been reported with less- or un-polarized multiple bonds,[6–20] especially with nitrile group-containing substrates.[7b,21–26]

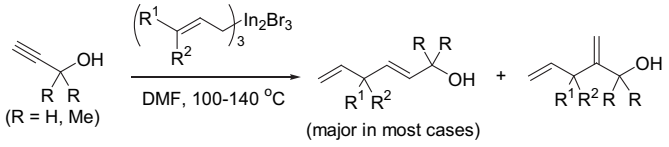
Very recently, Baba and co-workers reported the isolation and crystallographic characterization of cinnamylindium species generated from cinnamyl bromide and indium metal for the first time (Scheme 1).[5] The reaction of cinnamyl bromide (**1**) with indium metal gave two cinnamylindium species, cinnamylindium dibromide **2**, and dicinnamylindium bromide **3**. The individual species were isolated after complexation of appropriate pyridine-type Lewis bases. The use of 3,5-dibromopyridine ($Br_2py$) as Lewis base gave cinnamylindium dibromide with two $Br_2py$ ligands. Dicinnamylindium bromide was isolated with 4-(dimethylamino)pyridine ($Me_2Npy$) ligands. In both cases, the indium atom showed a trigonal-bipyramidal coordination sphere with the cinnamyl group(s) and bromide atom(s) in the equatorial sites, and the pyridine-type ligands occupying the axial positions. They also found that the diallyl species had a great reactivity than the monoallyl compound for carbonyl addition. The reaction of the in situ-generated allylindium compounds with benzaldehyde was monitored by NMR spectroscopy, and the results indicated that electronegative substituents retarded the nucleophilicity of the allylindium compounds.[5]

This brief review summarizes recent advances in indium-mediated, Barbier-type allylations of less- and un-polarized multiple bonds. We hope that the review will provide organic chemists with some insight in this field and serve as a helpful tool in designing synthetic strategies in their research.

## 2. Unpolarized multiple bonds

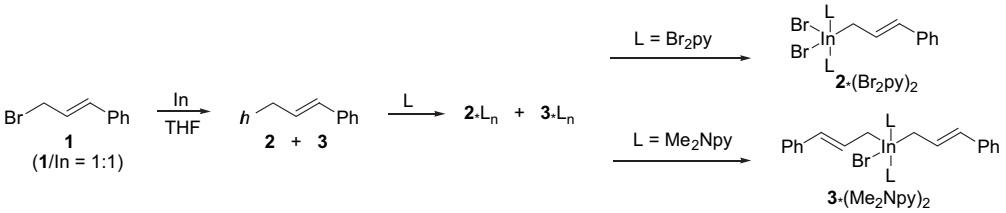
### 2.1. Carbon–carbon triple bonds

Butsugan and co-workers examined the reaction of allylindium reagents and carbon–carbon triple bonds for the first time.[6] Allylindium sesquihalides undergo smooth allylindation, at 100–140 °C in DMF, with terminal alkynes bearing a neighboring hydroxyl group, to give allylalkenols, as shown in Scheme 2. The coupling occurred at the γ-carbon of the allylindium reagents regioselectively via *syn*-addition, whereas, the regioselectivity concerning the alkynols depends upon the structures of both the allylindium reagents and the alkynol. The allylation of non-functionalized alkynes is less efficient, requiring higher reaction temperatures (150–180 °C), and giving lower yields. Mechanistic considerations suggest a hydroxyl-assisted concerted process for the allylindation of alkynols, whereas, a radical pathway is more likely for non-functionalized alkynes.

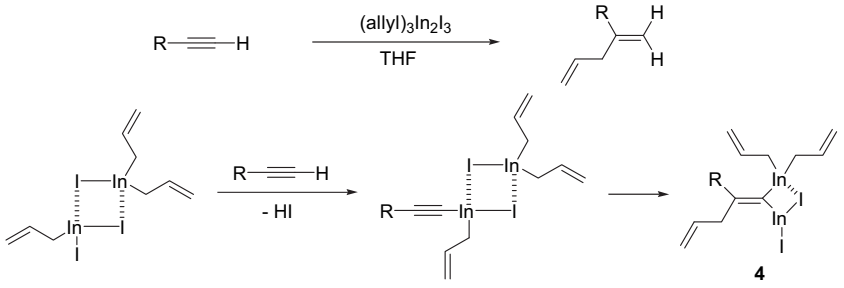



**Scheme 2.**

Later, Yamamoto and Fujiwara extended the In-mediated allylation reaction of terminal alkynols to unactivated alkynes.[7a,b] They carried out the reaction of allylindium reagents and unactivated alkynes in THF to obtain various 1,4-pentadienes in good-to-high yields. The Markovnikov product (vide infra) was obtained selectively and the involvement of a vinylic α,α-bis-indium intermediate **4** was proposed, as shown in Scheme 3.

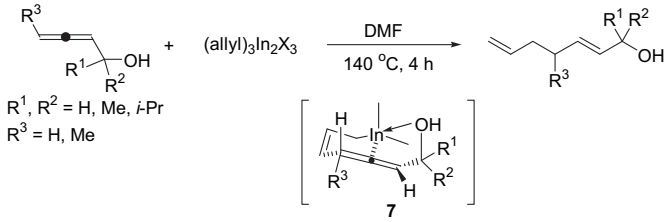



**Scheme 1.**



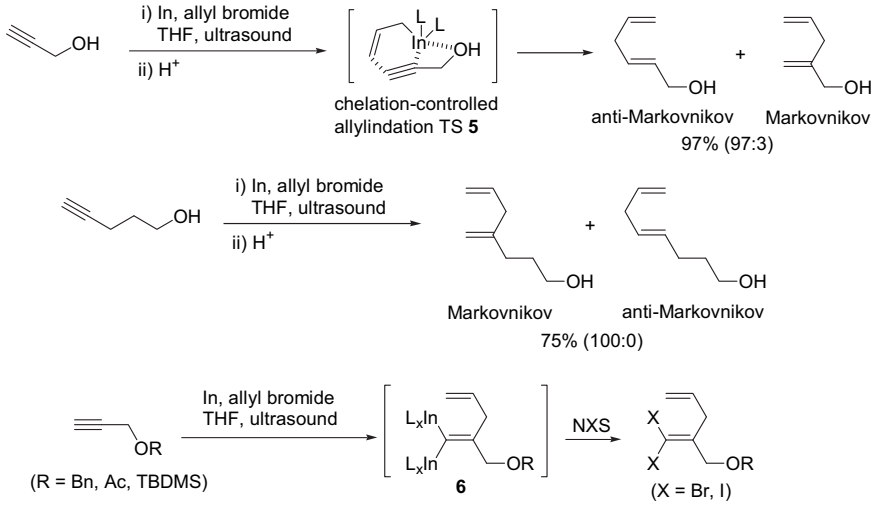

**Scheme 3.**

A more systematic study on the carboindation of carbon–carbon triple bonds was carried out by Klaps and Schmid in 1999, as shown in Scheme 4.[8] They found that unprotected alkynols reacted with allylindium reagents markedly faster, requiring only 2–4 h of ultrasonication in THF to produce the products in good yields. In this reaction, the regioisomeric outcome was found to depend on the distance between the hydroxyl group and the alkyne moiety; propargyl alcohol gave the *anti*-Markovnikov product via the involvement of a bicyclic chelation-controlled transition state **5**, while 4-pentynol and higher homologs exclusively afforded the branched 1,4-dienes, the Markovnikov products. Terminal alkynes with protected hydroxyl groups gave the corresponding Markovnikov product. In the latter reaction, they proposed a vinylic α,α-bis-indium intermediate **6**, which was successfully quenched with *N*-bromosuccinimide (NBS) or *N*-iodosuccinimide (NIS) to form tetrasubstituted dienes in good yields.



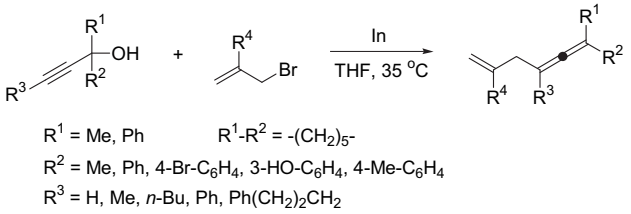

Scheme 6.

Kim and Lee have extended the reaction to functionalized 1,6-diols bearing an allenyne moiety.[11] Addition of the allylindium to the triple bond was not observed and the results imply that the homoallenyl alcohol is more reactive than the homopropargyl alcohol towards the allylindium reagents, as shown in Scheme 7.




Scheme 4.

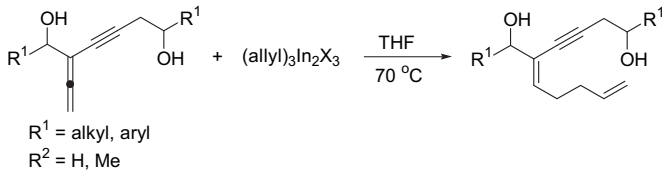
Lee and Lee have reported the synthesis of multi-substituted allenes from tertiary propargyl alcohols and allyl bromides by an In-mediated Barbier reaction (Scheme 5).[9] In their work an allyl moiety was introduced at the propargylic position regioselectively, and secondary propargyl alcohols did not react with allylindium reagents.




Scheme 5.

## 2.2. Allenes

Araki and co-workers have reported an In-mediated introduction of the allyl moiety into allenols.[10] They found that the reaction proceeds with high regio- and stereoselectivity via a hydroxyl-chelated bicyclic transition state **7**, as shown in Scheme 6.

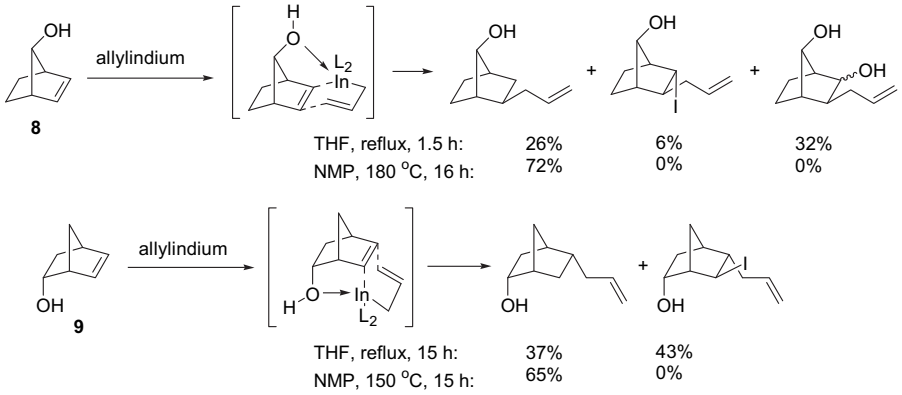



Scheme 7.

## 2.3. Carbon–carbon double bonds

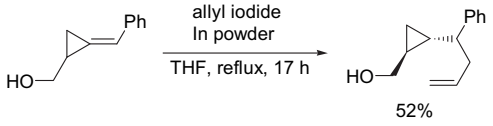
As described above, the additions of allylindium reagents to alkynes and allenes have been reported to proceed with high regio- and stereoselectivity.[6–11] The carbon–carbon multiple bonds with enhanced s character, such as, those in alkynes and allenes undergo smooth allylindation, whereas, ordinary carbon–carbon double bonds are inert. Successful allylindation was, however, reported for substrates having a neighboring hydroxyl group which can stabilize the indium intermediate. Araki and co-workers have reported a chelation-controlled regio- and stereoselective allylation of norbornenol derivatives.[12] The reaction of allylindium and *syn*-bicyclo [2.2.1]hept-2-en-7-ol (**8**) in THF at refluxing temperature afforded three products in moderate yields, whereas, the allylindation product was the major component (72%) in NMP (180 °C). Under the latter conditions, iodinated and oxygenated products were not

formed. The importance of the $C_7$-hydroxyl group for the smooth allylation was evidenced by the failure of the reaction of allylindium with norbornene. A similar result was observed in the reaction with *endo*-bicyclo[2.2.1]hept-5-en-2-ol (**9**). In these reactions, the regio- and stereochemistry of the addition of the allylindium reagents are highly regulated via chelation with the neighboring hydroxyl group, as shown in Scheme 8.




**Scheme 8.**

Hirashita and co-workers have reported an In-mediated stereoselective allylation of the carbon–carbon double bond of methylenecyclopropanes (MCPs) having a hydroxymethyl group with allylindium reagents.[13] The introduction of the allyl group occurred selectively at the external $sp^2$ carbon via cyclopropylindium intermediates, as shown in Scheme 9. They also found that the reaction of ethyl 2-cyclopropylideneacetate and triallylindium afforded the 1,4-adduct, along with dimeric products.




**Scheme 9.**

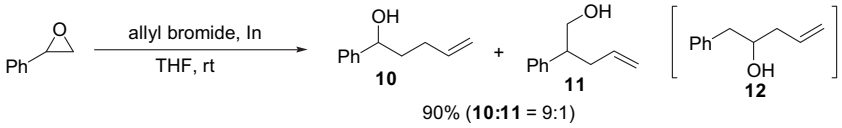
## 3. Strained three-membered cyclic compounds

### 3.1. Epoxides

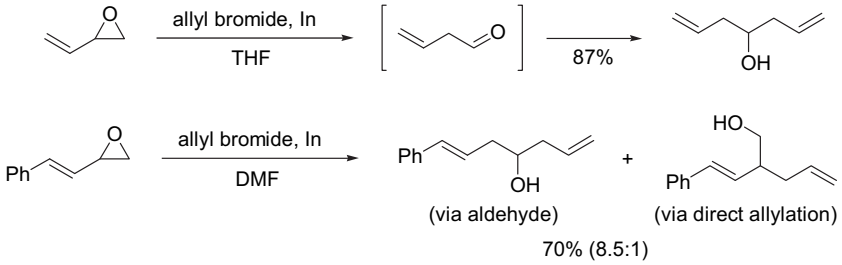
The first indium-mediated regioselective allylation of terminal epoxides was reported by Yadav and co-workers.[14] The reaction was carried out in THF at room temperature to produce a mixture of bishomoallyl alcohols in a regioselective manner. They reported that, as an example, the reaction of styrene oxide with allylindium reagents gave the corresponding bishomoallyl alcohols **10** and **11** in 90% yield in a 9:1 ratio, as shown in Scheme 10. The results, however, were found to be misinterpreted later by Araki and co-workers.[15] Compound **10** must be formed via the direct ring-opening reaction of styrene oxide by allylindium reagents; the spectroscopic data of **10** were, however, exactly matched with those of compound **12**, which can be produced via the initial rearrangement of styrene oxide to phenylacetaldehyde and the successive allylation with allylindium reagents.[15]

Later, Pae and co-workers extended the reaction to vinyl epoxides, such as, vinyloxirane and *trans*-cinnamyloxirane.[16] In these cases, rearrangement of the epoxide to the corresponding aldehyde occurred first via the ring-opening 1,2-hydride shift catalyzed by the Lewis-acidic allylindium species. As shown in Scheme 11, the bishomoallylic alcohol was obtained as the sole or major product in both cases.

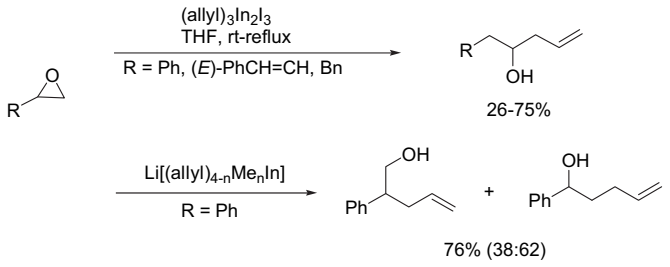
Although Pae and co-workers pointed out the importance of the alkenyl moiety as the substituent of the epoxide for effective rearrangement,[16] it was later found by Hirashita and co-workers that the allylindium sesquihalide has enough Lewis acidity to induce the rearrangement of epoxide prior to the direct allylation, and the resulting aldehydes undergo allylation to give the corresponding homoallylic alcohols irrespective of the substituent of the epoxides.[15] They also found that allylindium ate complexes can react directly with epoxides to give the ring-opening products to the contrary, as shown in Scheme 12.




**Scheme 10.**



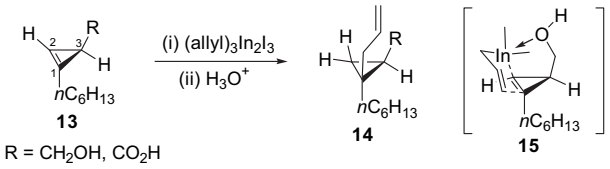

**Scheme 11.**




**Scheme 12.**

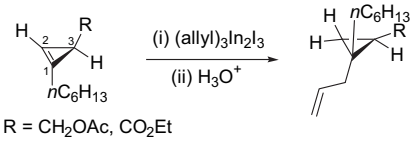
### 3.2. Cyclopropenes

Although regioselective carboindations were reported on alkynes[6–9] and allenes[10,11] with allylindium, the first allylindation of cyclopropenes appeared in 1998 by Araki and co-workers, as shown in Scheme 13.[17]




**Scheme 13.**

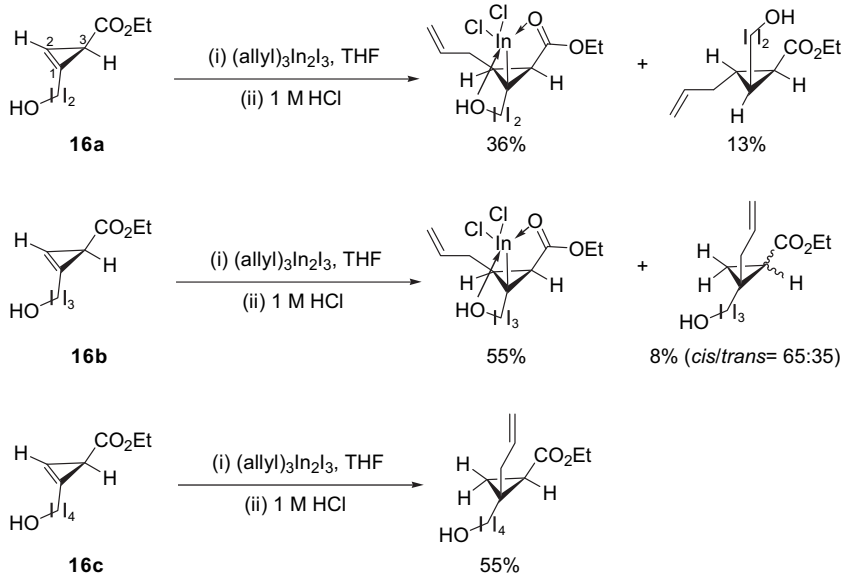
With *n*-hexylcyclopropene derivatives **13**, as an example, the allyl group was introduced exclusively at the substituted $C_1$ carbon and the indium atom at the less-hindered $C_2$ carbon, minimizing the steric repulsion between the bulky indium and the hexyl group. In this reaction, the substituent on the cyclopropene $C_3$ carbon plays an important role in determining the stereoselectivity of allylindation. The carboxyl and hydroxymethyl groups facilitate a high *cis*-addition based on the chelation (see **15**) to produce compounds **14**, whereas, the ester group directs a *trans*-addition owing to the steric interaction with incoming allylindium reagents, as shown in Scheme 14.



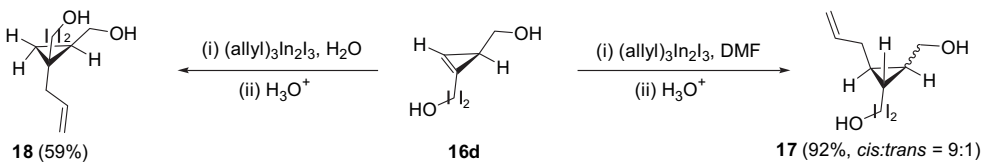

**Scheme 14.**

Araki and co-workers reported an in-depth study on the reaction of allylindium reagents and cyclopropene derivatives both in organic and aqueous media.[18] They first carried out a series of reactions with various 1-(ω-hydroxyalkyl)cyclopropenes, as shown in Scheme 15. The results for the 1-(ω-hydroxyalkyl)cyclopropenes **16a–c** clearly demonstrate that the allylindation is controlled by the chelation of the hydroxyl group in the side chain; when the side chain is short ($n$=2 and 3), the indium atom tends to be attached at the $C_1$ carbon, whereas, the 4-hydroxybutyl group ($n$=4) is long enough to direct the indium to the $C_2$ carbon and, consequently, the allyl group is introduced to the $C_1$ carbon. In these cyclopropenes, the ester group at the $C_3$ carbon assists the *cis*-allylation in cooperation with the chelation of the hydroxyl group.

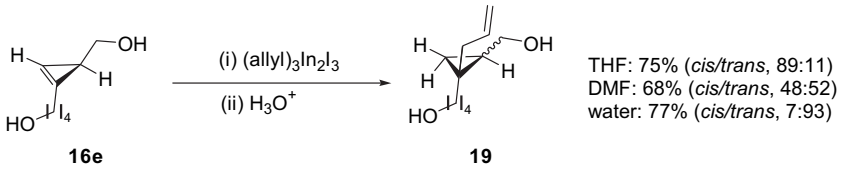
Next, they examined the reaction of cyclopropenes having two hydroxyalkyl substituents at the $C_1$ and $C_3$ positions (Scheme 16).[18] In the reaction of **16d** in DMF, the indium atom was introduced at the $C_1$ position to give *cis*-**17** as the major product, due to the chelation effect of indium and the hydroxymethyl group at the $C_3$ position. Strikingly, when this allylindation was conducted in water, both the regio- and stereoselectivity were totally reversed and compound **18** was formed exclusively. This is because the solvent,




**Scheme 15.**




**Scheme 16.**

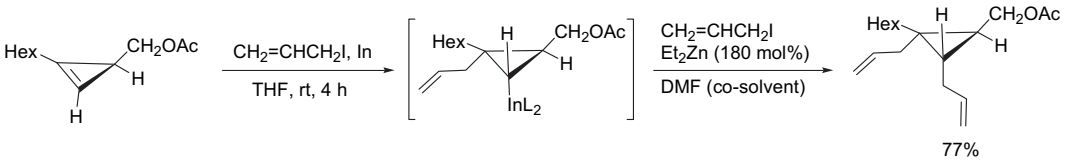



**Scheme 17.**

water, coordinates to the allylindium reagent, breaking the chelation of the hydroxyl groups; accordingly, the solvated reagent attacks from the less hindered trans face with preference of $C_2$ indation to avoid the steric crowding of the hydroxyethyl group at the $C_1$ carbon.

In the allylindation of **16e** with a 4-hydroxybutyl group, the longer side chain facilitates the $C_2$ indation, even in organic solvents, giving the $C_1$-allylation product **19** (Scheme 17).[18] Again, the *cis*/*trans* ratio largely depends upon the solvents; when the more polar solvent was used, a higher trans selectivity was obtained.

Recently, Hirashita and co-workers reported a successful consecutive double allylation of cyclopropene derivatives with allylindium reagents and allyl iodide (Scheme 18).[19] With an *n*-hexylcyclopropene derivative, as an example, the first allylindation occurred regio- and stereoselectively to give the intermediate, which was converted into *cis*-diallylcyclopropane in high yield with allyl iodide both in the presence of other organometallic compounds, such as, $Et_2Zn$ and a polar co-solvent.



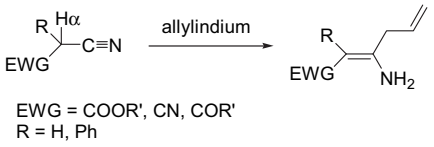

**Scheme 18.**

### 3.3. Azirines

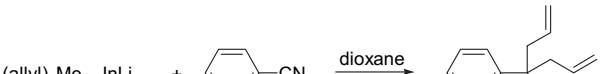
Recently Hirashita and co-workers reported the reaction of allylindium reagents and azirines to produce allylaziridines in good yields (Scheme 19).[20] Azirines are known to have a highly strained ring similar to cyclopropenes and are expected to be reactive substrates. The delivery of the allyl groups was well regulated by the substituents at the $C_3$ carbon of azirines. The *cis*-allylation with respect to the substituent was realized with azirines bearing a hydroxymethyl or an acetoxymethyl group, due to the chelation with allylindium reagents, whereas, the *trans*-allylation was observed with azirines substituted by non-chelating groups, such as, methyl, phenyl, or ester groups owing to the steric repulsion.

## 4. Nitriles

Allylindium reagents have been used extensively for the introduction of allyl groups in a Barbier type manner to various electrophiles.[3] Although many electrophiles including aldehydes, ketones, imines, and *N*-tosylimines have been used in the indium-mediated allylations,[3] the reaction of less reactive electrophiles, such as, nitrile has not been extensively used in organic synthesis. The first successful results of indium-mediated allylation of nitriles have been reported by Yamamoto and Fujiwara a decade ago (Scheme 20),[7b,21] although allylation of nitrile with allylindate instead of allylindium reagents was reported by Butsugan and co-workers in 1993 (vide infra, Scheme 21).[22] The allylation of nitriles with allylindium reagents was, however, limited to substrates having an electron-withdrawing substituent and an α-proton, as shown in Scheme 20.[7b,21]



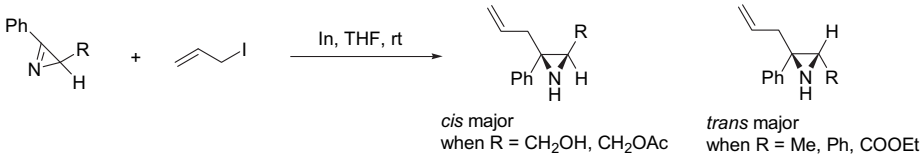

**Scheme 20.**



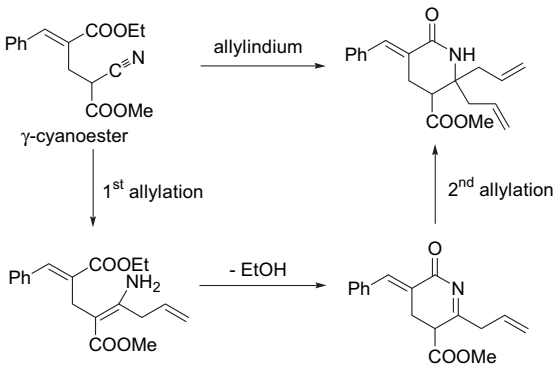

**Scheme 21.**

As mentioned above, Butsugan and co-workers reported a synthesis of primary amines by the reaction of allylindate on aromatic nitriles.[22] When aliphatic nitriles were used, however, starting materials were recovered.

Very recently, Kim and co-workers reported a series of indium-mediated, Barbier-type allylations of nitrile groups in γ-cyanoesters (Scheme 22),[23] γ-ketonitriles (Scheme 23),[24] and δ-ketonitriles (Scheme 24).[25] The intrinsic reactivity of the nitrile group towards the allylindium species was found to be sufficient to form the corresponding imine or enamine intermediates, and the corresponding δ-valerolactams,[23] pyrroles,[24] and isoquinolines[25] were obtained in good to moderate yields via the subsequent cyclization of the intermediates with an electrophilic moiety in the same molecule.

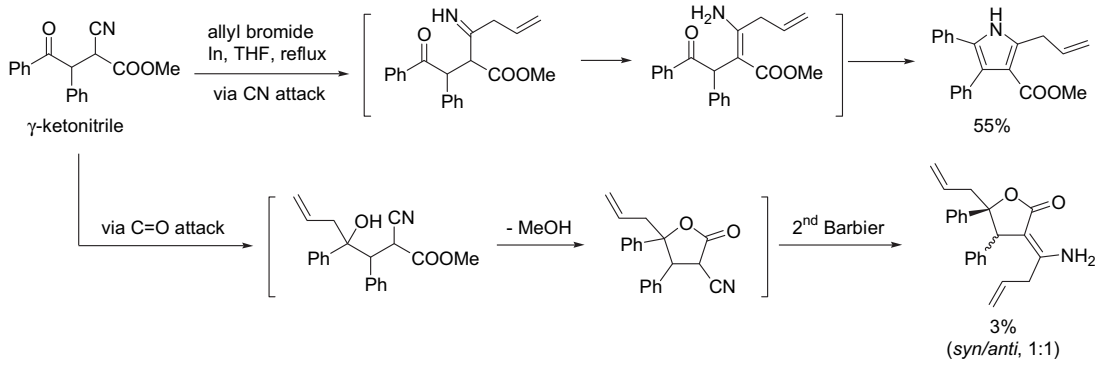



**Scheme 19.**

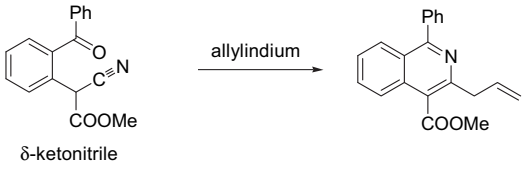



**Scheme 22.**

During these studies, they found that the nitrile group can react with allylindium reagents even in the absence of both an EWG and an α-proton when the imine or enamine intermediate can react with a nearby electrophile in the same molecule, such as, an ester[23] or a sterically hindered ketone.[24,25] In addition, they found that aromatic nitriles can also reacts with allylindium reagents when the substrate has a suitable electrophilic quencher in the same molecule.[25] In this context, they envisaged that *ortho*-cyanobenzoates could afford a 3,3-diallylisoindolone scaffold via the indium-mediated double allylation strategy, as shown in Scheme 25.[26] Various 3,3-diallyl isoindolones were synthesized via an indium-mediated Barbier type double allylation reaction of *ortho*-cyanobenzoates in good yields and in short reaction times.[26]




**Scheme 23.**

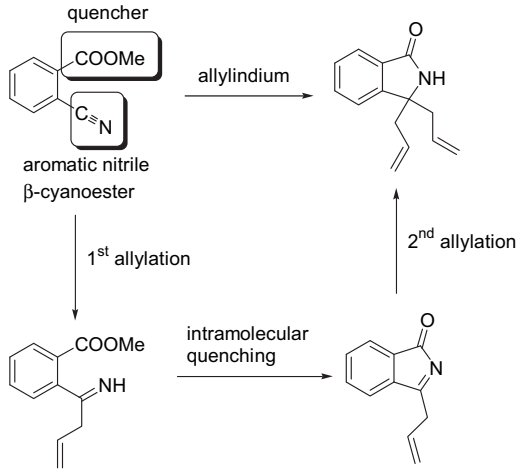



**Scheme 24.**

In their first series of allylation of nitriles, these workers used α-cyanoesters having another ester moiety at the γ-position (Scheme 22).[23] The first allylation proceeded to give the allylated enamine, as in Yamamoto's paper,[7b,21] but the enamine intermediate cyclized to the *N*-acylimine derivative, a reactive electrophile. A second allylation of this compound afforded the δ-valerolactam in moderate yield.

As the next substrate, Kim's group examined the reaction with γ-ketonitriles, as shown in Scheme 23.[24] The reaction provided an efficient synthetic strategy for poly-substituted pyrroles from γ-ketonitriles. Initial attack of the allylindium species occurred at the nitrile group selectively to form the enamine intermediate, which reacted with the ketone group intramolecularly to furnish the pyrroles. Interestingly, allylindium reagents attacked the cyano group faster than the ketone group in the same molecule. A lactone derivative was also produced in low yield (3%) via attack of the allylindium at the benzoyl moiety, lactonization, and a second allylation at the nitrile group.

Based on these results,[23,24] Kim and co-workers developed an efficient synthetic strategy for poly-substituted 1-arylisoquinolines via an indium-mediated, Barbier-type allylation from δ-ketonitriles (Scheme 24).[25] Initial attack of the allylindium species occurred at the nitrile group selectively to form the enamine intermediate, which reacted with the benzoyl group intramolecularly to furnish the isoquinolines.



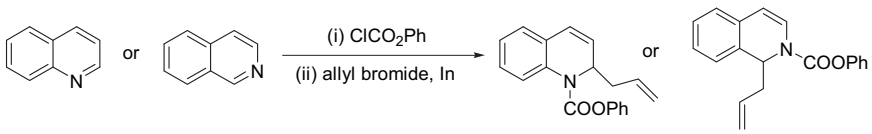

**Scheme 25.**

Based on the reported results of Kim and co-workers on the indium-mediated Barbier type allylation and/or consecutive allylation, the reaction of allylindium reagents and nitrile group-containing substrates could provide many interesting compounds in the near future.

## 5. Carbon–nitrogen double bonds in heterocycles

As mentioned in the introduction, the reactions of allylindium reagents with C=N bond-containing compounds have been extensively investigated.[3] The C=N bonds in heterocyclic compounds, such as, pyridine, quinoline, and isoquinoline did not, however, react with allylindium reagents under normal conditions. Recently, Yoon

and co-workers reported an indium-mediated allylation of quinoline and isoquinoline activated by phenyl chloroformate in THF at room temperature and obtained the allyl dihydroquinoline and allyl dihydroisoquinoline in good yields (Scheme 26).[27]



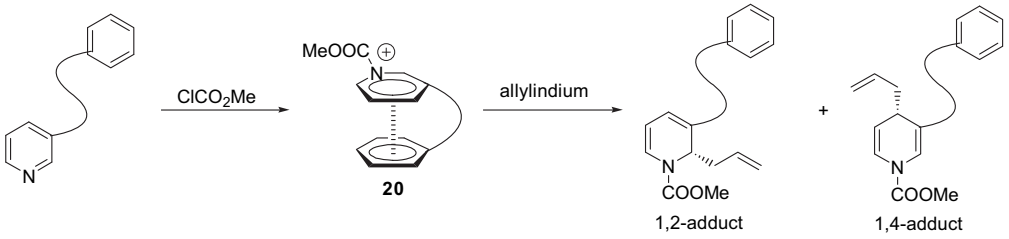

**Scheme 26.**

Based on the importance of allyl-substituted chiral dihydropyridines and dihydroquinolines, Yamada and Inoue developed an interesting methodology for these compounds.[28] Regio- and stereoselective allylation of pyridinium and quinolinium salts were performed by the addition of allylindium reagents to intermediary cationic-π-complexes, such as, **20** (Scheme 27).[28] As an example, the reaction of allylindium reagents and the pyridinium salt **20** afforded a 1,2-adduct, whereas, the addition of prenylindium reagents gave a 1,4-adduct with good regio- and stereoselectivities.

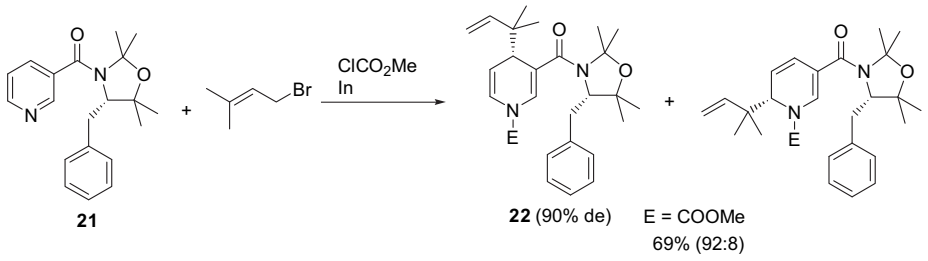
As shown in Scheme 28, the reaction of a pyridinium salt, in situ generated from **21** and methyl chloroformate, and a prenylindium reagent afforded a 1,4-adduct **22** as the major product (92:8) in a stereoselective manner (90% de).

unsaturated carbonyl and related compounds.[30] The reaction of allylindium sesquihalide with α,β-unsaturated carbonyl compound proceeded in a 1,2-addition mode, whereas, a 1,4-addition took place with triallylindium, as shown in Scheme 30. In addition, 1,4-addition was the major process in the case of α,β-unsaturated nitriles irrespective of the type of allylindium reagent.

Shanthi and Perumal have reported a one-pot synthesis of 4-allyl-2-amino-4*H*-chromene-3-carbonitrile (**23**) by an In-mediated, three-component reaction of salicylaldehyde and malononitrile with allyl bromide in water, as shown in Scheme 31.[31] The reaction mechanism was proposed to involve a Knoevenagel condensation of salicylaldehyde and malononitrile, a following cyclization to the iminocoumarin derivative, and conjugate addition of the allylindium reagent.




**Scheme 27.**

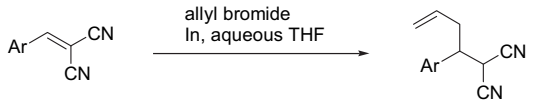



**Scheme 28.**

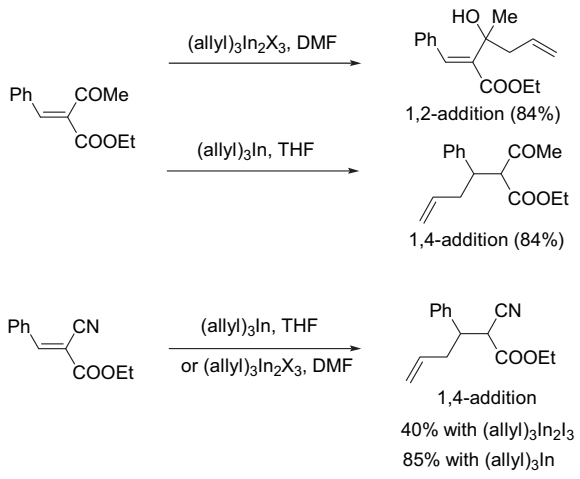
## 6. Conjugate additions

Zhang and co-workers reported an indium-mediated Michael addition of allyl bromide to 1,1-dicyano-2-arylethenes in aqueous media to produce the addition products in reasonable yields (Scheme 29).[29] The reaction failed, however, with other electron-deficient alkenes, such as, 1-cyano-1-ethoxycarbonylstyrene and cinnamyl cyanide.

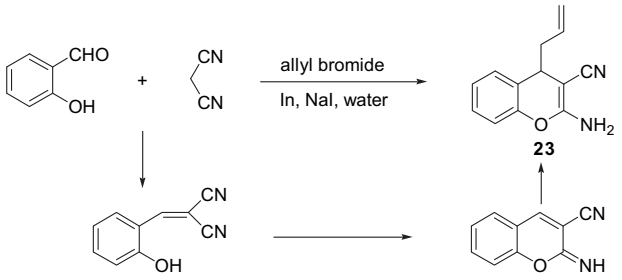
Later, Araki and co-workers reported the different reactivities of triallylindium and allylindium sesquihalides towards α,β-




**Scheme 29.**

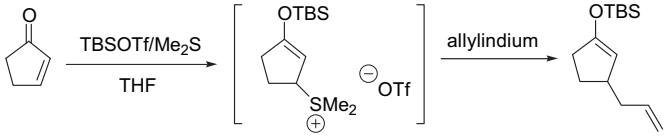



**Scheme 30.**



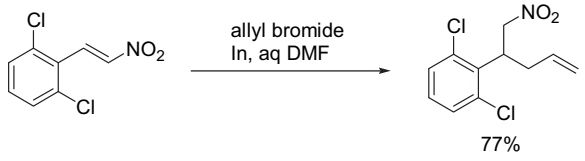

**Scheme 31.**

Lee and co-workers reported a formal conjugate addition of allylindium reagents to α,β-enone systems.[32] 3-*tert*-butyldimethylsilyloxyalk-2-enylsulfonium salts, generated in situ from the reaction of α,β-unsaturated ketones with dimethyl sulfide in the presence of TBSOTf, underwent a nucleophilic substitution with allylindium reagents to give the corresponding silyl enol ethers, which corresponds to formal Michael addition products, as shown in Scheme 32.




**Scheme 32.**

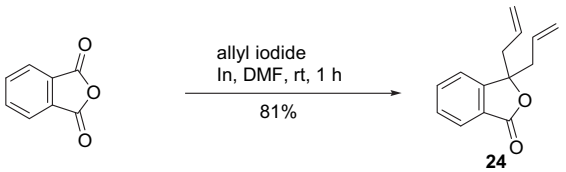
In-mediated conjugate addition of allyl bromide to nitroalkenes was also reported by Zhang and Zhang, as shown in Scheme 33.[33] The reaction was carried out in aqueous DMF to produce the conjugate addition products in moderate-to-good yields.




**Scheme 33.**

## 7. Cyclic imides and anhydrides

Butsugan and co-workers reported an indium-mediated allylation of acid anhydrides for the first time and obtained *gem*-diallyl esters in good yields.[34a] As an example, the reaction with phthalic anhydride gave the *gem*-diallyl ester **24**, as shown in Scheme 34. Later, Sabitha and co-workers reported the synthesis of spirolactones by a combination of the following two processes: (i) an indium-mediated allylation of cyclic anhydrides to form diallylated compounds, such as, **24** and (ii) a ring-closing metathesis (RCM) reaction with a Grubbs catalyst to form spirolactones.[34b]



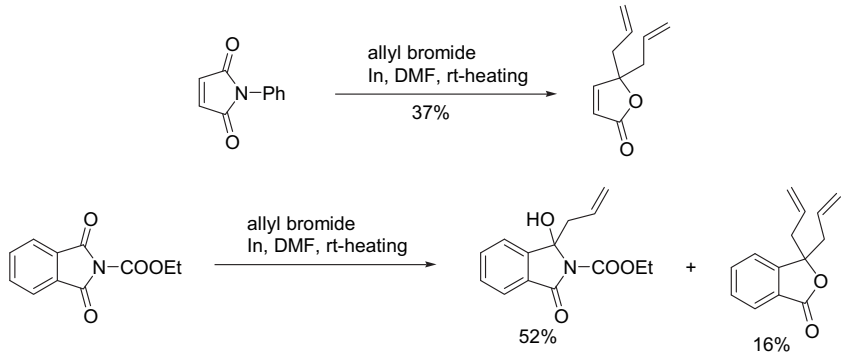

**Scheme 34.**

Two years later, Butsugan and co-workers reported an excellent paper on the preparation of allylindium reagents and their synthetic applications involving protolysis, oxygenations, and reactions with imides.[4] In this paper, they examined the coupling of allylindium reagents with cyclic imides and obtained diverse products, depending upon the structures of the substrates, as shown in Scheme 35.

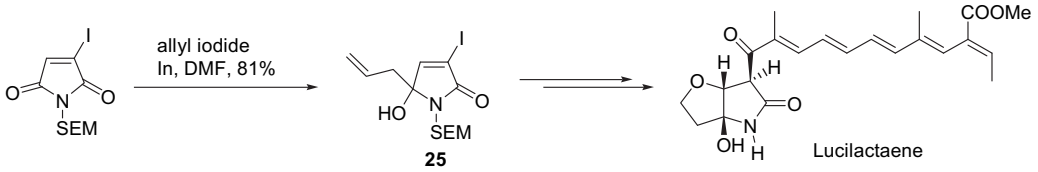
Recently, Coleman and co-workers used an In-mediated allylation of a cyclic imide in their total synthesis of Lucilactaene, as shown in Scheme 36.[35] In this reaction, a regioselective allylation of the carbonyl distal to the iodine was achieved using allylindium reagents in DMF (−15 °C, 3 d) to afford **25** as a separable 8:1 mixture of regioisomers.

## 8. Coupling and substitution reactions

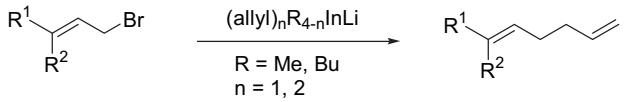
The first allylation of allylic halides has been reported by Butsugan and co-workers in 1995.[36] The more nucleophilic allylindate was, however, required instead of the allylindium sesquihalides, as shown in Scheme 37.




**Scheme 35.**

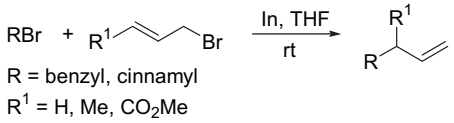



**Scheme 36.**



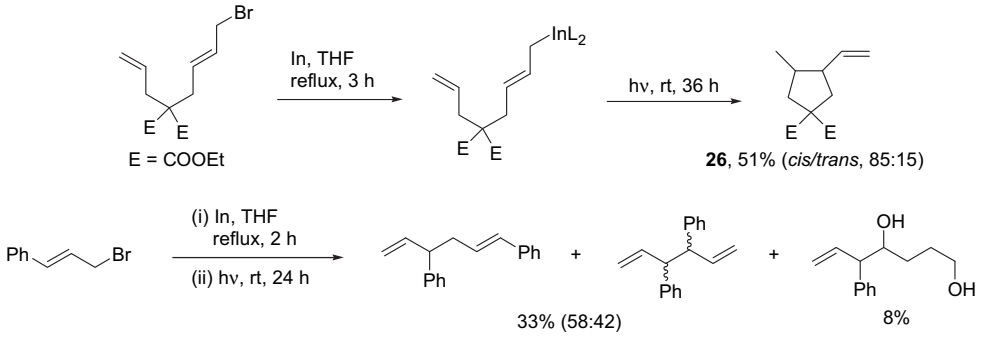

**Scheme 37.**

Ranu and co-workers reported a regioselective cross coupling of allylindium reagents with benzylic bromides (Scheme 38).[37] They carried out the reaction in THF at room temperature with various benzylic bromides and cinnamyl bromides to obtain a series of terminal alkenes.



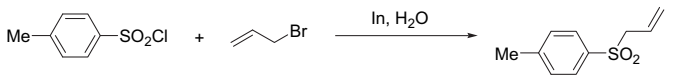

**Scheme 38.**

Hirashita and Araki reported intra- and intermolecular reactions of carbon-centered radicals generated by photolysis of organoindium compounds.[38] Allylic indium compounds, prepared from 8-bromooct-1,6-diene and powdered indium metal, underwent an intramolecular radical cyclization to afford the 5-*exo*-*trig* product **26**, as shown in Scheme 39. The intermolecular version of the reaction with cinnamyl bromide produced a mixture of two dimers and a small amount of diol, which was coupled with THF.



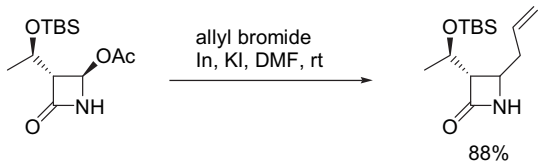

**Scheme 39.**

An indium-mediated coupling reaction of sulfonyl chloride and allyl bromide in water has also been reported.[39] As an example, the reaction of allyl bromide and *p*-toluenesulfonyl chloride in the presence of indium metal afforded the corresponding sulfone in 67% yield, as shown in Scheme 40.




**Scheme 40.**

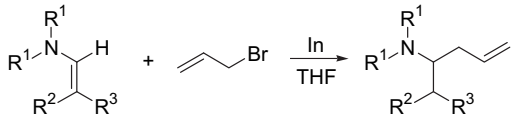
Lee and co-workers reported an indium-mediated allylation of 4-acetoxy-2-azetidinones by treatment with indium and allyl bromide in the presence of KI at room temperature, as shown in Scheme 41.[40] It was assumed that azetidinone behaved as the imine equivalent in the reaction to achieve the carbon–carbon bond formation at the $C_4$-position.




**Scheme 41.**

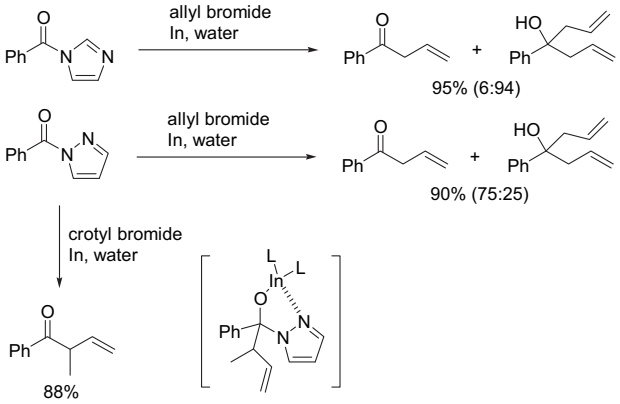
## 9. Miscellaneous (enamines, *N*-acylpyrazoles, *N*-acylimidazoles, and 2-pyridyl carboxylates)

Mosset and co-workers reported the reaction of enamines and allyl bromide in the presence of indium metal to obtain homoallylic amines in low-to-moderate yields.[41] The allyl group was introduced at the α-position relative to the nitrogen atom, as shown in Scheme 42.



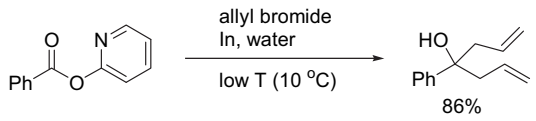

**Scheme 42.**

The reactions of *N*-acylimidazole and *N*-acylpyrazole derivatives with allylindium reagents were examined by Bryan and Chan in water.[42] As shown in Scheme 43, the reaction of *N*-benzoylimidazole produced a tertiary alcohol as the major product and a trace amount of allyl ketone, while the reaction of *N*-benzoylpyrazole afforded a ketone as the major product. The selective formation of a ketone derivative is presumably due to the stabilization of the intermediate by the chelation, and the ketone was the sole product for the crotylindium reagents.




**Scheme 43.**

Kim and co-workers reported the reaction of 2-pyridyl carboxylates and allylindium reagents in water at low temperature and obtained a tertiary alcohol in reasonable yield, as shown in Scheme 44.[43]

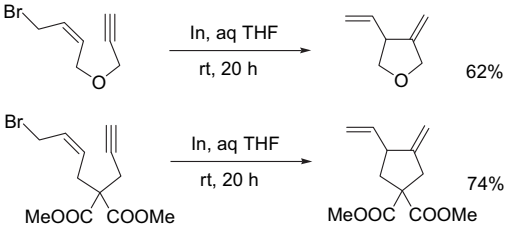



**Scheme 44.**

## 10. Intramolecular versions

Although intramolecular processes, in which the allyl moiety and the carbonyl function are parts of the same molecule, have been examined extensively,[3] a similar process with less- or unpolarized multiple bonds has not been reported to a large degree. As shown in Scheme 39, Hirashita and Araki reported intramolecular reactions of carbon-centered radicals generated by photolysis of organoindium compounds.[38]

An intramolecular version of the allylindation of alkynes with allylindium reagents has been examined by Salter and Sardo-Inffiri in 2002.[44a] The intramolecular cyclization of tethered allyl bromides on to terminal alkynes mediated by an indium metal proceeded smoothly and cleanly in aqueous THF to afford unsaturated carbocycles and heterocycles in good yields, as shown in Scheme 45. Later, these workers also found that the cyclization could be carried out in anhydrous THF with the aid of acid catalysts, and the reaction proceeded via a concerted *syn* carboindation and a following protonation.[44b]




**Scheme 45.**

## 11. Conclusions

In this mini review, we have described recent advances in the reactions of allylindium reagents with some less polarized and less reactive functional groups. As this review illustrates, the reactions of allylindium and related reagents with somewhat less reactive functional groups have grown rapidly growing during the last two decades and have provided a variety of important substances. Many kinds of functional groups, such as, carbon–carbon triple bonds, allenes, alkenes, epoxides, cyclopropenes, and nitriles have been used successfully. The indium-mediated allylation reaction is still, however, in its infancy. Based on the environmentally benign character of an indium metal and the high tolerance of allylindium reagents to water as solvent or to the atmosphere, indium-mediated allylations are likely to provide a more convenient methodology in the future.

## Acknowledgements

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