ARTICLE

Hydrogen autotransfer with alcohols for alkylations

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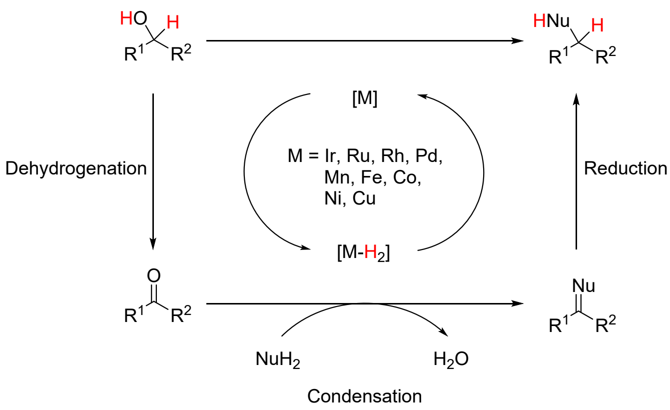
Despite the advancements enabled by organometallic complexes in organic synthesis, which have led to innovative transformations and tackled issues related to waste and atom economy, concerns have arisen regarding the expense of noble metals and ligands. Expanding on previous work, iron and ruthenium complexes with cyclopentadienone ligands, akin to Knölker catalysts, have demonstrated remarkable efficiency in bond reduction and alkylations using alcohols as pro-electrophiles. This review delves into novel alkylation methodologies involving hydrazides or ketones, inventive dehydrogenative coupling reactions yielding highly functionalized structures, and the optimization of metal-catalysed reactions through organometallic complex modifications. Metal-catalysed hydrogen auto-transfer, or hydrogen borrowing, offers a sustainable approach to forming C-C or C-N bonds from eco-friendly alcohols. While transitioning the diaminocyclopentadienone tricarbonyl ligand to first-row transition metals under mild conditions remains challenging, recent findings indicate that blue-light irradiation at room temperature can facilitate this transformation without external photosensitizers. Thus, while conventional studies without light remain demanding, light's additional role can enhance this research domain, where such catalysts may play a pivotal role. Moreover, further exploration of asymmetric catalysis is warranted. This review aims to impact not only the community working with Knölker derivative catalysts but also organic chemists for potential applications and inorganic chemists for catalyst development, ultimately striving to generate catalysts for asymmetric syntheses. Additionally, its sustainability makes it relevant for chemists dedicated to green chemistry.

1. Introduction

Over the past few decades, novel methodologies have emerged for forming C-N and C-C bonds through hydrogen autotransfer reactions. Coined "Borrowing Hydrogen" by Williams in 2004,[1] despite previous instances,[2,3,4,5] these reactions involve alcohols as alkylating agents instead of halide derivatives, which typically require additional synthetic steps and generate waste.[6,7] Thus, leveraging alcohols for synthesizing carbon- and nitrogen-containing compounds holds promise due to their natural occurrence and direct accessibility from biomass,[8,9] aligning with principles of green and sustainable chemistry.[10,11,12] The general mechanism involves dehydrogenation of an alcohol in the presence of an organometallic complex to yield the corresponding carbonyl derivative and a metal-hydride complex (Scheme 1). The resulting unsaturated species then undergoes condensation with a nucleophile, culminating in reduction by the metal-hydride complex.



Scheme 1. General mechanism of hydrogen autotransfer reactions (M = metal; Nu = nucleophile; R = substituent).

Several precious metals like iridium,[13] rhodium,[14,15] and ruthenium[16,17] have been documented for their efficacy in conducting such reactions. These reactions encompass the alkylation of diverse nucleophiles, including ketones,[18] amides or esters,[19] alongside amines,[20,21,22] nitriles,[23] and nitro derivatives (see Scheme 2).[24] Additionally, alkylations or syntheses of heterocycles have also been documented,[25,26,27,28]

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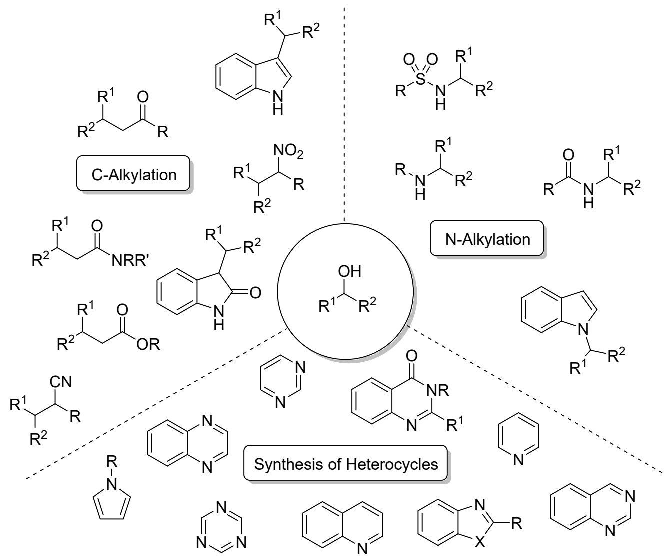
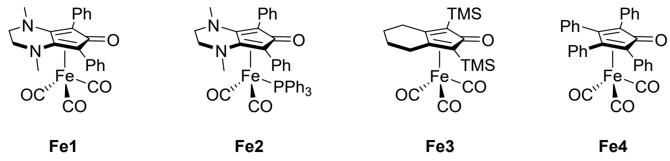
particularly with applications of acceptorless dehydrogenation.[29,30,31,32]



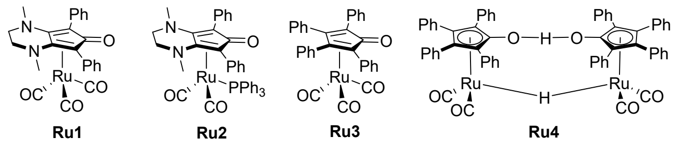
Scheme 2. Examples of alkylated products and heterocycles.

However, the scarcity of these metals and the constantly increasing demand have made their usage increasingly expensive. In recent years, Earth abundant transition-metal complexes, such as manganese, iron, or cobalt, have demonstrated their efficiency and competitiveness in alkylation reactions compared to noble metals.[33] Our research group became particularly interested in iron, which is the most Earth abundant transition metals and therefore the most economical (costing only a few cents per kilogram). The advancement of iron chemistry in recent years has been facilitated by the use of organophosphorus ligands. [34] However, these ligands are often sensitive to air and moisture and can be costly. The development of less expensive ligands such as cyclopentadienones aims to address these challenges. Building on the work of Knölker (**Fe3**, depicted in Scheme 3),[35,36,37] our group has synthesized various iron complexes featuring cyclopentadienone ligands (**Fe1** and **Fe2**, among others) and has contributed to their application in homogeneous catalysis, particularly in the reduction of carbonyls[38] and reductive amination.[39] Iron complex **Fe1** has demonstrated higher activity,[40,41,42,43,44] and better selectivity than the Knölker complex **Fe3** and has been employed in various alkylation reactions involving anilines,[45] indoles,[46] alcohols,[47] and ketones.[48,49,50,51] Actually, predictive catalysis studies[52,53] even led to enhancements using aldehydes with derivative **Fe1** catalysts,[54,55] employing the effective oxidation state and oxidation states localized orbitals of Gimferrer, Salvador and coworkers.[56,57]



Scheme 3. Knölker derivative iron complexes employed by the Renaud group.

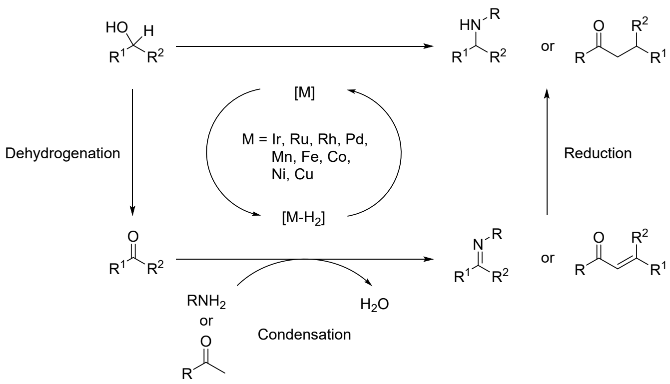
Continuing from these previous studies, the primary objectives of this review are to inspire the development of novel methodologies for forming C-N and C-C bonds, to investigate reaction mechanisms, and to enhance Knölker-type catalysts. The manuscript will be structured as follows: a comprehensive review will be provided on the state-of-the-art techniques for C-N and C-C bond formation using the hydrogen borrowing methodology,[58,59,60] for this particular couplings,[61,62] with a focus on 3d-metal catalysed reactions employing alcohols as alkylating agents,[63,64] including the last insights in the field,[65] particularly focusing on alkylation with hydrazide derivatives as N-nucleophiles, showcasing the limitations of iron complexes and comparing them to ruthenium analogues (Scheme 4). Synthesis of heterocyclic compounds will also be addressed. Finally, the review will delve into the novel room temperature alkylation methodology utilizing light as an energy source.



Scheme 4. Ruthenium complexes employed for hydrogenation, analogues of the Knölker derivative iron complexes (**Ru1**-**Ru3**) and Schvo catalyst (**Ru4**).

2. N-alkylation reactions catalysed by non-noble metals

Alkylation of amines or ketones typically necessitates the utilization of alkyl halides as electrophiles alongside a stoichiometric quantity of base.[66,67] However, this approach often encounters issues such as lack of selectivity, leading to over-alkylation reactions, and the generation of challenging-to-handle by-products like salts,[68] in particular, halogen salts. Consequently, novel methodologies have been devised, with hydrogen autotransfer emerging as a notable alternative.[69,70] In this methodology, the formation of C-N bonds typically involves the utilization of a nucleophilic nitrogen-containing reagent. Following dehydrogenation of an alcohol into the corresponding carbonyl by a metal complex, a condensation step yields an imine/iminium intermediate (Scheme 5). Subsequently, this intermediate is reduced by a metal-hydrogen species to yield the N-alkylated product. Meanwhile, for the formation of C-C bonds, ketones serve as pro-nucleophiles. The unsaturated intermediate arises from a Knoevenagel condensation between the ketone and the dehydrogenated alcohol. Finally, the C=C bond of the α,β-unsaturated ketone is reduced by the metal-hydrogen species to yield the α-alkylated ketone (Scheme 5). Importantly, the only by-product of this reaction is water, stemming from the condensation step.

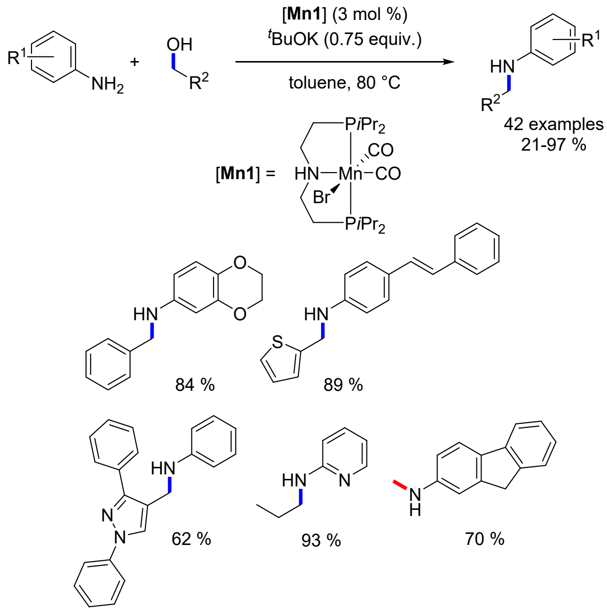


Scheme 5. Streamlined mechanism depicting the alkylation of amines and ketones via hydrogen autotransfer.

Extensive research has been conducted on hydrogen autotransfer reactions in recent decades.[16,27,34,71,72,73,74,75] Numerous catalysts, both noble and non-noble metals, have been documented to facilitate these reactions. This section will focus on the creation of C-N bonds through hydrogen autotransfer reactions utilizing alcohols catalysed by homogeneous first-row transition-metal catalysts.

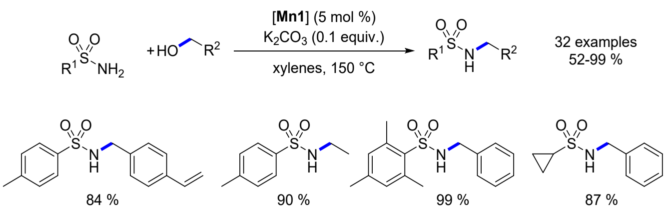
2.1. Manganese-catalysed *N*-alkylation reactions

In 2016, Beller and colleagues reported the initial alkylation of amines with alcohols utilizing the Mn-Macho catalyst.[76] Aniline derivatives underwent alkylation with primary alcohols, yielding exclusively the mono-alkylated product (Scheme 6). This reaction exhibited tolerance towards various functional groups, enabling the synthesis of substituted products. Methylation presented a greater challenge due to the higher energy requirement for the dehydrogenation of methanol compared to other alcohols (for instance, ΔH = +84 kJ/mol for methanol versus ΔH = +68 kJ/mol for ethanol). Nevertheless, the Mn-Macho complex effectively catalysed the methylation of aniline-type derivatives in the presence of one equivalent of base at 100 °C (Scheme 6). The resulting methylated anilines were obtained in yields ranging from 52% to 94%.



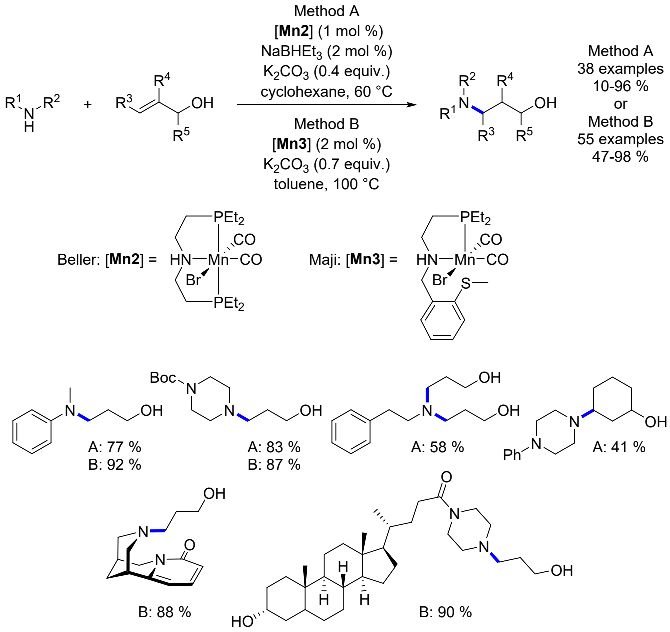
Scheme 6. Manganese-catalysed alkylation of amines.

In 2019, Morill reported the alkylation of sulphonamides catalysed by the Mn-Macho complex.[77] Utilizing this methodology, a range of N-substituted sulfonamides were synthesized, albeit requiring a high temperature (150 °C) to achieve satisfactory yields (Scheme 7).



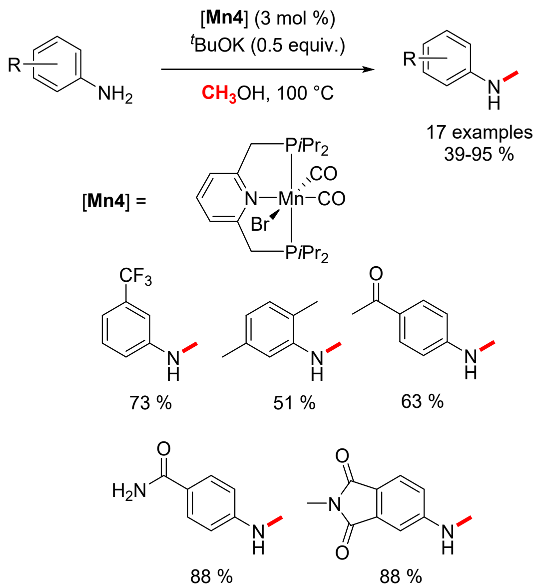
Scheme 7. Alkylation of sulfonamides.

In a more recent development, Beller and Maji described the hydroamination of allylic alcohols.[78,79] This reaction presents a deviation from previous alkylations as it involves a 1,4-addition reaction occurring on the α,β-unsaturated aldehyde intermediate, resulting in the formation of a γ-amino-alcohol as the final product (Scheme 8).



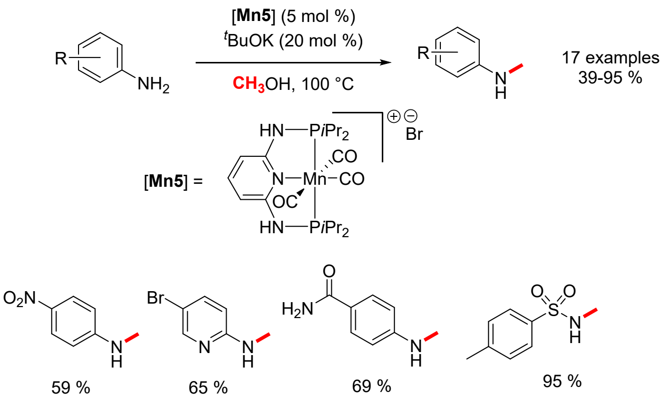
Scheme 8. Protocol of synthesis of γ-amino-alcohols described by Beller and Maji.

Substituting the Macho ligand with a PNP pincer-type ligand, characterized by a pyridine-diphosphine structure, resulted in enhanced methylation reaction outcomes. Under conditions of 100 °C and in the presence of 0.5 equivalents of base, N-methyl anilines were yielded from 39% to 95% (Scheme 9).[80]



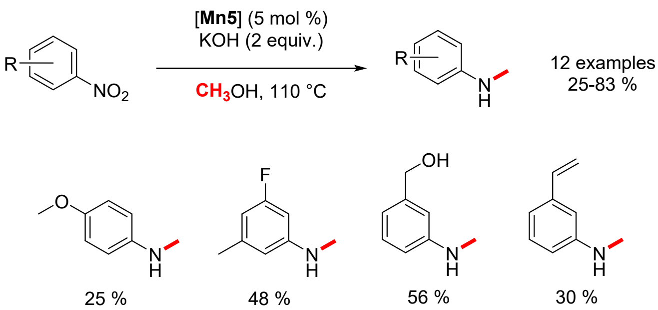
Scheme 9. Methylation of anilines derivatives.

Concurrently with Beller's work, Sortais explored the utilization of a different PNP-Mn complex in the methylation of aniline derivatives.[81] The process yielded N-methylated anilines in yields ranging from 39% to 95% (Scheme 10). Various electron-withdrawing groups (EWG) and electron-donating groups (EDG) were assessed to ascertain the extent of applicability of this reaction.



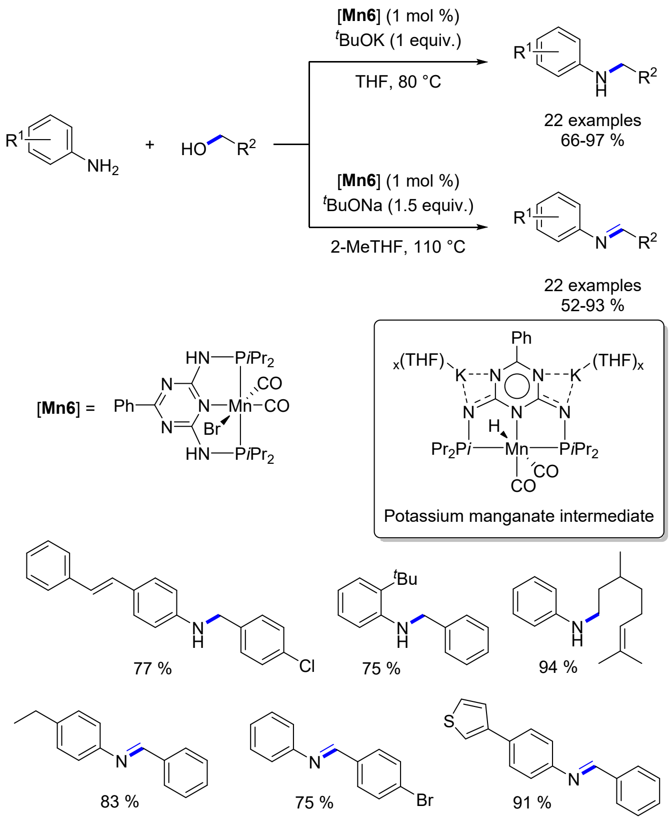
Scheme 10. Methylation of aniline derivatives reported by Sortais.

Morill devised a synthetic approach for the one-pot transformation of nitroarenes into N-methylaryl amines.[82] Initially, the cationic manganese complex facilitates the dehydrogenation of methanol and concurrently reduces the nitro group to an amine. Subsequently, methylation occurs, resulting in the formation of the methylated aniline (Scheme 11).



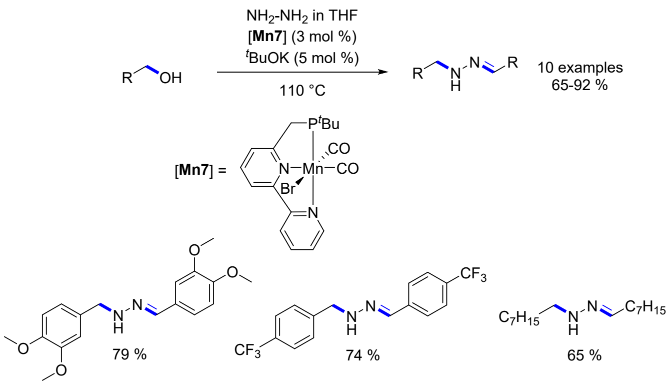
Scheme 11. Synthesis of methylaryl amines.

In 2018, Kempe introduced a base-switchable method for the synthesis of amines or imines.[83] A PNP ligand featuring a triazine motif was developed, and the resultant Mn-complex was employed in the alkylation of anilines. Depending on the base cation (K+ or Na+), starting from the same amine and alcohol, either the N-alkyl amine, through a hydrogen autotransfer process, or the imine, via dehydrogenative condensation, was isolated (Scheme 12). This shift in reactivity was attributed to the chelation capability of the cation and the corresponding manganese hydride intermediate's reactivity. The potassium manganate hydride reduced the imine faster than the sodium salt.



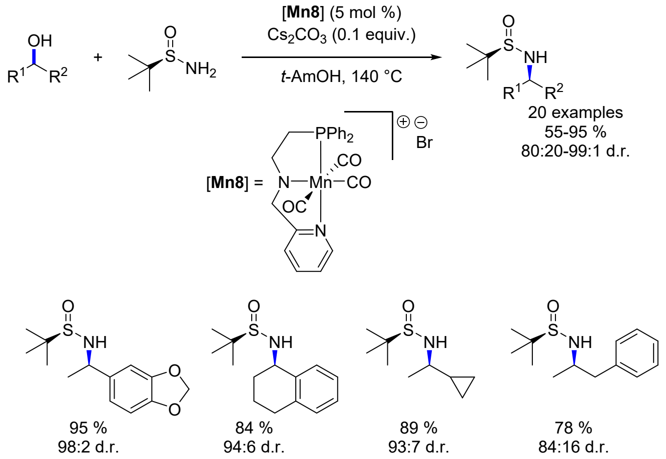
Scheme 12. Alkylation of anilines derivatives.

Refinement of the ligand enabled precise adjustment of reactivity. In 2017, Milstein substituted the PNP ligand with a phosphine-bipyridine ligand (PNN ligand) and utilized the resulting Mn-complex in the alkylation of hydrazine (Scheme 13).[84] Remarkably, this reaction yielded N-substituted hydrazones through a combination of hydrogen transfer for the alkylation step and dehydrogenation for the formation of the hydrazone moiety.



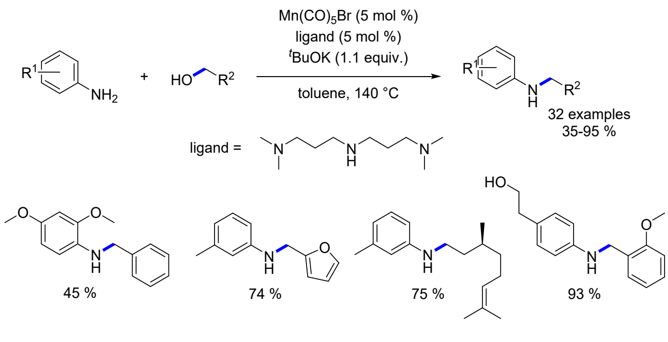
Scheme 13. Synthesis of N-substituted hydrazones.

Rueping introduced a modification in which the central pyridine ring of the ligand was substituted with an amine, resulting in the formation of a new cationic manganese complex.[85] This complex was employed in an asymmetric amination of secondary alcohols (Scheme 14). The presence of a tert-butyl group facilitated an asymmetric reduction of the imine intermediate. This tert-butyl group directed the Mn-H complex towards the less hindered side of the imine, thereby achieving diastereoselective reduction in up to 98:2 d.r.



Scheme 14. Asymmetric amination of secondary alcohols.

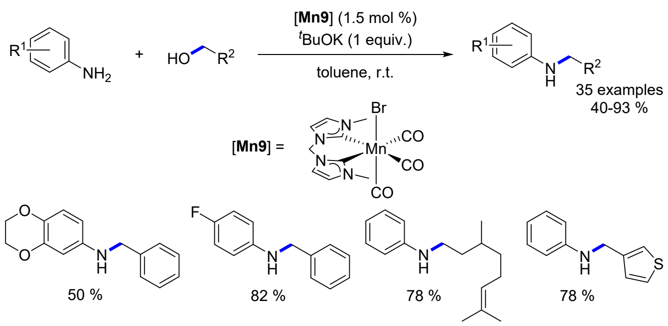
In 2018, Balaraman presented an economical method for the N-alkylation of anilines using benzylic and aliphatic alcohols.[86] A manganese salt ($Mn(CO)_5Br$) was combined with N1-(3-(Dimethylamino)propyl)-N_3,N_3-dimethylpropane-1,3-diamine (NNN ligand) to generate the catalytic agent. Both electron-rich and electron-deficient N-substituted anilines were obtained in yields ranging from 35% to 95% (Scheme 15). This approach proves competitive with the catalytic systems of Beller and Kempe, as the catalytic species is prepared in situ, albeit yielding slightly lower product yields.



Scheme 15. Alkylation of aniline derivatives.

The subsequent year, Ke introduced the first non-noble metal system operating at room temperature for the alkylation of aniline derivatives.[87] Employing a manganese complex with an N-heterocyclic carbene (NHC) ligand, the reaction of anilines with benzylic and aliphatic alcohols proceeded smoothly at ambient conditions. The resulting N-substituted products were obtained in yields ranging from 40% to 93% (Scheme 16). Investigation into methylation was also undertaken, revealing that a temperature of 100 °C was necessary to achieve methylated products in yields of 53% to 94%. Mechanistic elucidation via Density Functional Theory

(DFT) calculations highlighted an outer-sphere mechanism with a maximum energy barrier of 23.7 kcal/mol. This stands in contrast to the inner-sphere mechanism, which necessitated the de-coordination of a CO ligand, resulting in a maximum energy barrier of 46.4 kcal/mol.

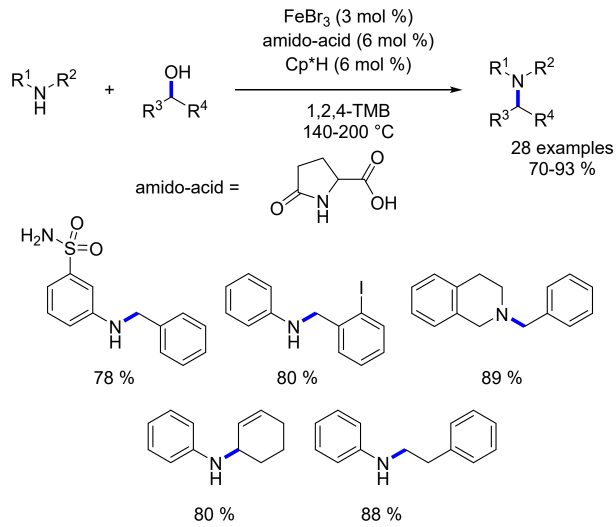


Scheme 16. Alkylation of anilines derivatives.

In 2023 Balaraman and coworkers explored a general hydrogenative cleavage/N-alkylation tandem of cyclic and acyclic diazo (N=N) compounds to synthesize value-added amines under manganese catalysis.[88] The reaction is catalyzed by a single-site pincer based molecular manganese complex and proceeds through tandem dehydrogenation, transfer hydrogenation, and borrowing hydrogenation mechanisms. Notably, the process utilizes abundantly available renewable feedstocks, such as alcohols, which serve as both (transfer)hydrogenating and alkylating agents.

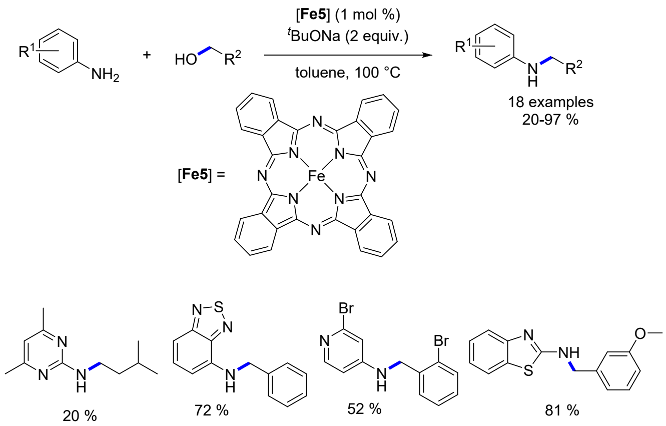
2.2. Iron-catalysed *N*-alkylation reactions

In 2011, Saito reported one of the early instances of iron-catalysed alkylation of amines with alcohols.[89] Utilizing iron tribromide (3 mol %) in conjunction with an amido-acid (6 mol %) and Cp*H (6 mol %), a diverse array of primary and secondary amines underwent alkylation with benzylic and aliphatic alcohols, yielding secondary and tertiary amines at temperatures ranging from 140 to 200 °C (Scheme 17). Furthermore, unsaturated alcohols were alkylated without undergoing any reduction of the C=C bond. The reaction necessitated high temperatures, and the exact nature of the catalytic species remained unclear. Additionally, the work reported only a limited number of substituents.



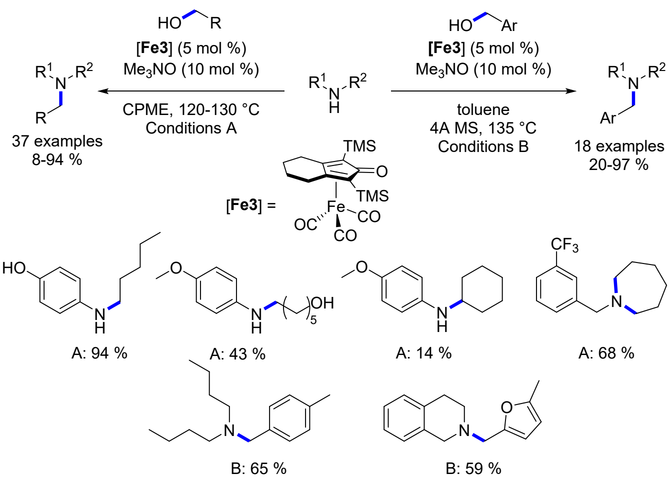
Scheme 17. Iron-catalysed alkylation of amines reported by Saito.

In 2013, Singh presented iron(II)-phthalocyanine as a catalyst for the alkylation of aromatic amines with alcohols.[90] This catalyst facilitated the mono-alkylation of arylamines with both benzylic and aliphatic alcohols (Scheme 18). However, lower yields were achieved with aliphatic alcohols, attributed to the increased energy demand for the dehydrogenation step compared to benzylic alcohols. Minakawa also reported the use of Fe(III)-phthalocyanine chloride for the same reaction, albeit with less tolerance for functional groups and requiring higher temperatures (130 °C).[91]



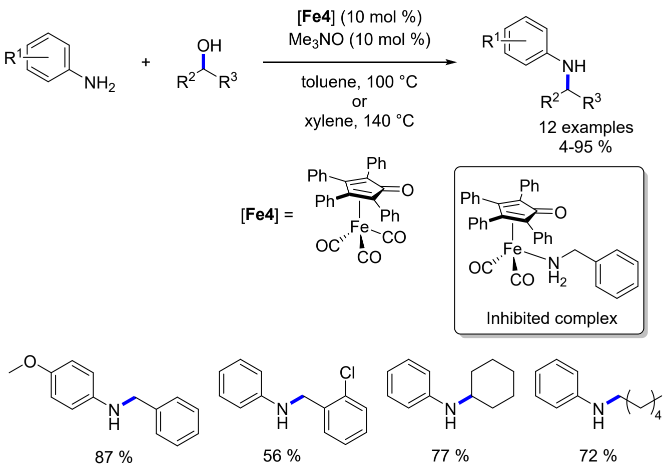
Scheme 18. Alkylation of amines reported by Singh.

Feringa and Barta detailed the alkylation of aryl and benzyl amines utilizing a cyclopentadienone iron complex, all without the presence of a base—a significant advantage within the realm of sustainable chemistry.[92] Interestingly, aliphatic alcohols yielded the alkylated amines in satisfactory yields, whereas the efficiency of the reaction with benzylic alcohols was somewhat lower. Furthermore, when anilines were reacted with diols, the result was the formation of amino-alcohol products instead of N-aryl cyclic amines. To address the diminished reactivity of benzyl alcohols, the authors proposed employing benzylamines in conjunction with aliphatic alcohols (or diols). This strategy yielded N-benzylamines in commendable yields (Scheme 19). It is noteworthy that N-alkyl benzylamine derivatives were synthesized through the monoalkylation of benzylamines with alcohols. Additionally, if benzyl alcohols were to be utilized in such alkylation procedures, it was necessary to substitute CPME with toluene and include molecular sieve.[92] However, this modification did not enhance reactivity with secondary alcohols.



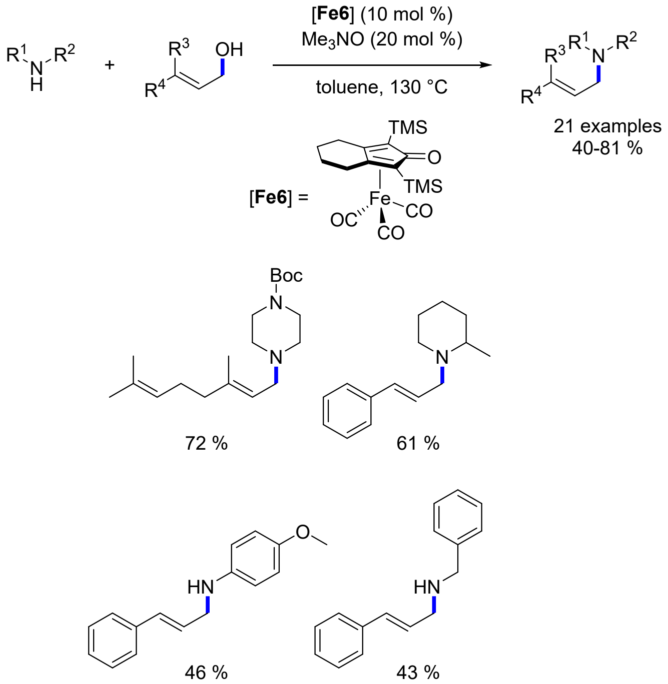
Scheme 19. Knölker-catalysed alkylation of amines described by Feringa and Barta.

Wills investigated a tetraphenylcyclopentadienone iron complex, also known as Schrauzer's complex,[93] for the alkylation of anilines with primary alcohols.[94] However, this reaction was constrained to methoxy- and chloro-substituted anilines and exhibited lower conversion rates compared to Knölker's complex, even necessitating higher catalyst loading and temperature (Scheme 20). Interestingly, when benzylamine was introduced, no product formation was observed. The authors postulated that benzylamine inhibited catalytic activity by forming a stable amino-iron complex with the active species, a phenomenon previously observed by Beller with Shvo's complex.[95]



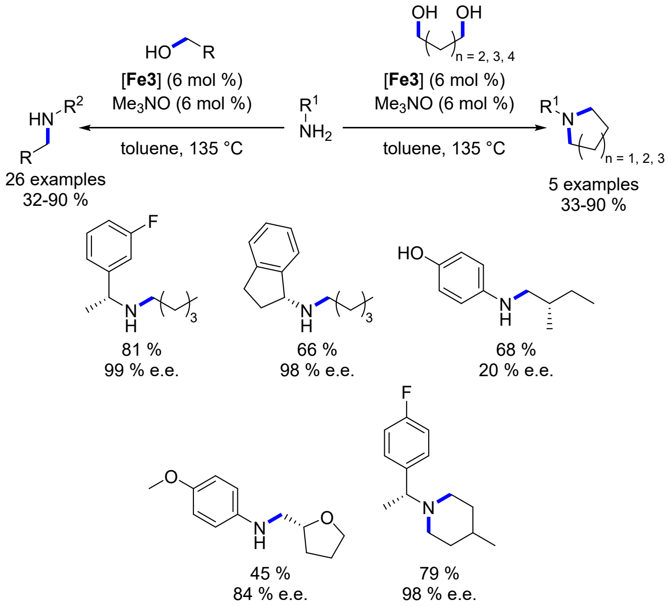
Scheme 20. Alkylation of anilines.

In 2016, Sundararaju documented the alkylation of amines with allyl alcohols catalysed by the Knölker's complex.[96] Unlike the hydroamination reaction described by Maji and Beller, the formation of the C-N bond occurred through condensation between the amine and the carbonyl intermediate generated in situ, yielding allyl amines instead of γ-amino-alcohols (Scheme 21).



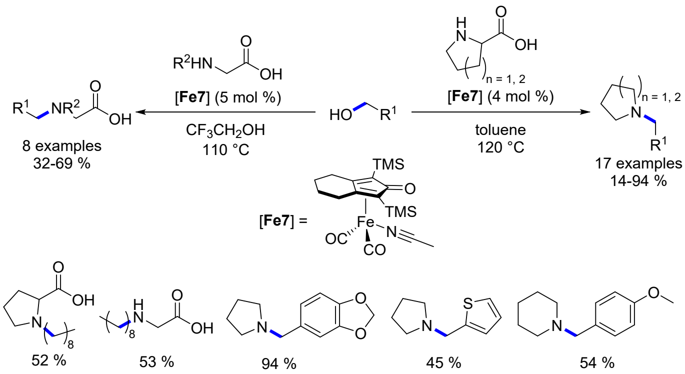
Scheme 21. Alkylation of amines with allylic alcohols.

Barta also explored the synthesis of chiral compounds commencing from chiral amines or alcohols.[97] Chiral benzylamines were subjected to reaction with aliphatic alcohols (or diols), yielding mono- or di-alkylated products in satisfactory yields (61-90%, Scheme 22). Employing a similar protocol with optically active alcohols resulted in the corresponding products with moderate to good yields (32-68%). However, lower enantiomeric excesses were achieved in this scenario, potentially due to racemization facilitated by enol (or enamine) formation post the dehydrogenation step.



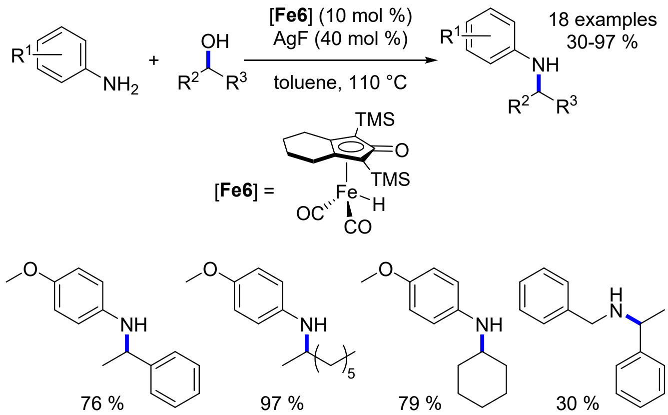
Scheme 22. Synthesis of chiral amines.

The same research group further explored the N-alkylation of unprotected amino acids.[98] They employed a derivative of the Knölker complex featuring an acetonitrile ligand, which replaced one CO ligand. Various primary alcohols were utilized in this reaction under acidic conditions, yielding the mono-alkylated product in moderate to good yields (32-69%, Scheme 23). This investigation was extended to the synthesis of pyrrolidine and piperidine derivatives using proline derivatives.[99] Utilizing non-acidic conditions facilitated the removal of the acid function via in situ decarboxylation.



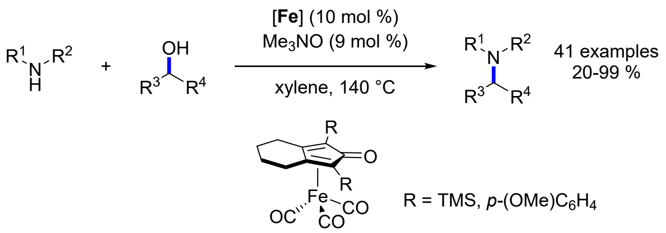
Scheme 23. Alkylation of amino-acids and synthesis of N-substituted cyclic amines.

Building upon Barta's findings regarding the reluctance of secondary alcohols as pro-electrophiles, Zhao introduced a method for their activation using silver fluoride as a Lewis acid.[100] Despite the continued high loading of both the iron complex and silver salt (10 mol % each), this approach provided a pathway to access N-aryl and N-benzyl α,α'-disubstituted amines in moderate to good yields (Scheme 24).



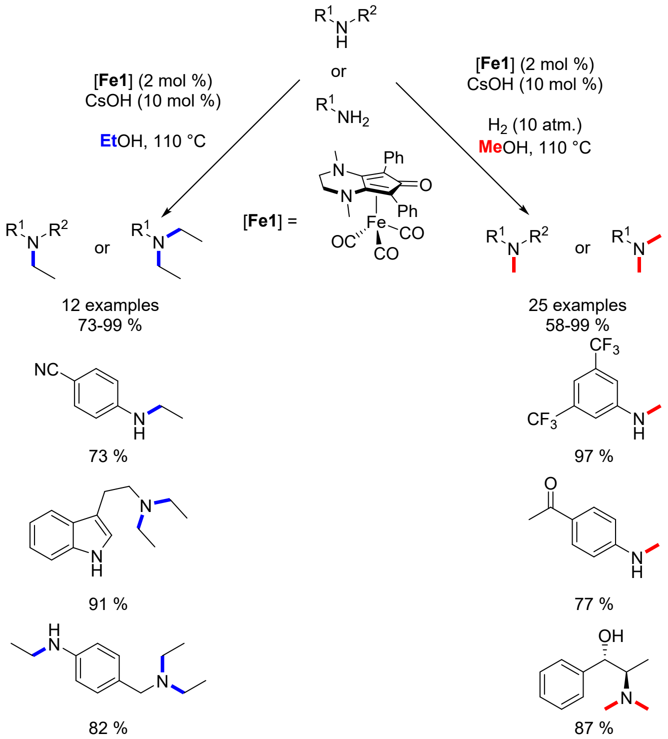
Scheme 24. Alkylation of amines with secondary alcohols.

Subsequently, Wills and coworkers revisited the alkylation of amines using a small collection of Knölker-type complexes.[101] This investigation involved substituting the trimethylsilyl groups of the cyclopentadienone with aryl rings carrying electron-donating or electron-withdrawing groups, and assessing the performance of various catalysts. The outcomes were substrate-dependent, varying based on the specific substrates involved in the reaction. While a complex containing a methoxy-aryl group exhibited favourable performance with most substrates, the original Knölker complex was utilized to illustrate the reaction (Scheme 25).



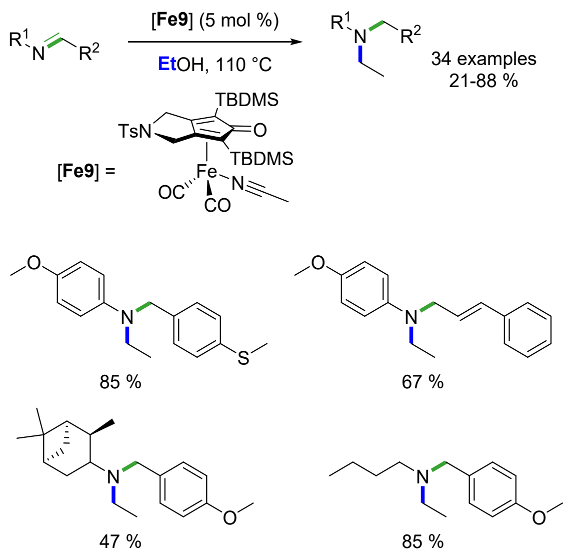
Scheme 25. Alkylation of amines with Knölker complex and analogues.

Continuing this line of inquiry, Renaud and Poater explored a modified Knölker-type complex featuring an electron-rich ligand for the methylation and ethylation of amines.[45] This diaminocyclopentadienone iron tricarbonyl complex, previously employed by the same authors for reductive amination reactions,[102] was also employed in that study. Alkylation using methanol and ethanol as pro-electrophiles has been minimally investigated and presents additional challenges due to the higher dehydrogenation energy associated with ethanol and methanol compared to other alcohols. However, this novel complex facilitated the synthesis of ethyl- and methyl-substituted amines in good to excellent yields with low catalyst loading (Scheme 26). Notably, the presence of a catalytic amount of base was necessary for these reactions. Furthermore, a hydrogen pressure of 10 atm was required to achieve the methylation reaction in good yields.



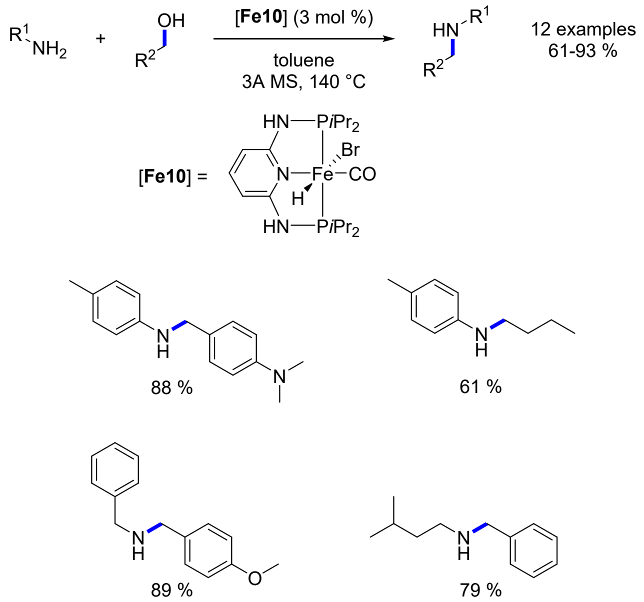
Scheme 26. Methylation and ethylation of amines reported by Renaud.

In the same year, Bour *et al.* detailed a reductive ethylation process of N-arylimines catalysed by a Knölker-type complex.[103] Originally introduced by Renaud *et al*. for reductive amination, this complex was repurposed for the sequential reaction. In this process, ethanol functioned both as the alkylating agent and the hydride source. The outcome yielded N-aryl-N-ethyl amines in yields spanning from 21 to 88% (Scheme 27).



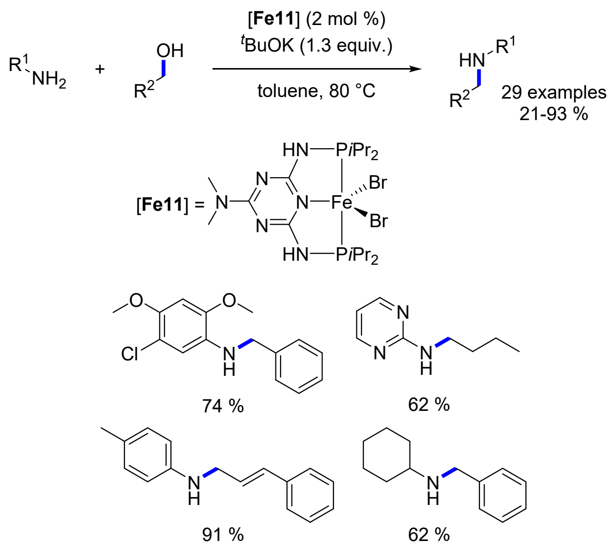
Scheme 27. Ethylation of imines reported by Bour.

Kirchner documented an iron complex analogous to Sortais PNP-Mn complex. This iron-hydride complex facilitated the alkylation of amines with primary alcohols.[104] Although low catalyst loadings were employed, achieving good yields necessitated high temperatures (Scheme 28).



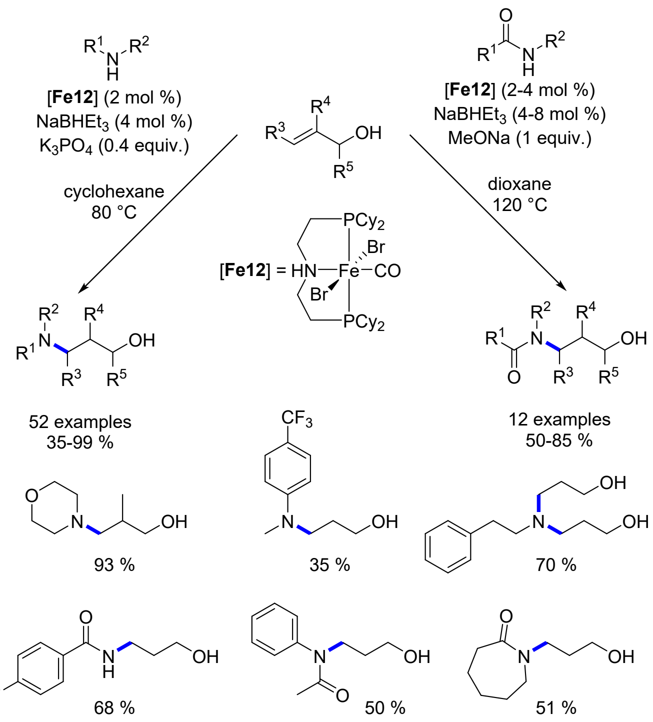
Scheme 28. Alkylation of amines.

Substituting the pyridine ring of the ligand with a dimethylamino triazine ring enhanced catalytic efficiency, resulting in a decrease in reaction temperature from 140 to 80 °C, and eliminating the need for molecular sieves (Scheme 29).[105] Nevertheless, secondary alcohols displayed low reactivity under these conditions, and the overall yield of the reaction was not enhanced.



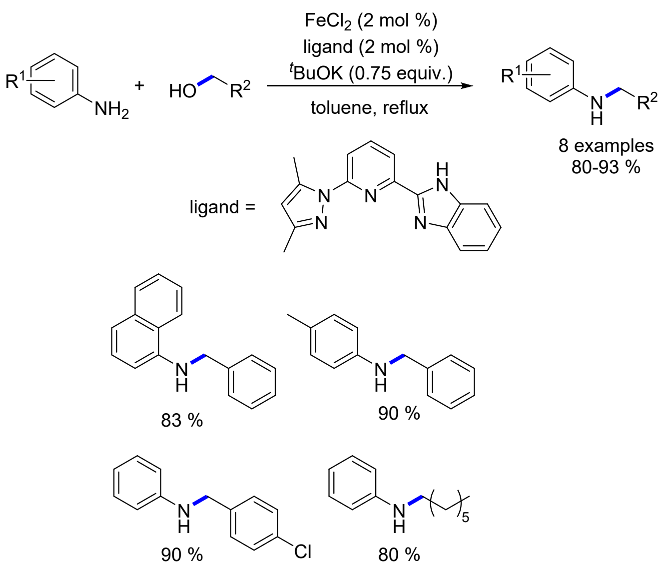
Scheme 29. Iron(II)-catalysed alkylation of amines reported by Kirchner.

In 2019, Wang documented the hydroamination of allylic alcohols.[106] The PNP-Fe complex catalysed the oxidation of the alcohol to form α,β-unsaturated aldehyde. Subsequent 1,4-addition by the amine yielded the amino-aldehyde, which was then reduced by the complex to produce the γ-amino-alcohols (Scheme 30). This approach was later adopted by Maji and Beller, utilizing manganese pincer complexes. Amides were also found to be compatible with this reaction, albeit requiring higher temperatures.



Scheme 30. Hydroamination of allylic alcohols reported by Wang.

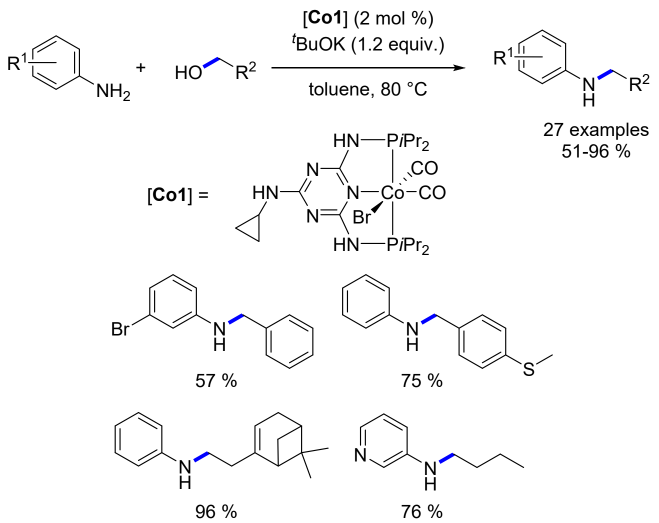
Liu presented an NNN-Fe(II) complex featuring pyrazoyl and imidazoyl groups for the alkylation of amines.[107] This catalyst facilitated the synthesis of alkylated anilines using primary alcohols, resulting in good yields (Scheme 31). However, only a few instances with restricted functional groups were illustrated.



Scheme 31. Alkylation of anilines reported by Liu.

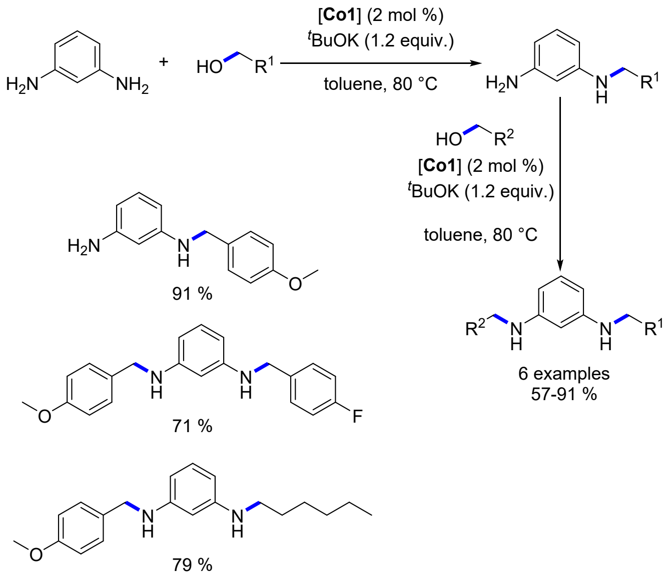
2.3. Cobalt-catalysed *N*-alkylation reactions.

Kempe detailed the initial cobalt-catalysed process of alkylating amines using alcohols.[108] A pre-catalyst was formed by combining CoCl2 with a PNP ligand featuring a triazine ring. This metal complex facilitated the alkylation of different aniline derivatives using both benzylic and aliphatic primary alcohols. Interestingly, the aliphatic primary alcohols proved to be equally effective as benzyl alcohols as pro-electrophiles (Scheme 32). Notably, this study did not include any instances involving secondary alcohols or aliphatic amines.



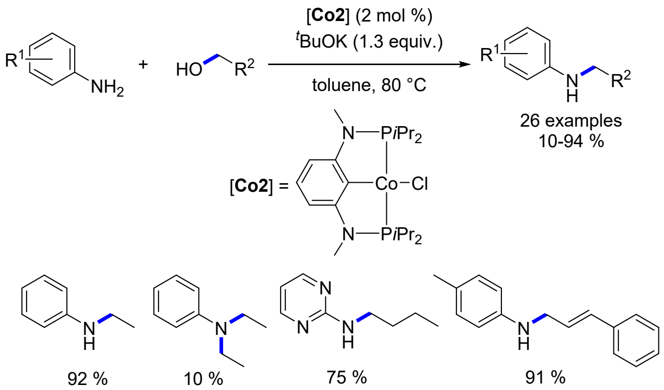
Scheme 32. Cobalt-catalysed alkylation of anilines.

Diamine alkylation was conducted in a stepwise procedure, enabling the production of non-symmetrical N,N'-di-substituted diamines. Moreover, the mono-substituted diamine could be obtained by utilizing an excess of diamine relative to the alcohol (Scheme 33).



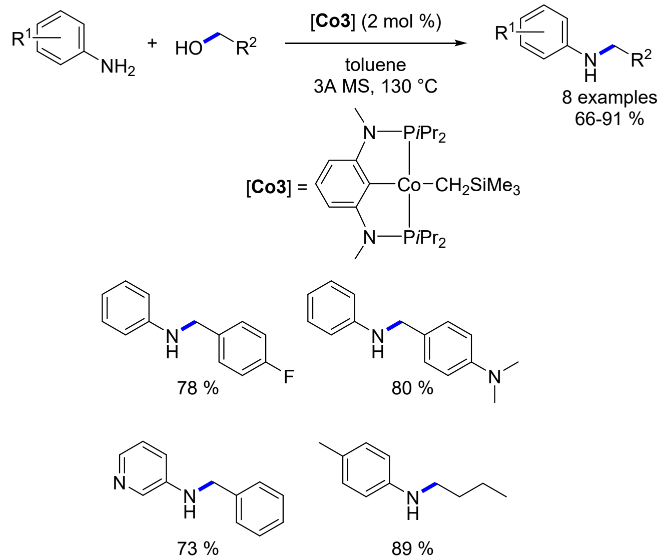
Scheme 33. Synthesis of non-symmetric diamines reported by Kempe.

Kirchner synthesized a cobalt(II) complex along with a PCP pincer-type ligand.[109] Utilizing this complex, Kirchner demonstrated its effectiveness in the alkylation of arylamines with primary alcohols, resulting in alkylated amines with yields ranging from 10% to 94% (Scheme 35). Notably, only aromatic amines were employed in this reaction, as aliphatic amines were found to potentially hinder the catalytic activity, a phenomenon previously observed by Wills using the Schrauzer-Reppe complex (Scheme 34).[94] Remarkably, the alkylation of cinnamyl alcohol was achieved without the reduction of the C=C bond. Although the dimethylation of aniline resulted in the formation of the corresponding dialkylated amine, the yield was notably low at 10%. Nevertheless, this instance marks a significant milestone as the first dialkylation of an aniline catalysed by an Earth-abundant metal complex.



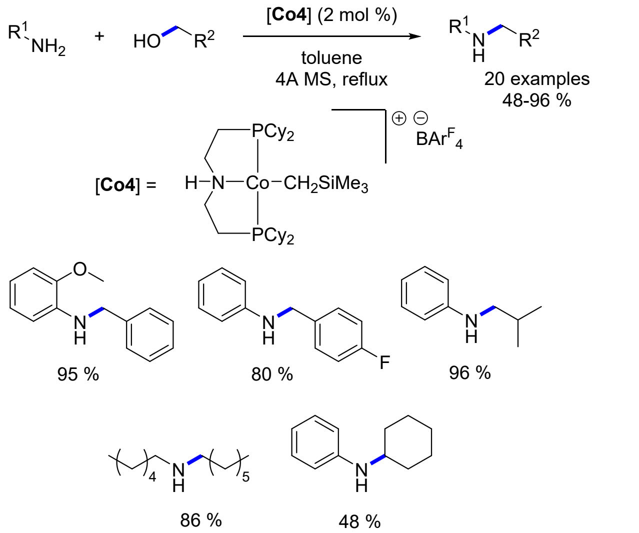
Scheme 34. Cobalt-catalysed alkylation of anilines reported by Kirchner.

A variant of this catalyst featuring a highly basic CH_2SiMe_3 ligand was also evaluated. This alternative catalyst proved to be effective for the targeted reaction and did not require the addition of a base. However, elevated temperatures were necessary for the reaction to proceed (Scheme 35).



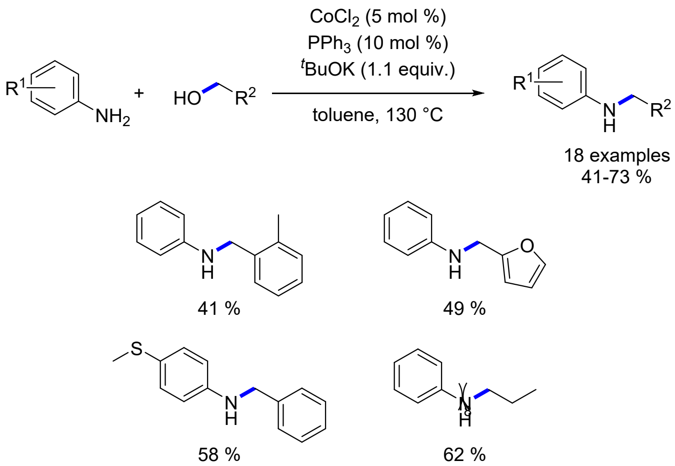
Scheme 35. Base-free alkylation of amines reported by Kirchner.

Zhang subsequently reported the utilization of this methylene trimethylsilyl ligand in a Macho-type cationic cobalt complex.[110] Once again, this ligand demonstrated the ability to circumvent the need for a base. Both aryl and aliphatic amines were successfully alkylated with a range of primary alcohols, yielding good to excellent results (Scheme 36). Notably, an example utilizing cyclohexanol as a secondary alcohol resulted in the alkylated aniline with a yield of 48%.



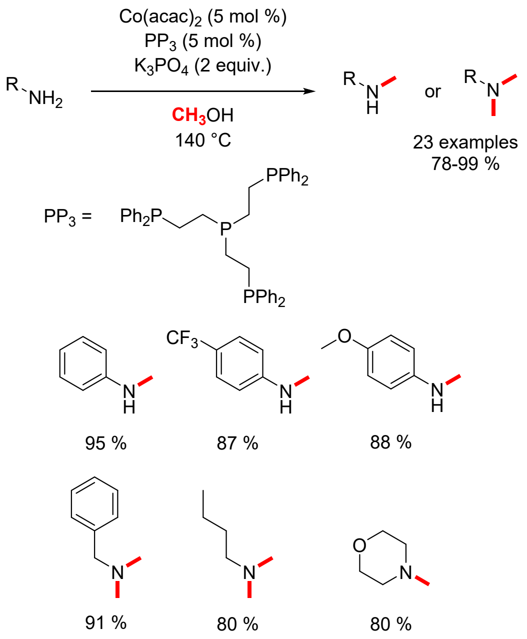
Scheme 36. Alkylation of amines described by Zhang.

Balaraman documented the combination of $CoCl_2$ with PPh_3 for the alkylation of anilines using primary alcohols.[111] Several substituted anilines underwent alkylation with both benzylic and aliphatic alcohols in this reaction. However, the yields were lower compared to previously reported cobalt-catalysed hydrogen autotransfer reactions (Scheme 37).



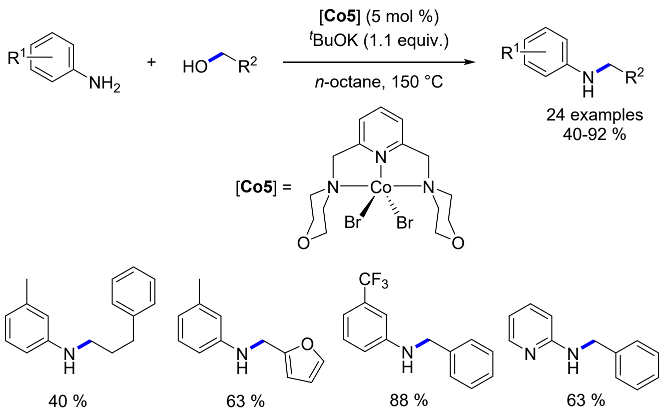
Scheme 37. Cobalt-catalysed alkylation of anilines reported by Balaraman.

In 2017, Liu conducted research on the methylation of both aryl and aliphatic amines.[112] By combining $Co(acac)_2$ with a tetraphosphine ligand, aromatic amines produced mono-methylated anilines, whereas aliphatic amines exclusively yielded the dimethylated product (Scheme 38).



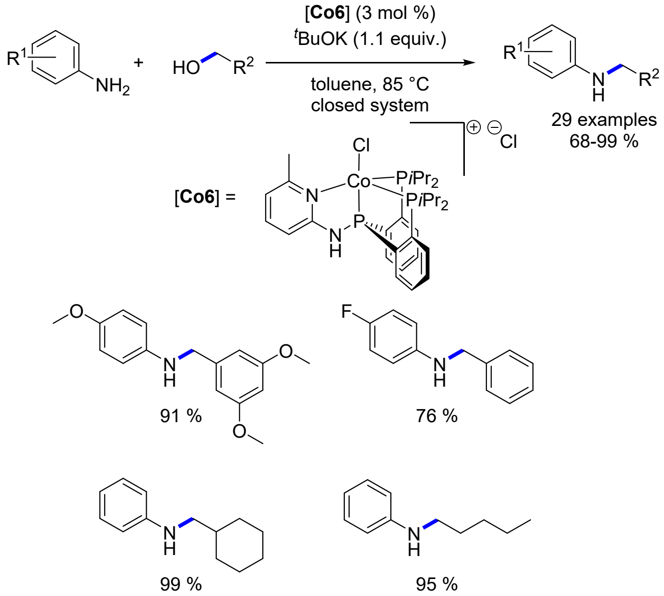
Scheme 38. Methylation of amines reported by Liu.

Balaraman *et al*. developed a novel NNN-Co complex,[113] which exhibited activity in the alkylation of aniline derivatives with alcohols. Although higher temperatures were necessary, the N-alkylated aniline compounds were isolated in yields ranging from 40% to 92% (Scheme 39).



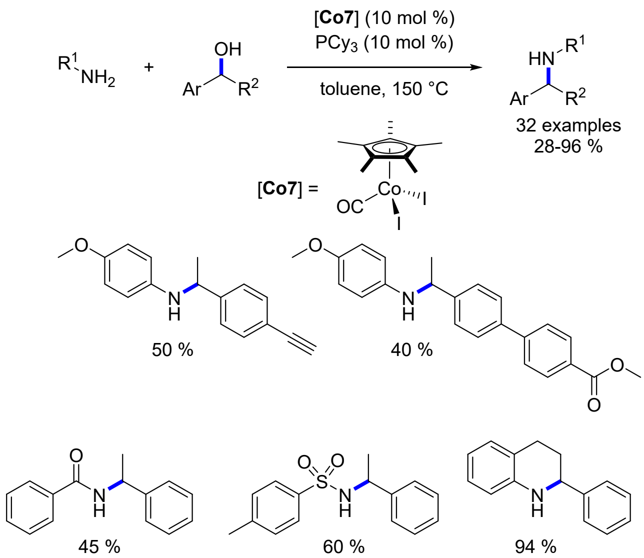
Scheme 39. Cobalt-pincer complex-catalysed alkylation of anilines.

More recently, Ding reported on a switchable synthesis of imines and amines catalysed by a PNPP ligand.[114] By adjusting the base loading, temperature, and system type (closed or open), either the imine or the amine product could be selectively obtained. This catalytic system demonstrated efficiency in the alkylation of anilines with primary alcohols; however, alkylated aliphatic amines were not produced (Scheme 40).



Scheme 40. Alkylation of anilines by Ding.

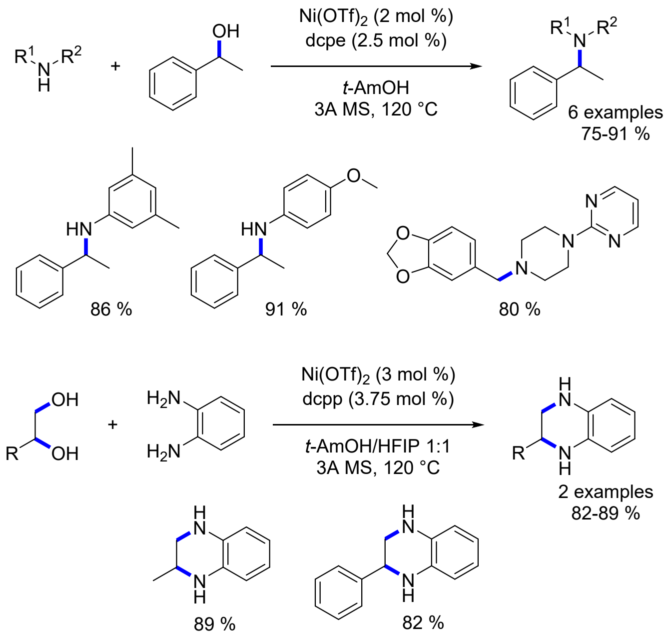
Among the cobalt-catalysed alkylations of amines discussed earlier, only one instance of alkylation with a secondary alcohol was reported by Zhang.[110] Alkylation with secondary alcohols poses a challenge due to the lower electrophilicity of ketones compared to aldehydes. In 2019, Sundararaju introduced a Cp*Co(III) complex for the alkylation of amines with secondary alcohols.[115] The reaction was conducted in toluene at 150 °C without the need for additional base (Scheme 41). This procedure resulted in the formation of alkylated anilines and amide derivatives using various secondary benzylic alcohols.



Scheme 41. Alkylation of amines and amides with secondary alcohols.

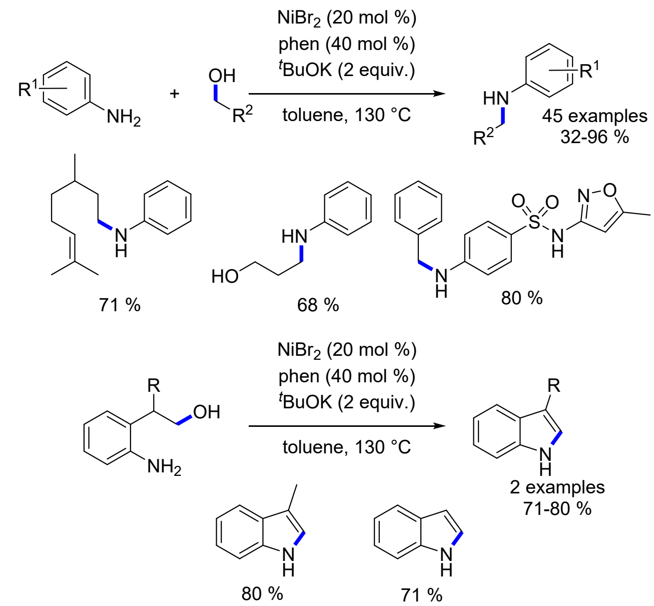
2.4. Nickel-catalysed N-alkylation reactions.

Zhou reported the first homogeneous nickel-complex-catalysed alkylation of amines in 2017.[116] A nickel salt was combined with a diphosphine ligand to catalyse the alkylation of amines with alcohols. This reaction facilitated the synthesis of substituted anilines, piperazines, and trisubstituted amines (Scheme 42). Additionally, the alkylation of acylhydrazides with alcohols was also reported later not with nickel, but with ruthenium.[117,118]



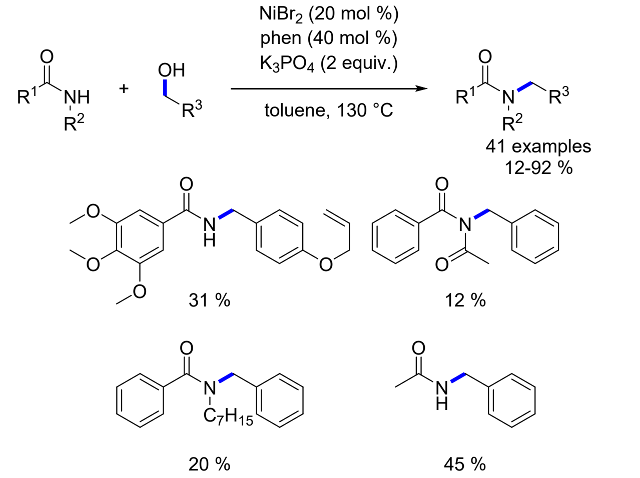
Scheme 42. Aklylation of amines reported by Zhou.

Banerjee described a straightforward method involving the in situ generation of a nickel-phenanthroline complex for catalysing the alkylation of aniline derivatives.[119] Indole derivatives could be synthesized under the same reaction conditions through an intramolecular cyclization and isomerization into the aromatic form (Scheme 43).



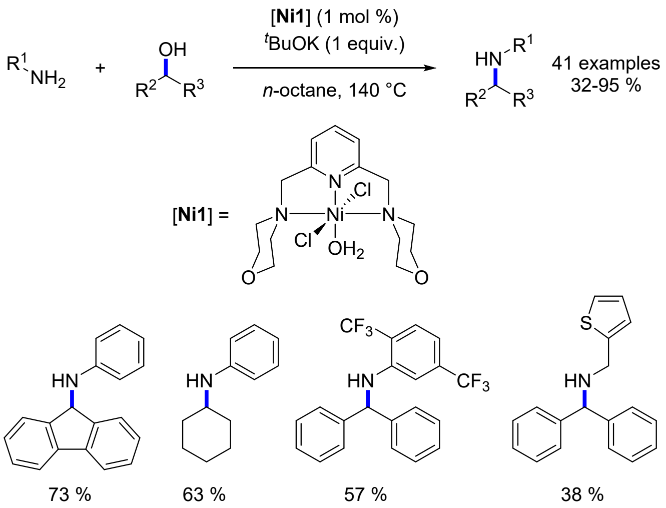
Scheme 43. Alkylation of anilines reported by Banerjee.

By employing K_3PO_4 as a base and reducing the catalyst loading, it was also possible to achieve the alkylation of amide.[120] This reaction facilitated the alkylation of a range of amides, including N-substituted amides and secondary amides. Lower yields were observed with less nucleophilic amides or aliphatic alcohols (Scheme 44).



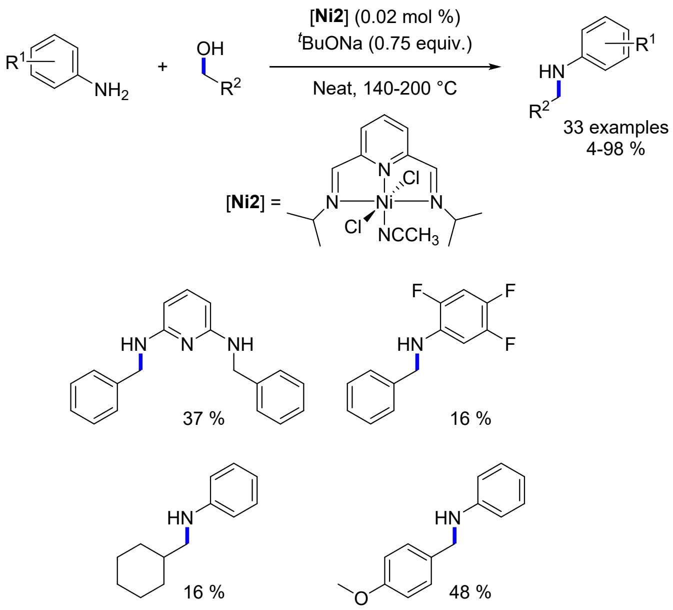
Scheme 44. Alkylation of amides reported by Banerjee.

Using the same NNN-ligand, Balaraman devised a nickel-catalysed alkylation process for aniline and benzylic amines with various secondary alcohols. This reaction was conducted at 140°C in n-octane (Scheme 45).[121] Under identical conditions, no product was obtained when using aliphatic amines and non-cyclic aliphatic secondary alcohols. Similarly, in analogous reaction conditions, only primary alcohols were reactive with the cobalt analogue of this complex previously reported by the same group.[113]



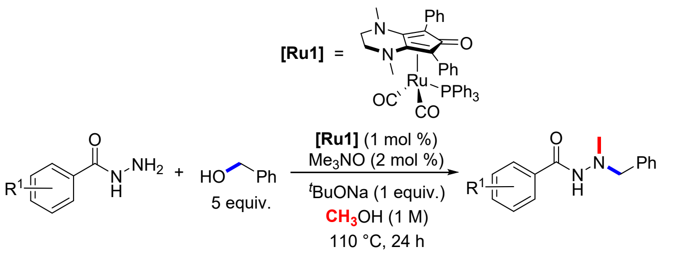
Scheme 45. Alkylation of amines with secondary alcohols reported by Balaraman.

Following Balaraman's work, Kumar introduced a pyridine-diimine-based nickel complex and utilized it for the alkylation of aniline compounds with benzylic alcohols. The reaction was conducted at temperatures ranging from 140 to 200 °C with a substoichiometric amount of ^{t}BuOK (0.75 equiv., Scheme 46). Good catalytic activities were achieved with turnover numbers (TONs) up to 4500 at 140 °C. Remarkably, significantly higher TONs (up to 34,000) were attained at elevated temperatures (200 °C) using only 0.002 mol % of the nickel complex.[122]



Scheme 46. Alkylation of amines reported by Kumar.

The first phosphine-free ruthenium complex-catalysed monoalkylation, dialkylation and cross dialkylation of acyl hydrazide using alcohols as pro-electrophiles was disclosed (Scheme 47). Various benzylic, cyclic and aliphatic primary and secondary alcohols were engaged in these processes. Actually, this was also the first ruthenium-catalysed one-pot cross dialkylation of hydrazides was described with methanol and ethanol.

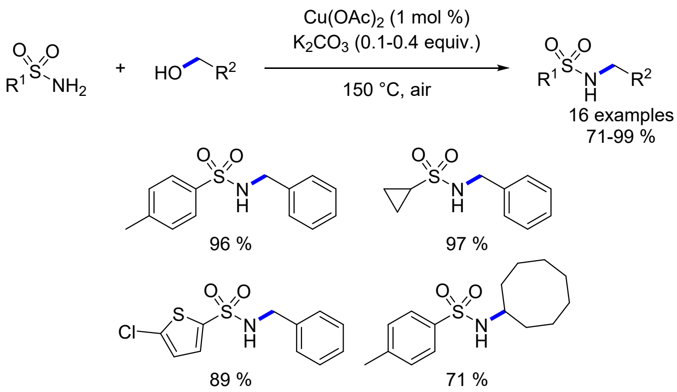


Scheme 47. Cross N',N'-dialkylation of hydrazides.

DFT calculations clearly explained the observed selectivity favouring the mono or the dialkylation with the calculation of the $\%V_{Bur}$.[53,123,124] They also confirmed that methanol was the most reactive pro-electrophile, favouring the formation of the dimethylated product. Although this result is the opposite of what is observed experimentally, it highlights the compromise between energy of dehydrogenation and electrophilicity. Although hydrazines are not commonly used, Fe complexes show no activity with a Ni complex, but they can be replaced by Ru complexes.[117,118,125] This alkylation can then be extended to a three-component cascade process, leading to *N,N*-dialkylated hydrazine derivatives.[118]

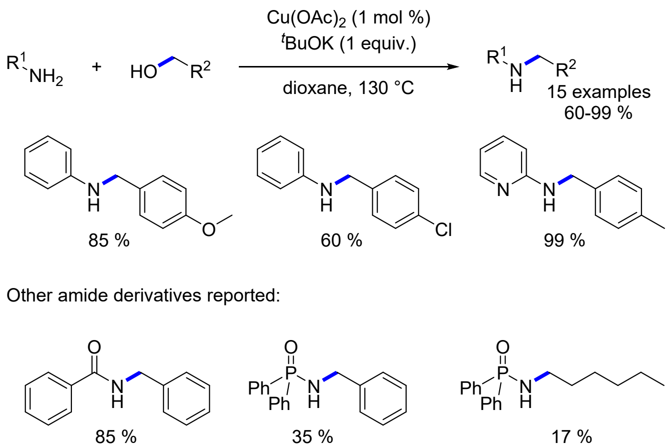
2.5. Copper-catalysed N-alkylation reactions.

Beller documented the inaugural ligand-free copper-catalysed alkylation of sulphonamides with alcohols in 2009.[126,127] Various sulphonamides underwent reactions with both benzylic and aliphatic primary and secondary alcohols, resulting in the formation of N-substituted sulfonamides. The process tolerated a diverse range of functionalized compounds (Scheme 48).



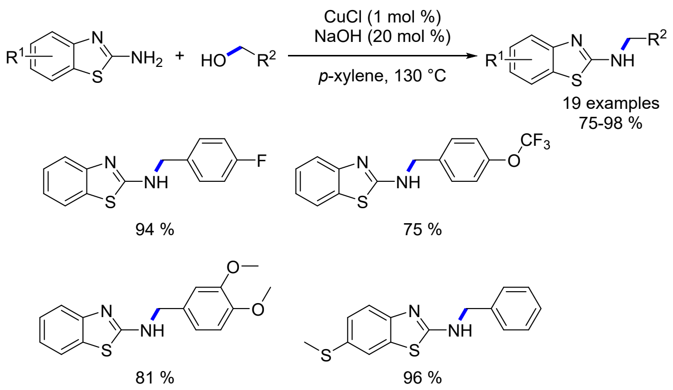
Scheme 48. Copper-catalysed alkylation of sulphonamides reported by Beller.

In 2010, Yus expanded upon this work by extending the alkylation of aniline derivatives to lower temperatures, employing a stronger base, higher base loading, and longer reaction times (2 days).[128] N-Alkylated anilines were obtained in yields ranging from 60% to 99% (Scheme 49). Furthermore, this research encompassed the N-alkylation of amides and amide derivatives.[129] A mechanistic exploration employing DFT calculations revealed an outer sphere mechanism for both the dehydrogenation and reduction steps of this reaction.[130]



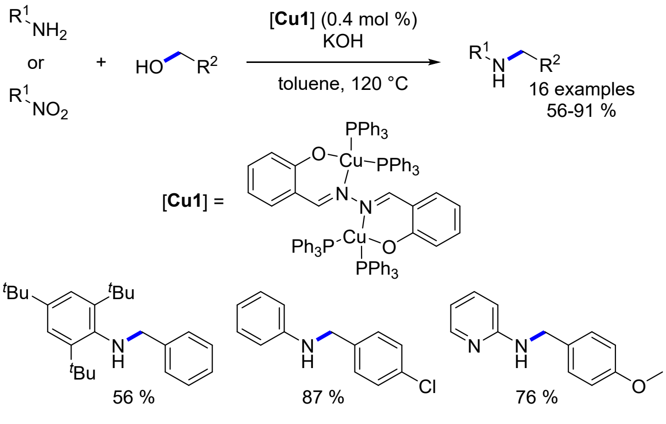
Scheme 49. Copper-catalysed alkylation of anilines and amides derivatives.

In 2011 Li documented the utilization of CuCl as a catalyst for the alkylation of 2-aminobenzothiazoles with benzyl alcohols.[131] The reaction yielded N-alkylated amino benzothiazoles in very good yields (Scheme 50). And the same year Saito and coworkers proposed a novel method for cross-coupling two different alcohols.[132] This C–C bond formation was achieved with a low catalyst loading of CuBr (0.05–0.2 mol %) and NaOH (4–20 mol %) under H_2 (1 atm). The reaction offeree an alternative approach for synthesizing longer-chain alcohols. Notably, the catalytic cycle differs from previously reported pathways for the Guerbet reaction, which typically involves "borrowing hydrogen".



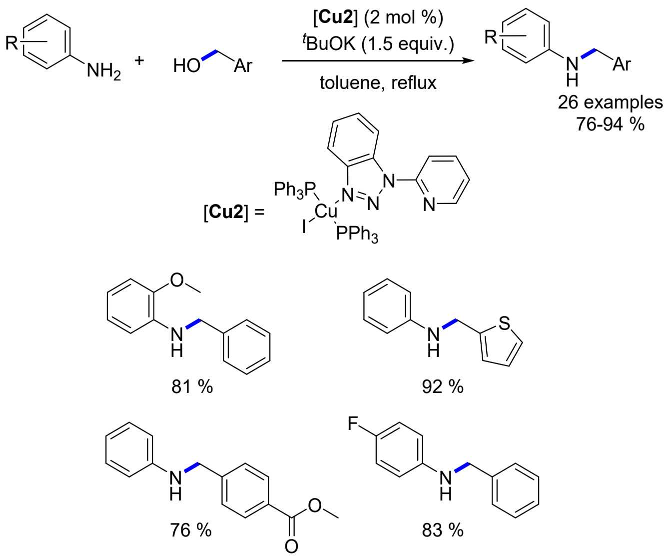
Scheme 50. Alkylation of amino benzothiazoles described by Li.

In 2015, Viswanathamurthi introduced a novel heteroleptic binuclear copper(I) complex for catalysing the alkylation of anilines with benzylic alcohols.[133] It is noteworthy that sterically hindered anilines were also alkylated with good yields (Scheme 51). Furthermore, nitroarenes were involved and reduced in situ to yield the corresponding N-alkylated compounds after subsequent alkylation.



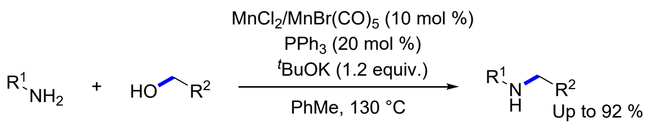
Scheme 51. Alkylation of anilines and nitroarenes.

In 2017, Wang presented a Triazole-Phosphine-copper complex for the synthesis of benzimidazoles and the alkylation of arylamines.[134] This system enabled the alkylation of various anilines with benzyl alcohols and exhibited tolerance towards substituted benzylic alcohols (Scheme 52). Notably, this method facilitated a reduction in the reaction temperature compared to ligand-free copper salt catalysts.[126,128,129,130,131] However, its scope was restricted to anilines and benzylic alcohol.



Scheme 52. Alkylation of anilines reported by Wang.

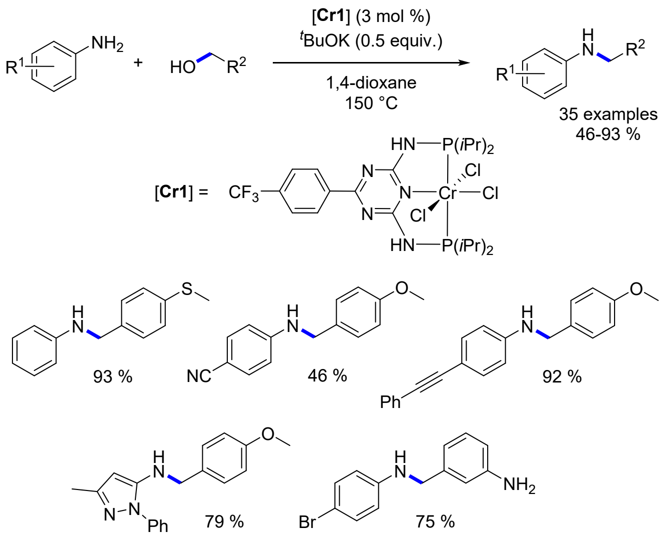
Actually, several Mn systems appear enabling selective *N*-alkylation of amines with alcohols,[135,136] including reusable nanocatalysts,[137] manganese dioxide changing amines by sulphonamides with yields up to 99%,[138] or heterogeneized manganese catalyst by pyrolysis of molecularly defined complexes.[139] In 2021, inexpensive and non-toxic $MnCl_2$ or $MnBr(CO)_5$ with triphenylphosphine were used as a ligand, enabling the efficient synthesis of a variety of aromatic, heteroaromatic, and aliphatic secondary amines in moderate to high yields (Scheme 53).[140] This simple and scalable method by Peng and coworkers is also applicable for the gram-scale synthesis of bioactive heterocycles, such as indole and resveratrol-derived amines, which are relevant for Alzheimer's disease treatment.



Scheme 53. Mn based salts catalysts for *N*-alkylation of amines with alcohols.

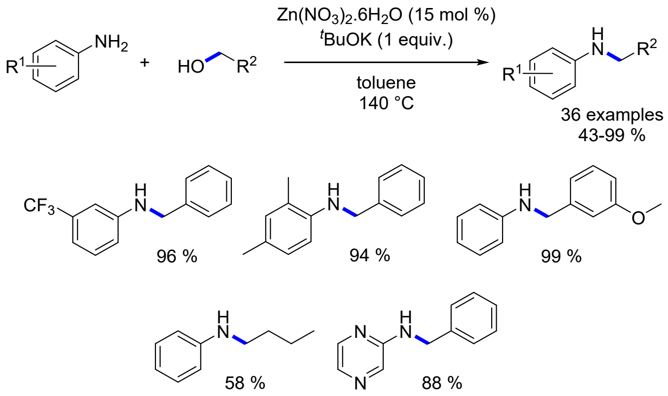
2.6. Other 3d-metal catalysed *N*-alkylation reactions.

In 2020, Kempe documented a chromium-PNP complex-catalysed alkylation of anilines with alcohols.[141] This reaction was constrained to benzylic and homobenzylic alcohols, but it tolerated a broad array of functionalized pro-electrophiles and pro-nucleophiles, resulting in the formation of N-alkyl anilines in good to excellent yields (46 to 93%, Scheme 54), albeit at high temperatures.



Scheme 54. Chromium-catalysed alkylation of anilines.

In the same year, Sivakumar and Mannathan elucidated a zinc-catalysed alkylation of anilines. Utilizing simple zinc nitrate salt, the desired alkylated anilines were obtained from both benzylic and aliphatic alcohols as pro-electrophiles (Scheme 55).[142]

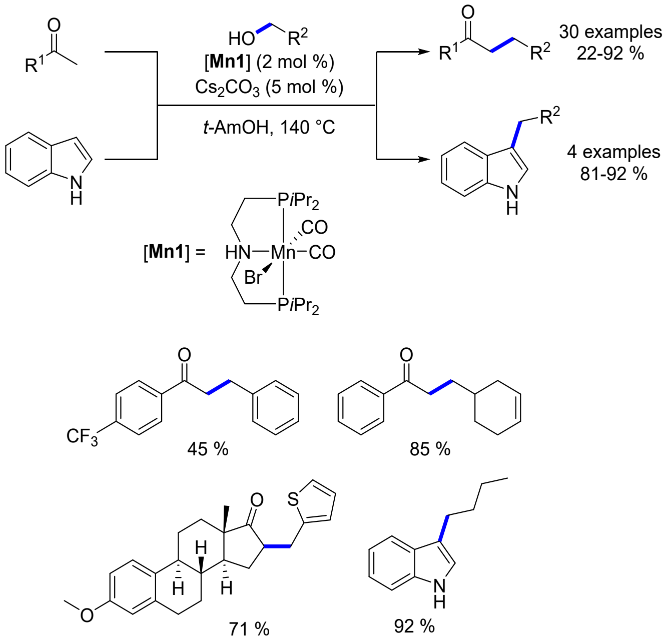


Scheme 55. Zinc-catalysed alkylation of anilines.

3. C-Alkylation Reaction Catalysed by First-Row Transition Metals.

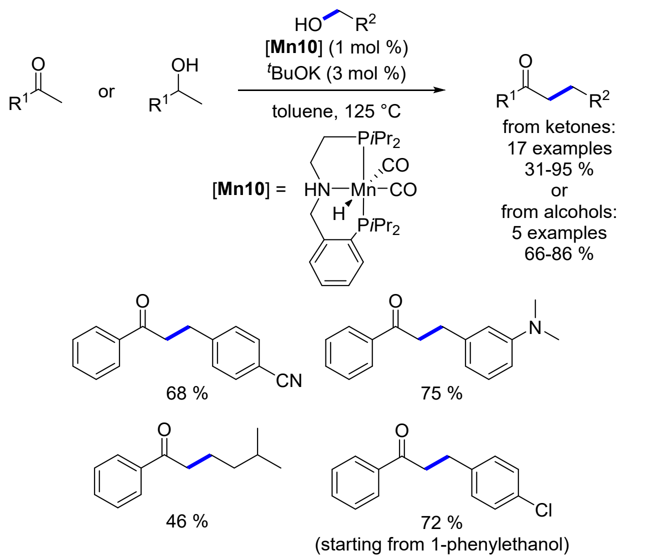
3.1. Manganese-catalysed *C*-alkylation reactions.

In 2016, Beller reported the first manganese-catalysed alkylation of ketones with primary alcohols.[143] The same manganese complex had previously been employed by the group for the alkylation of amines with alcohols.[76] For this C–C bond-forming reaction, a catalytic amount of Cs_2CO_3 (5 mol %) was used as the base, with tert-amyl alcohol as the solvent at 140 °C. A range of substituted ketones and alcohols were successfully alkylated, yielding functionalized products in moderate to good yields (Scheme 56). The reaction's efficiency was influenced by electronic effects, with ketones bearing electron-withdrawing groups resulting in lower yields. This methodology was also applied to oxindole derivatives, which produced alkylated products in good yields. Additionally, Liu and Jones utilized the same manganese complex to upgrade ethanol to 1-butanol at elevated temperatures,[144] a process that can also be achieved via the Guerbet reaction.[145,146]



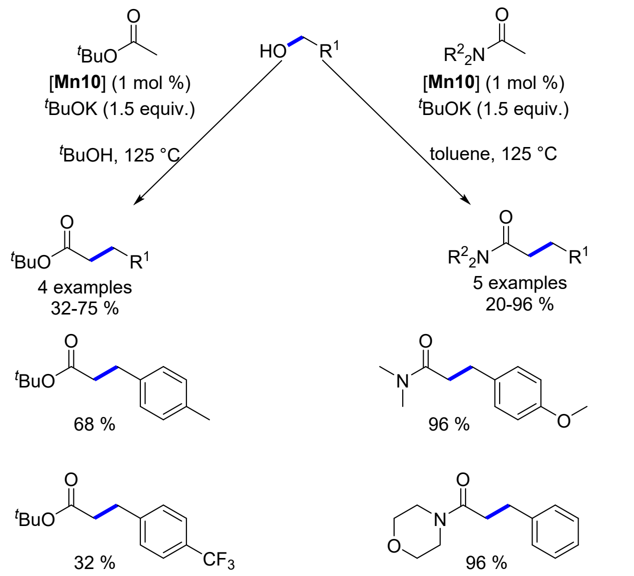
Scheme 56. Alkylation of ketones and oxindoles.

Milstein also explored the alkylation of ketones, amides, and esters using a PNP-Mn complex as the catalyst.[147] Aromatic ketones were successfully alkylated with various benzylic and aliphatic alcohols, though the yields were notably lower when aliphatic alcohols were used. Under the same reaction conditions, a single example of oxindole alkylation and five examples of 1-phenylethanol alkylation with benzyl alcohols to yield α-substituted ketones were reported. However, the reaction appeared to be limited to aryl ketones and benzylic alcohols as the preferred pro-nucleophiles (Scheme 57).



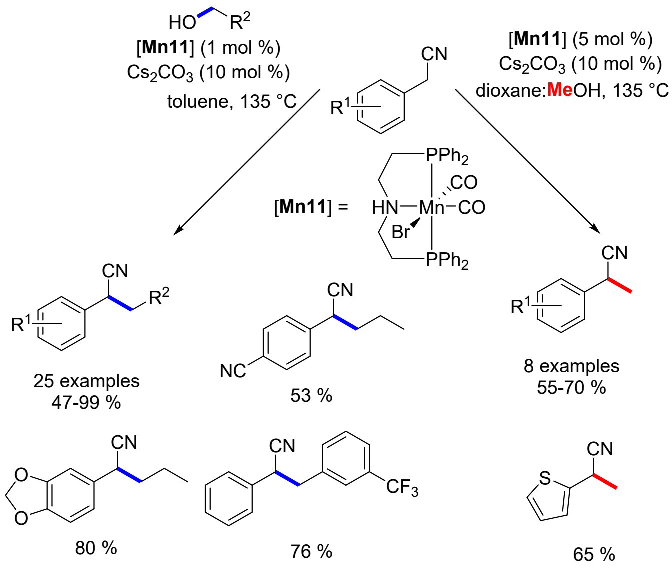
Scheme 57. Alkylation of ketones and secondary alcohols as described by Milstein.

The Macho-type manganese complex also facilitated the alkylation of esters and amides. In this reaction, the use of a stoichiometric amount of base was essential to achieve high conversions and good yields, ranging from 20 to 96% (Scheme 58).



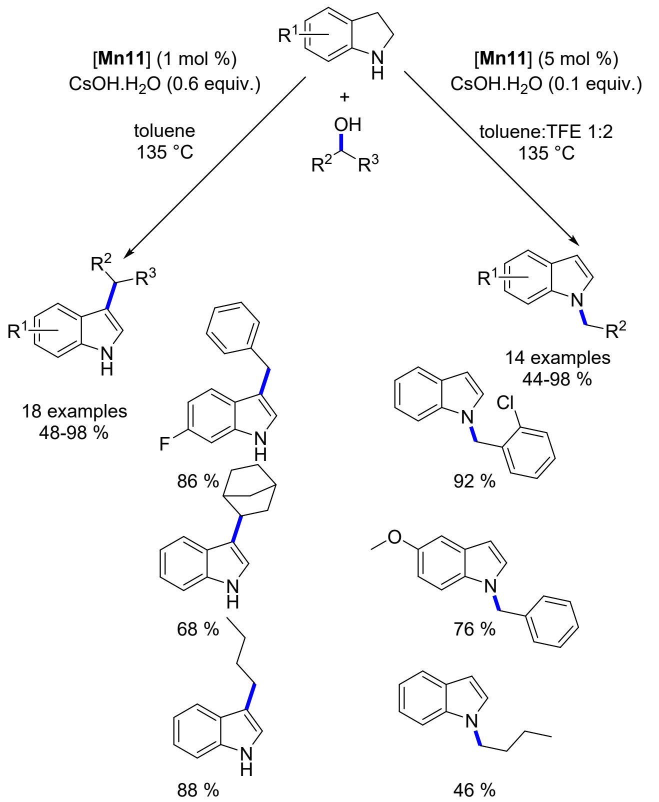
Scheme 58. Milstein's work on the alkylation of amides and esters.

Rueping explored the alkylation of nitriles, successfully converting various benzyl nitriles into alkylated products with moderate to good yields.[148] Notably, methanol was employed to achieve α-methylated benzyl nitriles, though the reaction was limited to primary alcohols (Scheme 59).



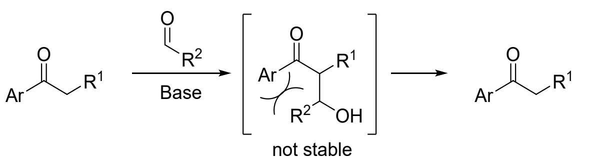
Scheme 59. Alkylation of Nitriles Reported by Rueping.

Building on previous research, the alkylation of indolines was explored using the same manganese catalyst.[149] This study revealed the potential for both N- and C3-alkylation of indolines. Initially, regardless of the conditions applied, indole derivatives were consistently produced. Moreover, the selectivity between N- and C3-alkylation could be effectively controlled by adjusting the base concentration and choosing the appropriate solvent. Under optimized conditions, C3-alkylated indoles were obtained in yields ranging from 48% to 98%, while N-alkylated indoles were produced with yields of 44% to 98% (Scheme 60).



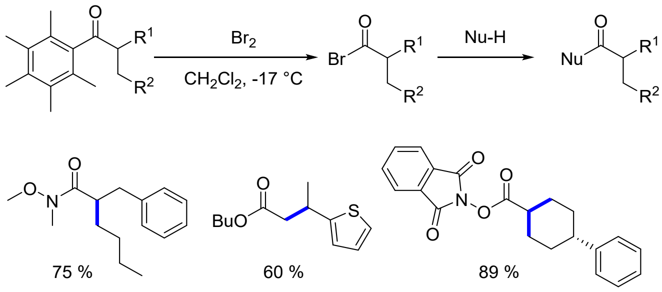
Scheme 60. Selective alkylation of indoline to N- or C3-substituted indoles.

While the mono-alkylation of various nucleophiles has been extensively studied with transition metals, the use of diols for the formation of cycloalkanes using Earth-abundant metal-based complexes is less frequently reported. The alkylation of α-substituted ketones presents additional challenges compared to methyl ketones due to the steric hindrance created by the aromatic ring at the α-position, which tends to favour the retro-aldol reaction over water elimination (Scheme 61). The incorporation of ortho-substituted acetophenones has been shown to mitigate this limitation effectively.[150] Indeed, the introduction of ortho substitutions results in the aromatic ring and the keto group being oriented perpendicularly rather than coplanar, effectively reducing steric interactions and eliminating conjugation between them. This orientation prevents the reduction of the ketone due to the steric hindrance imposed by the ortho substituents. Consequently, during the alkylation step, the minimized steric interactions favour the elimination reaction over the retro-aldol reaction. This strategy, first introduced by Donohoe's group, has been successfully applied to the synthesis of α,α-disubstituted ketones,[150] the alkylation of ketones with secondary alcohols,[151] and the synthesis of cycloalkanes.[152,153]



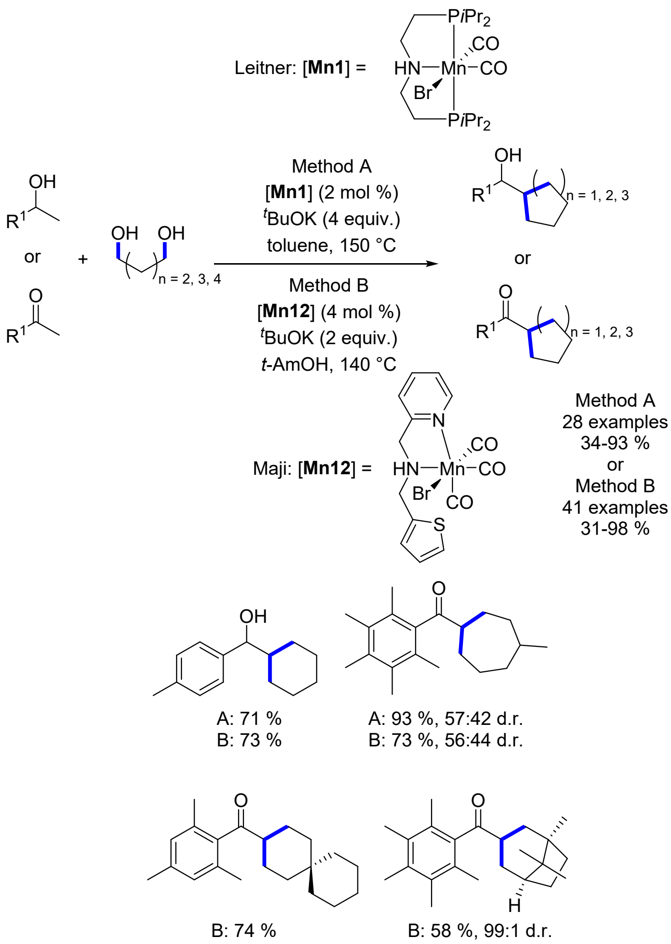
Scheme 61. Steric hindrance introduced by the aromatic moiety of the starting ketone.

This group specifically utilized 1-(2,3,4,5,6-pentamethyl)ethan-1-one, demonstrating the feasibility of substituting the pentamethylphenyl group with bromine through a retro Friedel-Crafts reaction.[154] This process yields an acyl bromide, which can then react with various nucleophiles to produce functionalized products (Scheme 62).



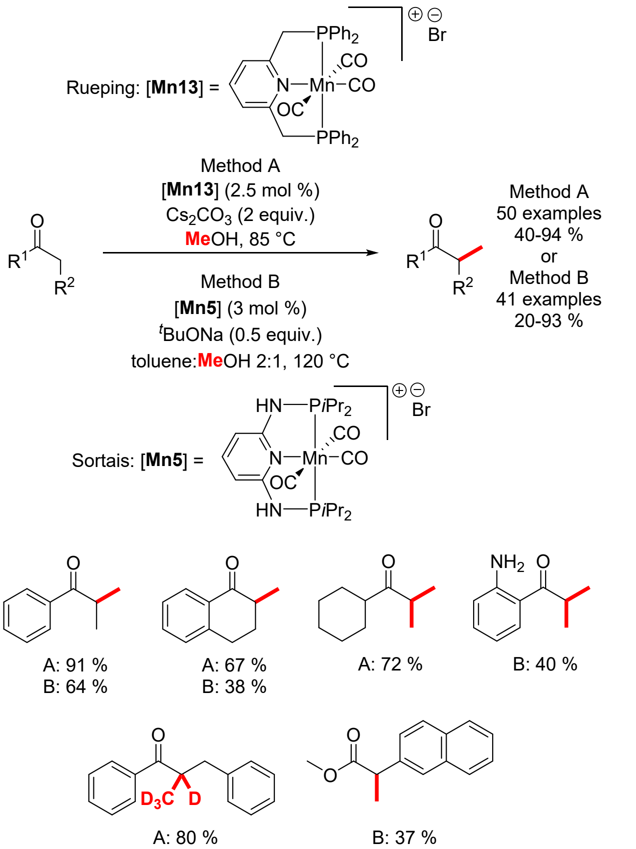
Scheme 62. Functionalisation of α-substituted ketones.

In 2019, Leitner reported the di-alkylation of ketones and secondary alcohols using diols as pro-electrophiles in the presence of the Macho-Mn complex (Scheme 63).[155] This methodology afforded a variety of 5-, 6-, and 7-membered rings. Maji further expanded this approach by employing an NNS-Mn complex, reducing both the base loading and reaction temperature.[156] As noted, the use of ortho-substituted ketones effectively prevented the final reduction of the carbonyl group.



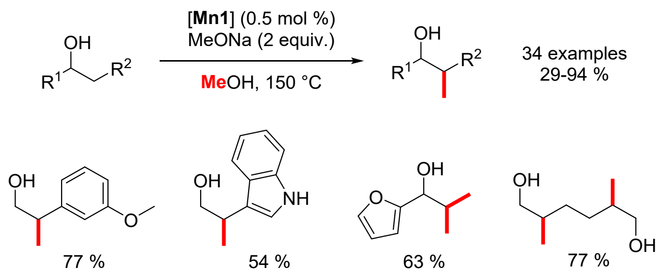
Scheme 63. Synthesis of cycloalkanes using di-alkylation of ketones and secondary alcohols reported by Leitner and Maji.

In 2019, Rueping reported the methylation of ketones using methanol or deuterated methanol,[157] despite the higher dehydrogenation energy of methanol (ΔH = +84 kJ/mol) compared to ethanol (ΔH = +68 kJ/mol). Conducted under mild conditions (85-105 °C), this method afforded mono- and di-methylated products in good yields (Scheme 64). Simultaneously, Sortais described a similar reaction using a pincer Mn complex,[158] which required higher temperatures (120 °C) and lower base loading. This methodology was also extended to the methylation of esters (Scheme 64).



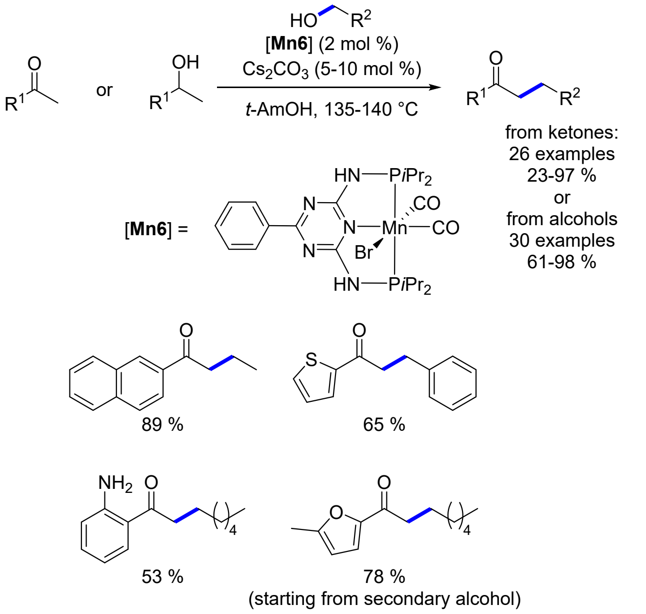
Scheme 64. Methylation of ketones and esters reported by Rueping and Sortais.

Leitner reported the β-methylation of alcohols using a stoichiometric amount of base and the Macho-Mn complex at 150 °C, resulting in β-branched products (Scheme 65).[159] Unlike iron complexes, which were limited to homo-benzylic alcohols, the manganese complex enables the introduction of both homo-benzylic and aliphatic alcohols without any adverse effects.



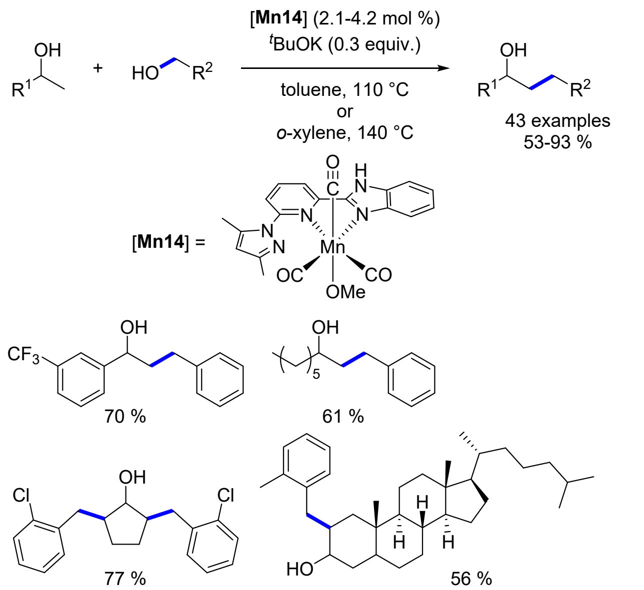
Scheme 65. Methylation of alcohols.

In 2019, Gunanathan reported methods for the α-alkylation of ketones and β-alkylation of alcohols, both leading to α-substituted ketones.[160] The key distinction between the two methodologies was the base loading, which varied from 10% to 5%. Both aliphatic and benzylic alcohols yielded the desired products in good quantities. For mono-ethylation of ketones, a mixed solvent system (t-AmOH:EtOH 1:1) was used. When keto-aniline derivatives were employed, selective C-alkylation was achieved, demonstrating the reaction's chemoselectivity (Scheme 66).



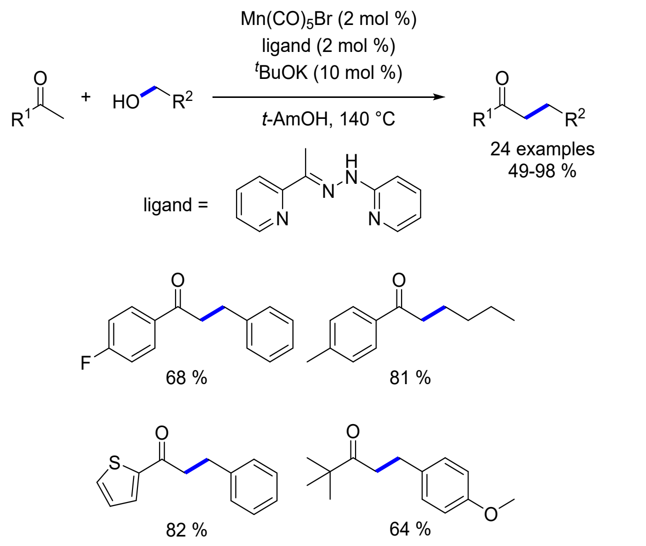
Scheme 66. Synthesis of α-substituted ketones.

Yu reported the alkylation of secondary alcohols with primary alcohols using a bifunctional NNN-Mn(I) complex, featuring a pyridine-benzimidazole-pyrrole ligand.[161] Unlike the results obtained by Milstein,[147] where the C=O bond of the alkylated ketone remained intact, Yu's approach led to the reduction of the C=O bond, resulting in β-substituted alcohols as the products (Scheme 67).



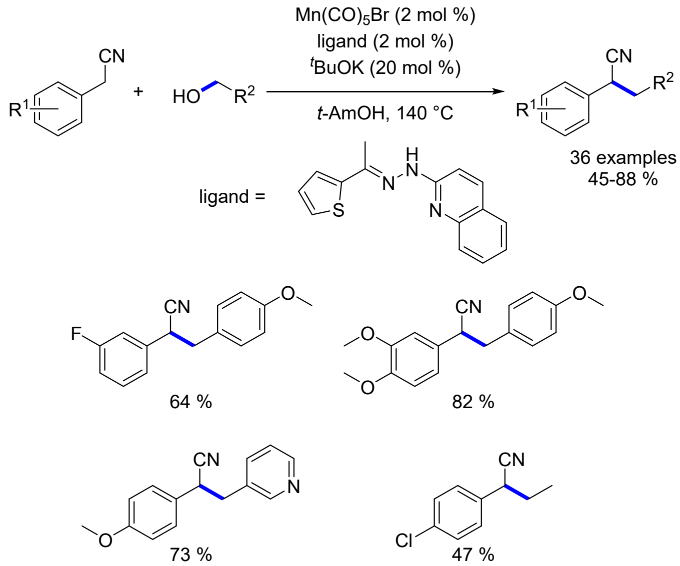
Scheme 67. Alkylation of secondary alcohols.

In 2018, Maji reported the use of a phosphine-free NNN-Mn complex for the alkylation of ketones.[162] This complex facilitated the reaction of various aryl and aliphatic ketones with primary alcohols, yielding α-substituted ketones with diverse functional groups (Scheme 68). Both aliphatic and benzylic alcohols were effective, although attempts at methylation did not produce any methylated products.



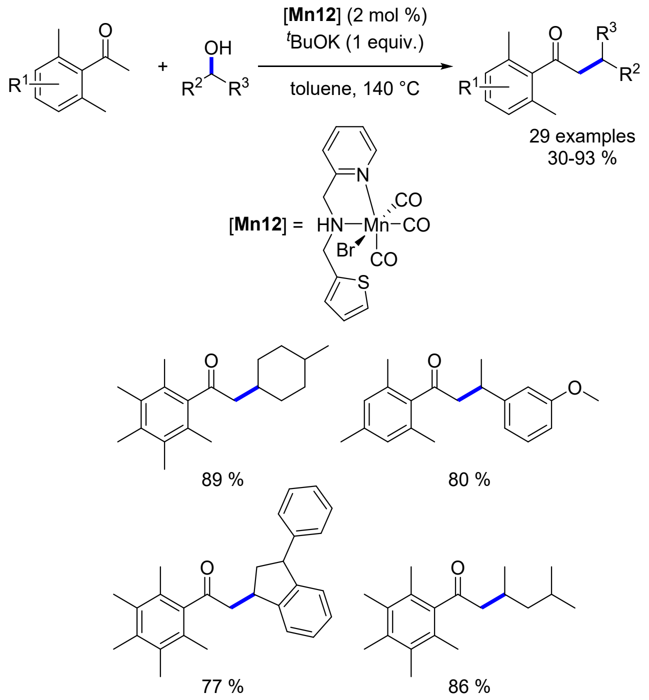
Scheme 68. Alkylation of ketones.

Replacing the pyridine hydrazone ligand with a thiophene hydrazone ligand enabled the alkylation of nitrile derivatives using various primary alcohols.[163] The reaction conditions were similar to those used for C-C bond formation between a ketone and an alcohol,[162] with the notable exception of an increased base loading from 10 to 20 mol %. Alkylated nitriles were obtained in moderate to good yields (45-88%, Scheme 69). This reaction tolerated a range of functional groups but was restricted to benzyl nitriles. Methanol was introduced, but no methylation was observed.



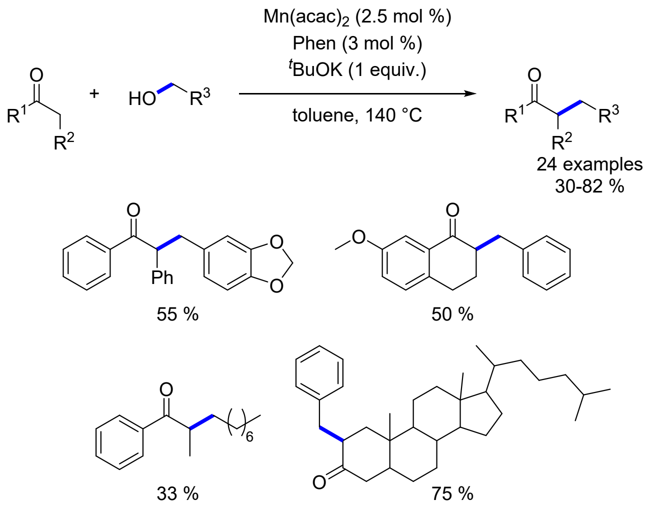
Scheme 69. Alkylation of nitriles.

In 2020, Maji explored the alkylation of ketones with secondary alcohols using a phosphine-free, bidentate NN-ligand Mn complex.[164] To prevent cross-alkylation, only 2,5-dimethyl acetophenone derivatives were employed as pro-nucleophiles. Under optimized conditions, various benzylic and aliphatic secondary alcohols were reacted, yielding β-branched ketones in good yields (Scheme 70).



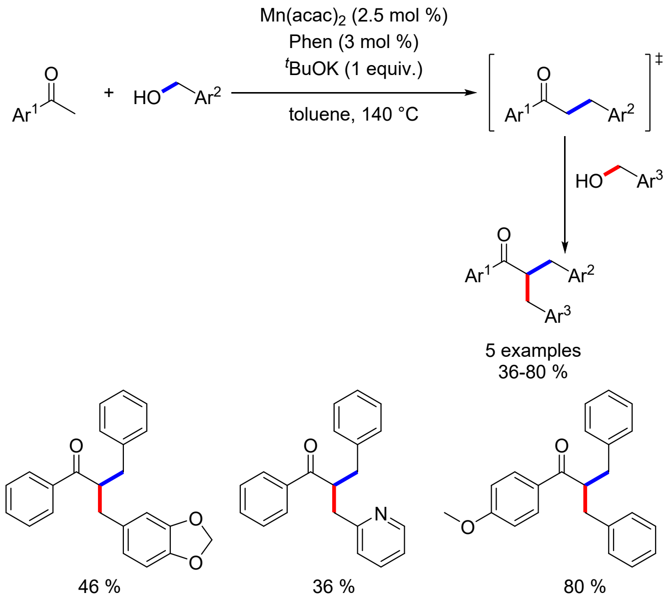
Scheme 70. Alkylation of ketones with secondary alcohols.

Banerjee investigated the alkylation of α-substituted ketones with primary alcohols using a catalyst system composed of $Mn(acac)_2$ and 1,10-phenanthroline.[165] The reaction required a stoichiometric amount of base to achieve the desired alkylated products (Scheme 71).



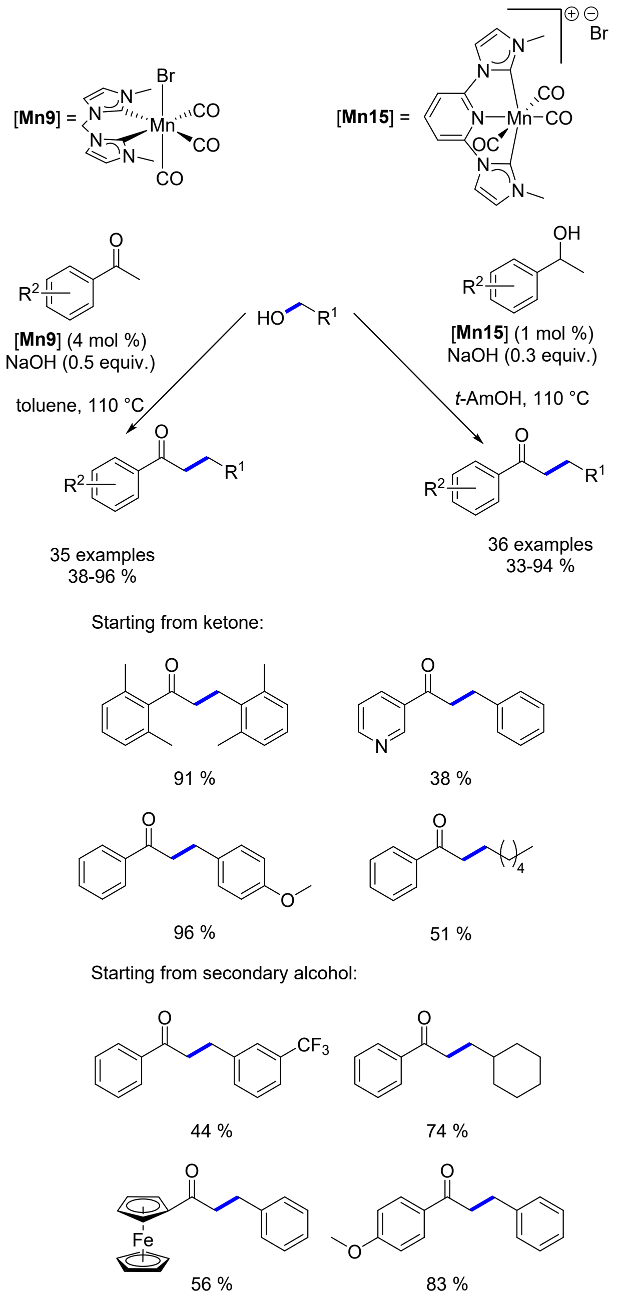
Scheme 71. Alkylation of α-substituted ketones reported by Banerjee.

In a two-step, one-pot reaction, acetophenones underwent dialkylation with a sequential addition of a second alcohol after 2 hours. This approach yielded dialkylated products in moderate to good yields (Scheme 72).



Scheme 72. Two-step one-pot dialkylation of ketones.

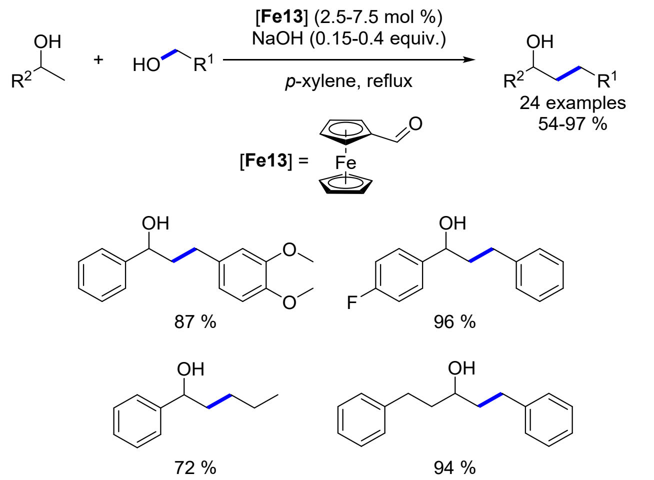
Organometallic complexes employed in borrowing hydrogen reactions often feature bifunctional or hemilabile ligands, which play a crucial role in the reaction mechanism. However, these ligands can be costly to produce, sensitive to air or moisture, and challenging to synthesize on a large scale. To address these issues, Ke investigated a non-bifunctional manganese complex for the α-alkylation of ketones with alcohols.[166] Preliminary DFT calculations compared the reduction of α,β-unsaturated ketones catalysed by this non-bifunctional complex with that of various previously described catalytic systems.[147,162] The theoretical study revealed that the non-bifunctional complex demonstrated a significantly lower hydrogenation energy (14.9 kcal/mol) compared to the Beller, Maji, and Milstein systems, which required 22.8, 23.7, and 26.6 kcal/mol, respectively. Experimental validation supported this finding, as the non-bifunctional complex efficiently catalysed the α-alkylation of ketones at 110 °C, in contrast to the higher temperatures (125-140 °C) needed for the other systems, and achieved the reaction in a shorter time frame of 2 hours (Scheme 73). Although this reaction required a catalytic amount of base (NaOH, 0.5 equiv.), it used less base compared to the amounts required by Beller, Maji, or Milstein. Furthermore, this non-bifunctional complex was subsequently modified to enable the β-alkylation of secondary alcohols to form α-substituted ketones.[167] Nevertheless, both systems were constrained to the alkylation of aryl ketones using primary alcohols.



Scheme 73. Synthesis of α-substituted ketones described by Ke.

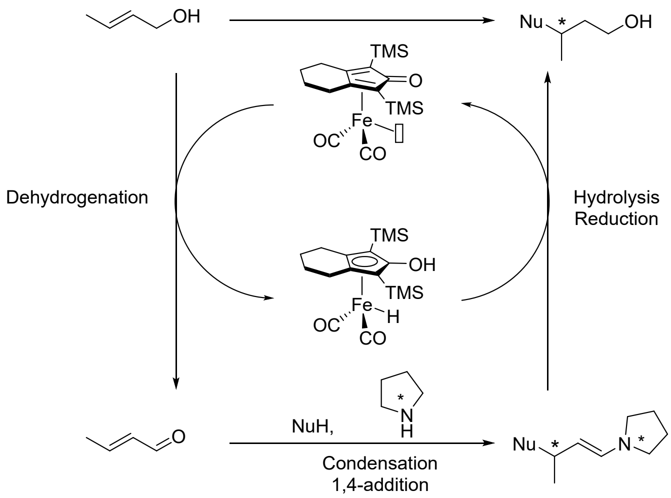
3.2. Iron-catalysed *C*-alkylation reactions.

Building on Saito's pioneering work on iron-catalysed alkylation of amines,[89] Sun reported in 2012 the first iron-catalysed C-C bond formation via borrowing hydrogen.[168] Using a simple ferrocene carboxaldehyde catalyst, a range of secondary alcohols were alkylated with benzylic and aliphatic alcohols to produce β-substituted alcohols. This method, while tolerant of only a few functional groups, yielded substituted alcohols in good to excellent yields (Scheme 74).



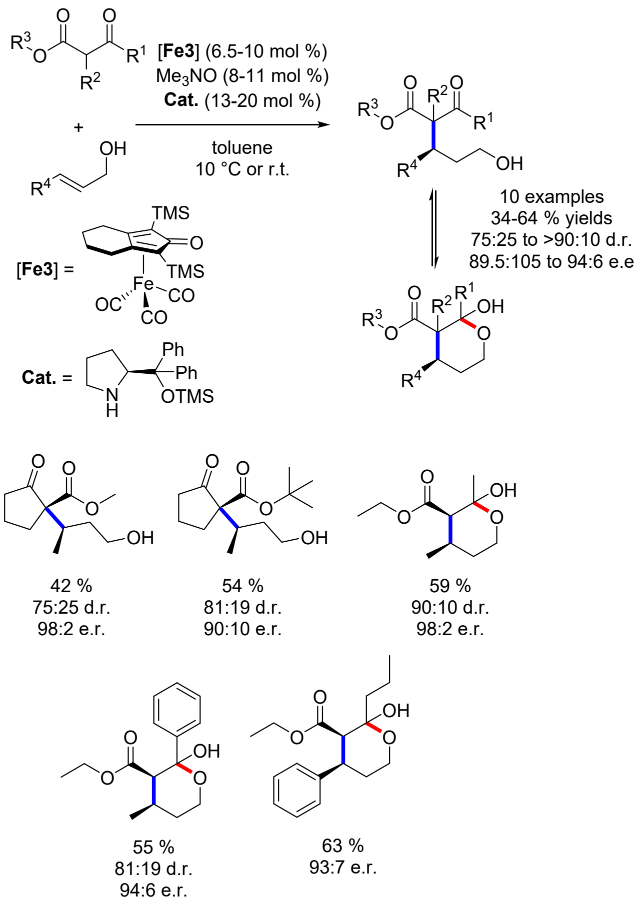
Scheme 74. Iron-catalysed β-alkylation of alcohols.

In 2013, Quintard and Rodriguez developed a dual catalytic cascade process for the enantioselective functionalization of allylic alcohols.[169] The process begins with the Knölker complex, which dehydrogenates the allylic alcohol to form an enal intermediate. This intermediate then undergoes condensation with a prolinol-type amine, followed by 1,4-addition with a nucleophile to yield a chiral enamine. The final steps involve hydrolysis and reduction to produce the β-substituted chiral alcohol (Scheme 75).



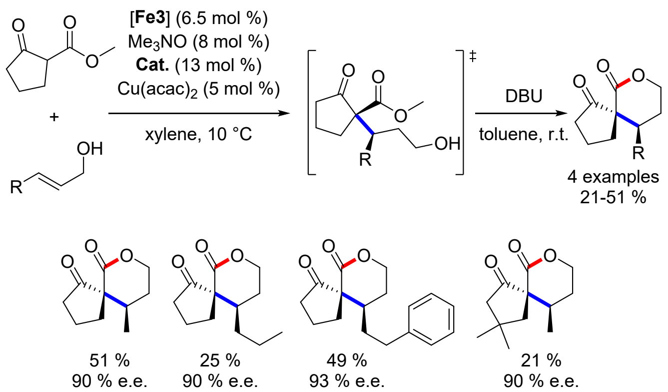
Scheme 75. Dual iron/organocatalysed alkylation of allylic alcohols.

This methodology was assessed using β-ketoesters as pro-nucleophiles, resulting in moderate to good yields (35-64%, Scheme 76) with excellent enantiomeric ratios (89.5:10.5 to 96:6) and good diastereomeric ratios (75:25 to >90:10) for crotyl and cinnamyl alcohols. The iminium intermediate played a crucial role in ensuring enantiocontrol and product formation, with less than 10% conversion observed in the absence of the amine catalyst.



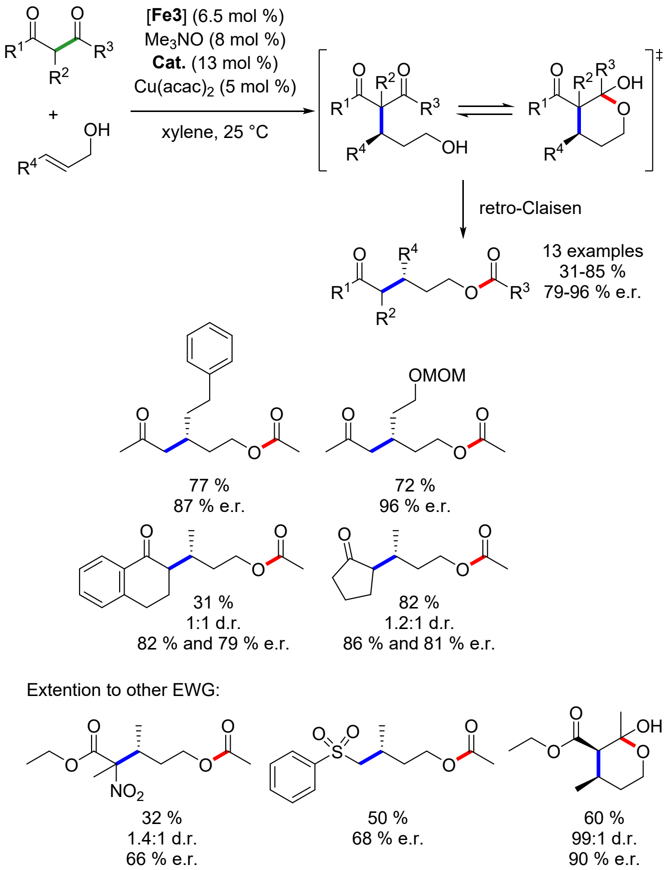
Scheme 76. Enantioselective alkylation of allylic alcohols.

In contrast to other substrates, cyclopentanone derivatives were not isolated in their cyclic form. Consequently, a final transesterification step was explored to enable the formation of chiral γ-lactones from 1,3-keto-esters.[170] DBU was introduced after the alkylation with allylic alcohol, facilitating the formation of the lactone product. The addition of a copper salt improved the enantiomeric ratios of the reaction (Scheme 77).



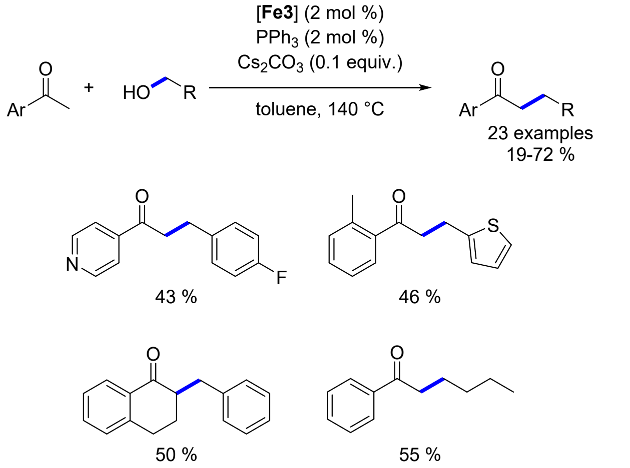
Scheme 77. Synthesis of γ-lactones.

The same group further applied this dual catalytic strategy to the synthesis of 3-alkyl pentanols.[171] The cascade process was complemented by a final retro-Claisen reaction (Scheme 78). Electron-withdrawing groups were not tolerated, and the choice of organocatalyst varied depending on the diketone used. The products were obtained in moderate to good yields (34-96%) with good enantiomeric ratios (70:30 to >96:4). Cyclic β-diketones showed no diastereoselectivity, likely due to non-selective protonation during the retro-Claisen fragmentation step. Optimization by adding a copper salt as a chelating agent in the Michael addition improved the enantiomeric ratio of the reaction (31-85%, 79-96% e.e.).[172] Additionally, other β-EWG-substituted ketones were employed as pro-nucleophiles, yielding products in moderate to good yields with good enantiomeric ratios (66-90% e.e.).



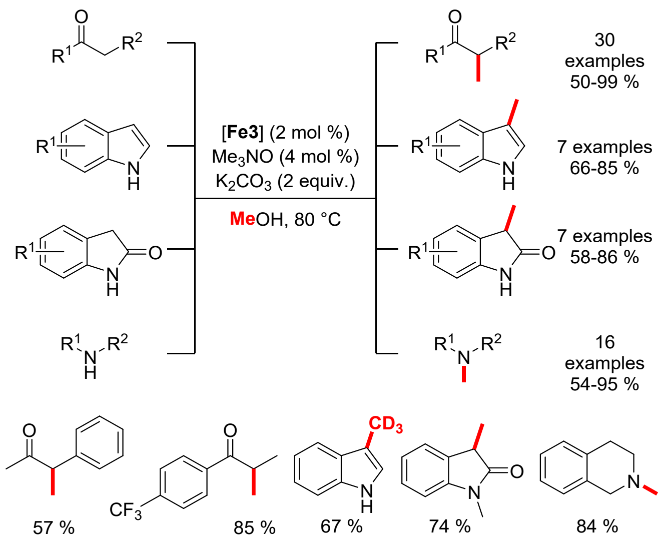
Scheme 78. Insertion of allylic alcohol in 1,3-diketones.

In 2015, Darcel reported the α-alkylation of ketones with primary alcohols using the Knölker complex at 140 °C.[173] The addition of triphenylphosphine was found to enhance the catalyst's activity, likely by extending the lifetime of the catalytic species. However, the methodology was limited to aromatic ketones, as aliphatic ketones only underwent reduction under these reaction conditions (Scheme 79).



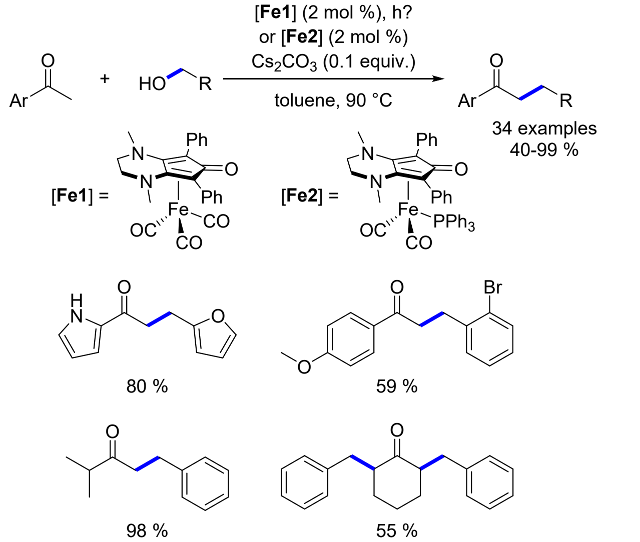
Scheme 79. Alkylation of ketones reported by Darcel.

Methylation reactions were subsequently explored by Morill.[174] Using the Knölker complex, various nucleophiles were reacted with methanol under mild conditions, yielding methylated products in good to excellent yields (Scheme 80).



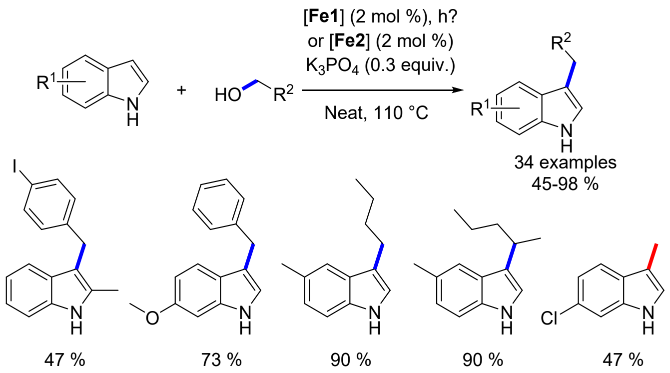
Scheme 80. Methylation of various nucleophiles.

In 2017, the modified Knölker catalyst, developed by Renaud,[102] was employed for α-alkylation of aryl ketones.[48] DFT calculations compared the original Knölker catalyst with Renaud's variant, revealing lower energy barriers and an exothermic reduction step for the diamino derivative. This theoretical insight allowed for a decrease in reaction temperature to 90 °C with reduced reaction times, leading to improved yields of alkylated products (Scheme 81). Unlike Darcel's findings,[173] this modification enabled the successful alkylation of aliphatic ketones without reduction.



Scheme 81. Alkylation of ketones reported by Renaud.

Following this work, the alkylation of indoles was explored,[46] requiring higher temperatures due to the lower nucleophilicity of indoles. The alkylated products were obtained in moderate to good yields. Additionally, two examples using secondary alcohols as pro-electrophiles were achieved, with yields ranging from 45-55% (Scheme 82).



Scheme 82. Alkylation of indoles reported by Renaud.

This reaction was also investigated using an iron-phthalocyanine complex as a catalyst.[175] Secondary alcohols resulted in lower yields compared to the alkylation with primary alcohols. Additionally, higher temperatures were required to achieve the reaction (Scheme 83).

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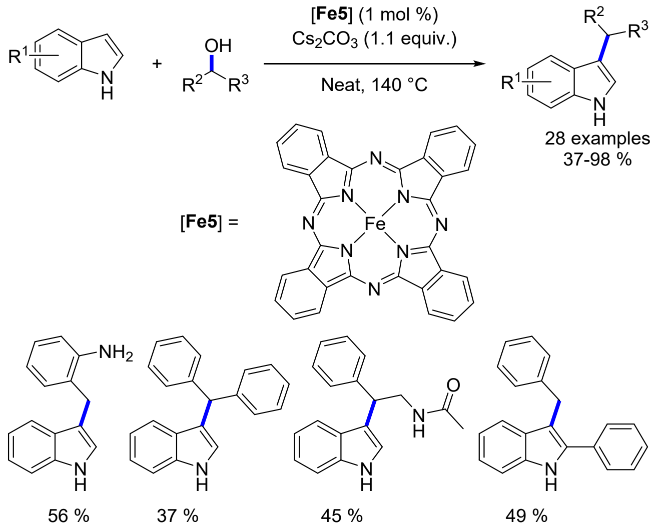
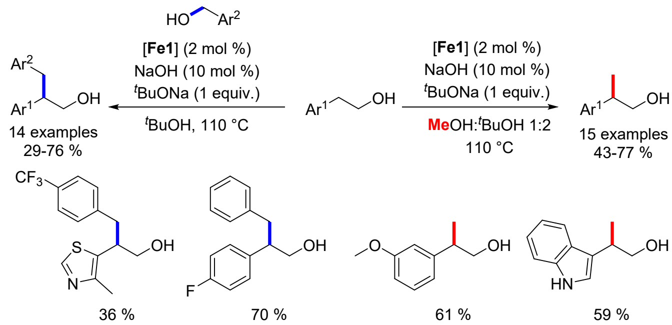


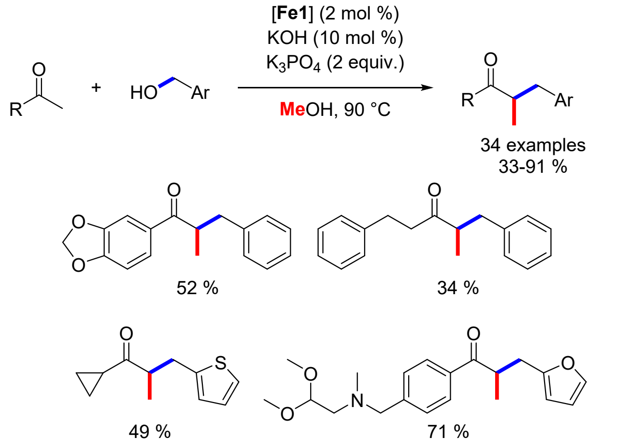
Scheme 83. Alkylation of indoles reported by Piersanti.

While the alkylation of ketones or secondary alcohols has been extensively studied, the β-alkylation of primary alcohols using earth-abundant metals had not been previously reported. In 2019, our group developed a method for the β-alkylation of homobenzylic alcohols with benzylic alcohols and methanol.[47] his approach engaged various substituted alcohols, yielding functionalized β-branched primary alcohols in moderate to good yields (Scheme 84). However, the reaction could not be extended to aliphatic alcohols due to potential cross-alkylation products. Despite this limitation, the procedure offers an atom-efficient alternative to the hydroformylation-reduction sequence and facilitates the synthesis of functionalized alcohols.



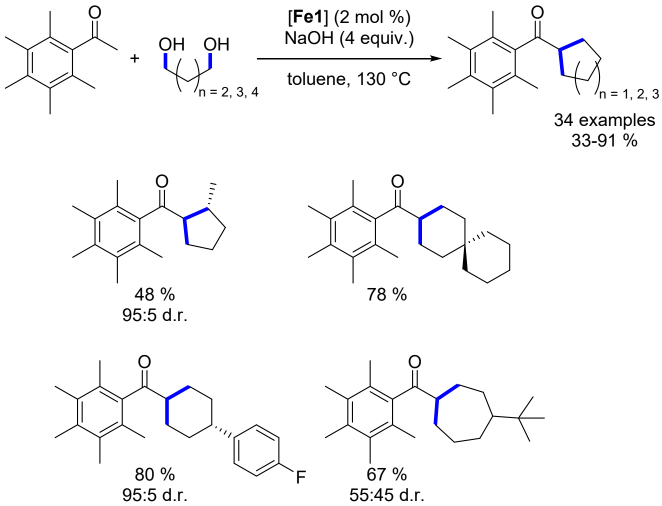
Scheme 84. Alkylation of primary alcohols.

Still, in 2019, our group developed a three-component alkylation reaction involving a ketone, a primary alcohol, and methanol to produce α-disubstituted ketones.[49] This methodology afforded various functionalized products (Scheme 85). The proposed mechanism involves an initial alkylation of the ketone with benzyl alcohol, followed by a second alkylation with methanol to yield the α-benzylmethyl ketone. This reaction was limited to benzylic primary alcohols as pro-electrophiles. Nonetheless, this approach provides an atom-economical method for synthesizing functionalized ketones.



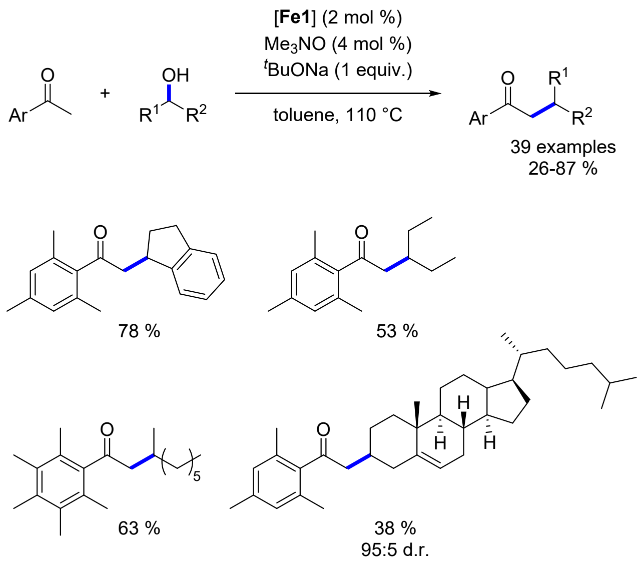
Scheme 85. One-pot three-component alkylation of ketones reported by Renaud.

To further assess the capabilities of this complex, we investigated the synthesis of cycloalkanes.[50] Using a similar methodology to that of Leitner and Maji,[155,156] various diols were reacted with pentamethyl acetophenone to produce the corresponding cyclic di-alkylated ketones in moderate to good yields. This approach enabled the formation of substituted 5- to 7-membered cycloalkanes. Notably, good control of diastereoselectivity was achieved with cyclopentanes and cyclohexanes, while cycloheptanes resulted in lower diastereomeric ratios (Scheme 86).



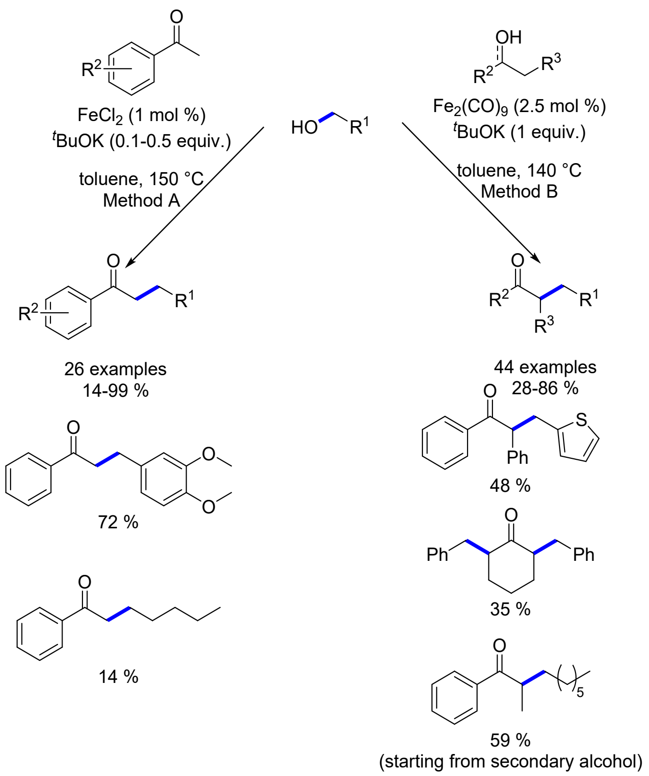
Scheme 86. Synthesis of cycloalkanes.

While extensive research has focused on the alkylation of ketones with primary alcohols, the use of secondary alcohols as pro-electrophiles remains underexplored, with few examples available across various metal-based complexes. To address this gap, we investigated the α-alkylation of ketones using secondary alcohols.[51] Employing pentamethyl acetophenone to minimize cross-alkylation, we successfully reacted various benzylic and aliphatic secondary alcohols, yielding β-branched ketones in moderate to good yields with significant functional group tolerance. Notably, a functionalized cholesterol derivative was synthesized with a 38% yield and complete control over diastereoselectivity (Scheme 87).



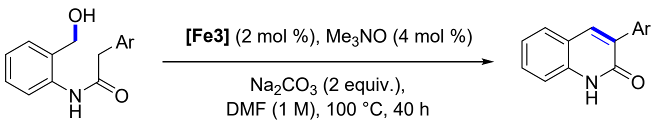
Scheme 87. Alkylation with secondary alcohols.

In 2019, Yang and Banerjee explored the synthesis of α-substituted ketones using ligand-free iron catalysts.[176,177] Yang utilized $FeCl_2$, while Banerjee employed $Fe_2(CO)_9$, both of which are precursors to previously reported bifunctional iron catalysts. These methods required high temperatures to facilitate the alkylation reactions. Banerjee's approach proved more versatile, showing better yields with aliphatic alcohols and not being restricted to benzylic ketones. Additionally, this methodology allowed the use of secondary alcohols as pro-nucleophiles, achieving similar yields of substituted ketones (Scheme 88).



Scheme 88. Synthesis of α-substituted ketones.

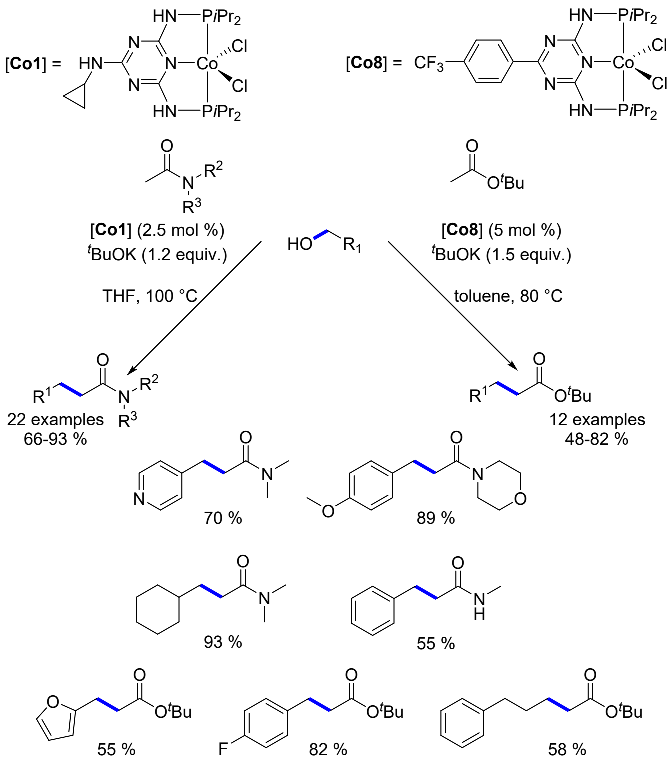
In 2024, Poater, Renaud and coworkers devised a novel method for synthesizing highly substituted quinoline-2(1H)-ones via iron catalysis with yields up to 83% (Scheme 89).[178] This approach is based on the intramolecular dehydrogenative coupling of amido-alcohols, resulting in the cyclization product. Various strategies were employed to prepare these starting materials. This methodology facilitates the synthesis of diverse substituted 3-arylquinolin-2(1H)-ones, with the ability to introduce substitutions at any position on the bicyclic structure. Moreover, it holds significant potential for the preparation of highly functionalized quinolinones.



Scheme 89. Synthesis of 3-arylquinolin-2(1H)-ones.

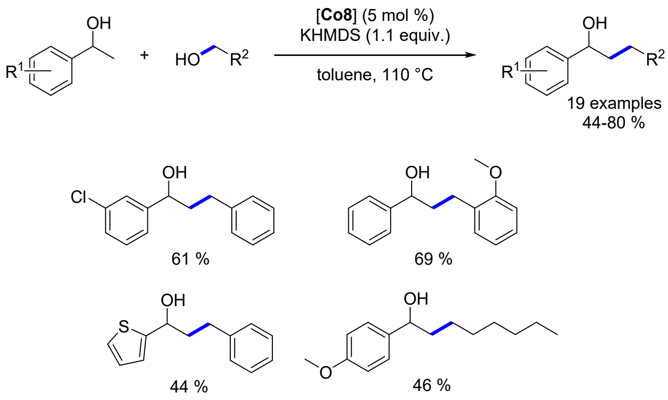
3.3. Cobalt-catalysed *C*-alkylation reactions.

The first cobalt-catalysed C-alkylation reaction was reported by Kempe in 2016.[179] Utilizing a cobalt complex with a triazine-containing PNP-type pincer ligand, Kempe demonstrated the successful alkylation of various acetamide derivatives and tert-butyl acetate with primary alcohols. The reaction conditions varied based on the pro-nucleophile; in contrast to ketone alkylation, amides and esters, being less acidic, required the pro-electrophiles to be used as limiting reagents. Under optimized conditions, a range of amides and esters were alkylated with both benzylic and aliphatic alcohols, yielding α-substituted products in good to excellent yields (Scheme 90). However, N-mono-substituted amides afforded lower yields due to the preferential deprotonation of the acidic hydrogen. Additionally, the scope was restricted to tert-butyl esters to avoid potential transesterification with tBuOK during the process.



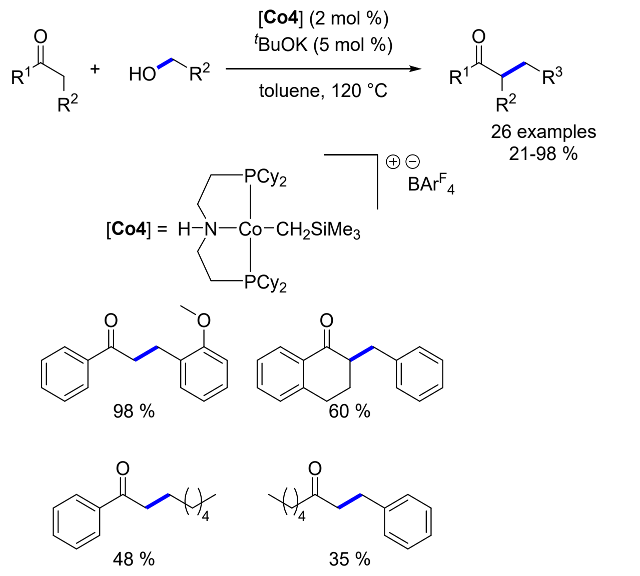
Scheme 90. C-alkylation of amides and esters.

The cobalt complex **Co8** was also utilized for the alkylation of secondary benzylic alcohols.[180] This process involved various benzylic and aliphatic alcohols, leading to β-alkylated products in moderate to good yields. However, lower yields were observed with aliphatic alcohols (Scheme 91).



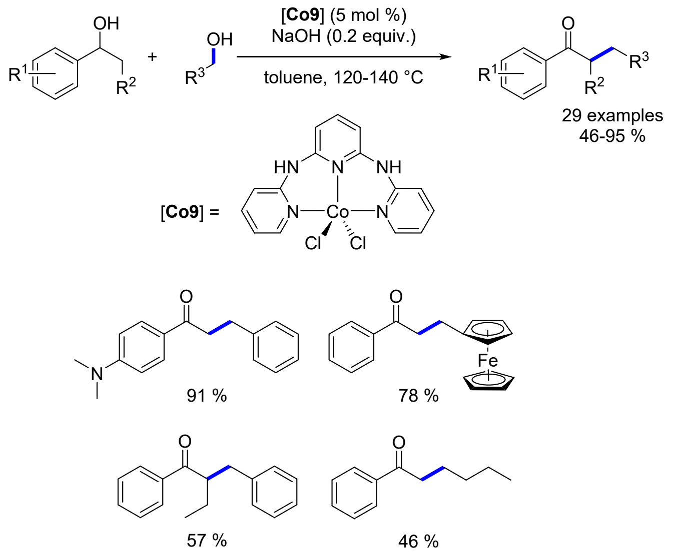
Scheme 91. Alkylation of secondary alcohols.

Zhang *et al*. also explored the alkylation of ketones using a cobalt complex.[181] The Macho-Co complex, previously utilized by the same group for the alkylation of amines,[110] was employed for the alkylation of aromatic ketones with benzylic and primary aliphatic alcohols. This reaction yielded products in relatively lower yields (Scheme 92). Additionally, when aliphatic ketones were used as pro-nucleophiles, the isolated yield of the alkylated ketone was modest.



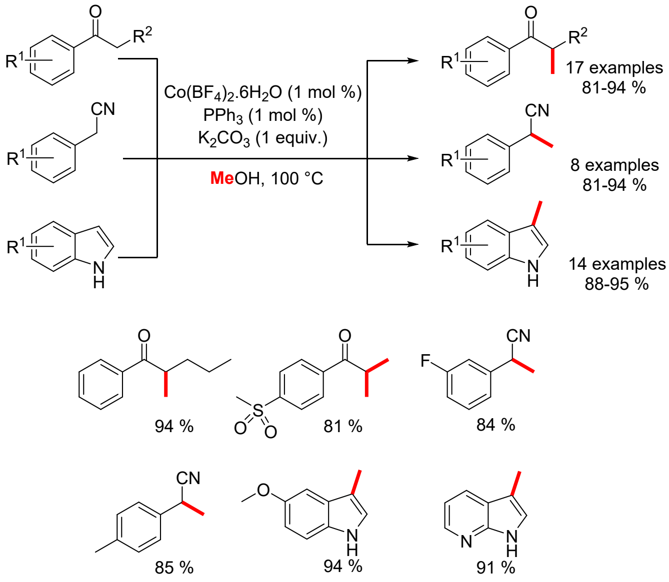
Scheme 92. Alkylation of ketones reported by Zhang.

Li *et al*. synthesized and utilized a cobalt(II) complex with a phosphine-free NNN pincer ligand for the alkylation of benzylic secondary alcohols with primary benzylic and aliphatic alcohols. The reactions were conducted in toluene at 120 °C with a catalytic amount of NaOH (20 mol %).[182] This approach afforded various ketones in yields ranging from 46% to 95% (Scheme 93).



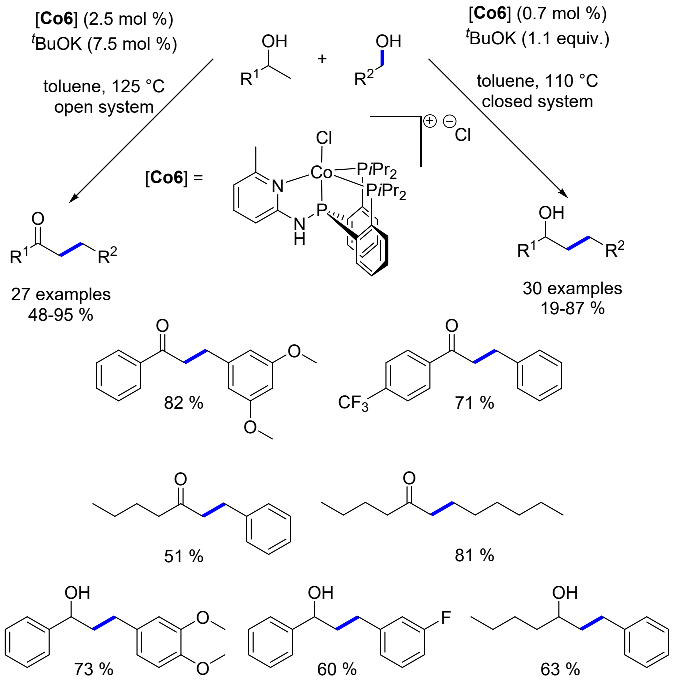
Scheme 93. Synthesis of α-substituted ketones reported by Li.

In 2017, Liu reported the methylation of ketones, benzyl nitriles, and indoles using a combination of $Co(BF4)_2 \cdot 6H_2O$ and PPh_3.[183] This method enabled the methylation of various substituted nucleophiles with methanol as the pro-electrophile, yielding products in good to excellent yields while accommodating a range of functional groups (Scheme 94).



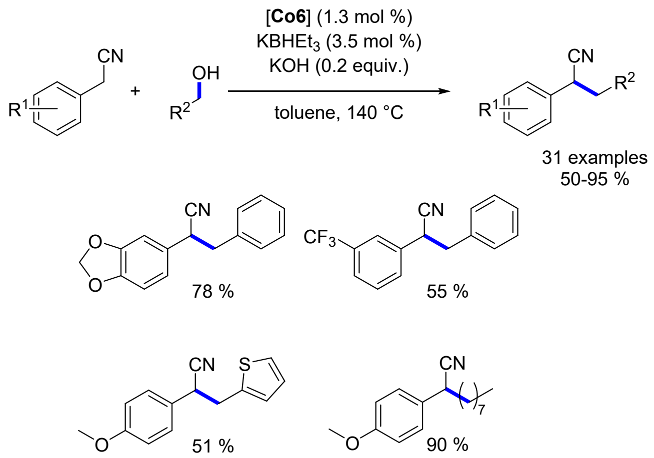
Scheme 94. Cobalt-catalysed methylation of various nucleophiles reported by Liu.

Ding presented a well-defined PNPP-Co catalyst for the β-alkylation of secondary alcohols with primary alcohols, yielding either β-alkylated alcohols or α-alkylated ketones depending on the reaction conditions, with temperatures ranging from 110 to 125 °C.[184, 185] This switchable synthesis can be controlled by adjusting parameters such as the base amount and whether the system is open or closed. Notably, this process employs a low catalyst loading (Scheme 95).



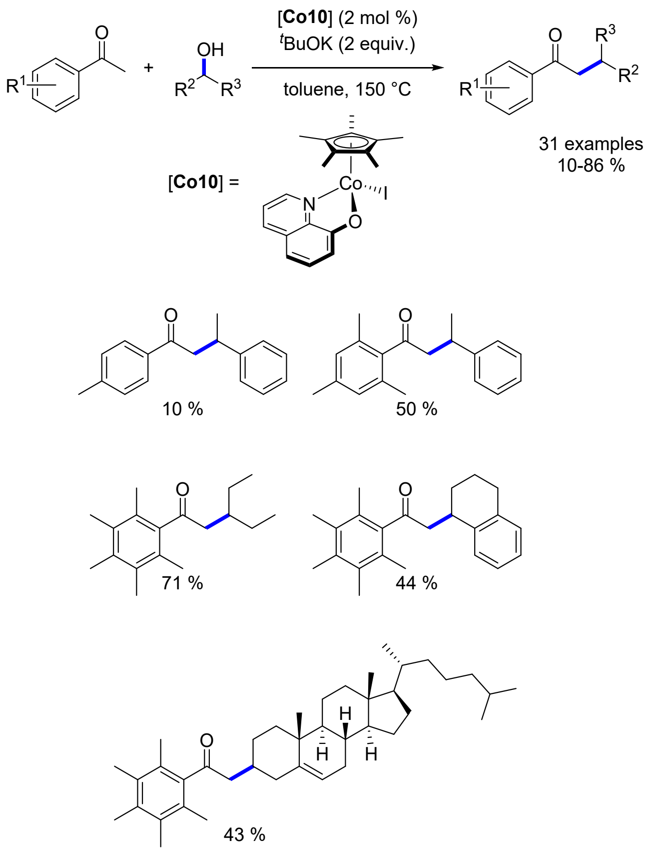
Scheme 95. Synthesis of α-substituted ketones and β-substituted alcohols.

The PNPP-Co complex was also employed for the alkylation of nitriles with primary alcohols.[186] This approach achieved yields of up to 95% with various benzyl nitriles and both benzyl and aliphatic alcohols (Scheme 96). However, other nitrile derivatives did not react under these conditions.



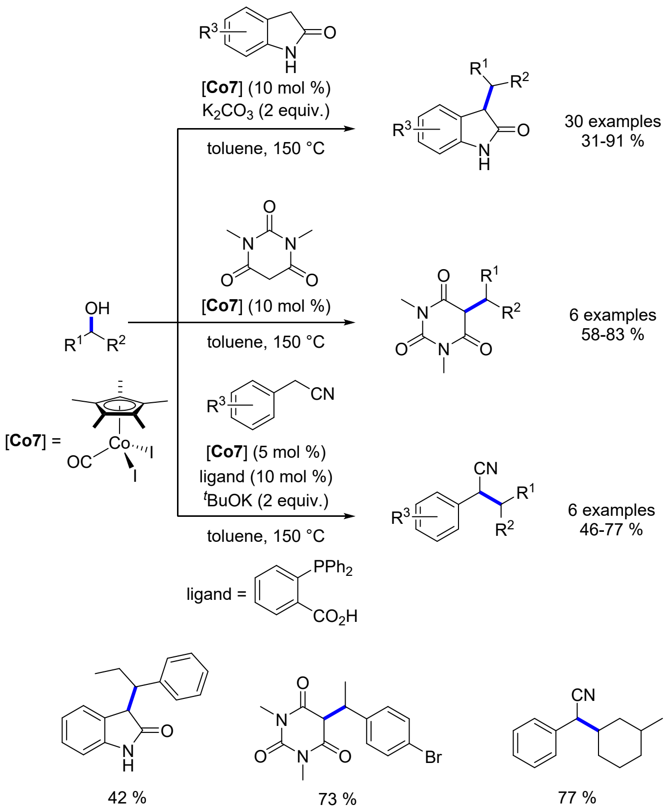
Scheme 96. Alkylation of nitriles reported by Ding.

In 2019, Sundararaju reported the α-alkylation of ketones using a Cp*Co(III) complex.[187] A similar complex was also effective for the alkylation of amines with secondary alcohols.[115] This methodology enabled the alkylation of substituted acetophenone derivatives with benzylic or aliphatic secondary alcohols, yielding β-disubstituted ketones in good to excellent yields (Scheme 97). As observed in manganese and iron chemistry, ortho,ortho-disubstitution of the acetophenone derivatives was crucial to prevent cross-alkylation and to enhance the reactivity.



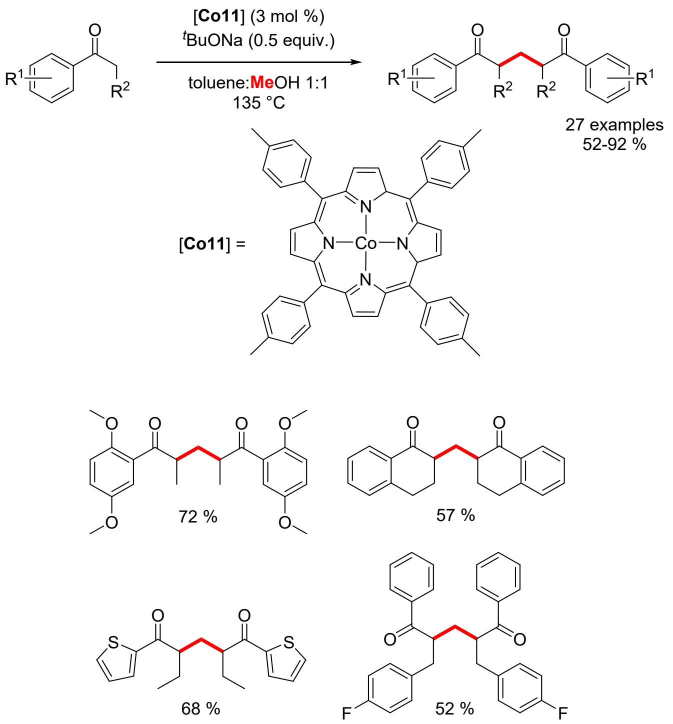
Scheme 97. Alkylation of ketones with secondary alcohols.

Another phosphine-free cobalt complex, described by Sundararaju *et al*., was utilized for the alkylation of oxindoles, N,N-dimethyl barbituric acid, and benzyl nitriles with secondary alcohols.[188] This bench-stable cobalt(III) complex selectively catalysed the alkylation of oxindole derivatives, yielding products in 31-91% yields (Scheme 98). The alkylation of barbituric acid did not require an additional base due to the substrate's acidic nature, and alkylated derivatives were obtained in 58-83% yields. In this case, only benzylic alcohols were used. For benzyl nitriles, alkylation was achieved only with cyclic aliphatic alcohols, resulting in yields of 46-77% (Scheme 98).



Scheme 98. Alkylation of oxindoles, barbituric acid and nitriles.

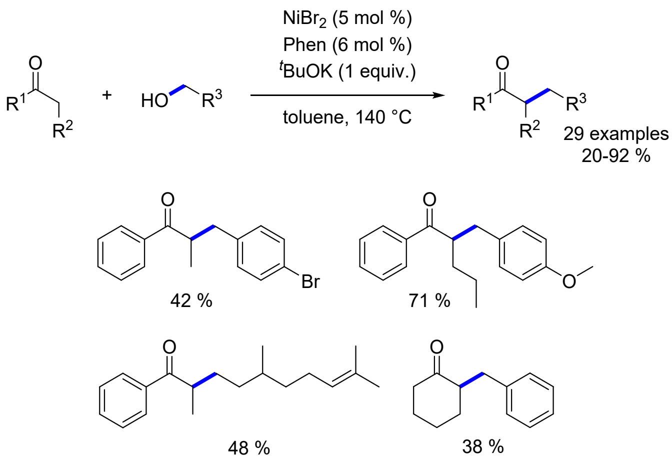
More recently, Chandrasekhar and Venkatasubbaiah reported the use of a porphyrin cobalt complex for the synthesis of 1,5-diketones through a dehydrogenative coupling reaction utilizing methanol as the C1 source.[189] In this process, formaldehyde generated in situ undergoes condensation to form α,β-unsaturated aromatic ketones. These intermediates then participate in a Michael-type addition with aromatic enolates, yielding the corresponding 1,5-diketones in 52-92% yields (Scheme 99). The catalytic cobalt species is regenerated after the release of hydrogen. This methodology afforded a variety of methylenated products, though it was limited to α-substituted benzylic ketones.



Scheme 99. Synthesis of 1,5-diketones.

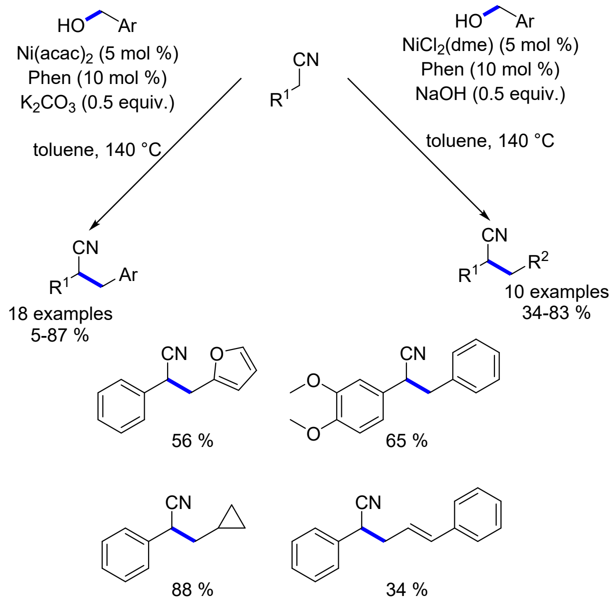
1) 3.4. Nickel-catalysed *C*-alkylation reactions.

The first nickel-catalysed alkylation of ketones with alcohols was reported by Banerjee in 2018.[190] The catalyst was generated in situ by combining $NiBr_2$ with 1,10-phenanthroline. This system effectively alkylated various α-substituted aryl ketones with benzylic alcohols, yielding moderate to good results. However, the alkylation of aliphatic ketones and the use of aliphatic alcohols resulted in lower yields and required higher base loadings (2 equiv. for aliphatic alcohols and 2.5 equiv. for aliphatic ketones). Further optimization with catalytic amounts of base (Cs_2CO_3 at 10 mol % or tBuOK at 20 mol %) did not improve the outcome with aliphatic alcohols, which failed to produce alkylated compounds under these conditions (Scheme 100).[191]



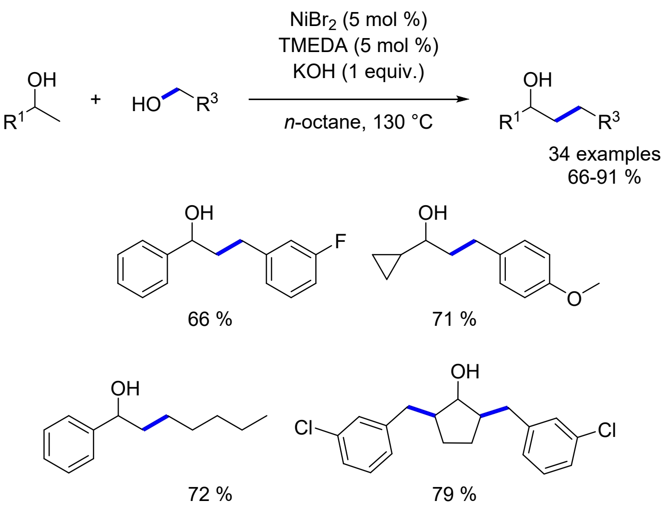
Scheme 100. Alkylation of α-substituted ketones.

Building on these studies, the same group later explored the alkylation of nitriles using primary alcohols.[192] In this work, the catalytic species was generated in situ by combining 1,10-phenanthroline with $Ni(acac)_2$. The reaction of benzyl nitriles with benzyl alcohols yielded alkylated products in low to good yields (Scheme 101). Aliphatic nitriles, such as 3-propionitrile, resulted in very low yields, and no reaction was observed with acetonitrile. However, by replacing $Ni(acac)_2$ and K_2CO_3 with $NiCl_2(dme)$ and NaOH, the system effectively facilitated alkylation with both aliphatic and allylic alcohols.



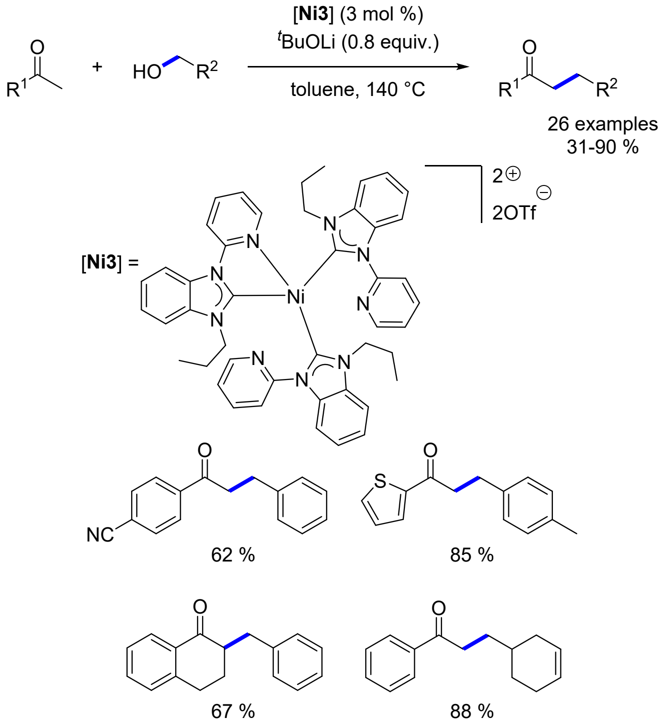
Scheme 101. Nickel-catalysed alkylation of nitriles.

In 2021, Balaraman reported a β-alkylation reaction of secondary alcohols with primary alcohols to produce β-substituted alcohols, using a catalyst system comprised of tetramethylethylenediamine (TMEDA) and $NiBr_2$.[193] This methodology successfully engaged a variety of alcohols as pro-electrophiles, yielding the desired products with no significant drop in yield, even for aliphatic and benzylic alcohols. Notably, aliphatic secondary alcohols also provided the desired products in good yields without necessitating changes in reaction conditions, demonstrating the method's broad applicability (Scheme 102).



Scheme 102. Nickel-catalysed β-alkylation of alcohols.

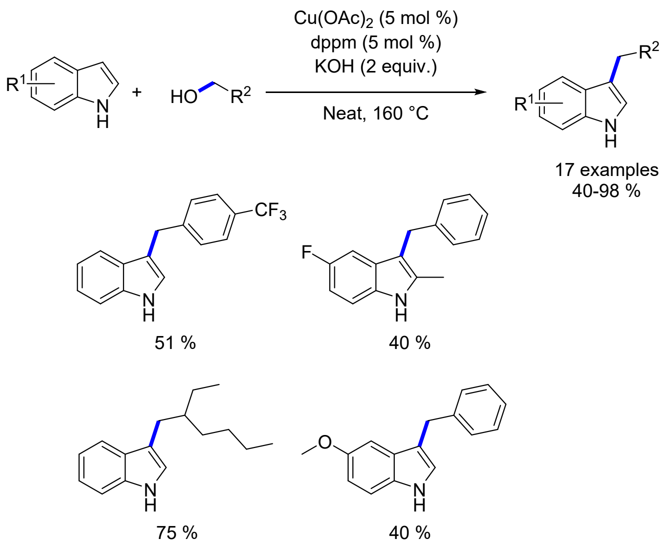
Liu described a Ni-NHC complex for the α-alkylation of ketones using benzyl alcohols.[194] This novel catalyst facilitated the formation of a range of alkylated ketones, achieving yields from low to good with the use of a catalytic amount of base at 140 °C (Scheme 103).



Scheme 103. Alkylation of ketones reported by Liu.

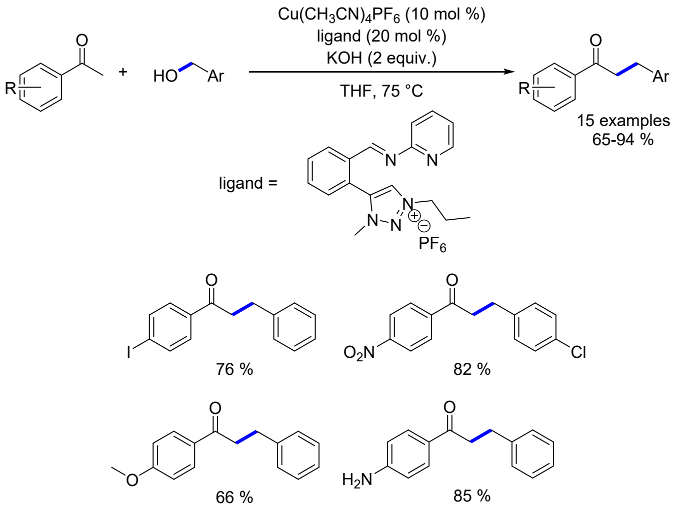
3.5. Copper-catalysed *C*-alkylation reactions.

Dang reported the first copper-catalysed alkylation of indoles using alcohols.[195] Copper acetate was combined with the bis-diphenylphosphinomethane (dppm) ligand to generate the catalytic species. This system facilitated the alkylation of indoles with both benzylic and aliphatic alcohols, yielding products in moderate to good yields (Scheme 104). However, high temperatures were necessary, and the scope of the reaction was limited, with only a few functionalized products being described. Additionally, no reaction was observed with N-substituted indoles, indicating that the presence of the hydrogen atom is crucial for the process.



Scheme 104. C3-alkylation of indoles. 3)

In the same year, Bala reported the alkylation of aryl ketones using benzyl alcohols.[196] The catalyst was generated in situ by combining $Cu(CH_3CN)_4PF_6$ with an appropriate ligand. This approach enabled the synthesis of a diverse range of functionalized ketones in good yields at 75 °C. This makes the reaction competitive with other alkylation methods, which typically require higher temperatures (Scheme 105).



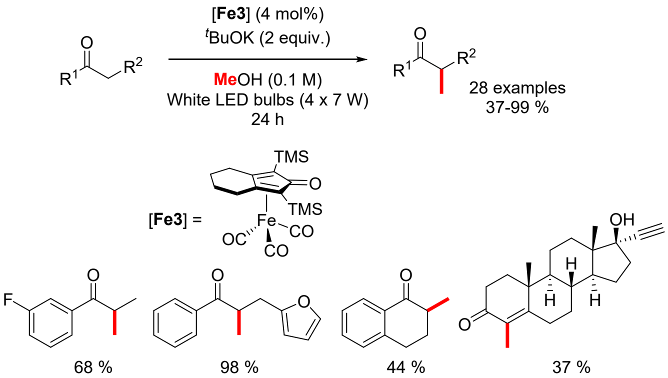
Scheme 105. Copper-catalysed alkylation of ketones.

I. 4. Alkylation reactions through borrowing hydrogen methodology

II. In the past decade, significant progress has been made in alkylation reactions, particularly in the hydrogen autotransfer alkylation of ketones and alcohols. Manganese, iron, cobalt, and nickel have proven effective in these processes, with various complexes and ligands enhancing catalyst efficiency, leading to milder conditions and shorter reaction times.[197] However, high temperatures are often still necessary. Recently, combining transition-metal catalysis with photoredox chemistry has introduced new reactions and reactivities, using light as an energy source instead of heat.[198] Despite this innovation, photocatalysts can sometimes be incompatible with the intended reaction, and challenges like electron or energy transfer between the photocatalyst and the metal complex may arise. To address these limitations, chromophoric transition-metal catalysts have been developed, enabling the use of a single catalytic species and avoiding these issues.

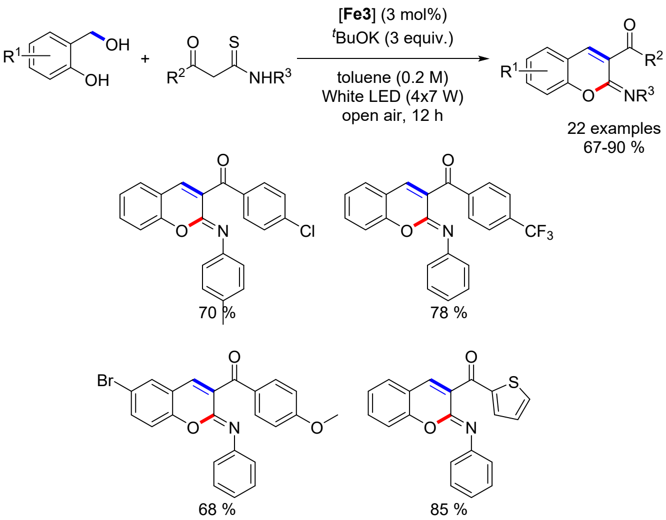
4.1. White light-induced alkylation reaction through borrowing hydrogen strategy

In 2022, Sundararaju reported an iron-catalyzed methylation of ketones under light irradiation.[199] Using Knölker's complex (4 mol %) and tBuOK (2 equiv.) in methanol, various acetophenones were methylated under four sets of 7 W white LED lights for 24 hours at 42 °C (Scheme 106). The process yielded α-methylated ketones in moderate to good yields (37-99%). Di-methylation of p-methyl acetophenone and cyclic substrates like tetralone produced lower yields, while ethisterone methylation resulted in a tetrasubstituted olefin due to isomerization.



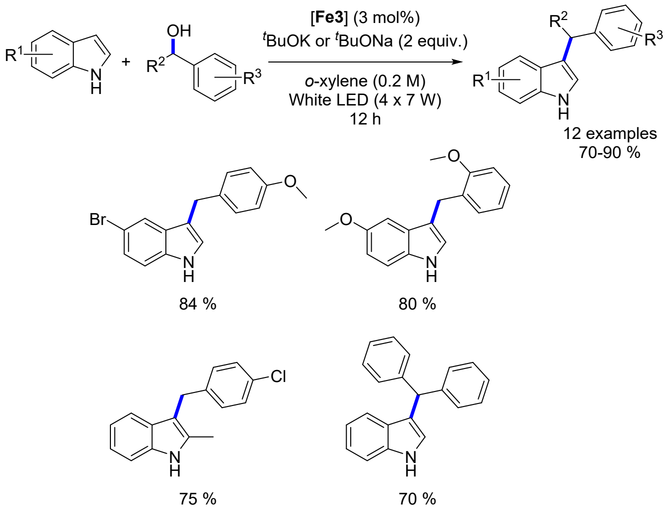
Scheme 106. Methylation of ketones under light irradiation.

Waheed recently reported the synthesis of 2-arylamino-2H-chromenes using an iron catalyst.[200] In this reaction, 2-hydroxybenzyl alcohols reacted with 1,3-keto-thioamides in toluene under air and light irradiation for 12 hours (Scheme 107), yielding 2-arylimino-2H-chromenes in good yields (67-90%). The reaction tolerated various substituents, including electron-donating and electron-withdrawing groups. A control experiment showed that salicylaldehyde could form the cyclic product without light irradiation, highlighting the iron complex's role in dehydrogenating benzyl alcohol. The proposed mechanism involves iron-catalyzed dehydrogenation, enol condensation, and final cyclization to form the chromene product.



Scheme 107. Synthesis of 2-arylamino-2H-chromenes.

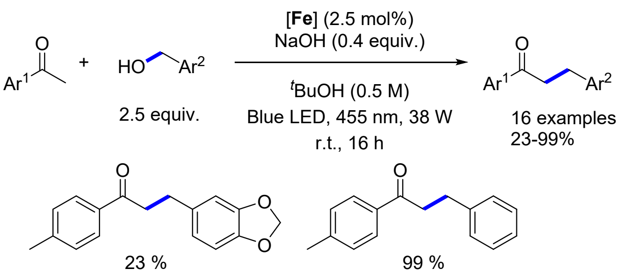
Waheed's group also reported the alkylation of indoles and the synthesis of flavanones using an iron catalyst. Indoles reacted with alcohols under optimized conditions (tBuOK, Knölker complex, light irradiation) to yield C3-alkylated indoles in 70-90% yields (Scheme 108).[201] Both primary and secondary alcohols were effective as pro-electrophiles. The group also synthesized bisindoylmethanes using similar conditions but in an open-air setup, where 1,4-addition occurred between the unsaturated intermediate and a second indole. Additionally, by increasing the base and reaction time, flavanones were synthesized in 70-92% yields, though with limited functional group tolerance.



Scheme 108. Alkylation of indoles.

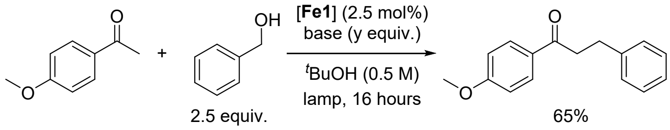
4.2. Blue light-induced iron-catalyzed α-alkylation of ketones

Renaud and coworkers began by examining the UV-visible spectra of iron complexes **Fe1-Fe3**,[202] which showed small absorption in the blue region despite their maxima falling within the UV spectrum (Scheme 109). The alkylation of 4-methoxyacetophenone with benzyl alcohol was optimized under various light sources and powers. Optimal conditions included using a 40W blue LED lamp, **Fe1** (2.5 mol %), and NaOH (0.4 equiv.) in tBuOH, leading to complete conversion in 16 hours. The scope of this blue light-induced alkylation was explored, yielding α-alkylated ketones in moderate to good yields across various substrates. Mechanistic studies suggested that light is crucial in the dehydrogenation and reduction steps of this process.



Scheme 109. Alkylation of aryl ketones with benzylic alcohols.

Renaud in 2024 unveiled a novel light-induced, iron-catalyzed α-alkylation of ketones at room temperature, utilizing alcohols as alkylating agents.[203] This study illustrates the versatility of cyclopentadienone iron complexes under various reaction conditions employing the borrowing hydrogen methodology (Scheme 110). The findings underscore the potential of these complexes in organic synthesis and catalysis, suggesting the possibility of expanding the reaction scope to include a broader range of substrates and functional group tolerances. As demonstrated in this study, it is now feasible to achieve alkylation between two aliphatic substrates and to use allylic and propargylic alcohols as pro-electrophiles. Additionally, the mild reaction conditions suggest the potential development of an efficient asymmetric version of this reaction.

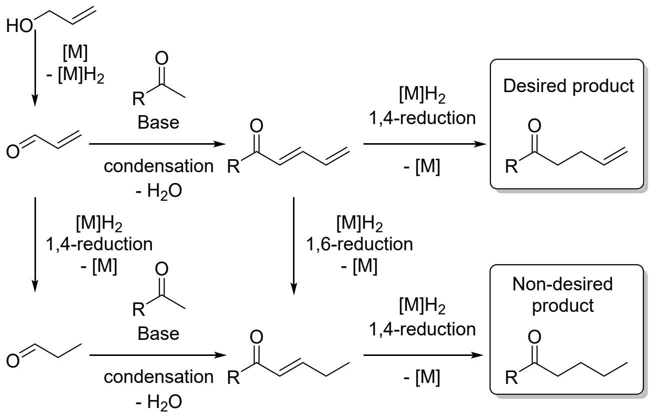


Scheme 110. Alkylation of 4-methoxyacetophenone with benzyl alcohol.

The key takeaway from this section is that the current methodology enables the use of both aliphatic alcohols and aliphatic ketones, delivering good yields. The successful alkylation of an aliphatic ketone with an aliphatic alcohol is significant, as thermal alkylation with **Fe1** had previously failed. In the past, homo-aldolization of the aliphatic aldehyde intermediate occurred more rapidly than alkylation. However, under the new conditions, light-induced alkylation at room temperature now outpaces other competing reactions.

4.3. Alkylation reactions with allylic alcohols

There are only a few reported instances in the literature where allylic alcohols are utilized as pro-electrophiles for C-C bond formation or for the chemoselective reduction[204] of unsaturated compounds.[205] This reaction poses a significant challenge because the potential 1,4-reduction of the α,β-unsaturated aldehyde could result in a saturated product. Additionally, the 1,6-reduction of the dienone intermediate, formed by the condensation of the α,β-unsaturated aldehyde with a ketone, may also yield a saturated product (Scheme 111). Renaud and coworkers performed α-alkylation of ketones using allylic and propargylic alcohols as pro-electrophiles.[203] The diaminocyclopentadienone iron tricarbonyl complex functions dually, capturing light and facilitating dehydrogenation and reduction without the need for an external photosensitizer. This allows the synthesis of γ,δ-unsaturated ketones at room temperature through a borrowing hydrogen methodology. Mechanistic studies show that steric hindrance at the δ-position of the dienone or eneynone intermediates is crucial in preventing 1,6-reduction, favouring the formation of non-conjugated enones and ynones over saturated ketones.

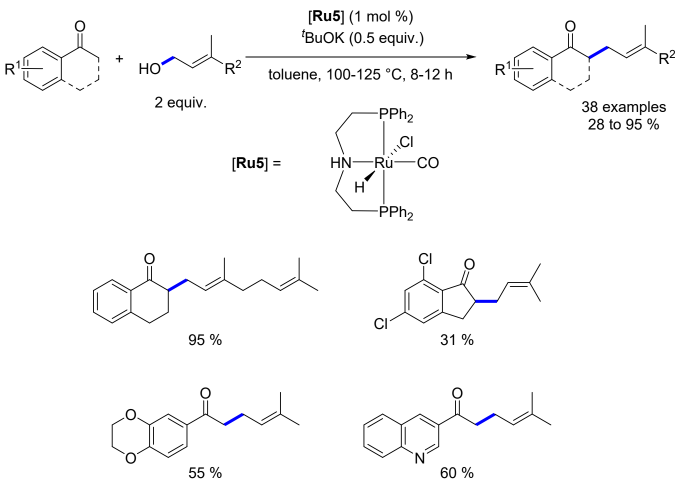


S

cheme 111. Challenges associated with using allylic alcohols as pro-electrophiles.

Gunanathan also recently reported the first successful alkylation of ketones with allylic alcohols,[205] leading to unsaturated ketones using a hydrogen autotransfer strategy. The α-alkylation of acetophenone derivatives with terpenol compounds was achieved using tBuOK (0.5 equiv.) and a Ru-Macho complex (1 mol %) at 100 °C in toluene over 12 hours. Under these conditions, α-tetralones and 1-indanones were alkylated with yields ranging from 28% to 95%. Acetophenone derivatives required a higher temperature (125 °C) and shorter reaction time (8 hours), yielding products in moderate to excellent yields (37% to 88%). However, this method was limited to terpenols as pro-electrophiles (Scheme 112).

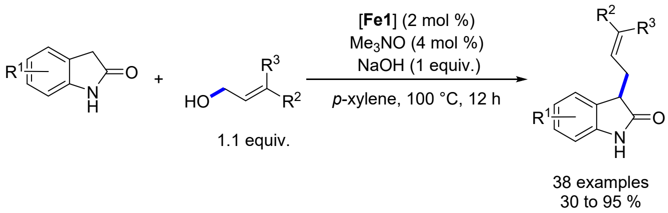
III.



Scheme 112. Ruthenium-catalysed alkylation of ketones with terpenols.

Mechanistic investigations by Gunanathan revealed challenges in the reaction.[205] The coordination of aldehydes to the metal catalyst inhibited its activity, leading to low yields when the aldehyde concentration was high. The researchers suggested that water generated during the condensation step might produce a metal-hydride species, aiding the reduction of the C=C bond.

In 2023, Sundararaju described the alkylation of oxindoles with terpenols and allylic alcohols.[206] The optimized conditions involved reacting oxindoles with allylic alcohol (1.1 equiv.), NaOH (1 equiv.), an iron complex (**Fe1**, 2 mol %), and Me_3NO (4 mol %) in p-xylene at 100 °C for 12 hours (Scheme 113). The reaction yielded a mixture of alkene isomers (α,β and β,γ-alkene), although the authors incorrectly identified the β,γ-alkene as the product, whereas the NMR spectra indicated a saturated by-product. The reaction tolerated various functional groups on the aryl rings, and the alkylated products were obtained in yields of 30% to 95%.



Scheme 113. Alkylation of oxindoles with allylic alcohols.

To validate the hydrogen autotransfer mechanism, deuterium labeling experiments were conducted. These experiments confirmed the pathway but did not explain the formation of the β,γ-alkene isomer as proposed by the authors. DFT calculations suggested that the 1,6-reduction is less energetically demanding than the 1,4-reduction by approximately 1 kcal/mol, which could explain the formation of the saturated by-product. Further investigations confirmed that the saturated by-product was likely due to the 1,4-reduction of the enal intermediate after dehydrogenation of the allylic alcohol.

5. Conclusions

Among the reported methodologies for the alkylation of N- and C-nucleophiles, those utilizing moisture- and air-stable organometallic complexes are relatively rare. The challenging synthesis of these sensitive catalysts further questions their practicality and applicability on an industrial scale. Alternative methods often involve metal salts, which typically require higher temperatures and base loadings, sometimes in stoichiometric amounts. In contrast, cyclopentadienone iron tricarbonyl complexes have demonstrated their effectiveness in various alkylation reactions under mild conditions, highlighting their potential for practical applications in this field.

The research conducted in this research field aligns with the work particularly over the past decade focusing on the development of more efficient catalysts using Earth-abundant metals. Expanding hydrogen autotransfer reactions to new substrates could broaden the applicability of this approach and its catalysts. Another potential direction is the design of a chromophoric Knölker-type catalyst capable of absorbing a wider range of visible light, which could enable alkylation reactions using safer white light instead of powerful blue LEDs. Additionally, the mild reaction conditions presented here could facilitate the development of stereoselective alkylation reactions. Finally, integrating two different catalysts in a dual catalytic system may allow for the formation of complex molecules in a one-pot process.

Even though HA systems offer significant potential for green chemistry, they are not without drawbacks. One major limitation is the restricted substrate scope. Many HA reactions struggle with functional group compatibility, particularly for more sensitive groups such as halides, ketones, or nitriles. This limitation can hinder broader applications, especially in fine chemicals or pharmaceutical industries. To overcome this, future research could explore the development of more robust catalysts that tolerate a wider range of functional groups. One possible solution is designing bifunctional catalysts that combine hydrogenation and transfer hydrogenation capabilities, enabling more selective transformations without sacrificing functional group compatibility. Another issue is the need for more than a stoichiometric amount of alkali base, particularly in alcohol-to-amine conversions. This excess base often plays a dual role: activating the alcohol and promoting dehydrogenation, but it can also lead to side reactions or decomposition. A potential solution involves developing milder base systems or even base-free catalytic designs, improving selectivity and sustainability. Finally, compared to Ru, Rh, and Ir catalysts, which offer excellent reactivity and selectivity, manganese and iron-based catalysts are more earth-abundant and cost-effective. However, they often suffer from lower activity and selectivity. Future strategies might focus on ligand engineering and catalyst design to enhance these earth-abundant metals' performance.

Author Contributions

All the authors wrote and revised the manuscript.

Biographies

Dr. Nicolas Joly obtained his Master Degree in Molecular Chemistry in 2020 at the ENSCR in Rennes. In 2023, he completed a PhD in Chemistry simultaneously at the University of Caen Normandy and the University of Girona under the supervision of Prof. Jean-Luc Renaud and Dr. Albert Poater. He is now a post-doctoral researcher in the group of Dr. Thibault Cantat at CEA Paris-Saclay. His research interests focus on organic synthesis, catalysis, and more particularly on molecular transformations through sustainable processes.

Dr. Sylvain Gaillard received his PhD from the Université Paul Cézanne/Aix-Marseille III. After a first postdoctoral position at the ENSCR in Rennes, he pursued with a second post-doctoral position under the supervision of Pr S. P. Nolan at the University of St Andrews. In 2010, he obtained an associate professor position in the group of Pr J.-L. Renaud at the University of Caen Normandy. His research interests is focused on molecular design of transition metal complexes tuning photophysical properties for applications in photocatalysis, hybrid materials and biological activity.

Dr. Albert Poater completed his PhD in Chemistry in 2006 at the University of Girona. After research stints in Chile, Montpellier, and a lengthy postdoc at the University of Salerno, he became an independent researcher in 2010 as a Ramón y Cajal fellow in Girona. He has also served as a Visiting Researcher in Saudi Arabia and Toulouse. In 2019, he was appointed Serra Húnter Associate Professor at the University of Girona and received the ICREA ACADÈMIA award. He has published over 300 papers with around 15,000 citations (H-index=66), specializing in DFT calculations for inorganic and organometallic catalysis, focusing on green chemistry.

Prof. Jean-Luc Renaud obtained his Ph.D. degree in 1998 under the supervision of Dr. Aubert and Prof. Malacria. He was a Lavoisier Postdoctoral fellow in 1999 with Prof. Lautens at the University of Toronto then moved to the University of Louvain-La-Neuve in the team of Prof. Riant. In 2000, he was appointed as Maître de Conférences at the University of Rennes and accepted a full Professor position at University of Caen Normandy in 2008. He is being invited researcher at the "Institut Parisien de Chimie Moléculaire (IPCM), Sorbonne University, since October 2023. The research interests focus on organometallic catalysis, organocatalysis, photoredox catalysis and their application towards the synthesis of biologically interesting molecules and processes relevant to fine chemical synthesis.

Abbreviations

Ac	Acetyl
acac	Acetyl acetonate
Am	Amyl
atm.	Atmosphere
Ar	Aryl
Boc	tert-butoxycarbonyl
Bpy	2,2'-bipyridine
Bu	Butyl
Cp*	1,2,3,4,5-pentamethylcyclopentadienyl
CPME	Cyclopentyl-Methyl Ether
Cy	Cyclohexyl
dba	Dibenzylideneacetone
DBU	1,8-Diazabicyclo[5.4.0]undec-7-ene
DCC	N,N'-dicyclohexylcarbodiimide
dcpe	1,2-bis(dicyclohexylphosphino)ethane
dcpp	1,3-bis(diphenylphosphino)propane
DDQ	2,3-dichloro-5,6-dicyano-1,4-benzoquinone
DFT	Density Functional Theory
DIBAL-H	Diisobulyl aluminium hydride
DIPEA	N,N-diisopropylethylamine
DMAP	4-dimethylaminopyridine
dme	Dimethoxyethane
DMF	N,N-Dimethylformamide
DMSO	Dimethyl sulfoxide
dppf	1,1'-bis(diphenylphosphino)ferrocene
dppm	1,1-bis(diphenylphosphino)methane
d.r.	Diastereoisomeric ratio
EDA	Ethylenediamine
EDG	Electron-Donating Group
equiv.	Equivalent
e.r.	Enantiomeric ratio
Et	Ethyl
EWG	Electron-Withdrawing Group
KHMDS	Potassium bis(trimethylsilyl)amide
LED	Light Emitting Diode
Me	Methyl
NHC	N-Heterocyclic Carbene
NMR	Nuclear Magnetic Resonance
Ph	Phenyl
THF	Tetrahydrofuran
TMEDA	Tetramethylethylenediamine
TON	Turnover Number

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

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