Transition-Metal-Catalyzed Decarbonylation of Carboxylic Acids to Olefins: Exploiting Acyl C–O Activation for the Production of High Value Products

Journal:	*Organic Chemistry Frontiers*
Manuscript ID	QO-HIG-06-2018-000585.R1
Article Type:	Highlight
Date Submitted by the Author:	06-Jul-2018
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Organic Chemistry Frontiers

HIGHLIGHT

Transition-Metal-Catalyzed Decarbonylation of Carboxylic Acids to Olefins: Exploiting Acyl C–O Activation for the Production of High Value Products

Received 00th January 20xx,
Accepted 00th January 20xx

DOI: 10.1039/x0xx00000x

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Transition-metal-catalyzed decarbonylation reactions of aliphatic carboxylic acids produce olefins via one carbon degradation. Recently, tremendous progress has been made in the development of new protocols for the synthesis of linear olefins by the formal acyl C–O activation mechanism of ubiquitous carboxylic acids. Various transition metals including nickel, palladium, iridium and iron have been shown to catalyze the reaction and achieve excellent yields and selectivity. The use of new ligand systems has resulted in unprecedented control of selectivity of elementary steps in the catalytic cycle. The development of new acyl precursors expands the access to α-olefins and offers promising perspectives for applications in preparative organic synthesis. In this article, we highlight the recent noteworthy developments in the transition-metal-catalyzed decarbonylation of carboxylic acids and discuss future challenges in this field.

Linear olefins are extremely important commodity chemicals that have found numerous applications in industrial and consumer products, including surfactants, lubricants and polymers.[1,2] The most common industrial technology for the production of high value linear alpha-olefins relies on polymerization of ethylene.[3] The diminishing resources of oil supply have fuelled the recent surge of interest in the conversion of biomass into chemicals that are currently produced by the petrochemical industry, including ethylene, and by extension linear olefins.[4] Thus, developing new chemical strategies for the production of high quality linear olefins from biomass has been a crucial issue in current chemistry research.[5]

Recently, tremendous progress has been made in the generation of linear olefins from carboxylic acids and esters. Since carboxylic acids can be derived from abundant natural product feedstocks, such as vegetable oils and animal fats, the direct conversion of carboxylic acids represents an attractive strategy to produce linear olefins from biomass resources.[2–5] Moreover, the availability of fatty acids with an even number of carbon atoms provides an inexpensive route to linear olefins containing an odd number of carbons, which are inaccessible by the current ethylene polymerization technologies.[1–3]

A plethora of attractive strategies for the catalytic decarbonylation of carboxylic acids to generate alkenes have been developed. The search for new metals, improved catalytic systems and new acyl precursors have facilitated the synthesis of high value commodity olefins from biomass resources, and resulted in a direct production of densely-functionalized fine chemicals that open new vistas for the increased application in organic synthesis. In this article, we will highlight the recent developments in the transition-metal-catalyzed dehydrative deoxygenation of carboxylic acids to alkenes by the formal acyl C–O activation mechanism[6,7] of ubiquitous carboxylic acids (Figure 1).

The most frequently used approach focuses on the direct decarbonylation of carboxylic acids, and usually requires stoichiometric quantities of a sacrificial anhydride to activate the carboxylic acid substrate (Scheme 1). After the carboxylic acid substrate is transformed into a mixed anhydride, the catalytic cycle involves the following steps: (i) oxidative addition, (ii) decarbonylation, (iii) β-hydride elimination, and (iv) reductive elimination to regenerate the catalyst. Simultaneously, isomerization to form internal alkenes occurs through re-insertion and β-hydride elimination. Thus, in order to obtain high quality olefins, the prime challenge is to control the selectivity of the olefin isomerization by a catalyst system.[2,4] Moreover, while distilling the α-olefin product from the reaction mixture at high temperatures is often used to minimize isomerization, this process is less ideal because only volatile olefins can be obtained by this method.

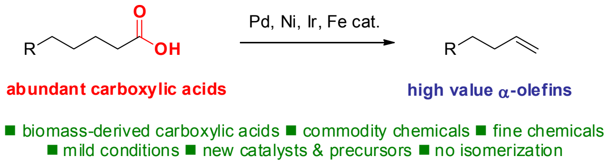

Figure 1 General decarbonylation of carboxylic acids to olefins.

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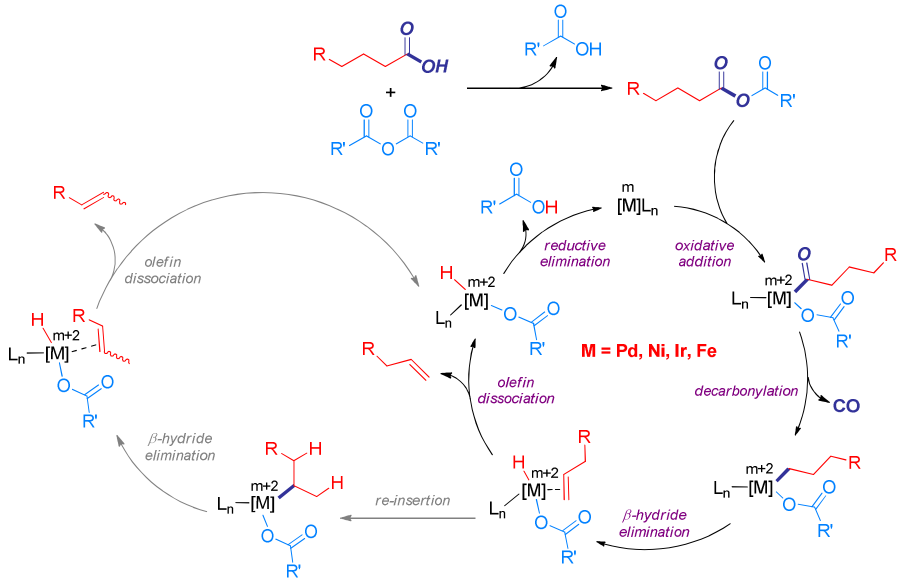


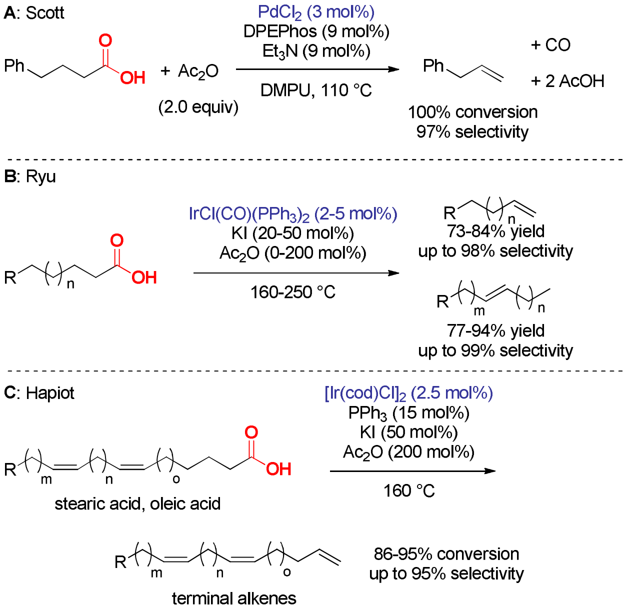
Scheme 1 General mechanism for transition-metal-catalyzed decarbonylation of carboxylic acids.

An important mechanistic point involves the origin of selectivity in the oxidative addition step of the mixed anhydride to a palladium catalyst. Mechanistic studies suggest reversibility of the oxidative addition with deprotonation of alkyl-palladium as the rate-determining step.[2,6–8]

Palladium is the most commonly used transition metal in deoxygenation of carboxylic acids.[8,9] In 2010, a palladium-DPEPhos-catalyzed decarbonylation was reported by Scott and co-workers (Scheme 2A).[10] The method allows for the conversion of aliphatic carboxylic acids to terminal alkenes in high yields and with high α-selectivity at temperatures as low as 110 °C. The addition of triethylamine as additive was critical to stabilize the catalytic species and effectively prevent isomerization of the terminal double bond.[11] The method represented a significant improvement over previous methods that require very forcing conditions (250 °C) or stopping the process at lower conversions to avoid olefin isomerization.[8]

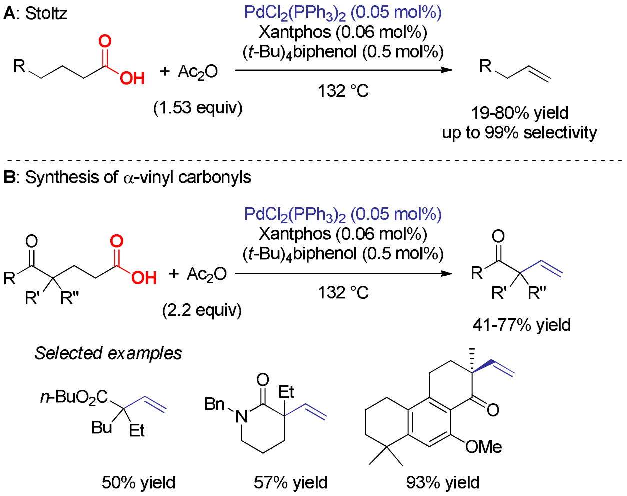
In the same year, the Ryu group developed an efficient iridium-catalyzed decarbonylation reaction of aliphatic carboxylic acids (Scheme 2B).[12] By using Vaska's complex, $IrCl(CO)(PPh_3)_2$, as catalyst, KI and Ac_2O as additives, long-chain aliphatic carboxylic acids can be converted to internal or terminal alkenes with high selectivity at controlled temperature. At 250 °C, the addition of KI alone (20 mol%) greatly improves the yield of internal alkenes, while maintaining perfect selectivity (>99%, with respect to the olefin regioisomer). At 160 °C and using both KI (50 mol%) and Ac_2O (200 mol%), terminal alkenes are obtained with high selectivity (up to 98%). The authors suggested that the addition of KI results in ligand exchange from Cl to I in Vaska's complex to give a more active catalyst. Interestingly, the reaction showed good functional group compatibility in that ester groups can also be tolerated during the reaction. More recently, the Hapiot group reported elegant Ir-catalyzed decarbonylation of biomass-derived fatty acids to obtain long linear olefins in good yields and with high selectivity (Scheme 2C).[13] These reactions were best accomplished in the presence of $Ir(cod)Cl_2$ (2.5 mol%) and PPh_3 (15 mol%) with KI (50 mol%) and Ac_2O (200 %) as additives. Importantly, the Ir catalyst could be recovered by simple distillation of the reaction mixture and recycled, albeit with lower conversions.

In 2014, Stoltz and co-workers achieved a palladium-catalyzed decarbonylation reaction of linear carboxylic acids at very low catalyst loadings using $PdCl_2(PPh_3)_2$ (0.05 mol%) and Xantphos (0.06 mol%) under solvent-free conditions (Scheme 3A).[14] During screening of the reaction conditions, two findings



Scheme 2 Pd- and Ir-catalyzed decarbonylation of carboxylic acids: A) Scott; B) Ryu; C) Hapiot. Scheme 2B: selectivity with respect to the indicated olefin regioisomer is shown.

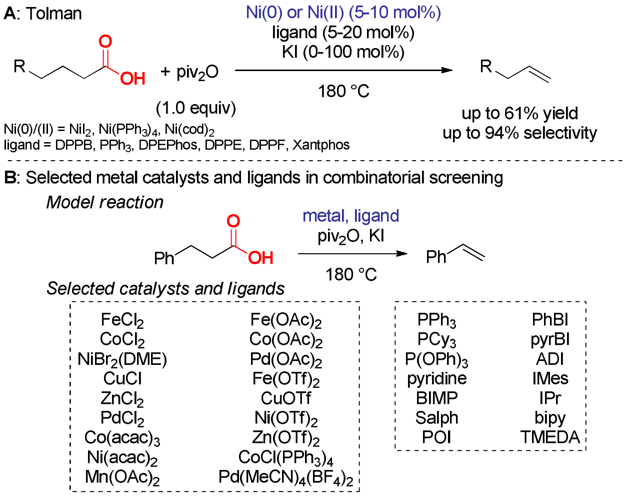
were crucial: (i) a protic additive, $(t\text{-Bu})_4$biphenol (0.5 mol%), promoted reactivity; (ii) the frequency of adding acetic anhydride had a major impact on α-selectivity; by portion-wise addition of acetic anhydride, the reaction could give α-olefins with exquisite selectivity (up to 99%) even without in situ distillation. The authors proposed that acidic additives, such as $(t\text{-Bu})_4$biphenol, result in higher reactivity of a catalyst system. Since the reaction can be performed under neat conditions, it can be easily scaled up without compromising α-selectivity. The method represents an important addition to the toolbox of technologies for the production of linear α-olefins from biomass resources. Later, the same group reported another important advance in the area by developing Pd-catalyzed decarbonylative dehydration to furnish α-vinyl carbonyl compounds (Scheme 3B).[15] This method was elegantly showcased in the total synthesis of Aspewentins A, B, C, norditerpene natural products. The study by Stoltz and co-workers convincingly demonstrated that the concept of decarbonylative olefin synthesis from readily available carboxylic acids provides a novel platform for the production of densely-functionalized molecules that would be challenging to prepare by alternative methods.



Scheme 3 Pd-catalyzed decarbonylation of carboxylic acids by Stoltz: A) α-linear olefins; B) α-vinyl carbonyl compounds.

Tolman, Hillmyer and co-workers have been extensively studying new protocols for deoxygenation of carboxylic acids. In 2012, they developed a Pd-catalyzed decarbonylation of biomass-derived carboxylic acids using continuous distillation protocol at 190 °C (not shown).[16] In their approach, cheap and weakly coordinating PPh_3 was shown to promote decarbonylation in similar yields and selectivity as bidentate Xanthphos and DPEPhos, while the catalyst loading could be lowered to 0.005 mol% without a significant decrease in the reaction efficiency.

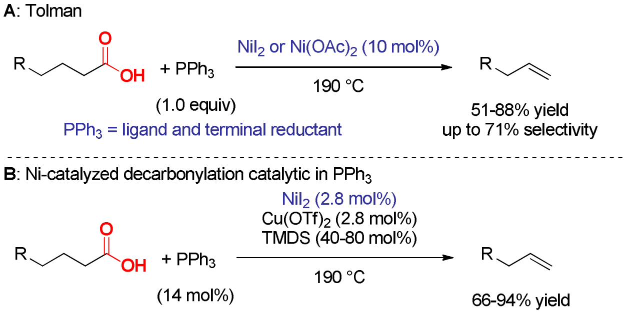
In 2016, Tolman and co-workers reported a major breakthrough in finding that catalysts based on inexpensive and abundant 3d transition metal, nickel, effectively promote decarbonylation of carboxylic acids (Scheme 4).[17] Using high-throughput experimentation techniques, a combination of Ni(0) or Ni(II) precatalysts (NiI_2, $Ni(PPh_3)_4$) and bidentate phosphine ligands (DPPB, DPEPhos) under a continuous distillation process at 180 °C was identified as the best catalytic system for the reaction. Interestingly, a 2:1 ligand: nickel ratio gave optimum results. As expected, the reaction was inhibited when the process was performed under the atmosphere of CO. DFT studies suggested that a rate-determining step may involve regeneration of the active monoligated Ni(0) species via CO dissociation. Furthermore, the proposed catalytic cycle involving the acyl-Ni intermediate mirrored the previous mechanistic studies on using palladium-based catalysts for decarbonylation of hydrocinnamic acid.[18] Given the recent interest in nickel-catalyzed cross-couplings, the facile decarbonylation of acyl-nickel species demonstrated by Tolman and co-workers opens the door for a plethora of decarbonylative processes of carboxylic acids by nickel-catalysis.[19]



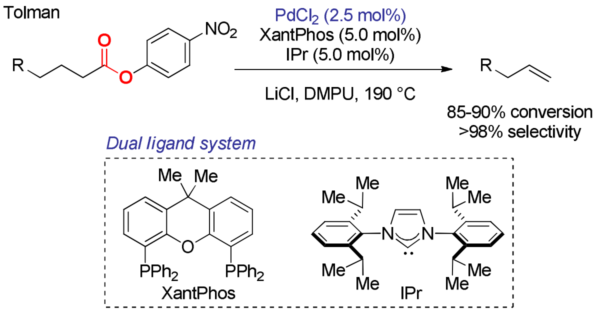
Scheme 4 Ni-catalyzed decarbonylation of carboxylic acids by Tolman: A) α-linear olefins; B) high-throughput screening.

In 2017, Tolman and co-workers reported another important contribution to the direct dehydrative deoxygenation of carboxylic acids by developing a solvent-free Ni/PPh_3-catalyzed deoxygenation of carboxylic acids to olefins without the use of activating additives (Scheme 5).[20] For the vast majority of decarbonylative reactions of carboxylic acids, the use of sacrificial anhydride is essential to generate the acyl-metal species.[2,4,8] However, they found that when PPh_3 is used in combination with Ni(II) salts, the phosphine acts as both ligand and reductant, resulting in the production of α-olefins in high yields and with good selectivity. Notably, the reaction is catalytic in PPh_3 by using TMDS (1,1,3,3,-tetramethyldisiloxane) and $Cu(OTf)_2$ that can regenerate PPh_3 from the phosphine oxide. Without $Cu(OTf)_2$/TMDS additives the reaction is stoichiometric in PPh_3. The impressive results of Tolman considerably extend the scope of decarbonylative processes of carboxylic acids by incorporating two complementary catalytic cycles to effect catalysis.

A very significant recent development by Tolman and co-workers involves a highly selective Pd-catalyzed decarbonylation of *p*-nitrophenylesters of fatty acids to linear α-olefins with a mixed phosphine/NHC (NHC = N-heterocyclic carbene) ligand system (Scheme 6).[21] After extensive screening of various ligands, they found that a combination of bidentate phosphine (Xantphos)[22] and sterically-bulky NHC ligand (IPr)[23] was optimal for the decarbonylation process (>98% selectivity, >90% conversion). DFT calculations showed that in the mixed phosphine-NHC ligand system the steric bias of IPr (buried volume of 45.4%)[24] and the coordination of XantPhos in both mono- and bidentate mode promoted a rapid and irreversible de-coordination of the product olefin, thus preventing the isomerization pathway. Collectively, the finding that ligands from two different classes act cooperatively to improve the reaction efficiency will undoubtedly find numerous applications in decarbonylative processes of acyl electrophiles.



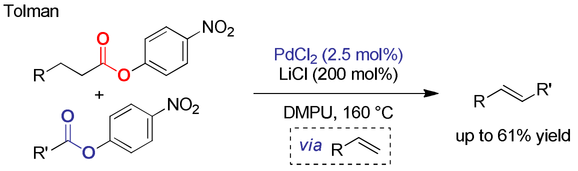
Scheme 5 Anhydride-free Ni-catalyzed decarbonylation of carboxylic acids by Tolman: A) stoichiometric PPh_3; B) catalytic PPh_3.



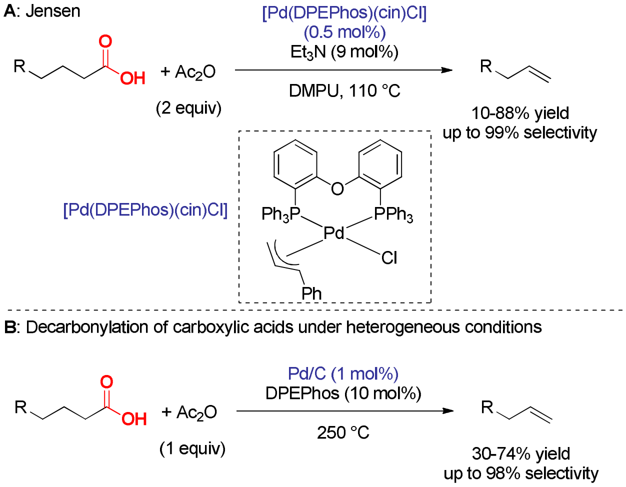
Scheme 6 Pd-catalyzed decarbonylation of carboxylic acid esters using a dual ligand system by Tolman.

In addition to direct decarbonylation of carboxylic acids and derivatives to olefins, the Tolman group has also studied the development of tandem protocols based on the in situ generation of olefin precursors (Scheme 7). In 2015, they reported a tandem double decarbonylation of *p*-nitrophenylesters/Heck reaction, which was catalyzed by $PdCl_2$ in the presence of LiCl.[25] The reaction sets an important precedent for rapidly building-up molecular complexity from biomass-derived fatty acids.[26]

Jensen and co-workers independently described another strategy to promote decarbonylative dehydration of fatty acids with high efficiency (Scheme 8A).[27] They developed a well-defined Pd(II) precatalyst, [Pd(DPEPhos)(cin)Cl], as a new catalyst for decarbonylation of fatty acids with high α-olefin selectivity. Impressively, the precatalyst was found to operate with more than 8 times higher TOF than standard in situ protocols. High functional group tolerance and operational-simplicity[28] are other noteworthy features of this approach. Subsequently, the Jensen group reported an improved protocol for the decarbonylation of fatty acids based on a heterogeneous Pd catalyst, Pd/C, in the presence of DPEPhos (Scheme 8B).[29] The catalyst could be recycled up to three times without any loss in activity and olefin selectivity. The work by Jensen opens new avenues for exploring decarbonylation of carboxylic acids by heterogeneous Pd catalysis.[30]



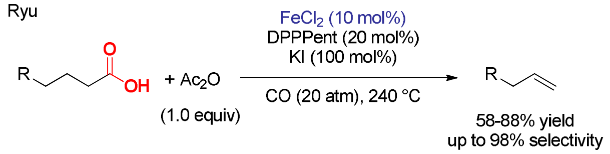
Scheme 7 Pd-catalyzed tandem decarbonylative Heck reaction of carboxylic acid esters by Tolman.



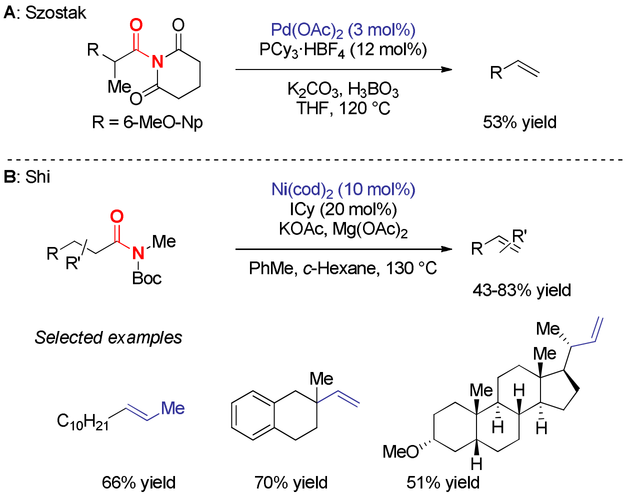
Scheme 8 Decarbonylation of carboxylic acids by Jensen: A) well-defined Pd(II) precatalyst; B) heterogeneous conditions.

In another approach to improve efficiency of the decarbonylation of carboxylic acids, the Ryu group reported highly selective decarbonylation of aliphatic carboxylic acids to α-olefins using iron catalysis (Scheme 9).[31] High yields and high selectivity were achieved by using $FeCl_2$ as catalyst, DPPPent as ligand, and KI and Ac_2O as additives. While the current drawback involves the need for pressurized CO to improve catalyst performance and α-olefin selectivity, likely due to generation of a catalytically-active iron-carbonyl species, this research shows that cheap, non-toxic and sustainable iron[32] represents an effective tool to perform catalytic decarbonylation of carboxylic acids.

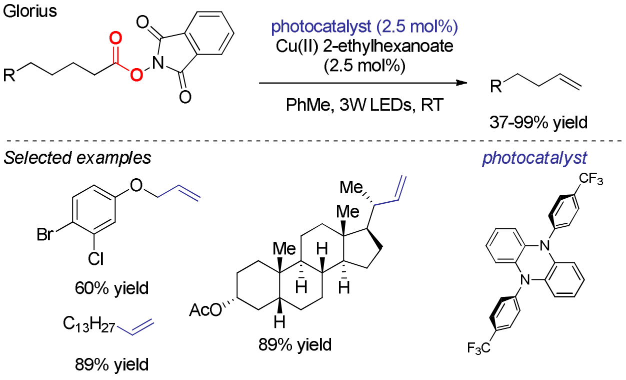
Two other recent developments in this area are noteworthy. In 2015, we reported the first decarbonylation of amides to olefins using Pd-catalysis (Scheme 10A).[33] Not only are the reaction conditions mild, but equally important is the finding that decarbonylation of carboxylic acid derivatives by N–C cleavage[34] provides an alternative pathway to decarbonylative dehydration by C–O scission. This process was subsequently expanded to Ni-catalysis by the Shi group (Scheme 10B).[35] A particularly attractive feature of this catalytic method is the ability to engage complex amide precursors to furnish congested olefins that would otherwise be difficult to prepare. More recently, Glorius and co-workers reported an impressive example[36] of merging photoredox/Cu(II) catalysis with redox active N-hydroxyphthalimide esters[37] to produce olefins from fatty acid derivatives via a decarboxylative pathway (Scheme 11). The method results in high selectivity for the formation of terminal olefins. The photoredox catalysis may not only enable more efficient decarboxylative olefination of carboxylic acid derivatives, but also open new vistas for oxidative decarboxylative methods by single electron transfer.[38]



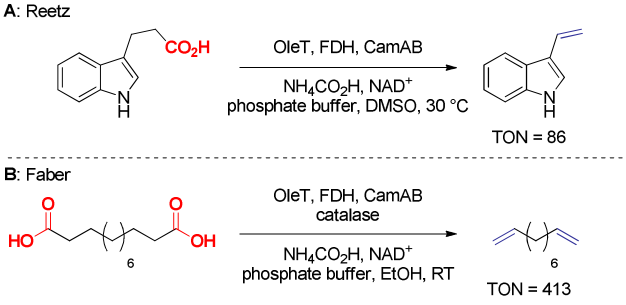
Scheme 9 Fe-catalyzed decarbonylation of carboxylic acids by Ryu. DPPPent = 1,5-Bis(diphenylphosphino)pentane.



Scheme 10 Pd- and Ni-catalyzed decarbonylation of amides by N–C cleavage: A) Szostak; B) Shi.



Scheme 11 Photoredox/Cu(II)-catalyzed decarboxylative olefination of redox-active carboxylic acid esters by Glorius.



Scheme 12 Oxidative decarboxylation catalyzed by the P450 monooxygenase OleT: A) Reetz; B) Faber. OleT = P450 monooxygenase Olet; CamA = putidaredoxin reductase; CamB = putidaredoxin.

Toward the development of efficient approaches for the synthesis of olefins from carboxylic acid derivatives, bioenzymatic methods should also be mentioned in passing. In particular, recent advances in oxidative decarboxylation of fatty acids by the p450 monooxygenase OleT provide a convincing illustration that bioenzymatic processes can lead to the development of practical methods for the synthesis of olefins from biomass resources (Scheme 12).[39] Ultimately, it can be expected that further improvements to enhance olefin complexity by tandem chemoenzymatic transformations[40] will be realized.

Conclusions

In summary, recently impressive advances in the transition metal-catalyzed decarbonylative reactions of carboxylic acids and derivatives to olefins have been accomplished. These methods provide efficient and straightforward synthetic solution to obtain high value linear alpha-olefins from biorenewable resources. Several powerful strategies have emerged, thus improving the yield, selectivity, and practicality of this class of reactions. The development of inexpensive base-metal catalysts, improved catalyst systems and new carboxylic acid precursors are undoubtedly a major step forward. In addition to providing the much-needed biomass alternative to petrochemical feedstock, the synthesis of densely-functionalized fine chemicals[41] illustrate the power o this class of reactions. With recently developed isomerization methods of linear olefins,[42] organic chemists are now well-equipped to fully exploit abundant carboxylic acids as key precursors in a broad range of chemical transformations.

Acknowledgements

Rutgers University and the NSF (CAREER CHE-1650766) are gratefully acknowledged for support.

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