Transition-Metal-Catalyzed Carboxylation of Organic Halides and Their Surrogates with Carbon Dioxide

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Received: 19.08.2017
Accepted after revision: 24.08.2017
Published online: 13.09.2017

Abstract Carbon dioxide is not only an essential component of ‘greenhouse gases’, but also an abundant, renewable C1 feedstock in organic synthesis. The catalytic incorporation of carbon dioxide into value-added chemicals has received enormous attention. This review summarizes recent developments in the transition-metal-catalyzed carboxylation of organic halides and their surrogates, such as aryl, vinyl, benzyl, allyl, propargyl, alkyl and halides and pseudohalides.

Key words carbon dioxide, carboxylic acids, carboxylation, electrophiles, halides

1 Introduction

The continuous increase of carbon dioxide concentration in the atmosphere has potentially caused the rise of atmospheric temperature and abnormal changes in the global climate. 1 Obviously, the control of CO2 emissions and the development of efficient carbon capture systems are in high demand. Carbon dioxide is not only an essential component of ‘greenhouse gases’, but also an abundant and renewable C1 feedstock in organic synthesis. 2 Therefore, there is great interest in transforming carbon dioxide into useful chemicals, from an environment-protection point of view. Due to the thermodynamically stable and/or kinetically inert of CO2, the activation and utilization of CO2 is still problematic. Most transformations of CO2 require highly reactive substrates and/or severe reaction conditions. In the case of C–C bond formation with CO2, the use of carbon nucleophiles is limited to phenolates and strongly nucleophilic organolithium, as well as Grignard reagents. 3 On the other hand, highly reactive substrates such as epoxides and aziridines are used to couple with CO2 to generate C–O or C–N bonds. 4 In this article, recent developments for the transition-metal-catalyzed carboxylation of electrophiles, such as aryl, vinyl, benzyl, allyl, propargyl, alkyl and halides and pseudohalides will be highlighted (Figure 1). The carboxylation of

Figure 1  The representative examples of carboxylation reactions in this review
2 Carboxylation of Aryl Halides and Pseudo-Halides

The carboxylation of arylzinc and arylboronic esters with CO₂ has been investigated intensively, due to the compatibility of various functionalities that were not tolerated with Grignard reagents. However as these compounds were derived from the corresponding aryl halides, the direct carboxylation of the aryl halides is a more straightforward transformation. The stoichiometric carboxylation of Ni-aryl complexes with CO₂ has been studied intensively. For example, the insertion of CO₂ into the Ni-aryl carbon bond of 1 and 2 delivers corresponding nickelalactones 1a and 2a, respectively (Scheme 1).6 The Ni(0)-mediated carboxylation of aryl halides 3 with CO₂ was demonstrated by Yamamoto, Osakada, and Sato. Oxidative addition of the aryl halide 3 to Ni(cod)₂ in the presence of 2,2'-bipyridine gives NiX(Ph/bpy) 4, which reacts with CO₂ to deliver the carboxylation products 5 (Scheme 1).7

Scheme 1 Ni-mediated carboxylation of aryl halides

Early examples of the Ni-catalyzed carboxylation of aryl halides were reported as electrochemical processes. For instance, Perichon, Fauvarque, and co-workers described the electroreductive carboxylation of aryl halides 3 with CO₂ in...
the presence of nickel catalyst.8 The proposed mechanism is shown in Scheme 2. Oxidative addition of aryl bromide 3 (X = Br) to Ni(0)(dppe) gives ArNiBr(dppe), which undergoes one-electron reduction to deliver a Ni(1) complex. Carboxylation of the arynickel(1) species and one-electron reduction closes the cycle by regeneration of Ni(0) and formation of arencarboxylate (Scheme 2). On the basis of the kinetic analysis of the CO2 insertion step, a Ni(III) intermediate is also proposed prior to the formation of ArCO2Ni(dppe).9

Similarly, Torii, Fauvarque, and co-workers disclosed an efficient Pd-catalyzed electroreductive carboxylation of aryl halides with CO2 (Scheme 3).10 Both aryl iodides 3 (X = I) and aryl bromides 3 (X = Br) are effective, however aryl chlorides did not give the corresponding products. It is noteworthy that the formation of arencarboxylate was not competitive with the formation of biaryl, which is the by-product for the metal-free electroreductive carboxylation.11

The transition-metal-catalyzed electroreductive carboxylation of aryl halides with CO2 is a promising tool for the preparation of arencarboxylic acids.12 However the reaction scope is quite restricted. In 2009, Correa and Martín reported a Pd-catalyzed carboxylation reaction of aryl bromides 6 using a substituted biphenyl monophosphine ligand L1 (t-Bu-Xphos) under 10 atm of CO2.13 The insertion of CO2 into the Pd–aryl σ-bond is suggested in the proposed mechanism. Diethylzinc behaves as the reducing agent to regenerate Pd(0) and zinc carboxylates are formed (Scheme 4). In 2012, Tsuji and co-workers described the Ni-catalyzed carboxylation of aryl chlorides 3 (X = Cl) under 1 atm of CO2 using Mn powder as a reducing agent.14 The proposed mechanism involves an oxidative addition of the aryl chlorides to Ni(0), formed by reducing Ni(II) with Mn. The resulting Ni(II) intermediate is reduced to a Ni(I) intermediate, which reacts with CO2 to give the product (Scheme 5).

Copper catalysts have been used in the carboxylation of arylboronates with CO2, and an aryl-copper species is suggested as a key intermediate for the reaction. In 2013, Tran-Vu and Daugulis reported the Cu-catalyzed carboxylation of aryl iodides 7 under 1 atm of CO2.15 The reaction is compatible with various functional groups such as ester, bromide, chloride, fluoride, ether, amino, hydroxy, and carbonyl. The carboxylation of aryl–Cu species is suggested to be rate-limiting step and the mechanism is likely to involve copper clusters (Scheme 6).
Besides aryl halides, aryl pseudohalides are suitable electrophiles for carboxylation reactions. For instance, Martín and co-workers demonstrated the Ni(II)-catalyzed carboxylation of C(sp^2)-O bonds with CO\(_2\), and it is necessary that the C–O bonds are pre-activated as esters, e.g. 8, derived from cheap alcohols.\(^{16}\) The reaction mechanism is similar to C–halides carboxylation using Mn as reducing reagent (Scheme 7). These carboxylation reactions provide alternative protocols for the preparation of arenecarboxylic acids with the advantage of functional group tolerance compared with the classic carboxylation of Grignard reagents. Obviously, the development of novel carboxylation reactions to avoid the use of stoichiometric amounts of metals (Mn or Zn) or zinc agents as reducing agents is in high demand.
In 2015, Tsuji and co-workers\textsuperscript{18} reported a cobalt-catalyzed reductive carboxylation reaction. In this work, various alkenyl triflates \textsuperscript{14} were converted into $\alpha$, $\beta$-unsaturated carboxylic acids \textsuperscript{15} under mild conditions (Scheme 10). In addition, a range of hindered aryl triflates substituted in the 2-aryl position were smoothly carboxylated.

In 2013, the Martin group reported the Ni-catalyzed carboxylation of benzyl chlorides \textsuperscript{16} with CO$_2$ (Scheme 12);\textsuperscript{20} the reaction tolerated various functional groups. Interestingly, with slightly modified reaction conditions, the carboxylation of secondary alkyl bromides \textsuperscript{19} was achieved (Scheme 13).\textsuperscript{20} The proposed mechanism suggests that a Ni$^\text{i}$ intermediate may be crucial in the catalytic cycle and MgCl$_2$ promotes the carboxylation of benzyl chloride with CO$_2$ by stabilizing the Ni–CO$_2$ adduct and accelerating the CO$_2$ insertion (Scheme 14).\textsuperscript{20,21}
In 2014, the Martin group also demonstrated the carboxylation of benzylic C(sp³)–O bonds via a similar pathway (Scheme 15). Notably, the carboxylation of secondary benzyl–type derivatives (e.g., 18f, h, i) was also effective. However, the protocol is limited to π-extended systems; simple phenyl-containing compounds are not effective. Taking advantage of hemilabile directing group,22 the Martin group elegantly developed the efficient carboxylation protocol with simple benzyl esters 20 (Scheme 16). Furthermore, the Martin group demonstrated that ammonium salts 21 could be used as benzyl electrophiles for carboxylation (Scheme 17). Interestingly, this reaction was insensitive to electronic changes on the arene and suitable for non-extended π-systems. Most striking, secondary benzyl ammonium salts 22 possessing α-hydrogen atoms were successfully carboxylated. The dimerization and α-hydride elimination pathways were avoided in this protocol (Scheme 18).
In 2015, He and co-workers reported the Pd-catalyzed carboxylation of benzyl chlorides 16 with CO\(_2\) (Scheme 19).\(^{24}\) The reaction afforded the corresponding phenylacetic acids 17 in combination with Mn powder as a reducing reagent and MgCl\(_2\) as an indispensable additive.

Lu and co-workers reported the asymmetric electrocarboxylation of 1-phenylethyl chloride (16b) with CO\(_2\) in the presence of Co catalyst (Scheme 20).\(^{25}\) Although the yield and the ee values are moderate, this elegant study provides an alternative method for the synthesis of optically active carboxylic acids.

### 5 Carboxylation of Allyl Halides and Pseudo-halides

In 1976, Inoue and co-workers described the carboxylation of allylic Pd species with CO\(_2\).\(^{26}\) In the 1980s, Perichon\(^{19b}\) and Fauvarque\(^{10}\) described the electroreductive carboxylation of allylic substrates with CO\(_2\) in the presence of cobalt and palladium catalysts, respectively (Scheme 21). Unfortunately, regioselectivity is not achieved under these conditions.

In 2014, the Martin group demonstrated the Ni-catalyzed carboxylation of allyl esters with CO\(_2\) (Scheme 22).\(^{27}\)
The regioselectivity is highly controlled by the ligand and both carboxylic acid products were achieved in a highly selective manner with 1,10-phenanthroline \( L_2 \) or quaterpyridine \( L_5 \) ligands.

Carboxylation with an allylic alcohol without pre-activation is a highly attractive transformation from the perspective of step-economy. Mita, Sato, and Higuchi elegantly demonstrated the Pd-catalyzed carboxylation of allylic alcohols \( 28 \) and \( 29 \) with CO\(_2\) using ZnEt\(_2\) as the reducing agent (Scheme 23).\(^\text{28} \) The allylic alcohol is likely activated by the Lewis acid ZnEt\(_2\) or by carbonate formation with CO\(_2\).\(^\text{29} \) This carboxylation is highly regioselective and gives predominantly branched carboxylic acid. The proposed mechanism is shown in Scheme 23.

In 2017, the Martin group elegantly demonstrated the switchable site-selective Ni catalyzed carboxylation of allylic alcohols with CO\(_2\). The regiodivergency can be modulated by the type of ligand employed (Scheme 24).\(^\text{29} \)

Also in 2017, Mei and co-workers developed an efficient Ni-catalyzed reductive carboxylation of allylic alcohols with CO\(_2\), providing linear \( \beta,\gamma \)-unsaturated carboxylic acids \( 24 \) as the sole regioisomer with generally high \( E/Z \) stereoselectivity (Scheme 25).\(^\text{30} \) In addition, the carboxylic acids were generated from propargylic alcohols via hydrogenation to give allylic alcohol intermediates, followed by carboxylation. A preliminary mechanistic investigation suggests that the hydrogenation step is made possible by a Ni–hydride intermediate produced by a hydrogen atom transfer from water.

### 6 Carboxylation of Propargyl Halides and Pseudohalides

In 2014, Tsuji, Fujihara and co-workers reported the Co-catalyzed carboxylation of propargyl acetates \( 32 \) with CO\(_2\) at room temperature using Mn powder as a reducing agent (Scheme 26).\(^\text{31} \) The proposed mechanism suggests a Co(II) C as a possible intermediate that reacts with CO\(_2\) in the catalytic cycle (Scheme 27).\(^\text{31} \)
Scheme 23  Pd-catalyzed regioselective carboxylation of allylic alcohol with CO₂

Scheme 24  Ni-catalyzed regiodivergent carboxylation of allylic alcohol with CO₂

Scheme 25  Ni-catalyzed carboxylation of allylic and propargyl alcohols with CO₂
7 Carboxylation of Alkyl Halides and Pseudohalides

In 2014, the Martin group developed the catalytic carboxylation of unactivated primary alkyl bromides 36 with CO2 with various functional groups (Scheme 28).32 Notably, alkyl sulfonates and trifluoroacetates 38 are also reactive (Scheme 29).32 The reaction is proposed to proceed by a free-radical pathway.

In 2016, the Martin group developed the catalytic carboxylation of unactivated primary, secondary, and tertiary alkyl chlorides 39 with CO2 (Scheme 30).33 The Martin group also described the Ni-catalyzed reductive cyclization/carboxylation of unactivated alkyl halides 40 and 42 with CO2 under mild conditions. This is an efficient way to synthesize elusive tetrastubstituted olefins 41 (R1 ≠ H) (Scheme 31).33,34
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Scheme 30 Ni-catalyzed carboxylation of alkyl chlorides with CO₂

In 2016, the Martin group employed the nickel-catalyzed reductive carboxylation protocol for the synthesis of cyclopropanecarboxylic acids 44 with carbon dioxide as a C1 synthon (Scheme 32). In 2017, the Martin group elegantly developed the nickel-catalyzed chain-walking carboxylation of alkyl halides at remote sp³ C–H sites, which was realized via iterative β-hydride elimination/migratory insertion sequences (Scheme 33). The use of ligand L₁₁ was crucial in achieving the site-selectivity. This discovery provides an efficient method to convert cheap starting materials into valuable fatty acids.

Scheme 31 Ni-catalyzed reductive cyclization/carboxylation of unactivated alkyl halides with CO₂

8 Direct Carboxylation of C–H Bonds

Direct carboxylation of C–H bonds is one of the most straightforward ways to afford carboxylic compounds. The Nolan and Hou groups both independently succeeded in the C–H carboxylation of aromatic compounds using N-heterocyclic carbene (NHC) transition-metal complexes as catalysts. The reaction relies heavily on the acidity of the C–H bonds and uses a gold complex (Scheme 34) or a copper complex (Scheme 35).
In 2011, the Iwasawa group reported a catalytic nucleophilic carboxylation reaction using carbon dioxide as the carbon source through C–H bond activation (Scheme 36).39 The proposed catalytic cycle is shown in Scheme 37.39 2-Phenylpyridine undergoes C–H bond activation to form intermediate \( F \), which releases methane to afford the key intermediate \( G \) that reacts with CO\(_2\) via nucleophilic addition.

In 2017, Hou and co-workers developed a copper-catalyzed allylic C–H bond carboxylation of allyl aryl ethers with CO\(_2\), which was achieved through deprotonative aluminolysis with an aluminum ate compound \([\text{-Bu}_3\text{Al(TMP)Li}]\) followed by NHC–copper-catalyzed carboxylation of the resulting aryloxy allylaluminum species (Scheme 38).40

Also in 2017, Sato and co-workers developed a catalytic direct allylic C(sp\(^3\))–H carboxylation by using the Co(acac)\(_2\)/Xantphos/AlMe\(_3\) system, which enabled highly regioselective transformation of allyl groups into linear but-3-enoic acid motifs with good functional group tolerance (Scheme 39).41 The proposed mechanism suggests a Co I intermediate \( N \) might be crucial in the catalytic cycle and AlMe\(_3\) plays a dual role in the reaction (Scheme 40).41
Besides these carboxylations of C–H bonds under transition-metal catalysis, some carboxylations of C–H bonds under transition-metal-free42 or light-promoted43 conditions were reported, which will not be discussed in detail here.

9 Conclusions and Perspectives

In the past few years, transition-metal-catalyzed carboxylation of electrophiles with carbon dioxide has become a promising new catalytic transformation. However, the development of this field is still in early stages. In particular, site-selective C–H carboxylation is still a challenge. Furthermore, enantioselective carboxylation is another clear front-tier in this area. Finally, the development of large-scale catalytic carboxylation reactions with low catalyst loadings is needed.

Funding Information

This work was financially supported by the Strategic Priority Research Program of the Chinese Academy of Sciences (Grant XDB20000000), ‘1000-Youth Talents Plan’, NSF of China (Grant 21421091, 21572245), and S&TCSM of Shanghai (Grant 15PJ1410200, 17JC1401200). We thank Wuyi University for supporting Yi-Qian Li and Li-Pu Zhang.