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Chapter
Imidazolium-Based N-Heterocyclic Carbenes (NHCs) and Metal-Mediated Catalysis

Vittal B. Gudimetla, Bony P. Joy and Sudeep Paul

Abstract

The journey of “carbenes” is more than a century old. It began with a curiosity to understand a then less familiar carbon moiety in its divalent state. It reached an important milestone in the form of 1,3-imidazolium-based N-heterocyclic carbenes (NHCs), where the quest for bottleable carbenes was achieved through simple and elegant synthetic routes. The properties of these carbenes were finely tunable through the steric and electronic factors via chemical modifications. Thus, it became one of the unique and extensively studied ligands for its properties and applications. This chapter first briefs about structural details of NHCs and different synthetic routes for the preparation of imidazolium-based NHC precursors. The later section focuses on various methods for characterizing the steric and electronic properties of these ligands and their metal intermediates, which are crucial for developing efficient catalytic processes. Finally, the chapter concludes with NHC-metal-mediated catalytic applications and its immediate challenges.

Keywords: N-heterocyclic carbenes, imidazolium salts, NHC-metal-mediated catalysis, steric and electronic properties, characterization of carbenes

1. Introduction

Carbon in its low coordinate divalent state is known as “carbene.” It is a well-known transient species in many catalytic reactions. Initially, the carbenes were considered to be very reactive and difficult to isolate. However, the carbenes were first stabilized as metal carbene complexes, which have found numerous applications in many important organometallic reactions. The challenge of isolating a stable metal-free carbene was ended in 1991, through the pioneering works of Arduengo et al. It was for the first time a stable metal-free N-heterocyclic carbene (NHC) was synthesized and isolated in the form of 1,3-di(adamantyl)imidazol-2-ylidene (1Ad) by deprotonation of its 1,3-imidazolium salt precursor [1]. Thus, it enabled the easy synthesis of NHCs using simple synthetic routes and thereby extended its scope in synthetic organic chemistry. One such celebrated success is the role of NHCs as ligands in olefin metathesis [2].

1,3-Imidazolium salts are simple and stable precursors of NHCs. They are a good source for in situ production of NHCs either by heating or upon reaction with a base. Chemically, these NHCs are nitrogen-containing heterocyclic compounds with a
divalent carbene center [3]. Due to the available lone pair of electrons on the carbon, the carbene in these NHCs were often compared with phosphine ligands and validated for its effectiveness. The stability of this electron-rich carbene and its unique electronic properties are primarily due to the presence of two adjacent nitrogen atoms, which will have a push-pull electronic influence at the carbene center (Figure 1). The effect is synergistic in nature, where the N atom in the NHC withdraws the σ-electrons inductively and donates π-electrons to the imidazolium ring mesomerically. The inductive effect of the N-atom lowers the highest occupied molecular orbital (HOMO) energy level occupied by the p-orbital and thereby increases the energy gap between HOMO and lowest unoccupied molecular orbital (LUMO) levels of NHC. Hence, the second electron gets paired in the HOMO level resulting in the singlet form of carbene. Furthermore, the N-atom mesomerically donates a pair of non-bonding electrons from its p-orbital and overlaps with the empty p-orbitals of the C-atom, which reinforces the stability of the singlet carbene. Moreover, the cyclic bent structure of NHCs forces the carbene to a singlet state, whereas in acyclic carbenes, it exists in the triplet state [3–8]. Singlet NHCs are capable of forming stable and stronger bonds with metals due to their good σ-donor and π-acceptor properties [9, 10], especially with electron-deficient metal atoms they act as good π-donors [11]. These unique electronic properties will equip NHCs to have similar or sometimes better reactivity than phosphines; hence, they are considered to be one of the important ligands in catalysis.

In addition to the unique electronic features, the structural diversity of the NHCs was another important aspect that attracted the attention of chemists. The scope for variation of the ring size from 4 to 7-membered ring structures and the possibilities for substituent variations either at the N-atom or on the C-atom of the ring have tremendously increased the structural diversity of NHCs. Dimer, trimer, and poly NHCs are also known in the literature. Thus, the relatively easy access to structurally diverse NHCs and its flexible metal coordination has resulted in a large number of NHC-metal complexes. Based on the metal coordination to the NHC unit, they have been classified as normal, abnormal, and remote NHCs (Figure 2). If it binds to the metal through the C2 atom, then it is known as normal NHC;

Figure 1.
Schematic representation of σ-withdrawing and π-donating electronic effects through the adjacent nitrogen atoms with the carbene carbon via inductive and mesomeric effects, respectively.

Figure 2.
Representative structures of (a) normal NHC; (b) abnormal NHC; and (c) remote NHC.
similarly if it is through the C4 atom, it is known as abnormal NHC. If there is an absence of a heteroatom in the α-position of the carbenic coordination center, it is known as remote NHC. Compared with normal NHCs, the abnormal NHCs have stronger donor ability and hence have direct impact on its catalytic efficacy [12].

The typical synthesis of NHCs were often accomplished by deprotonation of azolium salts, such as imidazolium, thiazolium, and triazolium. The focus of this chapter is primarily on the imidazolium-based NHCs. In the synthesis of imidazolium-based NHCs, there are three key components, which form the NHC framework. They are (1) carbon backbone, (2) pre-carbenic unit, and (3) amino unit [13]. Different synthetic strategies were evolved based on the construction of these three key components (Figure 3). Apart from the conventional synthetic methods, other methods such as electrochemical, microwave, and solvent free synthetic methods were also known [15–17]. Recently, the incorporation of one or more NHC units into a single carbon backbone was also reported, and these multidentate ligands were used to make poly NHC-metal complexes. These poly NHCs are capable of exhibiting different steric and electronic properties than the normal NHCs. Moreover, due to the inherent structural chirality, they are often studied for applications in asymmetric catalysis [18–23].

Considering the scope and potential applications of imidazolium-based NHCs via structural refinement, it is essential to understand the factors that will control its properties and catalytic efficiency. Therefore, the following sections elaborates the methods to assess the steric and electronic properties of the NHCs.

2. Methods for assessing electronic and steric parameters of NHCs

2.1 IR spectroscopy: Tolman electronic parameters (TEP)

The most extensively used method for the determination of electronic properties of NHCs is based on the Tolman electronic parameters devised by Tolman in 1977, specifically for phosphines [24]. This technique uses tetrahedral Ni(CO)3L as model complex [25], where L is the ligand whose donor-acceptor abilities are under investigation. Carbonyl being a good \( \pi \)-acceptor has strong metal-to-carbonyl (d\( \pi \)-p\( \pi \)) back bonding. The introduction of ligands (L) with strong electron-donor properties will enhance the electron density around the metal (Ni) center in the Ni(CO)3L complex.
Thus, by comparing the stretching frequencies of the carbonyl (CO) unit, various ligands (L) of interest were analyzed by their $\sigma$-donor properties. Ligands (L) with good $\sigma$-donor ability increase the metal-to-carbonyl back bonding. It results in stronger metal-ligand (Ni-L) bonding. Thus, it indirectly reduces the bond order of the carbonyl unit, and it will be reflected in the carbonyl IR stretching frequency (Figure 4). Nolan et al. were the first to systematically determine the TEP of NHCs using [Ni(CO)$_3$(NHC)] as model complex. The critical limitation of this method is the preparation of a variety of nickel complexes using different NHC ligands. This synthesis requires the handling of NHCs with low boiling and toxic Ni(CO)$_4$. Moreover, the TEP values are within a small window of 10 cm$^{-1}$ and hence require high-resolution IR spectrophotometers. Any anomalies inherent to the IR measurement technique make this method more challenging. TEP depends on the steric factors since the steric can influence the complexes geometry, thereby the overlapping orbitals affect the TEP value. To overcome few of these shortcomings with respect to synthesis of analytical probes, Crabtree et al. [26] in 2003 reported the use of [(NHC)M(CO)$_2$Cl], (M = Ir or Rh) complexes as the probe for determining the TEP. In 2008, Nolan et al. reported an extensive study on the Ir complexes for TEP determination of NHCs [27]. Compared with the earlier model complexes, an average of two carbonyl stretching vibration are taken into account due to cis arrangement of the carbonyl ligands in the [(NHC)M(CO)$_2$Cl], (M = Ir or Rh) complex. Thus, the IR spectroscopy was found to be an useful tool to assess the Tolman electronic parameters (TEP). TEP of selected NHCs are given in Table 1.

2.2 NMR spectroscopy: $\sigma$-donor and $\pi$-acceptor abilities of NHCs

NMR spectroscopy, especially $^{13}$C and $^1$H NMR, are the most efficient and reliable techniques to understand the properties of NHCs, the NHC precursors, and

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>NHC</th>
<th>TEP (cm$^{-1}$)</th>
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<tbody>
<tr>
<td>1.</td>
<td>IAd</td>
<td>2049.5</td>
</tr>
<tr>
<td>2.</td>
<td>IPr</td>
<td>2051.5</td>
</tr>
<tr>
<td>3.</td>
<td>SIPr</td>
<td>2052.2</td>
</tr>
<tr>
<td>4.</td>
<td>IMes</td>
<td>2050.7</td>
</tr>
<tr>
<td>5.</td>
<td>ItBu</td>
<td>2050.1</td>
</tr>
<tr>
<td>6.</td>
<td>ICy</td>
<td>2049.6</td>
</tr>
</tbody>
</table>

Table 1. TEP values for selected NHCs.
related NH$_2$-metal complexes. In general, imidazolium proton (-N-C(H)-N-) in
NH$_2$C$_3$ is acidic due to its connection to the two adjacent electron-withdrawing
nitrogen atoms. Hence, this proton appears in the deshielded region of proton
NMR, around 8–12 ppm. However, upon deprotonation, the imidazolium proton
signal disappears in the proton NMR. The $^{13}$C( $^1$H) NMR spectra of NH$_2$Cs exhibit
the carbene (-N-C-N-) carbon peak close to the highly deshielded region of
around 200–250 ppm for free carbene, whereas it is approximately 130–160 ppm
for its respective precursor imidazolium salt. Due to the increased shielding effect,
the highly shielded carbene carbon upon metal complexation, will undergo an
upfield shift. Apart from a diagnostic tool, the NMR technique is helpful to
explore various properties of NH$_2$Cs such as (a) the steric properties; (b) σ-donor
ability from ligand to the metal center; and (c) π-back bonding from metal to
carbene. Understanding these parameters of NH$_2$Cs is crucial for controlling
the catalyst selectivity, reactivity, and efficiency. Earlier, the Tolman electronic
parameters (TEP) obtained from the CO stretching frequencies of metal com-
plexes such as [Ni(CO)$_3$L] and [MCl(CO)$_2$L] (M = Rh or Ir) were used to assess
the electronic properties. However, this method has limitations due to inherent
inaccuracies in IR spectroscopy measurements of metal complexes. Also, the
necessity of preparing these complexes under highly inert conditions, the
requirement of expensive metals, and the usage of highly toxic CO gas are the
important drawbacks of the TEP method. Moreover, the TEP only gives informa-
tion about the overall electron density around the metal center but not indepen-
dent σ-donor or π-back bonding abilities.

Huynh et al. reported the unique use of NMR for studying the donor properties
of NH$_2$Cs [28]. This method utilizes the $^{13}$C-NMR technique, where the
trans-[PdBr$_2$( $^{\text{Pr}_2}$-bimy)L], $^{\text{Pr}_2}$-bimy = 1, 3-diisopropylbenzimidazolin-2-yldene; L = NHC ligand under investigation) complex was the spectroscopic
probe. In this complex, the presence of ligands (L) with the good σ-donor ability
induces a downfield shift of the carbene carbon peak of the NHC (i.e., $^{\text{Pr}_2}$-bimy).
Thus, it enabled easy comparison of NH$_2$Cs with other significant ligands, such as
phosphines, amines, and isocyanides. Moreover, this method utilizes easily
preparable spectroscopic probes. Based on such carbene carbon chemical shift
values, the NH$_2$C ligands are arranged on a unique σ-donor scale as shown in
Figure 5.

Betrand et al. in 2013 reported the determination of π-acceptor ability of NH$_2$C
ligands using the $^{31}$P chemical shift value of carbene-phosphine adducts, which
exist in two different resonance forms “I” and “II” (Figure 6) [29]. The
phosphaalkene form (I) has a P=C bond, and the form (II) has P-C dative bond
with P having two lone pairs of electrons. The upfield phosphorus NMR chemical
shift associated with P atom in the carbene-phosphine adducts agrees with the
electron-rich resonance form (II). It suggests that the carbene carbon prefers
da dative bond with phosphorus rather than a π bond. If the carbones have
π-accepting property, it should have reflected through a downfield shift in the
$^{31}$P NMR.

Therefore, the NMR-based method provides an independent way to
determine the π-accepting ability of NH$_2$C ligand, independent of its σ-donor
abilities, which was one of the limitations of Tolman’s method for determining
the electronic properties of NH$_2$Cs. The arrangement of a few known NH$_2$Cs according to
their π-accepting ability, based on the $^{31}$P NMR chemical shift values, are provided
in Figure 6.

Ganter et al. reported a similar technique in which the $^{77}$Se chemical shift of
carbene-selenium adducts were used to assess the π-acceptor properties of the NH$_2$C
ligands [30]. The carbene-selenium adduct exists in two different resonance forms
Carbene (III) and (IV) (Figure 7), similar to that of carbene-phosphine adduct. The increase in the \( \pi \)-accepting property of the NHC is reflected through an increase in the chemical shift value of \( ^{77}\text{Se} \) NMR. The arrangement of common NHCs according to their \( \pi \)-accepting ability was established based on the \( ^{77}\text{Se} \) NMR chemical shifts (Figure 7). In addition to the \( \pi \)-acceptor ability, the \( \sigma \)-donor abilities of NHCs can also be found using carbon-selenium coupling constant values [31].
Szostak et al. [32] in 2019 reported a simple and straightforward method for the determination of the $\sigma$-donor properties of NHCs based on the $C$-carbene-$H$ coupling constant ($J_{C-H}$). The significance of this method in comparison to the earlier reported NMR techniques and TEP determination method is that there is no need for the synthesis of any metal complexes or adducts for the analysis. The $^{1}H$ NMR is used for the characterization. The magnetic moment of a $^{13}C$ nuclei couples to a bonded proton through the intervening bonding electrons, and it is represented by the carbon-proton coupling constant ($J_{C-H}$). This value relies on the probability of finding bonding electrons at the two nuclei involved, that is, C and H. The likelihood of finding an electron at the nucleus of a pure $p$-orbital of carbon is zero, while it has a finite value in the case of an $s$-orbital. Based on this principle, an empirical relationship (i.e., $J_{C-H} = 500 \times s$) between the $C-H$ coupling constant and the $s$-character of carbon atom ($s$-value = 0.25 (for $sp^{3}$-C), 0.33 (for $sp^{2}$-C), and 0.50 (for $sp$-C)) was derived, for a 500 MHz $^1H$ NMR instrument. Therefore, carbon with increased "s" character is expected to have a large ($J_{C-H}$) coupling constant.

Thus, a large carbene carbon and proton coupling constant ($J_{C(carbene)-H}$) value corresponds to a weaker $\sigma$-donor property of the NHC ligand. The coupling constants ($J_{C(carbene)-H}$) were obtained from the $^{13}C$ satellite peaks of $^1H$ NMR and the $^1H$ coupled $^{13}C$ NMR spectra. Based on the $J_{C-H}$, coupling constant values, NHCs have been arranged according to their $\sigma$-donor properties (Figure 8).

### 2.3 NMR and UV-Vis spectroscopy: pKₐ of NHC precursors

Basicity and catalytic reactivity of NHC precursors (azolium salts) are intertwined. Therefore, the $pK_a$ studies of NHCs are crucial for understanding the properties of the carbenes. Imidazolium salts upon deprotonation form NHCs (Figure 9). The $pK_a$ values reflect the ease of imidazolium salts to form NHC precursors. It also provides information about the nucleophilicity of NHCs. Often
the NHCs are formed in situ and in many NHC-catalyzed reactions, nucleophilic addition is the first and most crucial step. Hence, the details related to nucleophilicity of NHCs have gained considerable interest [33]. Moreover, it will be helpful to draw the correlation between the substituents, nature of the azolium ring, and its catalytic activity. This section highlights the use of NMR and UV-Visible spectroscopy tools for studying the $pK_a$ values of NHC precursors, that is, imidazolium salts.

Alder et al. reported the $pK_a$ value of 1,3-diisopropyl-4,5-dimethylimidazolium cation to be 24.0 in DMSO-d$_6$ using $^1$H-NMR spectroscopy [34]. This study uses the NMR technique to assess the deprotonation ability of NHCs from acidic hydrocarbons of known $pK_a$ values (e.g., indene, 9-phenylxanthene, triphenylmethane, etc.) (Figure 10). If the NHC deprotonates the hydrocarbon (V), it gives a different proton signal for its corresponding anion (VI). Therefore, based on the proton integration and the equilibrium ratio of (V) and (VI), the $pK_a$ of NHCs can be determined.

Figure 8. Arrangement of NHCs according to their $\sigma$-donor ability based on the $J_{C(carbene)-H}$ coupling constant values [32].

Figure 9. Deprotonation of imidazolium salts to form N-heterocyclic carbenes.

Figure 10. Deprotonation of hydrocarbon by NHC to form hydrocarbon anion [34].
Streitwieser et al. reported that the anomalies in the determination of $pK_a$ of imidazolium salts, is due to the interaction of acidic solvent (DMSO) with carbene. It can be eliminated through the use of inert solvents such as THF by using bracketing/overlapping indicator method [35]. In this process, the deprotonated form of the fluorene-based indicator (of known $pK_a$ value) shows a significant change in the UV-Vis absorption value upon adding the NHC precursor salt. It helps to monitor the equilibrium and thereby the $pK_a$ can be determined. Chu et al. extended this method for various alkyl imidazolium salts [36]. Harper et al., applied this method to determine the $pK_a$ values of different types of electronically, sterically diverse alkyl and aromatic imidazolium salts (Figure 11) [33]. Later the $pK_a$ values of a few imidazolium salts in aqueous medium were also reported by Amyes et al. [37] using deuterium exchange studies. Similar exchange studies by O’Donoghue et al. [38] on triazolium salts facilitated a detailed understanding of the correlation between the NHC precursor salt’s cationic structures and its acidity.

Figure 11.
Arrangement of imidazolium salts based on their $pK_a$ values in DMSO as determined by Harper et al. using bracketing indicator method [33].

2.4 Electrochemical technique: redox potentials and basicity of NHCs

The architecture of NHC allows facile structural modifications, and hence, it provides an opportunity to fine-tune the properties. The reactivity of NHCs is controllable through the structural variations on its cyclic carbon backbone or the introduction of different heteroatoms such as S or O in the heterocyclic ring. The nature of counter anions in the precursor (i.e., imidazolium salts) will also affect the reactivity. Several external factors also contribute to the overall property of NHCs, such as the solvent effects, type of reagents in the reaction mixture, and temperature, etc. Therefore, considering all these factors, the electrochemical techniques will also be helpful for the easy identification of ideal conditions for optimizing the reactivity and efficient catalysis of NHCs. During the electrochemical reduction of imidazolium salt, the imidazolium proton (i.e., C2-H group of the cationic part) NHCH$^+$ is reduced to NHC. In this case, the reactivity mainly depends on the NHC generated from the conjugated acid, that is, NHCH$^+$. The electrochemical studies of NHCs were first reported by Enders and Simonet et al. using triaryl-triazol-ylidene [39]. The cyclic voltammetry (CV) of imidazolium salts exhibited a reversible reduction, which can be due to single-electron reduction of NHCH$^+$ to NHC (i.e., imidazolium salt to NHC) (Figure 12). Recently, Boydston et al. have also reported a systematic study on the redox behavior of a series of azolium salts, including benzothiazolium, thiazolinium, thiazolium, triazolium, imidazolium, and imidazolinium salts [40]. The study demonstrated that N-aryl moiety would be helpful to tune the reduction potential of the
imidazolium ring [41]. The carbene generation usually depends upon the acidity of the NHCH⁺; hence, with an increase in the reduction potential, the acidity of the NHCH⁺ also increases [42]. Therefore, based on the electrochemical method, it is possible to choose appropriate NHC precursors [43]. A number of electrochemical studies related to the NHC metal complexes were also reported [44–48], the data of few selective NHC precursors (i.e., azolium salts) and its corresponding reduction potential are summarized from the literature (Table 2).

![Schematic CV representation of oxidation and reduction peaks of a model NHC](image)

**Figure 12.** Schematic CV representation of oxidation and reduction peaks of a model NHC [39–41].

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Compounds</th>
<th>Reduction potential (E_{1/2}, in V) vs SCE</th>
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<tbody>
<tr>
<td>1.</td>
<td>R—N⁺⁻N⁺⁻R</td>
<td>R= Mes, -2.4 V</td>
</tr>
<tr>
<td></td>
<td>Imidazolinium salt</td>
<td></td>
</tr>
<tr>
<td>2.</td>
<td>R—N⁺⁻N⁺⁻R</td>
<td>R = 2,6-Dipp, -2.23 V</td>
</tr>
<tr>
<td></td>
<td>Imidazolinium salt</td>
<td>R = Mes, -2.87</td>
</tr>
<tr>
<td>3.</td>
<td>R—N⁺⁻N⁺⁻R</td>
<td>R = Me, -2.08 V</td>
</tr>
<tr>
<td></td>
<td>Benzimidazolium salt</td>
<td></td>
</tr>
</tbody>
</table>

**Table 2.** Reduction potentials for azolium salts, in V vs. SCE [40–43].
The overall electrochemical reduction potential will reflect the acidic nature of the cationic part of the NHC and its nucleophilicity (availability of lone pair). Therefore, the reduction potential data of the azolium salts will be helpful to gain insight into the nucleophilicity of different NHCs and identify the structural moieties that were crucial for a specific function or property. The catalytic efficiency of the NHC ligand primarily depends upon the nucleophilicity of carbene.

3. Steric properties of NHCs

Apart from the electronic properties, it is significant to understand the steric parameters of NHCs, since it plays a crucial role in the reductive elimination step of a catalytic cycle. In case of chiral NHCs, the steric parameters control the enantioselectivity of a catalytic reaction (Figure 13).

The earlier attempts to define the steric properties of NHCs were based on the Tolman cone angle [49], which is the solid angle made by an imaginary cone with metal atom at its apex, and ligands are at the outer edges (Figure 14a). The cone angle...
can be computationally calculated [51] or obtained from the single-crystal XRD data [52]. In the case of tertiary phosphine ligands, the cone angle was a well-defined concept; however, not in the case of NHCs, where it lacks a predominant three-dimensional symmetry. Thus, the determination of steric parameters, through the Tolman cone angle technique, was inappropriate for NHCs [49]. In order to overcome this, the concept of percentage of buried volume ($\%V_{\text{bur}}$) was introduced by Nolan et al. [53], which is the percentage of total volume occupied by the ligand in an imaginary sphere of a well-defined radius and the metal atom residing at the center of the imaginary sphere (Figure 14b). This parameter can be determined either from the single-crystal XRD data or can be calculated computationally (Figure 14c). The nature of backbone, N-substituents, and the ring size are the various factors that influence the percentage of buried volume ($\%V_{\text{bur}}$).

Several advancements in the steric parameter determination of NHCs came up with the introduction of Salerno molecular buried volume calculation (SambVca) by Cavallo et al. [54]. The online tool developed for this method utilizes the CIF file of NHC or metal-coordinated NHC as the input file to generate a two-dimensional color-coded contour map around the carbene, from which the catalytically active pockets of the complex or the sterics around the catalytic active sites can be visualized. A detailed steric map study of various types of NHC complexes was well explored by Nolan et al. [50].

4. Catalytic applications of NHC-metal complexes

In 1962, Wanzlick et al. made the early reports on the stability and reactivity of NHCs [55]. Later in 1968, the first NHC-mercury complex was isolated [56]. Despite this isolation, the studies related to the NHCs as ligands thrived only after the first isolation report by Arduengo et al. in 1991 [1]. This easy synthetic strategy facilitated the extensive studies of NHC-metal complexes and their catalytic applications. The catalytic applications of NHCs as ligands can be broadly classified into three types, and they are (a) NHCs for organocatalysis [57–59], (b) NHCs as ligands for transition metal catalysis, and (c) NHCs and main group elements-based adducts for catalysis [60]. The following section of this chapter focuses on few selective and important NHC-transition metal catalyzed reactions (Figure 15), since the complete details are beyond the scope of this chapter.
4.1 NHC-transition metal catalyzed cross-coupling reactions

The coupling reactions catalyzed by transition metal-NHC complexes involve both C-C bond formation reactions such as Mizoroki-Heck [61, 62], Sonogashira [63–65], Negishi [66–68], Hiyama [69–71], Suzuki-Miyaura [72–74], Kumada coupling [75, 76], C-X (X = B, N, O) bond formation reactions such as Buchwald-Hartwig amination [77–79] and Ullmann coupling [80–82] etc. Recently, the coupling reactions catalyzed by the NHC-transition metal complexes have found to be efficient with commercially viable metal salts such as iron, cobalt, and nickel. For example, the cross-coupling of methyl sulfonates and amines to afford sulfonamides uses Ni/NHC system to form the S-N bond [83]. Few well-known NHC-metal catalyzed reactions are shown in (Figure 16).

Recently, the Pd-NHC catalyzed metathesis of carbon-sulfur bonds seems to be one of the significant reactions, which is capable of altering the trends in the retrosynthetic approach for the preparation of organosulfur compounds [60] (Figure 17).

4.2 NHC-transition-metal-mediated metathesis reactions

One of the best examples to demonstrate the significance of organometallic complexes is their role as catalysts in olefin metathesis, which is having numerous synthetic applications and commercial significance. There are different types of

![Figure 16. Few well-known NHC-transition metal-based catalytic applications [13, 61–74].](image1)

![Figure 17. Carbon-sulfur bond metathesis using Pd-NHC complex [60].](image2)
olefin metathesis, namely ring-opening metathesis polymerization (ROMP), ring-closure metathesis (RCM), olefin cross metathesis, and enyne cross-metathesis. The ruthenium complex with a nonlabile NHC group and a labile phosphine group known to exhibit higher ring-closure metathesis (RCM) activity with better thermal stability and has tolerance toward many functional groups [14]. In general, the metathesis catalyst prefers the formation of thermodynamically favored E-isomer. However, subsequent modification on the NHC group yielded Z-isomer in significant yields. Chelating NHC-Ru complexes gave up to 95% Z selectivity. The unique steric and electronic parameters of chelating-Ru-based NHCs promote the olefin to attack cis to NHC and trans to the chelating group. This side-bound reaction mechanism results in Z-isomer as predominant product. One example of such Z-selective olefin metathesis using NHC chelated Ru-catalyst is shown (Figure 18) [84].

4.3 NHC-transition-metal-mediated addition reactions

Hydrogenation [85], transfer hydrogenation [86], hydrosilylation [87], hydroboration, and hydroamination [88] are the different types of NHC-transition metal catalyzed addition reactions. A brief outline of the various addition reactions catalyzed by NHC-transition metal complexes is summarized in Figure 19.

4.4 NHC-transition-metal-mediated catalysis—Flow chemistry

Continuous flow chemistry is a revolutionary technology that has developed rapidly during the past few years. The small size of channel reactors enables
increased mass transfer, efficient heat transfer, and enhanced reaction efficiency. Moreover, this method enables the handling of dangerously toxic reagents remotely and thus reduces the potential health risks [89–92]. Cole-Hamilton et al. [93] reported the first continuous flow-based olefin metathesis catalytic system with a homogeneous catalyst. In this method, the Ru-NHC catalyst was immobilized into silica pores, and CO₂ was passed as the carrier gas (Figure 20). It gave the metathesis products with an overall turnover number > 10,000.

Jenson et al. [94] reported a continuous nanofiltration method in which the metathesis catalyst (Ru-NHC) was allowed to react homogeneously; upon the reaction completion, the catalyst is trapped into a nano-filter setup, and it is flushed back to continue the reaction cycle. Unlike other conventional methods, there are no modifications done to the catalyst to recover and reuse it. Fabrication of NHC-metal complexes onto solid supports such as silica is another strategy used in NHC-centered flow chemistry [95–98]. Functionalized catalyst is packed into a reactor, and the reagents are forced to pass through it to yield final products (Figure 21).

5. Conclusions

The imidazolium-based N-heterocyclic carbenes (NHCs) have found to be excellent candidates for improvising their properties through chemical modifications. Basic understanding and assessment of the steric and electronic factors of NHCs are crucial to explore its catalytic applications. Therefore, this chapter attempts to provide a basic glimpse of imidazolium-based NHCs through the discussions on some important synthetic routes, different methods for characterizing the electronic and steric properties of NHCs, and finally, few selective catalytic
applications. Even though the literature pertaining to the imidazolium-based NHCs and its applications is vast and rapidly increasing, the discussions were limited to few important topics. Despite the extensive studies on imidazolium-based N-heterocyclic carbenes, there is plenty of scope for improvement, particularly enhancing the catalytic efficiency of NHCs with inexpensive metals, reducing the catalyst load, exploring new catalytic reactions with variety of substrates, and most significantly, making the NHC-based catalysts ready for more green and sustainable reactions.

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Appendices and nomenclature

Abbreviations

<table>
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<tr>
<th>Abbreviation</th>
<th>Definition</th>
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<tbody>
<tr>
<td>NHC</td>
<td>N-heterocyclic carbene</td>
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<tr>
<td>HOMO</td>
<td>highest occupied molecular orbital</td>
</tr>
<tr>
<td>LUMO</td>
<td>lowest unoccupied molecular orbital</td>
</tr>
<tr>
<td>TEP</td>
<td>Tolman electronic parameters</td>
</tr>
<tr>
<td>IAd</td>
<td>1,3-di(adamantyl)imidazol-2-ylidene</td>
</tr>
<tr>
<td>IMes</td>
<td>1,3-di(mesityl)imidazol-2-ylidene</td>
</tr>
<tr>
<td>IPr</td>
<td>1,3-di(2,6-diisopropyl)imidazol-2-ylidene</td>
</tr>
<tr>
<td>NMR</td>
<td>nuclear magnetic resonance</td>
</tr>
<tr>
<td>CV</td>
<td>cyclic voltammetry</td>
</tr>
<tr>
<td>SambVca</td>
<td>Salerno molecular buried volume calculation</td>
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