Recent Developments in the Synthesis of Pyrido[1,2-a]benzimidazoles

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Abstract Pyrido[1,2-a]benzimidazole is one of the most important azaheterocyclic compounds consisting of three fused aromatic rings. Molecules containing this core have displayed a wide range of applications in the field of medicinal chemistry. The synthesis of pyrido[1,2-a]benzimidazole and its derivatives has attracted organic chemists because of its tremendous utility in interdisciplinary branches of chemistry. In this context, this review discusses the main advances in the synthesis of pyrido[1,2-a]benzimidazoles via metal-mediated and metal-free reactions from 2000 to 2016.

1 Introduction

Pyrido[1,2-a]benzimidazole is one of the most important heterocyclic systems because of its occurrence as a synthon in various bioactive molecules and materials. This core exhibits remarkable biological properties such as antimalarial, anticancer, antiproliferative, antitumor, antifungal, antiviral, and antipyreptic activities (Figure 1).\textsuperscript{1} Pyrido[1,2-a]benzimidazole was initially prepared in the late 1930s,\textsuperscript{2} but has received attention only during the past decade, when some of its derivatives were found to have pharmaceutical applications.\textsuperscript{3} Moreover, the difficulties associated with the preparation of this heterocyclic system, often comprising of laborious and low-yielding methods, became the point of concern for organic chemists.\textsuperscript{4} The important biological properties shown by pyrido[1,2-a]benzimidazole and its derivatives have inspired organic chemists to develop simple and convenient synthetic methods. The review presented here on synthetic strategies for pyrido[1,2-a]benzimidazoles is organized according to whether the reaction is metal-catalyzed (type I) or metal-free (type II).

2 Synthetic Approaches to Pyrido[1,2-a]benzimidazoles

2.1 Type I: Transition-Metal-Catalyzed Methods

Transition-metal-catalyzed reactions have been studied since the very beginning of the past century and represent a great success in organic chemistry along with the birth and growth of organometallic chemistry.\textsuperscript{2} Transition-metal-catalyzed coupling reactions, which were initiated in the 1960s as a major topic in organometallic chemistry, have...
Biographical Sketches

Rajni Khajuria received her M.Sc. (2010) from the Department of Chemistry, University of Jammu, India and M.Phil. (2012) at the same university under the guidance of Prof. Kamal K. Kapoor. She then worked on the synthesis of novel aza-heterocyclic compounds as antimicrobial agents in the same laboratory and obtained her Ph.D. in 2016. Presently, she works as an assistant professor on contract basis in the Department of Chemistry and Chemical Sciences, Central University of Jammu. Her main research interests include the development of greener synthetic methods to access biologically active heterocycles and coupling reactions for C–C and C–X bond formation.

Sk. Rasheed received his M.Sc. (2009) in organic chemistry from Osmania University, Hyderabad, India and in 2010 he joined the Indian Institute of Integrative Medicine (CSIR-IIIM), Jammu as a CSIR Junior Research Fellow. In 2011, he registered with the Academy of Scientific and Innovative Research (AcSIR) for a Ph.D. program under the supervision of Dr. Parthasarathi Das on the research topic ‘Transition-Metal Catalyzed C–C and C–N Bond Formation: Synthesis of Carbazoles and Aza-Fused Heterocycles’ and received his degree in 2017. Presently, he is working as a senior research associate at Gland Pharma Ltd., Hyderabad, India.

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Kamal K. Kapoor received his Ph.D. (1996) from IIT, Kanpur, India. He joined the University of Jammu as lecturer in December 1995, where he is professor at present. His research interests include the synthesis of novel heterocyclic compounds having significance in scaffold hopping, biology, and material science. He was awarded DST-BOYSCAST and INSA Royal Society fellowships for visiting Japan and UK, respectively. He has served as lead scientist in Dabur Research Foundation, Sahibabad (UP) and Sphaera Pharma, IMT Manesar (Haryana), as advisory consultant to Curadev Pharma Pvt Ltd, Noida, and also as adjunct professor at the Central University of Jammu.

Parthasarathi Das received his Ph.D. (1999) from NCL Pune, India. After completing postdoctoral studies at RWTH-Aachen, Germany, Tohoku University, Japan, and Harvard University, USA, he returned to India to join Dr. Reddy’s Laboratories Ltd. (2004) and worked in the medicinal chemistry group with a research focus on various therapeutic areas (oncology, metabolic disorder, and antibacterial). In 2012, he shifted to academia and joined the CSIR-Indian Institute of Integrative Medicine Jammu, India. Recently, he moved to the Indian Institute of Technology (ISM) Dhanbad. His research interests include medicinal chemistry, the development of new synthetic tools, and the synthesis of biologically active natural products.
made significant progress in the last half century and become one of the most efficient and direct strategies for carbon–carbon bond formation. The extensive variations and modifications of transition-metal-catalyzed coupling reactions have enabled wide applications in organic synthesis and have been regarded as the most reliable, accurate, and powerful tools in the chemist’s arsenal. Many named reactions have been assigned and are well known nowadays, together with the development of novel chemical reagents. The great success and significance of transition-metal-catalyzed coupling reactions were highlighted by the 2010 Nobel Prize in chemistry.

In 2003, Junjappa et al. reported a dexterous method for the preparation of 1,2- and 2,3-substituted/annelated pyrido[1,2-α]benzimidazoles via regioselective annulation of 2-methylbenzimidazole or 2-(cyanomethyl)benzimidazole dianions with α-oxo ketene dithioacetals involving [3+3] cyclocondensation (Scheme 1). The dianion derived from 2-methylbenzimidazole undergoes 1,2-addition with α-oxo ketene dithioacetals, followed by intramolecular cyclocondensation in the presence of phosphoric acid to provide the corresponding 1-(methylthio)-2,3-substituted pyrido[1,2-α]benzimidazoles. The dianion of 2-(cyanomethyl)benzimidazole is involved in a one-pot 1,4-addition–elimination and cyclocondensation with α-oxo ketene dithioacetals to form 4-cyano-3-(methylthio)-1(or 1,2)-substituted pyrido[1,2-α]benzimidazoles.

The catalytic cycle proposed for the tandem double palladium-catalyzed amination of 2-chloro-3-iodopyridine with 2-aminopyridine (Scheme 3) starts with the oxidative addition of 2-chloro-3-iodopyridine to Pd(0), forming an organopalladium(II) complex 3. Insertion of 2-aminopyridine into intermediate 3 generates another intermediate 4,

In 2004, Maes et al. reported a tandem palladium-catalyzed Buchwald–Hartwig amination reaction for the synthesis of benzo and aza analogues of dipyrido[1,2-α:3’,2’-]imidazole (Scheme 2). The regio- and chemoselective one-pot inter- and intramolecular Buchwald–Hartwig amination of 2-chloro-3-iodopyridine with aminoazines/aminoazoles using Pd(BINAP)/Pd(XANTPHOS) catalysts in combination with an excess of Cs₂CO₃ base in toluene under reflux conditions afforded the corresponding dipyrido[1,2-α:3’,2’-]imidazole derivatives in excellent yields.
which upon deprotonation followed by reductive elimination gives \( N-(2\text{-chloropyridin-3-yl})\text{pyridine-2-amine} \). Then 5 undergoes oxidative addition to Pd(0) forming another organopalladium(II) complex 6. Coordination of the pyridine ring nitrogen with the metal center occurs, forming a palladacycle 7 over the competitive formation of palladium(II)–amine complex 7'. Deprotonation of 7 and subsequent reductive elimination gives the final desired product, along with the regeneration of the palladium catalyst.

Two years later, the same group reported the regioselective orthogonal (Pd- and Cu-catalyzed) or auto-tandem (Pd-catalyzed) inter- and intramolecular Buchwald–Hartwig amination reaction for the expedient synthesis of dipyrindo[1,2-a:2’,3’-d]imidazole and its benzo and aza analogues by using 2,3-dibromopyridine and amino(di)azines as starting materials (Schemes 4 and 5). The orthogonal tandem-catalyzed amination is based on a chemoselective oxidative addition, which involves consecutive Pd-catalyzed intramolecular amination and Cu-catalyzed intramolecular amination steps (Scheme 4).

In addition, an auto-tandem inter- and intramolecular Pd-catalyzed amination by a simple alteration of the reaction temperature was also presented. The auto-tandem Pd-catalyzed amination was performed at 140 °C (Scheme 5) and at refluxing temperature. Double amination of 2,3-dibromo-pyridine at 140 °C occurred smoothly with 2-aminoisoquinoline, 1-aminoquinoline and 3-aminopyridazine to give the corresponding dipyrido[1,2-a]quinolines, 1-aminoquinoline and 3-aminopyridazine to give the corresponding dipyrido[1,2-a:2’,3’-d]imidazo[4,5-b]imidazoles, whereas the same reaction of all amino(di)azines performed under reflux conditions gives only the respective intermediates, i.e. \( N-(3\text{-bromopyridin-2-yl})\text{azaheteroaryl amines} \).

In 2006, H. Ila and co-workers presented an efficient method for the synthesis of diversely substituted benzimidazo[1,2-a]quinolines in high yields (Scheme 6). They described the \( \text{Pd}(\text{PPh}_3)_4\)-catalyzed Buchwald–Hartwig intramolecular N-arylation of readily accessible 2-(2-bromoanilino)quinolines, using \( \text{K}_2\text{CO}_3 \) as a base in DMF at 130–140 °C. The requisite starting materials, i.e. 2-(2-bromoanilino)quinolines, were in turn prepared from 2-\{methylsulfonyl\}quinolines and various 2-bromoanilines under reflux conditions.

A plausible mechanism for the formation of benzimidazo[1,2-a]quinoline from 2-(2-bromoanilino)quinoline using \( \text{Pd}(\text{PPh}_3)_4 \) as a catalyst is presented in Scheme 7. Intermediate 8, formed by the oxidative addition of Pd(0) to 2-(2-bromoanilino)quinoline, undergoes an intramolecular nucleophilic attack at the basic quinoline nitrogen; this is followed by the elimination of HBr to give the six-membered palladacycle intermediate 9. Palladacycle 9, upon subsequent reductive elimination and N–C bond formation steps, yields the corresponding benzimidazo[1,2-a]quinoline.

One year later, the Maes group reported the application of their previously developed regioselective auto-tandem (Pd-catalyzed) and orthogonal-tandem (Pd- and Cu-catalyzed) protocols for the effective aminations of dihaloquinolines with amino(benzo)(di)azines (Schemes 8 and 9). The synthesis of pyrido[2’,1’:2,3]imidazo[4,5-b]quinoline and its benzo and aza analogues was achieved via \( \text{Pd}(\text{OAc})_2\)-rac-BINAP/XANTPHOS-catalyzed amination of 2-chloro-3-iodoquinoline with various amino(benzo)(di)azines (Scheme 8). In the orthogonal-tandem aminations, 2-(2-bromoanilino)quinolines were prepared using K₂CO₃ as a base in DMF at 130–140 °C. The requisite starting materials, i.e. 2-(2-bromoanilino)quinolines, were in turn prepared from 2-\{methylsulfonyl\}quinolines and various 2-bromoanilines under reflux conditions.
tion, the Pd$_2$(dba)$_3$–XANTPHOS and Cul combination gave an easy access to various benzo and aza analogues of pyrido[1′,2′:1,2]imidazo[4,5-b]quinoline using amino(benzo)(di)azines and 2,3-dibromoquinoline as starting materials (Scheme 9).

Subsequently, they reported that by controlling the reaction temperature of the Pd$_2$(dba)$_3$–XANTPHOS-catalyzed auto-tandem reaction, selective C-2 intermolecular amination of 2,3-dibromoquinoline with amino(benzo)(di)azines could be achieved to provide the corresponding N-(3-bromoquinolin-2-yl)aza heteroaryl amines as the sole products in good yields (Scheme 10).  

The Zhu group developed a novel strategy for the synthesis of pyridol[1,2-α]benzimidazoles through the direct intramolecular aromatic C–H amination of N-aryl-2-aminopyridines, in which the pyridine moiety serves as a directing group as well as an intramolecular nucleophile (Scheme 11). The reaction is co-catalyzed by Cu(OAc)$_2$ and Fe(NO$_3$)$_3$·9H$_2$O in DMF under an O$_2$ atmosphere to provide good to excellent yields of diversely substituted pyrido[1,2-α]benzimidazoles. The presence of electron-withdrawing groups at any position of the pyridine ring and in the meta position of aniline ring was found to be unfavorable for the reaction under the optimized reaction conditions. Fe(NO$_3$)$_3$·9H$_2$O itself does not promote the reaction, but increases the yield of the reaction significantly due to its ability to facilitate the formation of more electrophilic Cu(III) species, which readily undergo the SEAr (electrophilic aromatic substitution) process. Pivalic acid is used as an additive for this reaction to improve the yields of the final products.

The following mechanism was proposed by Zhu et al. for the Cu(OAc)$_2$–Fe(NO$_3$)$_3$·9H$_2$O co-catalyzed preparation of pyridol[1,2-α]benzimidazole from N-phenyl-2-aminopyridine (Scheme 12). In the absence of Fe(III) salt, the Cu(II) salt forms intermediate 11 from the initially formed Cu(II) adduct 10 through electrophilic aromatic substitution, followed by reversible protonation. In the presence of oxygen, intermediate 12 is converted into a more reactive Cu(III) intermediate 13 through oxidation; upon subsequent reductive elimination, the requisite product is produced along with the formation of Cu(I). In the presence of Fe(III) salt, the initially formed adduct 10 is oxidized to a more electrophilic Cu(III) intermediate 14. Then 14 undergoes electrophilic aromatic substitution to generate intermediate 13 through the formation of the six-membered transition state 15. Reductive elimination takes place very quickly, before reversible protonation, to yield the desired product. The formed Cu(I) is oxidized into Cu(II) in the presence of O$_2$, thus completing the catalytic cycle.

In 2010, Maes and co-workers reported further studies of the scope of their well-established methodology of auto- and orthogonal-tandem double aminations of dihalopyridines, i.e. 2-chloro-3-iodopyridine and 2,3-dibromopyridine, with unexplored benzodiazinamines, i.e. phthalazin-1-amine, quinoxalin-2-amine and quinazolin-4-amine as coupling partners (Schemes 13 and 14). The requisite benzodiazinamines were prepared by using the literature method of Hara and van der Plas. They observed that their previously developed auto-tandem double amination protocol for the coupling of 2-chloro-3-iodopyridine could not be generally applied for benzodiazinamines, whereas the orthogonal-tandem double amination protocol for the cou-
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The coupling of 2,3-dibromopyridine with benzodiazinamines revealed unexpected Smiles rearrangement at high temperature. To prevent this undesired rearrangement step, the rac,trans-cyclohexane-1,2-diamine ligand was used for the copper catalyst to achieve the intermolecular and intramolecular reactions for ring closure in a sequential manner.

The auto-tandem Pd(OAc)$_2$–XANTPHOS-catalyzed double amination of 2-chloro-3-iodopyridine with benzodiazinamine in refluxing toluene gave the desired pyrido[3′,2′:4,5]imidazo[1,2-α]quinoxaline in 80% yield (Scheme 13). Applying the same reaction conditions to phthalazin-1-amine and quinoxalin-2-amine did not give the desired products. Instead, the reactions stopped at the intermolecular amination step, with no further intramolecular C–N bond formation. However, the synthesis of pyrido[3′,2′:4,5]imidazo[1,2-α]quinoxaline was successfully achieved under the optimized auto-tandem double amination reaction conditions by simply replacing toluene with DME as solvent under reflux conditions (Scheme 13). For the coupling of 2-chloro-3-iodopyridine with quinazolin-4-amine, a one-pot approach was developed consisting of a Pd(OAc)$_2$–XANTPHOS-catalyzed intermolecular amination step, followed by the addition of Cul in combination with the rac,trans-cyclohexane-1,2-diamine ligand in a ratio of 1:2.

Scheme 10  Temperature-dependent Pd$_2$(dba)$_3$–XANTPHOS-catalyzed auto-tandem amination of 2,3-dibromoquinoline with amino(benzo)(di)azines

Scheme 11  Synthesis of diversely substituted pyrido[1,2-a]benzimidazoles via Cu(OAc)$_2$–Fe(NO$_3$)$_3$·9H$_2$O co-catalyzed intramolecular C–H amination of N-aryl-2-aminopyridines

Scheme 12  Mechanism proposed for the Cu(OAc)$_2$-catalyzed intramolecular C–H amination of N-phenyl-2-aminopyridine, with and without Fe(III) salt
upon completion of the first amination, to access the desired pyrido[3′,2′:4,5]imidazo[1,2-α]quinazoline (Scheme 13). The one-pot method was also developed for the coupling of 2,3-dibromopyridine with benzodiazinamines, by replacing Pd(OAc)2 with Pd2(dba)3 as a catalyst for ortho-gonal-tandem double amination (Scheme 14).

The mechanism proceeding via a Cu(II)/Cu(0) catalytic cycle was proposed in accordance with their findings and control experiments (Scheme 16). The first step is the coordination of CuII(OCOR)2 with N-phenylpyridin-2-amine, leading to the formation of intermediate 17, followed by intramolecular nucleophilic attack of its amidine nitrogen on the activated phenyl ring to give the σ-alkyl–Cu(II) intermediate 18. Subsequent β-hydride elimination of 18 gives the corresponding product and RCO2Cu(II)H. Reductive elimination of RCOOH from RCO2Cu(II)H yields Cu(0), which is re-oxidized to CuII(OCOR)2 with RCOOH in the presence of O2, thus completing one catalytic cycle.

Subsequently, Wu et al. developed a simple method for the expeditious synthesis of diversely substituted pyrido[1,2-α]benzimidazoles through a CuI–1,10-Phen-catalyzed inter- and intramolecular C–N coupling cascade process using haloanilines and halopyridines as the coupling partners in xylene at 120 °C (Scheme 17 and Scheme 18). Various substituted haloanilines and halopyridines bearing electron-donating and electron-withdrawing substituents were used, and the products were obtained in good yields.
intermediate 19 into 20 followed by intramolecular Ullmann-type C–N coupling leads to the formation of the desired product, as shown in Scheme 19.

In 2012, Fossey and co-authors reported a Cu(OTf)2-catalyzed intramolecular C–H bond amination reaction of purine and its derivatives, by employing PhI(OAc)2 as an oxidant in a 1:1 mixture of acetic acid and acetic anhydride as a solvent, for the efficient synthesis of purine-fused polycyclic compounds (Scheme 20). This was the first report on the utility of intramolecular C–H activation/amination reaction protocols for the synthesis of purine nucleosides, which offers an easy alternative access to many useful multi-fused ring purine heterocyclic compounds.

The mechanism for the Cu(OTf)2-assisted intramolecular C–H bond activation and amination of 6-anilinopurine based substrates is outlined in Scheme 21. oxidative addition of substrate 21 to Cu(OTf)2 yields intermediate 22, which undergoes an electrophilic substitution process to form Cu(II) intermediate 23. The final step is the reductive elimination of 23 to give the desired product, along with the regeneration of Cu(OTf)2 to complete the Cu(II)/Cu(0) catalytic cycle.
In 2015, Das et al. described a ligand-free Cu(II)-catalyzed, inter/intramolecular C–N bond formation for the synthesis of various benzimidazole-fused heteroaromatic compounds (Scheme 22). The robustness of this method was demonstrated by the synthesis of a series of benzimidazole-fused heterocycles, e.g., pyrido[1,2-\text{a}]benzimidazole, benzimidazo[1,2-\text{a}]quinolines, benzimidazo[1,2-\text{a}]pyrazine, directly from 2-aminoheteroarenes and 2-iodoarylboronic acids in one pot. The novel cascade protocol for C–N bond formation represents a distinctive example of a sole combination of Chan–Lam- and Ullmann-type coupling reactions.

The following plausible catalytic cycle was proposed for the formation of pyrido[1,2-\text{a}]benzimidazole as shown in Scheme 23. In the Chan–Lam type of coupling, the first step is the rapid coordination of the Cu(II) complex with 2-aminopyridine, forming \( \text{Cu(II)}(\text{OAc})_2 \), which subsequently enters into a transmetalation step with 2-iodophenylboronic acid to afford complex \( \text{Cu(II)}(\text{OAc})_2 \). Then Cu(II) complex \( \text{Cu(II)}(\text{OAc})_2 \) undergoes air oxidation to provide the higher oxidation Cu(III) complex \( \text{Cu(III)}(\text{OAc})_2 \), facilitating the smooth reductive elimination to furnish N-arylated product \( \text{Cu(III)}(\text{OAc})_2 \). In the Ullmann-type coupling, the first step involves the smooth coordination of \( \text{Cu(III)}(\text{OAc})_2 \) with Cu(I) to form complex \( \text{Cu(I)}(\text{OAc})_2 \), which upon intramolecular oxidative addition with aryl iodide furnishes complex \( \text{Cu(I)}(\text{OAc})_2 \), which subsequently converts into complex \( \text{Cu(I)}(\text{OAc})_2 \). As far as the oxidation state of copper is concerned, these types of reactions are supposed to proceed via Cu(I) and Cu(III) intermediates. Thus, Cu(III) complex \( \text{Cu(III)}(\text{OAc})_2 \), on smooth reductive elimination, furnishes the final cyclized product with concurrent formation of Cu(I). Finally, Cu(II) is generated by aerial oxidation to complete the catalytic cycle.
2.2 Type II: Metal-Free Approaches

Nevertheless, transition-metal-catalyzed coupling reactions are still limited in applications and confront challenges to some extent, owing to the innate drawbacks of the catalytic systems. First, most of the transition-metal catalysts are normally very expensive\(^\text{22}\) and the supporting ligands are usually even more expensive and sometimes difficult to prepare. Second, most of the transition metals are toxic to different extents, and removal of trace amounts of transition-metal residues from the desired products is quite costly and challenging, while crucial, especially in the pharmaceutical industry\(^\text{23}\). Third, many transition-metal catalysts are usually sensitive to oxygen (O\(_2\)) and moisture; thus, very strict manipulation is indispensable. Fourth, in many cases, special additives and co-catalysts are also critical to promote the efficiency and selectivity of transformations\(^\text{24}\). Last but not least, the large consumption of transition metals does not indeed meet the requirement of sustainable development.\(^\text{25}\) Obviously, alternative pathways to construct C–C bonds under transition-metal-free conditions to fulfill the classic transition-metal-catalyzed coupling reactions are highly appealing. Thus, studies on transition-metal-free coupling reactions are of great significance to provide a better understanding of how the reactions work with or without transition metals.

In 2009, the Yan group reported a one-pot, four-component method to afford diversely substituted pyrido[1,2-\(a\)]benzimidazoles, by employing aromatic aldehydes, malononitrile, chloroacetonitrile, and pyridine or 3-picoline as starting materials in refluxing acetonitrile (Scheme 24).\(^\text{26}\) A library of pyrido[1,2-\(a\)]benzimidazole derivatives with broad substrate scope was synthesized in moderate to good yields.

The postulated mechanism (Scheme 25) begins with the formation of two reaction intermediates: the N-cyano-methylpyridinium salt 31, formed by the addition of chloroacetonitrile to pyridine, and the benzylidenemalononitrile, formed by the pyridine-promoted Knoevenagel condensation of malononitrile with benzaldehyde. In the second step, the pyridinium ylide 32, formed by the pyridine-assisted deprotonation of the N-cyano-methylpyridinium intermediate 31, undergoes Michael addition with benzylidenemalononitrile to give an activated cyclopropane derivative 33. Upon subsequent deprotonation and ring-opening, 33 yields an allylic carbanionic intermediate 34, which reacts with the second molecule of benzylidenemalononitrile to form a cyano-stabilized carbanionic intermediate 35. The intramolecular nucleophilic addition of carbanion 35 to one of its cyano groups affords a fully substituted six-membered cyclic intermediate 36. The substitution of one cyano group in intermediate 36 by pyridine occurs to form another pyridinium ion 37. Pyridinium ion 37 experiences an intramolecular attack of an amino group on the ortho positive center of pyridine to form a cyclic pyridine derivative 38, from which one molecule of hydrogen cyanide and two hydrogen atoms are eliminated to form the desired pyrido[1,2-\(a\)]benzimidazole. In this mechanism, pyridine plays a multifaceted role, by acting as a tertiary amine to yield pyridinium cation, as a base to form the carbanion intermediate and as a nucleophilic reagent.

In 2011, the Kutsunura group reported a versatile method for the synthesis of pyrido[1,2-\(a\)]benzimidazoles via intramolecular dehydrogenative C-N coupling between
aryl C–H and N–H bonds of N-pyridin-2-ylanilines by using hypervalent iodine reagents under mild reaction conditions (Scheme 26).27

The synthesis of pyrido[1,2-a]benzimidazoles in moderate to excellent yields via photo-stimulated cyclization of 2-(2-halophenylamino)pyridines in liquid ammonia and in the presence of potassium tert-butoxide was reported by Rossi and co-workers (Scheme 27).28 The reaction procedure involves the photo-stimulated SRN 1 mediated C–N bond formation in 2-(2-halophenylamino)pyridines. Various substituents were well tolerated on both the phenyl and pyridine rings of the starting materials.

![Scheme 26](image)

Scheme 26 Hypervalent iodine-assisted intramolecular dehydrogenative C–N coupling reactions of N-pyridin-2-ylanilines

In 2013, a hypervalent iodine(III)-catalyzed C–H cycloamination reaction of N-aryl-2-aminopyridines was reported by Zhu et al. for the easy and efficient synthesis of various pyrido[1,2-a]benzimidazoles in good to excellent yields (Scheme 29).29 The hypervalent iodine(III) reagent phenyliodine diacetate (PIDA) was generated in situ from a catalytic amount of iodobenzene and a stoichiometric amount of peracetic acid. Various electron-donating and electron-withdrawing groups were well tolerated under the optimized reaction conditions to provide more diversified pyrido[1,2-a]benzimidazole derivatives.

![Scheme 27](image)

Scheme 27 Photo-stimulated cyclization of 2-(2-halophenylamino)pyridines to afford the corresponding pyrido[1,2-a]benzimidazole derivatives

![Scheme 28](image)

Scheme 28 Photo-stimulated SRN 1 cyclization of 2-(2-halophenylamino)pyridine

The authors proposed the followed reaction pathway (Scheme 30) for the C–H cycloamination reaction of N-phenyl-2-aminopyridine catalyzed by an in situ generated hypervalent iodine(III) reagent. The reaction starts with the formation of phenyliodine diacetate (PIDA) by the oxidation of iodobenzene with peracetic acid in the presence of acetic acid.

![Scheme 29](image)

Scheme 29 PIDA-catalyzed synthesis of pyrido[1,2-a]benzimidazole derivatives

The mechanism proposed for the photo-stimulated cyclization of 2-(2-halophenylamino)pyridine is shown in Scheme 28. The first step involves the generation of the radical dianion 39 of the substrate by a photo-induced electron transfer (ET) reaction. This radical dianion 39 upon fragmentation yields the distonic radical anion 40 and the halide anion, followed by the cyclization of the resonance distonic radical anion 40 to give the conjugated radical anion 41. Finally, an electron transfer from radical anion 41 to the anion of 2-(2-halophenylamino)pyridine leads to the formation of the final product, along with the intermediate 39, to continue the propagation cycle.
acid, followed by nucleophilic substitution of the aniline nitrogen of N-phenyl-2-aminopyridine on the iodine(III) center in PIDA to form intermediate 42, bearing an electrophilic N-iodo moiety. Subsequent nucleophilic attack from the pyridine nitrogen onto the aniline ring produces intermediate 43 along with the simultaneous release of PhI and acetate ion. The released PhI enters the catalytic cycle again upon its reoxidation by peracetic acid, which is used as a stoichiometric oxidant. In the final step, the deprotonative rearomatization of intermediate 43 takes place, leading to the formation of the desired final product, along with the generation of one molecule each of acetic acid and water as byproducts.

The mechanism proposed for this transformation (Scheme 32) begins with the coordination of PhI(OPiv)₂ with N-benzyl-2-aminopyridine, leading to the formation of an electrophilic N-iodo species 44, which undergoes ipso SEAr on the phenyl ring to furnish the delocalized carbocation 45 (Wheland intermediate). C–C bond cleavage in 45 occurs upon its nucleophilic addition by HFIP at the benzylic carbon, giving intermediate 46, which upon reaction with a second equivalent of PhI(OPiv)₂ produces the active complex 47. A second nucleophilic addition by HFIP to 47 results in C–N bond cleavage to give an activated electrophilic iodo species 48, along with the release of a methylene group in the form of an acetal. Electrophilic annulation on the pyridine nitrogen of 48 forms intermediate 49, which is deprotonated to the corresponding pyrido[1,2-α]benzimidazole in the final step.

In 2014, Antonchick et al. reported a metal-free annulation reaction between various substituted 2-aminopyridines/2-aminoquinolines and arenes to get an easy access to diversified pyrido[1,2-α]benzimidazoles (Scheme 33) and quinolino[1,2-α]benzimidazoles (Scheme 34) under mild reaction conditions.31

A plausible mechanism for the formation of pyrido[1,2-α]benzimidazole is outlined in Scheme 35. It begins with a ligand exchange between 2-aminopyridine and PhI(OAc)₂ to form intermediate 50, followed by nucleophilic attack of p-xylene, forming N-arylated 2-aminopyridine 51. Subsequent oxidation of 51 with a second equivalent of PhI(OAc)₂ and nucleophilic attack of the pyridine nitrogen on xylene produces another intermediate 53, which upon rearomatization gives the final annulated product.

To be highlighted in this report is the in situ synthesis of benzylidamine 56 via an unprecedented participation of the methyl group of methylnarene as a traceless, non-chelat-
To obtain the requisite starting material, the annulation reaction with 2-aminoquinoline (Scheme 36).ing and highly regioselective directing group in its cross-annulation reaction with 2-aminoquinoline (Scheme 36). To obtain the requisite starting material 56, xylene was treated with PhI(OAc)$_2$ to form benzylic radical 54, which was subsequently converted into cation 55 by the PhI(OAc)$_2$ free-radical species. Nucleophilic attack of 2-aminoquinoline onto cation 55 gave benzylic amine 56, which was converted into the final product via a mechanism akin to that described in Scheme 32.

In the same year, Das et al. reported a hypervalent iodine(III) [PhI(OH)OTs, Koser’s reagent] catalyzed, regio-selective C–H cycloamination reaction of various N-aryl-2-aminopyridines for the synthesis of pyrido[1,2-a]benzimidazoles via metal-free catalytic amount and was generated in situ by using iodosobenzene diacetate in a catalytic amount and p-toluenesulfonic acid monohydrate and m-chloroperbenzoic acid in stoichiometric amounts. Use of water as a solvent and open-flask chemistry makes the protocol greener and more significant for large-scale synthesis of diversified pyrido[1,2-a]benzimidazole derivatives.

The following plausible mechanism was proposed for the PhI(OH)OTs-catalyzed oxidative C–N bond-formation reaction of N-phenyl-2-aminopyridine (Scheme 38). The reaction starts with the interaction of in situ generated PhI(OH)OTs with N-phenyl-2-aminopyridine, generating the electrophilic N-iodo species 57. The formation of intermediate 58 occurs next by electrophilic annulation on the
pyridine nitrogen of \(N\)-iodo species 57, followed by deprotonation of 58 to give the final product. The eliminated PhI enters the catalytic cycle upon its oxidation by \(m\)-CPBA in the presence of PTSA\(\cdot\)H\(_2\)O to generate the reactive iodine(III) PhI(OH)OTs, thus completing the catalytic cycle. Further, the rationale behind the high regioselectivity of this method is the favored formation of intermediate 60 over 59 due to steric effects (Scheme 39), to afford one regioisomer exclusively.

The Patel group reported a one-pot, three-component cyclocondensation reaction of (aryloxy)pyrazole-4-carboxaldehyde, malononitrile, and 2-(cyanomethyl)benzimidazole catalyzed by piperidine to give newer (aryloxy)pyrazole-substituted pyrido[1,2-\(a\)]benzimidazole derivatives (Scheme 40). This methodology allows an easy and expedient assimilation of two promising bioactive nuclei, namely (aryloxy)pyrazole and pyrido[1,2-\(a\)]benzimidazole into a single molecule for antimicrobial screening.

In 2014, the Xu group described the use of hypervalent iodine(III) in the expedient preparation of imidazo[1,2-\(a\)]pyrimidine derivatives in good yields from readily available \(N\)-aryl-2-aminopyrimidines (Scheme 41). This process involves the intramolecular C\((sp^2)\)–H bond cycloamination reaction of \(N\)-aryl-2-aminopyrimidines promoted by hypervalent iodine(III) formed in situ from stoichiometric iodobenzene bis(trifluoroacetate) (PIFA). Various \(N\)-aryl-2-aminopyrimidines were employed to establish the wide scope of this method.

The authors proposed two mechanistic pathways to explain the hypervalent iodine(III)-catalyzed cycloamination of \(N\)-phenyl-2-aminopyridine (Scheme 42). A nucleophilic substitution reaction of the aniline nitrogen onto the iodine(III) center of PIFA forms intermediate 61. In path A, intermediate 61 is transformed into nitrenium ion 62 through an oxidative process, followed by the nucleophilic addition of the pyrimidyl nitrogen atom on the carbon center of the carbocationic form 63 of intermediate 62 to give a cyclic intermediate 64. Upon deprotonative rearomatiza-

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**Scheme 38** Plausible mechanism for Koser’s reagent catalyzed, regioselective C–H cycloamination of \(N\)-phenyl-2-aminopyridine

**Scheme 39** Reaction path for the regioselective C–H cycloamination of meta-substituted \(N\)-phenyl-2-aminopyridine

**Scheme 40** One-pot, three-component synthesis of various (aryloxy)pyrazole-substituted pyrido[1,2-\(a\)]benzimidazole compounds
tion of 64, the desired product is produced. Alternatively, the direct nucleophilic substitution of the pyrimidyl nitrogen on the aniline ring of intermediate 61 affords the cyclic intermediate 64, along with the release of one molecule each of PhI and CF₃COO⁻.

Scheme 42  Mechanism proposed for the intramolecular C(sp²)–H bond cycloamination of N-phenyl-2-aminopyrimidines

Foroumadi and his group synthesized a series of pyrido[1,2-α]benzimidazole derivatives by the reaction between 2-(1H-benzo[d]imidazol-2-yl)acetanilide and ethyl 2,4-diazo-4-arylbutanoate, using piperidine as a base in refluxing EtOH (Scheme 43). Various ethyl 2,4-diazo-4-arylbutanoates were used to establish the substrate scope of the method. Mild reaction conditions, short reaction times and easy purification of the obtained compounds are the significant advantages of this reaction from a synthetic point of view.

Scheme 43  Piperidine-catalyzed synthesis of pyrido[1,2-α]benzimidazole derivatives

The mechanism that explains this conversion (Scheme 44) starts with the formation of intermediate 65 by a Knoevenagel condensation reaction between 2-(1H-benzo[d]imidazol-2-yl)acetanilide and ethyl 2,4-diazo-4-phenylbutanoate. Intramolecular nucleophilic addition of the benzimidazole ring nitrogen on the carbonyl carbon occurs, followed by dehydration to give the desired pyrido[1,2-α]benzimidazole derivative.

Scheme 44  Proposed mechanism for the synthesis of diversely substituted pyrido[1,2-α]benzimidazoles

Subsequently, Deng and his group developed an expedient, molecular iodine-mediated preparation of pyrido[1,2-α]benzimidazole derivatives, using 2-aminopyridines and non-aromatic cyclohexanones as starting materials under metal-free conditions (Scheme 45). Molecular oxygen was employed as a green oxidant for the dehydrogenation-aromatization of non-aromatic cyclohexanones which were used as an aryl source in this protocol. A library of pyrido[1,2-α]benzimidazoles was prepared in good to excellent yields by using various 2-aminopyridines and cyclohexanones to establish the general applicability of this method.
Two plausible reaction pathways were proposed to explain the metal-free synthesis of pyrido[1,2-\(a\)]benzimidazole, as shown in Scheme 46. Iodination of cyclohexanone forms 2-iodocyclohexanone (66), which, upon nucleophilic substitution by 2-aminopyridine, generates the second intermediate 67. Subsequent intramolecular cyclization of 67 followed by deprotonation and dehydration leads to 6,7,8,9-tetrahydrobenzo[4,5]imidazo[1,2-\(a\)]pyridine intermediate 68 (path A). Molecular oxygen assisted dehydrogenation of 68 forms the final product. In an alternative pathway, the initial step is the condensation of 2-aminopyridine with cyclohexanone to give imine intermediate 69, which is subsequently isomerized to intermediate 70 (path B). Iodination of 70 forms intermediate 71, which is isomerized into another intermediate 72. Intramolecular substitution of the iodo group with amine in 72 also affords intermediate 68.

In 2016, Zhang et al. reported a phenyliodine(III) diacetate (PIDA) mediated intramolecular C(sp\(^2\))−H bond cycloamination reaction of 4-anilinoquinazolines using mild reaction conditions to afford erlotinib drug-related benzimidazo[1,2-c]quinazoline derivatives in appreciable yields (Scheme 47).\(^{37}\) This metal-free C−N coupling protocol was found tolerable to both electron-donating and electron-withdrawing groups at various substitution positions of the aniline fragment of the starting materials used.

A plausible mechanism (Scheme 48) involves initiation by the interaction of PhI(OAc)\(_2\) with 4-anilinoquinazoline to give intermediate 73 that contains the electrophilic N-iodo moiety, with the subsequent loss of a molecule of acetic acid. Electrophilic annulation on the pyridine nitrogen through the cleavage of the N−I bond leads to the formation of another intermediate 74 along with the concurrent release of one molecule each of PhI and acetic acid. In the final step, the deprotonative rearomatization of intermediate 74 occurs, leading to the formation of the desired product.
During the same year, Yu and his group demonstrated the use of molecular iodine as an oxidant for the intramolecular C(sp^2)-H bond cycloamination of N-arylpyridin-2-amines to construct a diverse range of pyrido[1,2-a]benzimidazoles, employing K_2CO_3 as a base under mild reaction conditions (Scheme 49). The optimized reaction conditions worked well with various substituted N-arylpyridin-2-amines.

Depending upon the substitution on the aryl ring of the N-arylpyridin-2-amines, three plausible mechanisms (Schemes 50–52) were proposed for their direct I_2-mediated C–H cycloamination. The substrates with methyl substitution at the para position of the N-phenyl ring undergo base-mediated oxidative iodination to produce the electrophilic N-iodo species 75, followed by N–I bond cleavage and subsequent intramolecular C–N bond formation to generate intermediate 76, which undergoes deprotonative rearomatization to form the corresponding final product (Scheme 50). When N-phenylpyridin-2-amine is used as the starting material, the initial step is the attack of a molecule of N-phenylpyridin-2-amine on the para position of its N-iodo form to give dimer 77; subsequent I_2-mediated oxidative cycloamination affords the product (Scheme 51). 2,4,6-Trimethylphenyl-bearing substrates undergo intramolecular nucleophilic substitution of the pyridine nitrogen onto the aryl ring carbon to give intermediate 78. Iodide-ion-assisted demethylation of 78 yields the corresponding final product (Scheme 52).


A plausible mechanism for the formation of benzimidazo-fused polyheterocycles (Scheme 54) involves the initial reaction between the alkenyl aldehyde and o-phenylenediamine to furnish the corresponding imine intermediate 79. Subsequent intramolecular nucleophilic attack of the amino group on the imine bond generates the cyclic intermediate 80, which upon auto-oxidation forms the benzimidazole-
fused intermediate 81. A second intramolecular nucleophilic attack by the benzimidazole ring nitrogen on the electrophilic alkyne bond produces the unstable vinylic anion 82, which is protonated to give the final product.

Scheme 53  Metal-free synthesis of various benzimidazo-fused heterocyclic compounds from alkynyl aldehydes and o-phenylenediamines

3 Conclusion

In summary, pyrido[1,2-a]benzimidazole and its analogues have taken a leading role in the recent literature, because of their wide variety of applications in various disciplines such as medicinal chemistry and materials science. Several novel synthetic routes have been developed to produce these scaffolds, involving mainly construction of the imidazole ring on the pyridine nucleus and scantly the opposite. These newer synthetic routes are based on the combination of several interesting strategies such as multicomponent reactions, tandem sequences, and C–H activation. As is evident from the discussion in this review, these synthetic procedures offer easy access to pyrido[1,2-a]benzimidazole from simple and readily available precursors without the need of any prefunctionality. The development of these synthetic procedures is very useful, especially for medicinal and materials chemists.

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References
