RSC Advances



REVIEW

View Article Online

View Journal | View Issue



Cite this: RSC Adv., 2018, 8, 18576

Recent metal-catalysed approaches for the synthesis of cyclopenta[b]indoles

Thavaraj Vivekanand, Bishnupada Satpathi, Siddheshwar K. Bankar and S. S. V. Ramasastry • *

Received 23rd April 2018 Accepted 14th May 2018

DOI: 10.1039/c8ra03480j

rsc.li/rsc-advances

The cyclopenta[b]indole scaffold is ubiquitously present in several bioactive natural products and pharmaceutically interesting compounds. Of the numerous methods known for the synthesis of cyclopenta-fused indoles, this review highlights only the metal-catalysed approaches reported from the year 2015 onwards. This review encompasses our own efforts leading to the synthesis of cyclopentannulated indoles, in addition to the seminal contributions of several other researchers.

1. Introduction

The majority of natural products, synthetic drugs, agrochemicals and other biologically significant molecules are heterocyclic compounds, predominantly nitrogen-containing heterocycles.¹ Consequently, synthesis of N-heterocycles became one of the main branches of synthetic chemistry.² Among N-heterocycles, indole and indoline scaffolds are privileged substructures owing to their occurrence in a large number of natural products, bioactive compounds and materials of industrial relevance.³,4

Among indole derivatives, cyclopenta[b]indoles are of great significance because of their prevalence in a large number of alkaloids possessing wide-ranging biological activities.⁵ For example, fischerindole L shows cytotoxicity against HCl-H460 cell lines,⁶ terpendole E is an important mitotic kinesin Eg5 inhibitor,⁷ yuehchukene possesses anti-fertility and estrogenic activities,⁸ bruceollines are traditionally used for treating malaria and other parasitic diseases,⁹ paspaline exhibits anti-bacterial and insecticidal activity,¹⁰ and drugs such as laropiprant, which is believed to have a cholesterol lowering effect,¹¹ possess a cyclopenta[b]indole core, while polyveoline¹² represents an example of natural products having a cyclopenta [b]indoline scaffold (Fig. 1).

Due to their significant biological properties, various synthetic protocols have therefore been described to prepare cyclopenta[b]indoles. Some of the prominent approaches include, [3 + 2]-cycloaddition, ¹³ Yonemitsu condensation, ¹⁴ gold(i) catalysed Rautenstrauch rearrangement, ¹⁵ bismuth(III) catalysed condensation, ¹⁶ Nazarov cyclisation, ¹⁷ Heck–Suzuki cascade, ¹⁸ Fischer indole synthesis, ¹⁹ indole electrophilic

Organic Synthesis and Catalysis Lab, Department of Chemical Sciences, Indian Institute of Science Education and Research (IISER) Mohali, Knowledge City, Sector 81, S. A. S. Nagar, Manauli PO, Punjab 140306, India; Web: http://14.139.227.202/faculty/sastry/. E-mail: ramsastry@iisermohali.ac.in; ramsastrys@gmail.com

substitution reactions,²⁰ [3,3]-sigmatropic rearrangement,²¹ Dieckmann condensation,²² vinylogous Michael addition/Friedel–Crafts reaction,²³ enzymatic synthesis,²⁴ *etc.*

In the past few decades, chemists have extensively explored various routes for the synthesis of cyclopenta[b]indoles via metal catalysis and these efforts have been reviewed recently. ²⁵ The scope of the present review is to provide a detailed account of various metal-catalysed approaches reported for cyclopenta [b]indoles from the year 2015 onwards. The works highlighted herein have been categorised based on the metal catalyst employed.

2. Palladium-catalysed approaches

In 2017, Lu and Han reported a Pd(π)-catalysed tandem cyclisation of alkynones 1 to synthesise pentaleno[2,1-*b*]indoles 2 (Scheme 1).²⁶ Tetracyclic indoles bearing two neighbouring stereogenic centres, one being all-carbon quaternary, were constructed in a single operation in an excellent diastereoselectivity. The tandem cyclisation is initiated by the *trans*-amino palladation of the alkyne moiety to generate 3. A subsequent nucleophilic addition of the C–Pd bond to the intramolecular carbonyl group followed by the protonolysis of 4 results in the formation of product 2. Thereby, this reaction offers an efficient and atom-economic alternative for the synthesis of pentaleno[2,1-*b*]indoles 2.

In 2018, Cheng and Zhai demonstrated a novel Pd-catalysed decarboxylative coupling reaction of vinyl benzoxazinanones **6** with aryne precursors **5** to achieve the synthesis of *cis*-tetrahydroindeno[2,1-*b*]indoles **7** in good yields (Scheme 2).²⁷ The authors propose that the mechanism involves a nucleophilic attack at the central carbon of vinyl benzoxazinanone-derived π -allyl palladium species **8** that gives a palladacyclobutane intermediate **9**, which then reacts with arynes to afford the polycyclic heterocycles such as **7**.

Fig. 1 Representative natural products and medicinally significant compounds possessing cyclopenta[b]indole core.

Kotha and Gunta reported an interesting approach for the synthesis of fused N-heterocycles (for example, **12** and **13**) *via* C-H activation and ring-rearrangement metathesis (RRM) of 2-bromo-*N*-protected anilines **10** (or **11**) with norbornadiene (Scheme 3).²⁸ Through this method, various structurally intricate polycyclic amides were prepared, and some of the products obtained herein represent the core structures of the bioactive

Scheme 1 Palladium-catalysed tandem cyclisation leading to the formation of pentaleno[2,1-b]indoles.

Scheme 2 A Pd-catalysed synthesis of tetrahydroindeno[2,1-b] indoles.

Scheme 3 Kotha's synthesis of fused-indolines *via* C–H activation and ring-rearrangement metathesis.

Scheme 4 Martensson's synthesis of bioactive cyclopenta[b]indoles.

Scheme 5 Wang's approach for cyclopenta-fused indolines.

alkaloids epimeloscine, deoxycalyciphylline B, daphlongamine H and isodaphlongamine H. Key advantages of the C-H activation/RRM strategy are: (i) it is atom-economical, and (ii) provides access to intricate molecular scaffolds amenable for further synthetic transformations.

In 2015, Mårtensson and co-workers developed a diversity oriented synthesis of 3-arylidine-cyclopenta[b]indol-2-ones 17

Scheme 6 Vitale's synthesis of fused cyclopentannulated indolines.

Scheme 7 Shi's catalytic synthesis of chiral cyclopenta-fused indolines.

via Pd-catalysed Heck–Suzuki reaction cascade (Scheme 4).²⁹ Indole-3-acetic acids **14** were converted to iodoindoles **15** in four steps. A tandem Heck–Suzuki reaction of **15** provided access to cyclopenta-fused indoles **16**, which were converted to enones **17** in two straight forward steps. Among several analogs of **17** prepared, **17**′ particularly displayed impressive anti-melanoma

Scheme 8 Hyland's diastereoselelctive synthesis of cyclopenta[*b*] indolines.

Review RSC Advances

Scheme 9 Wang's synthesis of cyclopenta[*b*]indolines *via* Pd-catalysed asymmetric dearomative cycloaddition.

Scheme 10 Pd-catalysed iso-Nazarov-type cyclisation.

properties by inhibiting Aurora A, Aurora B, BRAF V600E, IRAK4 and also inhibiting cell proliferating PBMC. In addition, 17' also displayed interesting fluorescent properties, enabling its intracellular accumulation to be visualised.

Synthesis of dihydro[1,2-b]indenoindole-9-ols **19** through a Pd-catalysed cascade process was developed by Wang and coworkers (Scheme 5).³⁰ The mechanism involves an oxidative addition of Pd(0) with an aryl iodide **18** leading to the formation of a chelation stabilised intermediate **20**. Subsequently, base-mediated generation of nine-membered palladacycle **21** undergoes reductive elimination to form 8-membered β -arylated compound **22**. Further base-mediated intramolecular cyclisation furnished **19** in good yields. The control experiments and the isolation of 8-membered β -arylated intermediate **22** further ascertain the proposed palladium cycle.

In 2017, Vitale and co-workers disclosed a highly efficient and atom-economical Pd(0)-catalysed dearomative [3 + 2]-

Scheme 11 Rh-catalysed intramolecular hydroacylation for the synthesis of dihydrocyclopenta[b]indol-1(2H)-ones.

Scheme 12 Rh-catalysed approach for cyclopenta-fused indolines.

cycloaddition of 3-nitroindoles 23 with vinylcyclopropanes 24 to obtain cyclopentannulated indolines 25 possessing three stereogenic centers in high diastereoselectivity (Scheme 6). The zwitterionic 1,3-dipole 26 undergoes Michael addition with the electrophilic 3-nitroindoles. This follows an irreversible intramolecular attack of the nitronate anion onto the π -allyl palladium(II) moiety to afford 2,3-fused cyclopenta[b]indolines 25 in a stereo-defined fashion.

In 2018, Shi and co-workers demonstrated the catalytic asymmetric dearomative [3 + 2]-cycloaddition of electron-

Scheme 13 Hu's one-pot sequential dehydrogenative coupling reaction.

Scheme 14 Xu's synthesis of cyclopenta[b]indoles

deficient indoles with 1,3-dipoles (Scheme 7).³² For example, phosphoramidite 27 catalysed reaction of 3-nitroindoles 23 with vinyl cyclopropanes 24 provided chiral cyclopenta[b]indolines 28 in high enantioselectivities (up to 97% ee). This also presents a case for catalytic asymmetric dearomatisation (CADA) reactions, which are well-known for electron-rich indoles, but in this case, the authors have demonstrated the CADA concept on electron-poor indoles to obtain chiral cyclopenta[b]indolines of the type 28.

In 2017, Hyland and co-workers reported a Pd-catalysed diastereoselective synthesis of cyclopenta[b]indolines **29** from 3-nitro indoles **23** and vinylcyclopropane dicarboxylates **24** by Pd-catalysed dearomative [3 + 2]-cycloaddition process (Scheme 8).³³ The authors have identified that the halide addition [in the form of tetrabutylammonium iodide (TBAI)] is critical for the diastereo induction in products. It was hypothesised that the halide allows a Curtin–Hammett control of the reaction there by introducing diastereoselectivity. Unlike Vitale's work,³¹ a switch

Scheme 15 Rh-catalysed synthesis of pentannulated indoles.

in the diastereoselectivity was observed with the vinyl and nitro groups being *trans* to each other. The difference between the transition states involved in Hyland's work (**A**) and Vitale's work (**B**) is presented in Scheme 8.

In 2018, Wang's group reported a Pd-catalysed asymmetric dearomative [3 + 2]-cycloaddition strategy for the construction of optically active cyclopenta-fused indolines **31** (Scheme 9).³⁴ For example, the reaction of 3-nitroindoles **23** with vinyl cyclopropanes **24** in the presence of a chiral box (**30**)/Pd(0) complex delivered 8*b*-nitro hexahydrocyclopenta[*b*]indoles **31** containing up to three contiguous chiral centres in high yields and good regio-, chemo-, and enantioselectivities. The synthetic utility of this method was demonstrated through direct functionalisation of the carbon–carbon double bond of **31**. The salient features of this transformation include good functional group tolerance, stereospecificity, atom-economy, and scalability.

Recently, our group demonstrated a Pd-catalysed Trost–Oppolzer type Alder-ene reaction of 2,4-pentadienyl acetates for the synthesis of cyclopentadienes and cyclopentene-fused arenes and heteroarenes. For example, in the presence of a catalytic amount of palladium chloride, the allyl acetate 32 afforded the cyclopenta[b]indole 33 in good yield (Scheme 10). The reaction is believed to involve the formation of a π -allyl palladium complex and an intramolecular Alder-ene reaction as in the model depicted in Scheme 10. The overall reaction also represents an unprecedented acid-free iso-Nazarov-type cyclization.

3. Rhodium-catalysed approaches

In 2017, Vickerman and Stanley reported an enantioselective approach for the synthesis of N/O/S-heterocycles 35 by the intramolecular Rh-catalysed hydroacylation of olefins 34 (Scheme 11).³⁶ Employing this strategy, 1,4-dihydrocyclopenta [b]indol-3(2H)-ones and 3,4-dihydrocyclopenta[b]indol-1(2H)-ones are accessible in high yields and in excellent enantioselectivities. This protocol allowed the alkene hydroacylation of 3-vinylfuran-, 3-vinyl benzothiophene-, and 3-vinyl thiophene-2-carboxaldehydes to generate the corresponding oxygen, and sulphur-containing heterocycles in chiral fashion.

Doyle and co-workers developed a highly regio-and enantio-controlled formal [3 + 2]-annulation of indoles and electrophilic enol carbenes for the synthesis of chiral cyclopenta-fused indolines **39** (Scheme 12).³⁷ An enantioselective vinylogous addition of enoldiazoacetamides **37** to *N*-substituted indoles **36** (without 2- or 3-substituents) was facilitated by the prolinateligated dirhodium(II) catalyst **38**. Interestingly, the donoracceptor cyclopropane **40** was realised to be the carbene precursor in this transformation. It is interesting to note that prior to this study, dearomatising [3 + 2]-annulation of 2- or 3-unsubstituted indoles that occurs with good chemo-, regio-, and enantiocontrol was not achieved.

In 2016, Hu and co-workers reported a Rh-catalysed highly diastereoselective three-component reaction for the generation of polyfunctionalised cyclopenta[b]indoles 43 (Scheme 13).³⁸ Rh₂(OAc)₄ catalysed dehydrogenative coupling between indoles 36 and diazoacetates 41 generates intermediate 44. A subsequent trapping of 44 with α , β -unsaturated- α -keto esters 42

Review

$$R^{2} \xrightarrow{\text{OEt}} \text{OEt} \xrightarrow{\text{1. (S)-DTBM-Segphos(AuCl)}_{2}} \frac{\text{R}^{1}}{\text{AgBF}_{4}, \text{CH}_{2}\text{Cl}_{2}} \xrightarrow{\text{R}^{2}} \text{O}$$

$$\frac{\text{AgBF}_{4}, \text{CH}_{2}\text{Cl}_{2}}{2. p\text{TSA, acetone/H}_{2}\text{O}} \xrightarrow{\text{TS H}} \overset{\text{R}^{2}}{\text{CO}_{2}} \text{R}^{3}$$

Scheme 16 Toste's Au-catalysed dearomative Rautenstrauch rearrangement for the synthesis of cyclopenta[b]indoles.

through Michael addition results in the formation of the enol 45. An aerobic intramolecular direct Csp²-Csp² cross-coupling of indole-enol is promoted by CuCl2. Further, XPS and control experiments revealed the role of Cu(II) in the single electron transfer oxidation [a catalytic cycle of Cu(II) to Cu(I)] of the enol 45 to \alpha-chloro carbonyl intermediate 46. An intramolecular Friedel-Crafts-type alkylation of 46 delivers the cyclopenta[b]indoles 43.

In 2017, Xu and co-workers developed a Rh-catalysed asymmetric β-arylation of indole-derived α,β-unsaturated esters and aryl boronic acids for the synthesis of 3-(1H-indol-2-yl)-3arylpropanoates 49 in good yields and excellent enantioselectivities (Scheme 14).³⁹ The method is applicable to α,β -unsaturated benzofuran- and benzothiophene-derived acrylates as well. The βarylated products obtained herein were transformed to cyclopenta[b]indoles 50 via a multistep sequence. A 2,3-dichloro-5,6dicyanobenzoquinone (DDQ)-mediated oxidation of 50 further provided functionalised cyclopenta-fused indoles of the type 51.

In 2016, Tang and Shi demonstrated a ring expansion of styrylazides 52 via Rh(II)-catalysed single electron transfer mechanism (Scheme 15).40 The reaction path follows an initial Rh-nitrene 54 formation via nitrogen elimination and subsequent single electron transfer to generate the radical 55. The radical addition to the olefin generates the spirocyclic radical 56 which undergoes another SET to form 57. Further, 1,2-alkyl migration of 57 and elimination affords the imine 58. In situ borohydride reduction of the imine 58 delivers pentannulated indoles 53 in a highly diastreoselective manner. The authors also provided an evidence in favor of the generation of RhIII-RhII-nitrene with DFT studies.

Gold-catalysed approaches

In 2015, Toste and co-workers reported a highly enantioselective dearomative Rautenstrauch rearrangement of propargyl acetals 59 catalysed by cationic (S)-DTBM-Segphos gold(1) (Scheme 16). This reaction provides a straightforward method for the preparation of enantioenriched cyclopenta[b]indoles 60.

The proposed mechanism involves an anti-attack of ethoxy ether of the acetal on to the Au-coordinated alkyne leading to the formation of oxonium species 61. An eventual extrusion of acetaldehyde generates gold-substituted 1-amino pentadienyl intermediate 62. An enantio-determining imino-Nazarov cyclisation of 62 followed by protodeauration affords product 60.

Recently, our group reported the synthesis of 1,2,3-trisubstituted cyclopenta[b]indoles 64 from 1-(2-aminophenyl)prop-2-ynols 63 via one-pot relay Au(1)/BrØnsted acid catalysis (Scheme 17).41

Scheme 17 A sequential Au(ı)/BrØnsted acid catalysis

 $\begin{array}{c} R^{2}R^{3} \\ AgSbF_{6} (3 \text{ mol}\%) \\ \hline CH_{2}Cl_{2}, 25 \, ^{\circ}C \\ 43.84\% \\ \hline CO_{2}Me \end{array} \begin{array}{c} R^{1} \\ \hline R^{2}R^{2} \\ \hline R^{2}R^{2}R^{2} \\ \hline R^{2}R^{2} \\ \hline R^{2}$

Scheme 18 Occhiato's tandem Au(ı)-catalysed rearrangement/Nazarov cyclisation.

The reaction of ynols **63** under Au(1) catalysis generates indolines **65**, which undergoes an acid mediated cation–ene reaction with 1,3-dicarbonyls and a subsequent intramolecular Friedel–Crafts-type reaction to provide **64**. It is noteworthy to mention that Au(1) or Ag(1) alone or a combination of Au(1) and silver based Lewis acids failed to deliver the indoline **65**, whereas Au(1) with a combination of a base (such as K_2CO_3) was found to be effective. The reaction tolerates a wide range of ynols possessing electron donating as well as withdrawing groups. A variety of 1,3-dicarbonyls, 1,2,3-tricarbonyls, β -ketoesters and β -ketoamides are also tolerated under the reaction conditions.

Occhiato and co-workers developed a tandem gold(i)-catalysed rearrangement/Nazarov cyclisation of enynyl acetates **66** to obtain cyclopenta[b]indol-1-ones **67** in good yields (Scheme 18).⁴² The process entails the gold(i)-catalysed [3,3]-sigmatropic rearrangement of the propargylic acetates **66** to generate requisite pentadienyl cation **68**. The Nazarov cyclisation

followed by hydrolysis of the enol acetate 69 generates cyclopenta[b]indol-1-ones 67. The potential of this synthetic methodology was demonstrated in the total synthesis of Bruceolline H.

Liu and co-workers presented a gold-catalysed cycloisomerisation of 1,6-diynes 70 containing a ynamide propargyl ester functionality, leading to the synthesis of densely functionalised 1,4-dihydro cyclopenta[b]indoles 71 (Scheme 19).⁴³ The reaction proceeds through a selective activation of ynamide propargyl ester by Au(i) to afford α -vinyl gold carbenoid 72. Intramolecular attack of the alkyne moiety on to the gold carbenoid (in 73) affords vinyl cationic species 74, which undergoes [1,5]-H shift to furnish the product 71 (path a). On the other hand, transfer of the gold carbenoid moiety across the alkyne in 73 generates 76, via the cyclopropene intermediate 75. Intramolecular cyclisation of the enol acetate on to the gold

Scheme 19 Liu's synthesis of dihydrocyclopenta[b]indoles.

Scheme 20 Shi's Au- and Pt-catalysed cycloaddition of indolyl-allenes.

Review **RSC Advances**

Scheme 21 One-pot synthesis of cyclopentannulated indoles by using sequential gold(I) and Brønsted acid catalysis.

84
$$Ir/L^*$$
 R^2 CO_2Me CO_2Me CO_2Me R^2 CO_2Me R^2

Scheme 22 You's Ir-catalysed intermolecular allylic alkylation reaction of 3-substituted indoles.

carbenoid in 76 followed by deprotonation and protodeauration provides 71 (path b).

In 2015, Shi and co-workers reported a catalyst-dependent stereodivergent and regioselective construction of indolefused heterocycles 78 and 79 from indolyl-allenes 77 (Scheme 20).44 This is an atom-economical method to access indolefused tricyclic systems under mild conditions. Interestingly, reversion in the stereochemistry of an all-carbon quaternary stereocentre in 78 and 79 was observed depending on whether gold or platinum complexes were employed during the [3 + 2]cycloaddition of allenes with indoles. The authors have proposed mechanisms for these transformations based on deuterium labeling studies and control experiments.

Recently, we have disclosed a one-pot indole cyclopentannulation of 1-(2-aminophenyl)pent-4-en-2-ynols which involves a tandem gold(1)-catalysed intramolecular hydroamination of alkynes followed by Brønsted acid catalysed 4π -electrocyclisation sequence (Scheme 21).⁴⁵ The proposed mechanism involves an initial Au(1)-catalysed 5-exo-dig cyclisation to form 2-allylidene indolinols 82. Subsequently, under

Scheme 23 Meggers' asymmetric Nazarov cyclisation catalysed by chiral-at-metal Ir-complex.

acidic conditions, intermediate 82 generates a pentadienyl cationic system 83, which undergoes Nazarov cyclisation to give 81. This strategy was successfully applied to the synthesis of core carbon structure of the natural product polyveoline, in addition to synthesising several other complex molecular architectures.

5. Iridium-catalysed approaches

In 2015, You and co-workers reported an Ir-catalysed asymmetric allylic alkylation of 3-substituted indoles 84 to access

Scheme 24 Rueping's asymmetric Nazarov cyclisation.

RSC Advances Review

Cu(ı)-catalysed borylative cyclisation Scheme 25

structurally complex cyclopentannulated indolines 86 (Scheme 22).46 The transformation is initiated by a Tsuji-Trost reaction between π -allyl iridium complex and indoles (as in 87) leading to the formation of indolines 88. Intramolecular attack of the malonate anion on to the iminium ion (in 88) generates product 86. Versatility of this method was demonstrated via the synthesis of a diverse set of furoindolines, pyrroloindolines and cyclopentaindolines in high regio-, diastereo- and enantioselective manner. Other salient features of this method are: easily accessible starting compounds and inception of three contiguous stereocentres in products.

In 2018, Meggers and co-workers have come up with the synthesis of cyclopenta[b]indoles 91 via asymmetric Nazarov cyclisation by employing chiral-at-metal Ir-complex 90 (Scheme 23).47 The mechanism involves an initial O,O-bidentate

induction is provided by the helical chirality of the C_2 symmetric iridium complex 90. Subsequent deprotonation and reprotonation of 94 furnished the catalyst-bound Nazarov product 95. Base-mediated epimerisation of the 2,3-cis-Nazarov product leads to the thermodynamically stable 2,3-trans product 96. The role of the solvent 1,1,1,3,3,3-hexafluoroisopropanol (HFIP) was found to be crucial in releasing the catalyst bound product 95, which was attributed to its weak acidity. Thereby, functionalised pentannulated indoles 91 were obtained in good yields and excellent enantiopurities. Some of the advantages of this work are: low catalyst loading of Λ -IrS (90, 2 mol%), avoiding dry solvents and inert atmosphere, etc.

Scheme 26 Kwon's Nazarov cyclisation

Copper-catalysed approaches

coordination of the unsaturated β -ketoester 89 to the iridium

complex (92). A conrotatory electrocylisation leads to the

formation of the cationic intermediate 93, and the asymmetric

A Cu-catalysed asymmetric Nazarov cyclisation of indoles was demonstrated by Rueping and co-workers (Scheme 24).48 Through this approach, highly enantioenriched cyclopenta[b] indoles 99 were synthesised in the presence of a chiral [Cu^{II}(box)] complex 98 in good yields. The proposed mechanism involves a six-membered boat conformation 100, formed between Cu(II) and β -keto ester 97 by coordinating with two carbonyl groups. Subsequent isomerisation to 101 and a 4π -electrocylisation afforded desired products 99 in excellent enantioselectivities. The authors have further explained the origin of the enantioselectivity with the aid of DFT studies.

In 2018, Shen and Xu described a borometalation-imine addition cascade reaction for the synthesis of 2,3-cis-disubstituted indolines 103 by using Cu(OTf)2 as precatalyst (Scheme 25).49 The indolines preinstalled with ortho-bromo aryl groups (at indoline C-2 position) were further elaborated to varieties of Review RSC Advances

Scheme 27 Liu and Feng's cascade process leading to the synthesis of polycyclic spiroindolines.

cis-tetrahydroindenoindoles **104** in excellent yields through an intramolecular Suzuki coupling. The exclusive diastereoselective formation of *cis*-2,3-disubstituted indolines is partly attributed to the hypothetical imine–copper coordination complex **105**.

7. Other metal-catalysed approaches

In 2016, Kwon and co-workers demonstrated an interesting Lewis acid mediated Nazarov cyclisation of 1,4-pentadien-3-ols 106 (Scheme 26).⁵⁰ An inexpensive and environmental friendly FeBr₃ was used as a catalyst for the transformation. A diverse range of cyclopenta[*b*]indoles 107 were synthesised in a highly regio- and stereoselective manner under mild Lewis acidic conditions. Regarding mechanism, in presence of FeBr₃, 108 undergoes Nazarov cyclisation to generate the cationic intermediate 109. A subsequent stereoselective intramolecular nucleophilic amination on to 109′ forms 110, which isomerises to cyclopenta[*b*]indoles 107.

Scheme 28 Ag(i)-catalysed approach for cyclopentalblindoles.

In 2015, Liu and Feng have reported an asymmetric dearomatisation of indoles through a cascade Michael/Friedel– Crafts-type reaction sequence to construct polycyclic spiroindolines **114** (Scheme 27).⁵¹ The reaction of 2-isocyanoethyl indoles **111** and alkylidene malonates **112**, catalysed by a chiral *N,N'*-dioxide/Mg^{II} complex **113**, furnished highly functionalised polycyclic indolines **114** possessing up to three stereocentres in good yields, and excellent diastereo- and enantioselectivities. The reaction proceeds *via* an initial Michael addition of isocyanides to alkylidene malonates which subsequently undergo Friedel–Crafts/Mannich-type reaction to generate complex structures.

Recently, we have developed an efficient synthetic protocol for the synthesis of 1,3-disubstituted cyclopenta[b]indoles **116** via a sequential Ag(ι)/Brønsted acid catalysis from easily accessible 3-(2-aminophenyl)-4-pentenyn-3-ols **115** (Scheme 28).⁵² The reaction is initiated by a Ag(ι)-catalysed 5-exo-dig cyclisation (**117**) followed by a Brønsted acid catalysed Nazarov-type cyclisation of pentadienyl cationic system **118** to obtain cyclopenta [b]indoles **116**. This divergent strategy also provides access to furo[3,4-b]indoles **119** via a sequential one-pot Ag(ι)/Bi(ι)/Pd(ι) catalysis.

In 2017, Liu reported an interesting triflic acid-catalysed cascade reaction involving 2-alkylnylbenzyl alcohols **120** and 1-(2-aminophenyl)prop-2-ynols **121** to access an unusual set of *N*,*O*-containing pentacyclic cyclopenta[*b*]indole scaffolds **122** (Scheme 29).⁵³ The transformation involves an *in situ* generation of triflic acid [by combining acetic acid and Sc(OTf)₃], which promotes cycloisomerisation of alkynol **120** to **123** followed by intermolecular substitution to afford an allene intermediate **124**. A sequence of conjugate additions and cyclisation events provide the final product **122**. Several control experiments were performed to get insights about the mechanism. The efficiency of this method lies in its ability to construct pentacyclic cyclopentannulated indoles in a single operation, in which two C–C bonds, one C–O bond and one C–N bond form.

RSC Advances Review

Scheme 29 Liu's cascade approach for the synthesis of pentacyclic cyclopenta[b]indoles.

8. Conclusion

Among indole derivatives, cyclopenta[b]indole scaffold is an important structural motif which is widely found in bioactive natural products and pharmaceutically important compounds. Consequently, an array of synthetic protocols have been developed to prepare this heterocyclic core.⁵⁴ Among which, metalcatalysed approaches are popular due to their versatility, broad substrate scope, scalability, wide functional group tolerance, etc. Through this review, a summary of metal-catalysed transformations leading to the synthesis of cyclopenta[b] indoles is presented. In addition to the inspirational contributions from various research groups, our own efforts pertaining to the one-pot synthesis of cyclopentannulated indoles have also been discussed herein. From these deliberations, it is evident that there exist potential opportunities to devise efficient and straightforward enantioselective approaches, especially promoted by non-precious metals. Towards this, the development of one-pot multiple bond-forming multicomponent strategies can offer a potential solution.

Another important aspect that deserves attention at this stage is the development of biomimetic approaches for the synthesis of cyclopenta[*b*]indoles.⁵⁵ For example, Nature prepares majority of these heterocycles starting from the amino acid tryptophan. So, the evolution of novel chemical transformations leading to the construction of complex molecular architectures by employing readily available materials is desired. We anticipate that more progress would be realised in this direction.

Conflicts of interest

The authors declare no conflict of interest.

Acknowledgements

We sincerely thank IISER Mohali for financial support. T. V. and S. K. B. thank IISER Mohali for research fellowships and B. S. thanks UGC for the research fellowship.

Notes and references

- 1 E. Vitaku, D. T. Smith and J. T. Njardarson, *J. Med. Chem.*, 2014, 57, 10257.
- 2 For general reviews on the synthesis of nitrogen heterocycles, see:(a) G. S. Singh and Z. Y. Desta, *Chem. Rev.*, 2012, **112**, 6104; (b) W. A. Nack and G. Chen, *Synlett*, 2015, **26**, 2505; (c) B. Zhang and A. Studer, *Chem. Soc. Rev.*, 2015, **44**, 3505.
- 3 For selected reviews on indole natural products, see:(a) K. Higuchi and T. Kawasaki, Nat. Prod. Rep., 2007, 24, 843; (b) A. J. Kochanowska-Karamyan and M. T. Hamann, Chem. Rev., 2010, 110, 4489; (c) M. Ishikura, T. Abe, T. Choshi and S. Hibino, Nat. Prod. Rep., 2013, 30, 694; (d) I. S. Marcos, R. F. Moro, I. Costales, P. Basabe and D. Díez, Nat. Prod. Rep., 2013, 30, 1509; (e) W. Xu, D. J. Gavia and Y. Tang, Nat. Prod. Rep., 2014, 31, 1474.
- 4 For recent reviews on the biological significance of indoles, see:(a) S. Olgen, *Mini-Rev. Med. Chem.*, 2013, 13, 1700; (b)
 N. K. Kaushik, N. Kaushik, P. Attri, N. Kumar, C. H. Kim, A. K. Verma and E. H. Choi, *Molecules*, 2013, 18, 6620; (c)
 J. S. Sidhu, R. Singla, E. Y. Mayank and V. Jaitak, *Anticancer Agents Med. Chem.*, 2015, 16, 160.
- 5 (*a*) S. Lim, K. Sim, Z. Abdullah, O. Hiraku, M. Hayashi, K. Komiyama and T.-S. Lam, *J. Nat. Prod.*, 2007, 70, 1380;
 (*b*) S. B. Jones, B. Simmons, A. Mastracchio and D. W. C. MacMillan, *Nature*, 2011, 475, 183; (*c*) D. H. Dethe, R. D. Erande and A. Ranjan, *J. Org. Chem.*, 2013, 78, 10106; (*d*) R. Neelamegam, T. Hellenbrand,

Review

F. A. Schroeder, C. Wang and J. M. Hooker, *J. Med. Chem.*, 2014, 57, 1488.

- 6 (a) K. Stratmann, R. E. Moore, R. Bonjouklian, J. B. Deeter, G. M. L. Patterson, S. Shaffer, C. D. Smith and T. A. Smitka, J. Am. Chem. Soc., 1994, 116, 9935; (b) J. M. Richter, Y. Ishihara, T. Masuda, B. W. Whitefield, T. Llamas, A. Pohjakallio and P. S. Baran, J. Am. Chem. Soc., 2008, 130, 17938.
- 7 J. Nakazawa, J. Yajima, T. Usui, M. Ueki, A. Takatsuki, M. Imoto, Y. Y. Toyoshima and H. Osada, *Chem. Biol.*, 2005, 10, 131.
- 8 (a) Y. C. Kong, K. H. Ng, K. H. Wat, A. Wong, I. F. Saxena, K. F. Cheng, P. P. H. But and H. T. Chang, *Planta Med.*, 1985, 304; (b) C. Kong, K.-F. Cheng, R. C. Cambie and P. G. Waterman, *J. Chem. Soc., Chem. Commun.*, 1985, 47; (c) H. Chen, J. Bai, Z.-F. Fang, S.-S. Yu, S.-G. Ma, S. Xu, Y. Li, J. Qu, J.-H. Ren and L. Li, *J. Nat. Prod.*, 2011, 74, 2438.
- (a) J. A. Jordan, G. W. Gribble and J. C. Badenock, Tetrahedron Lett., 2011, 52, 6772; (b) D. Scarpi, C. Faggi and E. G. Occhiato, J. Nat. Prod., 2017, 80, 2384.
- 10 S. C. Munday-Finch, A. L. Wilkins and C. O. Miles, *J. Agric. Food Chem.*, 1998, 46, 590.
- 11 E. Lai, I. De Lepeleire, T. M. Crumley, F. Liu, L. A. Wenning, N. Michiels, E. Vets, G. O'Neill, J. A. Wagner and K. Gottesdiener, *Clin. Pharmacol. Ther.*, 2007, 81, 849.
- 12 (a) A. Cave, H. Guinaudeau, H. M. Leboeuf, A. Ramahatra and J. Razafindrazaka, *Planta Med.*, 1978, 33, 243; (b) B. Nyasse, I. Ngantchou, J.-J. Nono and B. Schneider, *Nat. Prod. Res.*, 2006, 20, 391; (c) I. Ngantchou, B. Nyasse, C. Denier, C. Blonski, V. Hannaert and B. Schneider, *Bioorg. Med. Chem. Lett.*, 2010, 20, 3495; (d) S. F. Kouam, A. W. Ngouonpe, M. Lamshoft, F. M. Talontsi, J. O. Bauer, C. Strohmann, B. T. Ngadjui, H. Laatsch and M. Spiteller, *Phytochemistry*, 2014, 105, 52.
- 13 (a) W. Tan, X. Li, Y. X. Gong, M. D. Ge and F. Shi, Chem. Commun., 2014, 50, 15901; (b) H. Li, R. P. Hughes and J. J. Wu, J. Am. Chem. Soc., 2014, 136, 6288.
- 14 S. Gérard, A. Renzetti, B. Lefevre, A. Fontana, P. Maria and J. Sapi, *Tetrahedron*, 2010, **66**, 3065.
- 15 W. Zi, H. Wu and F. D. Toste, *J. Am. Chem. Soc.*, 2015, **137**, 3225.
- 16 (a) G. M. Shelke, V. K. Rao, R. Tiwari, B. S. Chhikara, K. Parang and A. Kumar, *RSC Adv.*, 2013, 3, 22346; (b) M. Rueping and B. J. Nachtsheim, *Top. Curr. Chem.*, 2011, 311, 115.
- 17 (a) J. A. Malona, J. M. Colbourne and A. J. Frontier, *Org. Lett.*, 2006, 8, 5661; (b) J. Davies and D. Leonori, *Chem. Commun.*, 2014, 50, 15171; (c) N. S. Sheikh, *Org. Biomol. Chem.*, 2015, 13, 10774.
- 18 (a) A. Ekebergh, I. Karlsson, R. Mete, Y. Pan, A. Börje and J. Mårtensson, *Org. Lett.*, 2011, 13, 4458; (b) A. Ekebergh, A. Börje and J. Mårtensson, *Org. Lett.*, 2012, 14, 6274.
- 19 (a) B. A. Haag, Z. G. Zhang, J. S. Li and P. Knochel, Angew. Chem., Int. Ed., 2010, 49, 9513; (b) A. G. K. Reddy and G. Satyanarayana, Synthesis, 2015, 47, 1269.
- 20 A. Ganesan and C. H. Heathcock, *Tetrahedron Lett.*, 1993, 34, 439.

- 21 (a) O. Miyata, N. Takeda, Y. Kimura, Y. Takemoto, N. Tohnai,
 M. Miyata and T. Naito, *Tetrahedron*, 2006, 62, 3629; (b)
 O. Miyata and T. Naito, *Chem. Commun.*, 1999, 2429.
- 22 A. Palmieri and M. Petrini, J. Org. Chem., 2007, 72, 1863.
- 23 F. Shi, H.-H. Zhang, X.-X. Sun, J. Liang, T. Fan and S. –J. Tu, Chem.–Eur. J., 2015, 21, 3465.
- 24 E. P. Balskus, R. J. Case and C. T. Walsh, *FEMS Microbiol. Ecol.*, 2011, 77, 322.
- 25 M. Petrovic and E. G. Occhiato, Chem.-Asian J., 2016, 11, 642.
- 26 J. Chen, X. Han and X. Lu, J. Org. Chem., 2017, 82, 1977.
- 27 S. Duan, B. Cheng, X. Duan, B. Bao, Y. Li and H. Zhai, Org. Lett., 2018, 20, 1417.
- 28 S. Kotha and R. Gunta, J. Org. Chem., 2017, 82, 8527.
- 29 A. Ekebergh, C. Lingblom, P. Sandin, C. Wennerås and J. Mårtensson, *Org. Biomol. Chem.*, 2015, 13, 3382.
- 30 S. S. K. Boominathan and J.-J. Wang, *Chem.-Eur. J.*, 2015, 21, 17044.
- 31 M. Laugeois, J. Ling, C. Férard, V. Michelet, V. Ratovelomanana-Vidal and M. R. Vitale, *Org. Lett.*, 2017, 19, 2266.
- 32 M. Sun, Z.-Q. Zhu, L. Gu, X. Wan, G.-J. Mei and F. Shi, *J. Org. Chem.*, 2018, **83**, 2341.
- 33 (a) Y. S. Gee, D. J. Rivinoja, S. M. Wales, M. G. Gardiner,
 J. H. Ryan and C. J. T. Hyland, J. Org. Chem., 2017, 82,
 13517; (b) D. J. Rivinoja, Y. S. Gee, M. G. Gardiner,
 J. H. Ryan and C. J. T. Hyland, ACS Catal., 2017, 7, 1053.
- 34 J.-Q. Zhang, F. Tong, B.-B. Sun, W.-T. Fan, J.-B. Chen, D. Hu and X.-W. Wang, *J. Org. Chem.*, 2018, **83**, 2882.
- 35 S. K. Bankar, B. Singh, P. Tung and S. S. V. Ramasastry, *Angew. Chem., Int. Ed.*, 2018, **57**, 1678.
- 36 K. L. Vickerman and L. M. Stanley, Org. Lett., 2017, 19, 5054.
- 37 C. Jing, Q.-Q. Cheng, Y. Deng, H. Arman and M. P. Doyle, *Org. Lett.*, 2016, **18**, 4550.
- 38 L. Jiang, W. Jin and W. Hu, ACS Catal., 2016, 6, 6146.
- 39 C.-Y. Wu, Y.-N. Yu and M.-H. Xu, Org. Lett., 2017, 19, 384.
- 40 K. Chen, Z.-Z. Zhu, J.-X. Liu, X.-Y. Tang, Y. Weib and M. Shi, *Chem. Commun.*, 2018, 54, 2870.
- 41 S. Dhiman and S. S. V. Ramasastry, *Chem. Commun.*, 2015, **51**, 557.
- 42 D. Scarpi, M. Petrović, B. Fiser, E. Gómez-Bengoa and E. G. Occhiato, *Org. Lett.*, 2016, **18**, 3922.
- 43 J. Liu, M. Chen, L. Zhang and Y. Liu, *Chem.-Eur. J.*, 2015, 21, 1009
- 44 L.-Y. Mei, Y. Wei, X.-Y. Tang and M. Shi, *J. Am. Chem. Soc.*, 2015, 137, 8131.
- 45 S. Dhiman and S. S. V. Ramasastry, Org. Lett., 2015, 17, 5116.
- 46 X. Zhang, W.-B. Liu, H.-F. Tua and S.-L. You, *Chem. Sci.*, 2015, **6**, 4525.
- 47 T. Mietke, T. Cruchter, V. A. Larionov, T. Faber, K. Harmsa and E. Meggers, *Adv. Synth. Catal.*, 2018, 360, DOI: 10.1002/adsc.201701546.
- 48 S. Raja, M. Nakajima and M. Rueping, *Angew. Chem. Int. Ed*, 2015, **54**, 2762.
- 49 H.-M. Wang, H. Zhou, Q.-S. Xu, T.-S. Liu, C.-L. Zhuang, M.-H. Shen and H.-D. Xu, *Org. Lett.*, 2018, **20**, 1777.
- 50 Z. Wang, X. Xu, Z. Gu, W. Feng, H. Qian, Z. Li, X. Suna and O. Kwon, *Chem. Commun.*, 2016, 52, 2811.

RSC Advances

- 51 X. Zhao, X. Liu, H. Mei, J. Guo, L. Lin and X. Feng, *Angew*. 54 While this m
- Chem. Int. Ed, 2015, 54, 4032.
 52 Manisha, S. Dhiman, J. Mathew and S. S. V. Ramasastry, Org. Biomol. Chem., 2016, 14, 5563.
- 53 X.-F. Mao, X.-P. Zhu, D.-Y. Li, L.-L. Jiang and P.-N. Liu, *Chem. Commun.*, 2017, 53, 8608.
- 54 While this manuscript was under review, the following gold-catalysed approach for the synthesis of cyclopenta[*b*]indoles was published: M. Lin, L. Zhu, J. Xia, Y. Yu, J. Chen, Z. Mao and X. Huang, *Adv. Synth. Catal.*, 2018, DOI: 10.1002/adsc.201800001.
- 55 D. H. Dethe and B. V. Kumar, Org. Chem. Front., 2015, 2, 548.