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REVIEW



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N-Propargylic β -enaminocarbonyls: powerful and versatile building blocks in organic synthesis

Nitrogen-containing heterocyclic compounds are not only prevalent in an extensive number of natural products and synthetic pharmaceuticals but are also used as building blocks in organic synthesis. The efficient preparation of highly functionalized *N*-heterocycles from cheap and easily available starting materials has therefore become of central interest for synthetic organic chemists. This review gives

an overview of new developments in synthesis of highly substituted N-heterocycles, including

pyrroles, pyridines, pyrrolines, piperidines, azepines, and related compounds, from N-propargylic

 β -enaminocarbonyls (N-propargylic β -enaminones and β -enaminoesters) in recent years. Mechanistic

aspects of the reactions are considered and discussed in detail.

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1. Introduction

Needless to say, nitrogen-based heterocycles, including pyrroles, pyridines, pyrrolines, piperidines, azepines, and related compounds, are key structural units for a large array of drugs and natural products.¹ Therefore, the development of practical and convenient methodologies that benefit from cheap, readily available, and relatively simple substrates for the construction of these *N*-heterocyclic compounds is highly

^bDepartment of Chemistry, Tabriz Branch, Islamic Azad University, Tabriz, Iran. E-mail: Ledjlali@iaut.ac.ir desirable. *N*-propargylamines represent one of the low-cost, readily accessible, and versatile building blocks in organic synthesis for generation of *N*-heterocyclic molecules.² *N*propargylic β -enaminocarbonyls are one of the novel and specific class of these compounds having diverse reaction patterns and applied in the assembly of various heterocycles (Fig. 1). Since a large number of developments in the use of *N*propargylic β -enaminocarbonyls in heterocyclic synthesis have occurred from 2006 to present, a comprehensive review on this interesting field seems to be timely. In this review, we have classified these reactions based on the desired products. Mechanistic aspects of the reactions are considered and discussed in detail.



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2. Pyrroles

Pioneering works devoted to the synthesis of functionalized pyrroles 2 through intramolecular cyclization of *N*-propargylic β -enaminones 1 have been reported by Cacchi *et al.*, who used Cs₂CO₃ as catalyst. This reaction was run in anhydrous DMSO at room temperature and tolerated the presence of a variety of sensitive functional groups, such as hydroxyl, nitro, methoxy, acetyl, ester, bromo, and chloro groups (Scheme 1). This made possible the further derivatization of the products. According to the author proposed mechanism, this transformation proceeded *via* a 5-*exo-dig* cyclization/protonation/isomerization sequential process.³

Subsequently, the Komeyama laboratory reported the synthesis of 3-carboxylated pyrroles 5 through a bismuth catalyzed intramolecular cyclization of *N*-propargylic β -enaminoesters **A**



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sity, Tabriz Branch as Associate Professor. Her research interests include organic synthesis and new methodologies in organic synthesis. (generated *in situ* from *N*-propargyl amine **3** and β -keto esters **4**) in refluxing toluene (Scheme 2a). They showed that the use of **1**,3-diketones (instead of β -keto esters) as starting materials gave mixtures of pyrroles **5** and **6** (Scheme 2b). These observations would be explained by the instability of ⁺C(O)OR. Thus, in the case of β -keto esters, deprotonate is preferred to decarboxylation. But in the case of **1**,3-diketones, competition between the deprotonation and deacylation gave a mixture of products (Scheme 3).⁴

Following these works, Saito, Konishi, and Hanzawa were able to demonstrate that a series of 3-carboxylated pyrroles 8 could be obtained from corresponding *N*-propargylic β -enaminoesters 7 through a silver catalyzed amino-Claisen rearrangement/ heterocyclization sequential process. This [(IP)Au(MeCN)]BF4 catalyzed reaction is equally efficient for both the internal and external alkynes. The reaction was run in CH₂Cl₂-HFIP (3 : 1) at room temperature and generally provided the highly substituted pyrroles 8 in good to high yields (Scheme 4a).⁵ Shortly afterward, Chiba et al. developed a new methodology for the construction of 4-carbonylpyrroles 10 by the copper-mediated aerobic carbooxvgenation of N-propargylic β -enaminoesters 9 under oxygen atmosphere (Scheme 4b). Among the various copper catalysts like CuBr+SMe₂, CuCl₂, CuCl, CuBr₂, Cu(OAc)₂; CuCl₂ was the most efficient for the transformation. DABCO (1,4-diazabicyclo[2.2.2] octane) is required as additive and the DMSO as the solvent for this method and this protocol is applicable for the both electron reach and electron poor substrates.6

In 2012, Zhao and co-workers published an efficient protocol for the synthesis 2-ethylthio-pyrroles **13** *via* base catalyzed 5-*exodig* cyclization of *N*-propargylic β -enaminoes **A** were prepared *in situ* by intermolecular Michael addition of N-propargylamines **11** to α -acylketene dithioacetals **12** (Scheme 5). The authors determined that the use of K₂CO₃/DMF system provided the optimal conditions for this reaction. The most striking feature of this protocol is excellent functional group tolerance to



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Scheme 1 Base-catalyzed synthesis of pyrroles 2 from *N*-propargylic β -enaminones 1.



Fig. 1 Some important synthetic compounds derived from N-propargylic β -enaminocarbonyls.

produce highly functionalized pyrroles **13** from simple starting materials. It is noted that when external *N*-propargylamines ($\mathbb{R}^1 = \mathbf{H}$) were used as substrates, the reaction was performed in the absence of an external base and the corresponding products were obtained in high to excellent yields.⁷

Recently, Jin and co-workers demonstrated that polysubstituted pyrroles **16** can be readily prepared in the reaction of *N*-propargylamines **14** with activated alkynes **15** in the presence of 20 mol% of K_3PO_4 as catalyst in DMSO at 120 °C (Scheme 6) The authors suggested that the reaction proceeds *via* the formation of *N*-propargylic β -enaminoester intermediates **A** through Michael addition of *N*-propargylamines **14** to alkynes **15**, which after a 5-*exo-dig* cyclization process delivers the 3carboxylated pyrroles **16** in good yields.⁸

Later, Zhang's research team reported a direct synthesis of polysubstituted pyrrole derivatives **18** *via* base-catalyzed intramolecular cyclization of *N*-propargylic β -enaminones **17** (Scheme 7). Thus, the careful analysis of the optimized reactions revealed that the optimum condition for this transformation was the addition of 1 equiv. of ^tBuOK, at room temperature, to a solution of *N*-propargylic β -enaminones **17** in DMF. The reaction conditions allowed the use of substrates bearing a variety of sensitive functional groups including flouro, chloro, methoxy, and acetyl functionalities. According to the author proposed mechanism, the reaction proceeded *via* a propargyl–allenyl isomerization/5-*exo-dig* cyclization/proton transfer sequential process.⁹

A notable contribution to this field was reported by Wan and co-workers in 2012. They found that β -(arylsulfonyl)methyl pyrroles **20** could be prepared from *N*-propargylic β -enaminoesters **19** using 10 mol% of Cs₂CO₃ as base in DMF at 80 °C.



Scheme 2 (a) One-pot synthesis of pyrroles 5 from *N*-propargyl amine 3 and β -keto esters 4; (b) Synthesis of pyrroles 5 and 6 from *N*-propargyl amine 3 and 1,3-diketones 4.



Scheme 3 Possible route for the formation of 5 and 6.



Scheme 4 (a) Synthesis of highly substituted pyrroles 8 through Au-catalyzed cyclization of *N*-propargylic β -enaminoesters 7; (b) Synthesis of 4-carbonylpyrroles 10 via copper-mediated aerobic carbooxygenation of *N*-propargylic β -enaminoesters 9.







Scheme 6 Synthesis of polysubstituted pyrroles 16 from N-propargylamines 14 and activated alkynes 15.



- R^4 = Ph, 4-Me-C₆H₄, 4-Ph-C₆H₄, 4-F-C₆H₄, 4-Cl-C₆H₄, 3-MeO-C₆H₄, 2-Me-C₆H₄, 2-Cl-C₆H₄, 3,4-Cl₂-C₆H₃
- Scheme 7 Base-catalyzed synthesis of pyrrole derivatives 18 described by Zhang.

According to a plausible mechanistic pathway, this reaction proceeds through an aza-Claisen rearrangment/cyclization/ sulfonyl group migration/aromatization sequential process (Scheme 8a). The authors claimed their reaction was the first example of sulfonyl group migration in pyrrole synthesis. The results demonstrated that the electronic characters of substrates had little effect on the rate of the reaction. Under optimized conditions, the reaction tolerates both electrondonating and electron-withdrawing substituents and gave the corresponding highly substituted N–H free pyrroles **20** in high to excellent yields. Interestingly, when the reaction was carried out in DMF at 140 °C under catalyst-free conditions, α -(aryl-sulfonyl)methyl pyrroles **21** were isolated instead of β -(arylsulfonyl)methyl pyrroles **20**. The mechanism proposed by the authors to explain this transformation is outlined in Scheme 8b.¹⁰ Recently, the same authors applied this methodology to synthesis of a series of 2-trifluoromethyl-5-(arylsulfonyl)methyl pyrroles from corresponding trifluoromethyl-substituted *N*-propargylic β -enaminoesters.¹¹

The groups of Wan also were able to demonstrate that a series of sulfonyl vinyl-substituted pyrroles **23** could be obtained from the corresponding phenoxysubstituted *N*-propargylic β -enaminoesters **22** employing 20 mol% of Cs₂CO₃ as catalyst in anhydrous DMF (Scheme 9). The reaction proceeds along the similar mechanistic pathway that described in Scheme 4a to afford intermediate **A**. This intermediate undergoes spontaneous phenol elimination to produce the observed products **23**.¹²

More recently, Cui and co-workers described a general and efficient synthesis of a diverse collection of biologically important highly substituted *N*-(2-pyridyl)pyrroles **25** *via* the KOHpromoted regiospecific cyclization of the corresponding *N*-



Scheme 8 (a) Base-catalyzed synthesis of β -(arylsulfonyl)methyl pyrroles 20 developed by Wan; (b) thermal cyclization of 19 for the synthesis of α -(arylsulfonyl)methyl pyrroles 21 reported by Wan.



 $\label{eq:R1=Ph} \begin{array}{l} R^1 = Ph, \ 4-Me-C_6H_4, \ 4-F-C_6H_4, \ 4-Br-C_6H_4, \ 4-I-C_6H_4, \ 2-OMe-C_6H_4, \ 2-Cl-C_6H_4, \ 2-CF_3-C_6H_4, \ 1-naphthyl \\ R^2 = Ph, \ 4-Me-C_6H_4, \ 4-Cl-C_6H_4 \end{array}$





Scheme 10 Base-mediated cascade synthesis of N-(2-pyridyl) pyrroles 25 from N-propargylic β -enaminones 24 developed by Cui.

propargylic β -enaminones 24 under reflux conditions in acetonitrile (Scheme 10). This procedure simultaneously facilitated the construction of a pyridine scaffold and generation of a pyrrole ring from simple starting materials and the only by-

3. Pyrrolines

G to produce final product 25.13

In 2014, the Karunakar group have developed a new and straightforward approach for the synthesis of substituted 1-pyrrolines **29** *via* a one-pot, Au(I)-catalyzed reaction between *N*-

product is one equivalent of water. The proposed mechanism for this reaction involves the following steps (Scheme 11):

(i) formation of a pyrrole anion intermediate B through

intramolecular 5-exo-dig cyclization of N-propargylic β -enami-

none 24; (ii) formation of a 7-oxa-5-aza-bicyclo[4.1.0]hepta-2,4-

diene intermediate F from another molecule of N-propargylic

 β -enaminone 24 via propargyl-allenyl isomerization/

intramolecular 7-exo-dig cyclization/ 6π -electrocyclization/walk

rearrangement sequential process; (iii) S_N2 attack of interme-

diate B to dihydropyridine F to generate trans-2,3- dihydropyr-

idine intermediate G; and (iv) protonation and aromatization of



Scheme 11 Mechanism that accounts for the formation of 25



Scheme 12 (a) Synthesis of pyrrolines 29 developed by Karunakar; (b) plausible mechanism for the formation of 29



 $R^3 = Me, Ph, 4-CN-C_6H_4$

Scheme 13 Cu(i)-catalyzed synthesis of pyridines 31 from *N*-propargylic β -enaminones 30.

propargylic β -enaminones **26** and arynes **28** (generated *in situ* from 2-(trimethylsilyl)aryl trifluoromethanesulfonates **27** and CsF) (Scheme 12a). AuClPEt₃/AgSbF₆ was the best catalytic system and acetonitrile was the best solvent for this reaction.

The results demonstrated that the enaminones bearing electron donating groups, like Me and OMe, gave higher yields than those having an electron withdrawing group, like F group. The author proposed mechanism for this transformation is depicted in Scheme 12b.¹⁴

4. Pyridines

After the pioneering work of Cacchi and co-workers in 2008, who showed that highly substituted pyridines **31** could be readily synthesized in one step from easy available *N*-propargylic β -enaminones **30** through Cu-catalyzed 6-*endo-dig* cyclization strategy (Scheme 13),³ this methodology has developed into a general powerful tool for the synthesis of a wide range of pyridine derivatives, including natural products.¹⁵ In 2013, Wan's group developed a convenient one-pot three step methodology for the synthesis of 2,3,4,6-tetrasubstituted pyridines **33** from the *N*-sufonylated *N*-propargylic β -enaminoesters **32** through an intramolecular cyclization/sulfinyl acids elimination cascade





Scheme 14 Synthesis of 2,3,4,6-tetrasubstituted pyridines 33 described by Cacchi.



Scheme 15 Synthesis of 5-iodopyridines 35 from N-propargylic β-enaminones 34 via iodinemediated electrophilic cyclization.



Nu-H = indoles, pyrroles, imidazoles, pyrazoles, and carbazole

process (Scheme 14). Thus, in the first step a solution of **32** (0.2 mmol) in ethanol (2 mL) was heated at 70-100 °C for 16 h under argon atmosphere. In the next step the ethanol solvent was removed *in vacuo*. Finally, to the residue was added DMF (1 mL) and the mixture was heated at 140 °C for 4-36 h under argon atmosphere.¹⁶

Recently an alternative intramolecular electrophilic cyclization of *N*-propargylic β -enaminones was reported by Zora and coworkers. In this study, 5-iodopyridines **35** were obtained in good yields by reaction of *N*-propargylic β -enaminones **34** with 3.0 equiv of I₂ in MeCN at 82 °C in the presence of NaHCO₃ as base. The reaction proceeded *via* a 6-*endo-dig* process, giving only the six-membered rings. The authors proposed a mechanism initiated by the reaction of the alkyne moiety of starting β enaminone **34** and iodine followed by an electrophilic cyclization with subsequent deprotonation/oxidation to explain the cyclized products obtained (Scheme 15).¹⁷ Subsequently, the above cyclization products, applied by the same authors to the synthesis of more functionalized pyridines *via* transition metalcatalyzed processes, such as Sonogashira and Suzuki–Miyaura cross-coupling reactions.^{18,19}

Recently, Cheng *et al.* developed a simple and efficient methodology for the synthesis of 2-(1-heteroaryl) pyridines **38** by the reaction between 1,3-diphenyl-3-(prop-2-ynylamino)prop-2en-1-one **36** and *N*-heteroarenes **37** (Scheme 16).²⁰ NaOH was the most efficient catalyst among the bases such as LiO^tBu, NaO^tBu, K₂CO₃, KOH, Et₃N *etc* for this reaction. This NaOH-



Scheme 17 Mechanistic proposal for the reaction in Scheme 15.



Scheme 18 (a) Rh-catalyzed synthesis of 1,6-dihydropyridine-3-carboxylates 40 reported by Kim and Lee; (b) Mechanism that accounts for the formation of 40.



Scheme 19 Au-catalyzed synthesis of highly substituted 2,5-dihydropyridines 43 from *N*-propargyl amines 41 and β -keto esters 42 through a *N*-propargylic β -enaminoester intermediate A.

catalyzed reaction is applicable for a diverse set of nitrogen nucleophilic source, such as indole, pyrrole, imidazole, pyrazole, carbazole, and benzimidazole. However, the reaction of benzimidazole and **36** gave the desired product in unsatisfactory yield and aniline, benzylamine, succinimide, acetanilide, and benzyl thiol failed to participate in the reaction. According to the suggested reaction mechanism (Scheme 17), the reaction proceeds *via* a propargyl–allenyl isomerization/enolization/7*exo-dig* cyclization/ 6π -electrocyclization/walk rearrangement/ epoxide ring opening/dehydrative aromatization sequential process.

5. Dihydropyridine

N-propargylic β -enaminoesters **39** were found by Kim and Lee to undergo intramolecular cyclization in the presence of catalytic amount of [Rh(C₂H₂)₂Cl]₂, using P(4 F-C₆H₄)₃ as ligand and DABCO as base in DMF at room temperature, to afford 1,6-dihydropyridine-3-carboxylates **40** in moderate yields (Scheme 18a). The mechanistic course of this reaction sequence is shown in Scheme 18b, and involves the initial formation of the rhodium vinylidene complex **A** from the reaction of alkyne moiety of **39** with rhodium. Intramolecular cyclization of **A** yields intermediate **B**, which undergoes deprotonation to furnish intermediate **C**. Finally, protodemetalation of intermediate **C** affords the observed dihydropyridines **40**.²¹

The preparation of 2,5-dihydropyridines 43 can be achieved through a 6-*endo-dig* cyclization of *N*-propargylic β -enaminesters **A** (generated *in situ* from condensation of *N*-propargyl



Scheme 20 Construction of trifluoromethylated 1,2-dihydropyridines 45 through Au(i)-catalyzed 6-*endo-dig* cyclization of *N*-propargylic β -enaminones 44.



Scheme 21 Synthesis of highly substituted 1,2-dihydropyridines 47 through Cu(i)-catalyzed 6-*endo* cyclization of *N*-propargylic β -enamino-carbonyls 46.



Scheme 22 (a) N-iodosuccinimide-induced electrophilic iodocyclization of N-propargylic β -enaminoesters 48 to 3-iodo-1,2-dihydropyridine product 49; (b) Proposed mechanism for formation of 49.

3



Scheme 23 Catalyst-free synthesis of 3-azabicyclo[4.1.0]hepta-2,4-dienes 52 reported by Karunakar.



R = H, "Pr, Ph, 4-OMe-C₆H₄, 4-NO₂-C₆H₄, 2-NO₂-C₆H₄, 2-Br-C₆H₄, 2-CO₂Me

Scheme 24 Wang's synthesis of azaanthraquinones 54 from *N*-propargylamino quinones 53.

amines **41** and β -keto esters **42**) (Scheme 19). The best condition used for this transformation was 5 mol% of NaAuCl₄ and MeOH at 40 °C.²²

In 2013, Martins and co-workers disclosed a mild and practical access to trifluoromethylated 1,2-dihydropyridines **45** through Au(I)-catalyzed 6-*endo-dig* cyclization of corresponding *N*-propargylic β -enaminones **44** (Scheme 20). A number of 1,2dihydropyridines containing aromatic or aliphatic motifs were readily afforded in high yields. Mechanistically, the triple bond is activated by coordination with silver to form a π -alkyne complex **A**, which then undergoes a 6-*endo-dig* cyclization to produce cationic intermediate **B**. Subsequently, an intramolecular proto-demetalation leads to the product 44.²³ In a closely related investigation, the Oguri group found that *N*propargylic β -enaminocarbonyls 46 were converted to the corresponding substituted 1,2-dihydropyridines 47, *via* 6-*endo-dig* cyclization using [Cu(Xantphos)(MeCN)]PF₆ as catalyst in DCM at room temperature (Scheme 21).²⁴

Recently, Wan and co-workers performed the iodocyclization of *N*-propargylic β -enaminoesters **48** with *N*-iodosuccinimide as electrophilic source and developed a route to obtain 3-iodo-1,2 dihydropyridines **49** in good yields (Scheme 22a). A plausible mechanism for these electrophilic cyclizations is shown in Scheme 22b, where intermediate **A**, generated by the attack of iodonium ion to the alkyne moiety, undergoes 6-*endo-dig* cyclization, and then deprotonation, to afford 3-iodo-1,2-dihydropyridine product **49**.²⁵



Scheme 25 Formation of 3-iodo-1-azaanthraquinones 56 by the iodocyclization of N-propargylamino quinones 55.

Review

In 2014, Karunakar *et al.* synthesized 3-azabicyclo[4.1.0] hepta-2,4-dienes **52**, a cyclopropane fused dihydropyridine system, by the catalyst- and base-free cascade reaction between internal *N*-propargylic β -enaminones **50** and acetylenedicarboxylates **51** (Scheme 23). Among the various solvents like DMF, THF, DCM, EtOH, EtOAc, CHCl₃, MeCN, toluene, 1,4-dioxane, H₂O; MeCN was the most efficient for this reaction. The results demonstrated that *N*-propargylic β -enaminones bearing electron-donating groups afforded higher yields in comparison to those bearing electron- withdrawing groups. Following is the decreasing order of reactivity of acetylenedicarboxylates in this reaction: diethyl but-2-ynedioate > di-*tert*-butyl but-2-ynedioate > dimethyl but-2-ynedioate.²⁶

6. 1-Azaanthraquinones

In 2010, the groups of Wang published an elegant and novel protocol for the synthesis of substituted azaanthraquinones using Au(i)-catalyzed 6-*endo-dig* cycloisomerization of *N*-propargylamino quinones **53**.²⁷ Thus, the optimized reactions revealed that the optimum condition for this cyclization reaction was the combination of Ph₃PAuCl (10 mol%) and AgOTf (10 mol%) as catalytic system using acetic acid as the solvent, at 100 °C. Under optimized conditions, the reaction tolerates both terminal and internal alkynes and gave the products **54** in good yields (Scheme 24). This reaction proceeds through 6-*endo-dig* cyclization followed by a sequential tautomerization/aromatization. It is noted that the protocol was successfully applied for the synthesis of alkaloid cleistopholine and its analogues.

In a subsequent study, the same research team reported the preparation of a variety of 3-iodo-1-azaanthraquinones **56** in moderate to high yields *via* iodocyclization of *N*-propargylamino quinones **55** (Scheme 25). The reactions were carried out in

nitromethane at 100 °C with 3 equiv of molecular iodine as the electrophilic source and NaHCO₃ (2 equiv) as the base. The mechanism shown in Scheme 26 was proposed for this process. It consists of the following key steps: (1) initial formation of iodonium ion **A** *via* coordination of iodine with the C–C triple bond of alkyne; (2) nucleophilic attack by the double bond of the aminoquinone through 6-*endo-dig* manner to afford the intermediate **B**; and (3) oxidative aromatization of intermediate **B** to give the observed product **36**.²⁸ Soon after, the authors extended this chemistry to synthesis of 3-chloro-1-azaanthraquinones employing CuCl₂ as electrophilic source.²⁹

Follow these works, the authors reported the preparation of a variety of pentacyclic pyrido[4,3,2-mn]acridin-8-ones **58** in good to high yields *via* an Au(i)-catalyzed domino reaction of *N*propargylaminoquinones **57** (Scheme 27). Among the various gold catalysts like AuCl, AuCl₃, Ph₃PAuCl, NaAuCl₄·H₂O; Ph₃-PAuCl was the most efficient for the transformation. The results demonstrated that the substrates bearing electron-donating groups on the aniline ring afforded relatively higher yields in comparison to those bearing electron withdrawing groups.³⁰

7. 1,4-Oxazepines

In 2015, the Karunakar group have developed a new and straightforward approach for the synthesis of 1,4-oxazepine derivatives **60** *via* a one-pot gold-catalyzed intramolecular cyclization of *N*-propargylic β -enaminones **59** (Scheme 28). Thus, the careful analysis of the optimized reactions revealed that the optimum condition for this cyclization was the addition of AuCl₃ (10 mol%), and AgSbF₆ (15 mol%), at 28 °C, to a solution of *N*-propargylic β -enaminones in MeOH. The reaction scope appears that the *N*-propargylic β -enaminones with electron-donating groups on the benzene rings are reactive than



Scheme 26 Mechanism that accounts for the formation of 56.



Scheme 27 Au(1)-catalyzed synthesis of pentacyclic pyrido[4,3,2-mn]acridin-8-ones 58 from N-propargylaminoquinones 57.



Scheme 28 Au-catalyzed intramolecular cyclization of N-propargylic β-enaminones 59 for the synthesis of 1,4-Oxazepine derivatives 60.

those with electron-poor aryl groups. According to mechanistic studies, it proceeds through the coordination of AuCl₃ to the triple bond of 59, following the 7-exo-dig cyclization via nucleophilic attack of carbonyl oxygen onto the activated triple bond to give intermediate **B**, which undergoes protodemetalation to yield 1,4-oxazepine derivatives 60.31

8. Azepines

The reported methods for synthesis of azepine cores via intramolecular cyclization of *N*-propargylic β -enaminocarbonyls are very scarce and to the best of our awareness there is only one report for such reactions. More recently, Sahoo's research team reported a beautiful protocol for synthesis of hitherto unknown cyclobutene fused azepine heterocycles 62 by cycloisomerization of corresponding alkyne-tethered ketene N.N-acetals 61 in the



Scheme 29 Au-catalyzed intramolecular cyclization of alkyne-tethered ketene N,N-acetals 61 for the synthesis of cyclobutene fused azepine heterocycles 62.



Scheme 30 Mechanistic proposal for the reactions in Scheme 18.

presence of [JohnphosAu(I) (MeCN)]⁺SbF₆⁻ as catalyst (Scheme 29). This reaction was run in 1,2-dichloroethane at room temperature and tolerated various sensitive functional groups (including nitro, cyano, chloro, ketone, and ester), and in all cases provided fused azepines 2 in moderate to good yields.32 In this study, the authors also evaluated the mechanistic details of this electrophilic cyclization. To determine the advanced intermediates of the reaction, the authors monitored the reaction by ¹H NMR spectroscopy. Among the data that could be obtained by ¹H NMR spectroscopy, the most relevant for the proposal was those shown in Scheme 30.

9. Summary and outlook

Synthesis of nitrogen-based heterocycles via cyclization of Npropargylic β -enaminocarbonyls, in both inter- and interamolecular manner, have witnessed rapid and comprehensive development in the past ten years. In comparison with many well-established traditional and modern methods, the preparation of N-heterocycles (such as pyrroles, pyrrolines, pyridines, piperidine as well as azaanthraquinones, and so forth) from titled compounds showed a wider tolerance to important functional groups. This made possible the further derivatization of the products. As illustrated, high atom economy and shorter synthetic routes are the key features of these reactions. Also interesting is the fact that most of the cyclization reactions covered in this review could be easily adapted to the gram-scale synthesis of N-heterocycles. The present methodologies are meaningful and particularly attractive for the fact that those Nheterocycles are the structural component of a vast number of biologically active natural and unnatural compounds. We believe that these salient features of *N*-propargylic β -enaminocarbonyls in the synthesis of N-heterocycles will further elicit widespread attention in the quest for more applications and utilities, serving as a powerful and versatile substrate in the synthesis of important N-heterocycles and complex natural products.

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