Gold and silver nanoparticle-catalyzed synthesis of heterocyclic compounds

Rupinder Kaur¹, Jitender Bariwal^{2,3}, Leonid G. Voskressensky⁴,
Erik V. Van der Eycken^{3,4*}

¹ ISF College of Pharmacy,

Moga 142001, Punjab, India; e-mail: rupinder.pharmacy@gmail.com

² College of Pharmacy, University of Nebraska Medical Center,

Omaha, NE-68198, USA; e-mail: jitender.bariwal@gmail.com

³ University of Leuven,

Celestijnenlaan 200F, Leuven 3001, Belgium; e-mail: erik.vandereycken@kuleuven.be

⁴ RUDN University,

6 Miklukho-Maklaya St., Moscow 117198, Russia; e-mail: lvoskressensky@sci.pfu.edu.ru

Submitted March 1, 2018

Accepted March 28, 2018

In recent years, metallic nanoparticles have been a constant subject of attention for researchers. The transition of metal from microparticles to nanoparticles leads to a substantial change in its physical and chemical properties. Nanoparticles as catalyst in organic reactions provide additional benefits such as catalyst recycling, scale-up of reactions using continuous flow processes, and easy purification of the reaction mixture offering green and cost-effective alternatives. This review highlights some of the significant gold and silver nanoparticle-catalyzed reactions for the synthesis of various heterocyclic compounds. A brief synthetic methodology for different heterocyclic compounds is discussed along with the scope of the reaction.

Keywords: heterocyclic compounds, indole, spiroindoline, triazole, nanoparticle.

Heterocyclic compounds are of great importance due to their biological properties. From an industrial point of view, the majority of the pharmaceuticals, bioactive agrochemicals, additives, and modifiers are heterocyclic in nature. The high prevalence of heterocycles as pharmaceuticals is because of their vast distribution in nature and their abundance as building block for biomacromolecules such as DNA or RNA. The designing of new therapeutic molecules is usually to mimic the natural ligands or sub-

strates of receptors or enzymes with the aim to improve the potency of the ligand by enhancing its pharmacokinetic profile.¹ Therefore, researchers are in a continuous pursuit to find new and efficient synthetic transformations for heterocyclic compounds.

The field of nanocatalysis has undergone an explosive growth in recent years involving the application of nanomaterials as catalysts under various homogeneous and heterogeneous conditions.² The efficacy of nanomaterials is 37

very high compared to conventional catalysts due to their high activity, selectivity, excellent stability, low energy consumption, and long shelf life. Their extremely small size (typically 10–80 nm) and shape provides exceptionally large surface-to-volume ratio and leads to unique and immense changes in the physical and chemical properties of the material.³

Metal nanoparticles (MNPs) confer great potential in areas such as medicine and catalysis.⁴ The large surface area of MNPs has a positive influence on the reaction rate and is the main explanation of their higher catalytic activity. MNP catalysis provides rapid and selective chemical transformations with excellent product yields combined with the ease of catalyst separation and recovery.⁵ The first example of gold NPs use was reported in 1989 by Haruta et al. for the oxidation of carbon monoxide and hydrogen at low temperatures.⁶

Importantly, among metal-based NPs, gold and silver NPs as catalyst have attracted the attention of the scientific community owing to their exceptional reactivity, selectivity, stability, and recyclability in catalytic reactions.^{4a,7} Over the past few years, there have been several books and reviews published on gold- and silver-catalyzed organic reactions.⁸ Various comprehensive reviews on gold NP catalysis have been published covering the physical properties and characterization of gold NPs, the formation of the carbon–heteroatom bond, the preparation of supported gold catalysts as well as both homogeneous and heterogeneous catalysis.^{8b–d,f,g,i}

Gold as a catalyst is of great importance in organic synthesis, as it promotes the construction of C–C and C–heteroatom bonds (C–O, C–N, and C–S) by nucleophilic attack on multiple reactive bonds.⁹ Similarly, silver NPs have gained interest due to their catalytic properties for some important organic reactions such as multi-component (A^3 -coupling) reactions, Diels–Alder [4+2] cycloaddition reactions, etc.¹⁰ In 2009, a review appeared on the green synthesis of silver NPs and their antimicrobial applications against gram-positive and gram-negative bacteria.¹¹

This small review summarizes some important reports of gold or silver NPs used as catalyst for the construction of heterocyclic compounds. We have covered the literature from last 3 years, although only prime reports are highlighted. The main aim of this review is to provide a platform to further explore gold and silver NPs for the synthesis of new heterocycles. For better understanding, the report is subdivided into two parts as given below: 1) gold NP-catalyzed synthesis of heterocycles, 2) silver NP-catalyzed synthesis of heterocycles.

1 Au NP-catalyzed synthesis of heterocycles

Au NPs have received immense interest due to their well-characterized electronic and physical features. The characteristic features of Au NPs are their small size (1–100 nm) and correspondingly large surface-to-volume ratio. Their physical and chemical properties can be altered as per the requirements of size, composition, and shape, high robustness, and unique target-binding properties.^{4c,12} These

features have made Au NPs one of the most widely used nanomaterials for catalysis, imaging, disease diagnostics, and gene expression. Features that made Au NPs as catalyst of choice include their ability to be active under mild conditions, even at ambient temperature or less, and to increase the selectivity of the reaction, as well as the fact that they are durable and resistant to poisoning.¹³

Indoles are important heterocycles with characteristic properties due to the presence of an electron-rich pyrrole ring that can interact noncovalently with other molecules by hydrogen bonding through the NH group and by π – π stacking. The indole ring is a constituent of proteins in the form of tryptophan residues and exhibits a range of pharmacological activities.¹⁴ Tokunaga and coworkers have reported a one-pot reaction of (2-nitrophenyl)alkynes **1** to form indoles, catalyzed by Au NPs supported on Fe_2O_3 under hydrogenation conditions.¹⁵ Two methods were reported for the synthesis of indoles. The first method involves one-step synthesis of indoles from (2-nitrophenyl)-alkynes **1** using Au NPs supported on Fe_2O_3 at 120°C in toluene (Scheme 1). The second method includes the one-pot two-step reaction, where the first step was performed at 60°C, 2.0 MPa H_2 for 1 h, followed by release of H_2 at atmospheric pressure (0.1 MPa). Then the second step involves the heating of the reaction mixture at 120°C for 1 h. It was observed that the second method affords slightly better yields. Under the optimized conditions, a wide variety of alkynes substituted with large steric groups such as *p*-Tol, *t*-Bu, and cyclohexenyl, underwent the reaction to give the corresponding indoles **2** in excellent yields. However, an electron-withdrawing group on the alkyne, such as a trifluoromethylphenyl, gave the corresponding indoles in moderate yields, whereas a TMS group was found incompatible in the reaction and led to complete loss of the product. Substituent on the benzene ring does not affect the yield of the desired product.

Scheme 1

Lopez-Sanchez, Helaja, and coworkers have reported an efficient method for the synthesis of indoles **4** by heterogeneous cycloisomerization of 2-alkynylanilines **3** catalyzed by carbon-supported Au NPs at 90°C in toluene within 24 h (Scheme 2).¹⁶ Under the optimized reaction conditions, substrates with various substituents on the alkyne and/or aryl ring underwent the cycloisomerization reaction in high to excellent yields. The presence of an electron-deficient substituent R^1 in the substrate led to a decrease in reactivity and catalytic performance, whereas an electron-rich *p*-methoxyphenyl group R^1 increased the

Scheme 2

1 reactivity. However, the use of an aliphatic alkyne resulted 2 in a low product yields, and had detrimental effect on the 3 catalytic activity. The presence of chlorine at the C-4 or 4 C-5 of the aniline (R^2) was found to be beneficial for the 5 catalytic activity. Most of the substrates provided excellent 6 yields of the desired product **4**, except 2-alkynyl-4-nitro- 7 anilines. Interestingly, the use of a high catalyst loading at 8 low temperature (90°C) affords product of the the homo- 9 coupling, e.g., 3,3'-bisindoles **5**, in good yields with the excep- 10 tion of 4-propyl- and 4-amino-2-alkynylaniline substrates.

11 Further, the authors reported an unprecedented synthesis 12 of cyclooctatetraene condensed with four indole rings **7** 13 using 2,2'-(buta-1,3-diyne-1,4-diyl)dianiline **6** as a 14 substrate. For the completion of this reaction, a higher 15 catalytic loading (5 wt %) along with high temperature 16 were required in comparison with the above-mentioned 17 cycloisomerization of 2-alkynylanilines **3** (Scheme 3).

Scheme 3

18 Savva and coworkers have prepared Au NPs-containing 19 polyvinylpyrrolidone-crosslinked electrospun fibers and 20 investigated their catalytic efficiency in the intramolecular 21 cyclization of 2-(phenylethynyl)aniline **8** to give access to 22 2-phenyl-1*H*-indole **9** (Scheme 4).¹⁷ It has been observed 23 that the catalytic performance of the Au NPs-containing 24 fibers is directly influenced by the size of the Au NPs, 25 where small-sized Au NPs gave the best results. The 26 catalytic efficiency was found to decrease after three 27 consecutive reaction cycles. This may be attributed to the 28 morphological changes in the fibers merging.

Scheme 4

Spiroindolines have attracted immense interest due to 29 their presence in various natural products and drug-like 30 molecules. Van der Eycken and coworkers have reported 31 an expeditious synthesis of spiroindolines **11** catalyzed by 32 supported Au NPs *via* cycloisomerizations and C–C bond 33 formations under microflow conditions.¹⁸ The hetero- 34 geneous gold catalyst Au@Al-SBA15 was prepared *via* a 35 ball-milling process. The sterically hindered Ugi-adducts 36 **10** were cyclized to spiroindolines **11** in a stainless steel 37 packed-bed microreactor filled with Au@Al-SBA15 at 38 120°C in a mixture of EtOH and water as solvent, using 39 hexafluoroisopropyl alcohol (HFIP) as proton shuttle 40 (Scheme 5). Under the optimized conditions, substrates **10** 41 bearing aliphatic and aromatic substituents afforded the 42 corresponding spiroindolines **11** in good to excellent 43 yields. *p*-Methoxybenzyl and various aliphatic moieties as 44 the R^2 substituents were well tolerated. The presence of a 45 *t*-Bu or a Cy group as the R^3 substituents gives good 46 product yields. Also, the effect of water on the selectivity 47 of the reaction was investigated, indicating that the 48 presence of water expedites the protodecoordination of the 49 Au NPs and thus, stimulates the formation of spiroindoline 50 by improving the catalytic process. Furthermore, deacti- 51 vation of the catalyst occurs only after an extended use, and 52 leaching was not detected from the Au@Al-SBA15 53 catalytic bed. 54

Scheme 5

The benzoxazole and benzimidazole cores are common 55 structural units in many marketed pharmaceuticals and 56 drug candidates.¹⁹ Wang and coworkers have described a 57 highly efficient synthesis of 2-substituted benzoxazoles **14** 58 and benzimidazoles **16** using Au NPs supported on 59 titanium dioxide (Au/TiO₂) in toluene or water.²⁰ 2-Aryl- 60 benzoxazoles **14** were selectively synthesized using 61 Au/TiO₂ as a catalyst in a reaction of 2-nitrophenols **12** 62 with alcohols **13** (Scheme 6). Under the optimized reaction 63 conditions, substituted benzylic alcohols (electron-donating 64

1 or electron-withdrawing groups) furnished the desired 2 products in excellent yields. However, the steric hindrance 3 of the substituents at *ortho* position of the benzene ring 4 hampers the reaction. Replacement of the benzene ring 5 with that of naphthalene provided access to the desired 6 product in excellent yield. The presence of either electron- 7 donating or electron-withdrawing groups on the phenyl 8 ring of nitrophenol **12** was well tolerated. Under similar 9 reaction conditions, using toluene or water as a solvent, 10 *o*-nitroanilines **12** and benzylalcohols **15** were converted to 11 2-arylbenzimidazoles **16** in high to excellent yields. 12 Interestingly, the use of *N*-methyl-*o*-nitroaniline as substrate 13 led to an improved product yield. The catalytic activity of 14 Au/TiO₂ catalyst was decreased after six catalytic cycles.

Scheme 6

14 X = O; R¹ = H, 4-Me, 5-Me, 4-OMe, 5-F, 4-F, 4-Cl;
R² = Me, *t*-Bu, *n*-Pent, Cy, Ph, 4-MeC₆H₄,
3-MeC₆H₄, 2-MeC₆H₄, 4-FC₆H₄, 3-FC₆H₄,
4-ClC₆H₄, 4-BrC₆H₄, 4-CF₃C₆H₄, 1-Naphth
16 X = NH, NMe; R¹ = H; R³ = H, 4-Me, 4-OMe, 4-F, 4-Cl

15 1,2,3-Triazoles are valuable heterocyclic motifs that 16 have a widespread occurrence in different compounds 17 characterized by several pharmacological applications.²¹ 18 Muthusubramanian and coworkers have employed 19 nanoporous titania-supported Au NPs for the green 20 synthesis of 1,2,3-triazoles **19** in aqueous medium.²² The 21 Huisgen [3+2] cycloaddition was achieved by reaction of 22 substituted phenacyl azides **17** with alkynes **18** in the 23 presence of Au/TiO₂ in water alone or in a *t*-BuOH/water 24 mixture providing an excellent yield of 1,4-disubstituted 25 1,2,3-triazoles **19** as a single regioisomer (Scheme 7). 26 Under the optimized reaction conditions, various aliphatic 27 and (un)substituted aromatic 1-alkynes underwent the 28 regioselective reaction with different azides affording 29 products **19** in excellent yields. The use of symmetrical 30 internal alkynes **20** in this reaction was also evaluated. It 31 was found that in contrast to the noncatalytic reaction, the 32 presence of the Au/TiO₂ catalyst provided excellent yields 33 of products **21** in a short time. This increase in the product 34 yield can be attributed to the alkynophilic nature of the 35 gold that activates the internal alkyne leading to an 36 enhancement in the reaction rate. 37 Quinolines have attracted much attention due to the 38 broad range of their pharmacological properties.²³ Che and

Scheme 7

co-workers have developed a new one-pot protocol to 39 access nitrogen-containing heterocycles **24** and **26** via silica- 40 supported Au NPs catalytic system by reacting anilines **23** 41 or polycyclic aniline **25** with aldehydes **22** using oxygen as 42 an oxidant in toluene at 110°C (Scheme 8).²⁴ Under the 43 optimized reaction conditions, a variety of electron- 44 donating substituents on aniline **23** provided good to 45 excellent product yields. However, electron-deficient 46 substituents have a detrimental effect on the product yield. 47 Hydrocinnamaldehyde and high boiling aldehydes were 48 found to be good substrates and provided good to excellent 49 product yields. For the synthesis of polycyclic anilines, 50 bulky anilines were found suitable under this reaction 51 conditions and provided the desired product in good yields. 52 An additional advantage of this method is the easy 53 recovery of the silica-supported gold catalyst, which can be 54 reused for seven consecutive runs without significant loss 55 of catalytic activity. 56

Scheme 8

Ag NP-catalyzed synthesis of heterocyclic compounds

Among the various metal catalysts, silver has higher accessibility for industrial and heterogeneous catalysis because of its relatively low price (as less than 1/50 of gold, and about 1/25 of palladium) and is being relatively more friendly to the environment.²⁵ Ag NPs as catalyst have distinct physical and chemical properties compared to the bulk material due to their small size. The researcher's interest in silver nanoparticles has expanded rapidly in the last few years because of their distinct reactivity, stability, and recyclability in catalytic reactions. Silver nanoparticle catalysis has great potential in organic transformations and play an important role in the total synthesis of natural products and pharmaceutical molecules.^{10a}

Tetrazoles are widely used in drug discovery as an isosteric replacement for carboxylic acids, and owing to their wide range of biological and commercial applications.²⁶ Awasthi and coworkers have developed an efficient synthetic methodology for the synthesis of 5-substituted 1*H*-tetrazoles **29** and **30** using Ag nanoparticles as catalyst via [3+2] cycloaddition reaction of benzonitriles **27** or **28** and sodium azide in DMF at 120°C (Scheme 9).²⁷ Under the optimized conditions, benzonitriles, bearing electron-withdrawing and electron-donating substituents on the aromatic ring, were efficiently converted. However, electron-withdrawing substituents provided better product yields. Heterocyclic nitriles are also well tolerated in this reaction and provided access to the corresponding tetrazoles in moderate to high yields. Interestingly, the Ag-catalyst can be reused up to four catalytic cycles without significant loss of catalytic activity.

Scheme 9

Xanthene derivatives exhibit a diverse range of biological applications. Xanthene dyes have been used for diagnostic and imaging purposes.²⁸ Safaei-Ghomi and coworkers have reported an efficient, facile, and economic

method for the preparation of 14-aryl-14*H*-dibenzo-37 [a,j]xanthenes **33** under solvent-free conditions using AgI NPs as a catalyst by the reaction of 2-naphthol (**31**)³⁹ and benzaldehydes **32** at 140°C (Scheme 10).²⁹ The reaction time was significantly reduced by using AgI NPs⁴¹ compared to using bulk AgI. This efficient method furnishes⁴² the products with diversely substituted benzaldehydes **32** in⁴³ excellent yields and high purity (≥95%). Aldehydes bearing⁴⁴ electron-withdrawing groups (NO₂, Cl and Br) at the *para*⁴⁵ position provided better results with respect to yield and⁴⁶ rate of the reaction. The present method offers high yields,⁴⁷ short reaction times, easy purification, and low catalyst⁴⁸ loading along with recyclability of the catalyst. The latter⁴⁹ was recovered by simple filtration followed by washing with⁵⁰ chloroform and methanol and then drying at 70°C for 10 h. ⁵¹

Scheme 10

Van der Eycken and coworkers have described an⁵² Al-SBA-supported Ag NP-catalyzed 5-*exo-dig* cyclization⁵³ reaction of 3-substituted indoles **34** bearing a side-chain⁵⁴ alkynyl group to provide access to 3-spiroindolenines **35** in⁵⁵ high to excellent yields (Scheme 11).³⁰ The substrates⁵⁶ comprising terminal alkyne group (R² = H) gave better⁵⁷ results with respect to yield and reactivity as compared to⁵⁸ the internal alkynes (R² = Me, Et) which cyclized slowly⁵⁹ and required longer reaction times, high temperature, and⁶⁰ high catalyst loading for completion of the reaction. Surp-⁶¹risingly, 6-*endo-dig* cyclization products were also formed,⁶² which were difficult to separate from the *exo* products. The⁶³ presence of electron-withdrawing or electron-donating⁶⁴ substituents on the C-5 position of the indole produces⁶⁵ negligible impact, although a chlorine atom at the C-6⁶⁶ position has detrimental effect on the yield. Substitutions⁶⁷ on the amide N atom (R¹) have insignificant effect on the⁶⁸ yield of desired product. ⁶⁹

Scheme 11

Further, Van der Eycken and coworkers have reported a⁷⁰ post-Ugi cyclization of Ugi-adducts **36** using Al-SBA-⁷¹ supported Ag NPs as catalyst, to get access to spiro-⁷²

1 indolenines **37** at 40°C in good to excellent yields and with
 2 satisfactory diastereoselectivity (Scheme 12).³⁰ The sub-
 3 strates comprising a terminal alkynyl group ($R^2 = H$)
 4 provided good yields with trace amounts of the undesired
 5 tetracyclic product. Substrates comprising internal alkynyl
 6 group ($R^2 = Me$) were not converted under these
 7 conditions. Substituents on both C-5 and C-6 atoms of the
 8 indole were well tolerated. However, a sterically
 9 demanding R^3 substituent such as butyl, has been found
 10 deteriorating for the product yield. Further, various R^1 alkyl
 11 substituents were well tolerated and had minimal effect on
 12 the reaction outcome. The above catalyst could be used up
 13 to ten catalytic cycles without having desactivation of
 14 crystal ripening and with extremely low leaching.

Scheme 12

15 Maleki and coworkers have developed an eco-friendly
 16 method for the synthesis of 2-amino-4-aryl-6-(2-oxo-2H-
 17 chromen-3-yl)nicotinonitriles **42** catalyzed by magnetic
 18 cellulose/Ag nanobiocomposite.³¹ The synthetic metho-
 19 dology for the preparation of chromene-linked nicotino-
 20 nitriles **42** commenced with the MCR reaction of 3-acetyl-
 21 coumarin **38**, benzaldehydes **39**, malononitrile (**40**), and
 22 ammonium acetate (**41**) in the presence of a catalytic
 23 amount of magnetic cellulose/Ag nanobiocomposite in
 24 ethanol at 60°C (Scheme 13). The magnetic cellulose/Ag
 25 nanobiocomposite comprises $\gamma\text{-Fe}_2\text{O}_3$ NPs supported onto
 26 the cellulose layers and Ag NPs immobilized on the surface
 27 of the cellulose. Under the optimized conditions, different
 28 benzaldehydes **39** substituted with electron-donating or
 29 electron-withdrawing groups furnished the corresponding
 30 products **42** in high yields. Aldehydes bearing electron-
 31 withdrawing substituents underwent the reaction faster.
 32 This approach has the advantages of using an inexpensive
 33 catalyst, catalyst recyclability (up to five times), easy
 34 separation of catalyst from the reaction mixture, an
 35 environmental friendly procedure, short reaction times,
 36 avoiding hazardous organic solvents, and high yields.

Scheme 13

Jeong and coworkers have reported a convenient and **37**
 efficient approach for the synthesis of pyrimido[1,2-*b*]-**38**
 indazoles **46** catalyzed by Ag NPs under solvent-free **39**
 conditions.³² The authors have prepared environmentally **40**
 friendly Ag NPs from the extract of the plant *Radix* **41**
Puerariae via a novel chemical route. One-pot three-**42**
 component coupling reaction between 3-aminoindazole **43**
 (43), aldehydes **44**, and alkynes **45** catalyzed by Ag NPs **44**
 under solvent-free conditions at 80°C furnished pyrimido **45**
 [1,2-*b*]indazoles **46** in excellent yields (Scheme 14). Under **46**
 the optimized reaction conditions, a wide range of **47**
 aldehydes were well tolerated and provided access to the **48**
 desired products **46** in high yields. Alkyne substrates, such **49**
 as 1-ethynylbenzene and 1-ethynyl-4-methylbenzene gave **50**
 pyrimido[1,2-*b*]indazoles in good to excellent yields. **51**
 However, aliphatic alkynes failed to give the desired **52**
 products. The promising points of this approach include **53**
 ease of the catalyst preparation and reusability, simple **54**
 workup procedure, higher reaction rates, and avoiding the **55**
 use of hazardous solvents. **56**

Scheme 14

Sorocenol B, an isoprenylated phenol, was isolated from **57**
 the root bark of *Sorocea bonplandii* Baillon (Moraceae). **58**
 Chemically, sorocenol comprises of a bicyclo[3.3.1] core **59**
 which is biosynthetically derived from oxidative cycli-**60**
 zation of 2'-hydroxychalcone-derived Diels–Alder cyclo-**61**
 adduct.³³ Porco and coworkers have developed a method **62**
 for the total synthesis of ($\pm$)-sorocenol B **54** utilizing silver **63**
 nanoparticles as catalyst.³⁴ Diels–Alder cycloaddition **64**
 reaction between 2'-hydroxychalcone **47** and diene **48** was **65**
 catalyzed by silica-supported Ag NPs (0.1 mol %). The **66**
 desired cycloadduct was obtained in 90% yield as a **67**
 separable mixture of *endo/exo* diastereomers **49** and **50** in **68**
 2:1 ratio (Scheme 15). Further, the bicyclo[3.3.1] frame-**69**
 work was constructed by using Pd(II)-catalyzed oxidative **70**
 cyclization. Substrate **51** was synthesized from *endo* **71**

Scheme 15

1 diastereomer **49**, using Stoltz's conditions for oxidative
 2 Wacker cyclization (the $\text{Pd}(\text{OAc})_2$ /pyridine catalytic
 3 system in toluene under O_2 atmosphere).³⁵ This afforded
 4 the desired bicyclic product **52** and its C-4 epimer **53** (in
 5 2:1 ratio) in 50% yield. Finally, ($\pm$)-sorocenol B **54** was
 6 accessed in 74% yield by hydrolyzing MOM ether **52** in
 7 refluxing acidic MeOH . The synthetic natural product
 8 displayed low micromolar cytotoxic activity, particularly
 9 against prostate cancer PC-3 (GI_{50} 1.1 μM), melanoma LOX
 10 IMVI (GI_{50} 1.4 μM), leukemia MOLT-4 (GI_{50} 1.4 μM), and
 11 colon cancer HCC-2998 (GI_{50} 1.4 μM).

12 Several protocols for the synthesis of heterocyclic
 13 compounds catalyzed by Au and Ag NPs were sum-
 14 marized. Rapid and green synthetic methods using micro-
 15 flow conditions have shown great potential for the
 16 synthesis of heterocyclic compounds using NPs as a
 17 catalyst. The use of supported materials such as Fe_2O_3 ,
 18 TiO_2 , SiO_2 , and carbon enhances the reactivity of Au NPs.
 19 The Au and Ag NP-catalyzed synthetic methods for
 20 heterocyclic compounds are environmentally friendly
 21 procedures and provide several advantages including
 22 increased reaction rates, higher yields, simple workup
 23 procedure and reusability of the catalyst. We strongly
 24 believe that NP-catalyzed reactions have great potential for
 25 the synthesis of heterocyclic compounds and will attract the
 26 attention of organic chemists. We also expect an exponen-
 27 tial increase in NP-catalyzed reactions in the near future.

The authors are thankful to ISF College of Pharmacy, 28
 Moga, Punjab, India, University of Nebraska Medical Center, 29
 Omaha, NE, USA, KU Leuven, Belgium and for support of 30
 RUDN University, Moscow, Russia (Program 5-100). 31

References

1. Broughton, H. B.; Watson, I. A. *J. Mol. Graphics Modell.* 2004, 23, 51. 32
2. Thomas, J. M.; Thomas, W. J. *Principles and Practice of* 33
Heterogeneous Catalysis; John Wiley & Sons: New York, 34
 2014. 35
3. (a) Li, L.-s.; Hu, J.; Yang, W.; Alivisatos, A. P. *Nano Lett.* 36
 2001, 1, 349. (b) Jin, R. *Nanotechnol. Rev.* 2012, 1, 31. 37
4. (a) Daniel, M.-C.; Astruc, D. *Chem. Rev.* 2004, 104, 293. 38
 (b) Goluch, E. D.; Nam, J.-M.; Georganopoulou, D. G.; 39
 Chiesl, T. N.; Shaikh, K. A.; Ryu, K. S.; Barron, A. E.; 40
 Mirkin, C. A.; Liu, C. *Lab Chip* 2006, 6, 1293. (c) Rosi, N. L.; 41
 Mirkin, C. A. *Chem. Rev.* 2005, 105, 1547. (d) Pasquato, L.; 42
 Pengo, P.; Scrimin, P. *J. Mater. Chem.* 2004, 14, 3481. 43
 (e) Bond, G. C.; Louis, C.; Thompson, D. *Catalysis by Gold*; 44
 Hutchings, G. J., Ed.; Imperial College Press: London, 2006, p. 1. 45
5. Isomura, Y.; Narushima, T.; Kawasaki, H.; Yonezawa, T.; 46
 Obora, Y. *Chem. Comm.* 2012, 48, 3784. 47
6. Haruta, M. *CATTECH* 2002, 6, 102. 48
7. (a) Li, J.; Tang, G.; Wang, Y.; Wang, Y.; Li, Z.; Li, H. *New J.* 49
Chem. 2016, 40, 358. (b) Wang, H.; Yang, K.-F.; Li, L.; Bai, Y.; 50
 Zheng, Z.-J.; Zhang, W.-Q.; Gao, Z.-W.; Xu, L.-W. 51
ChemCatChem 2014, 6, 580. (c) Dong, X.-Y.; Gao, L.-X.; 52
 Zhang, W.-Q.; Cui, Y.-M.; Yang, K.-F.; Gao, Z.-W.; Xu, L.-W. 53
ChemistrySelect 2016, 1, 4034. 54
 55
 56

18. (a) Mielby, J.; Kegnæs, S.; Fristrup, P. *ChemCatChem* **2012**, *4*, 1037. (b) Zhang, Y.; Cui, X.; Shi, F.; Deng, Y. *Chem. Rev.* **2012**, *112*, 2467. (c) Corma, A.; Leyva-Pérez, A.; Sabater, M. J. *Chem. Rev.* **2011**, *111*, 1657. (d) Grzelczak, M.; Pérez-Juste, J.; Mulvaney, P.; Liz-Marzán, L. M. *Chem. Soc. Rev.* **2008**, *37*, 1783. (e) Hashmi, A. S. K. *Acc. Chem. Res.* **2014**, *47*, 864. (f) Hashmi, A. S. K. *Chem. Rev.* **2007**, *107*, 3180. (g) Pflästerer, D.; Hashmi, A. S. K. *Chem. Soc. Rev.* **2016**, *45*, 1331. (h) *Gold Catalysis. An Homogeneous Approach*; Toste, F. D.; Michelet, V., Eds.; Imperial College Press: London, 2014. (i) Dorel, R.; Echavarren, A. M. *Chem. Rev.* **2015**, *115*, 9028. (j) Obradors, C.; Echavarren, A. M. *Acc. Chem. Res.* **2014**, *47*, 902. (k) Dorel, R.; Echavarren, A. M. *J. Org. Chem.* **2015**, *80*, 7321. (l) Muratore, M. E.; Homs, A.; Obradors, C.; Echavarren, A. M. *Chem.-Asian J.* **2014**, *9*, 3066.
19. (a) Fürstner, A. *Chem. Soc. Rev.* **2009**, *38*, 3208. (b) Cossy, J. *Pure Appl. Chem.* **2010**, *82*, 1365.
20. (a) Dong, X.-Y.; Gao, Z.-W.; Yang, K.-F.; Zhang, W.-Q.; Xu, L.-W. *Catal. Sci. Technol.* **2015**, *5*, 2554. (b) Chopra, R.; Sharma, K.; Kumar, M.; Bhalla, V. *J. Org. Chem.* **2016**, *81*, 1039.
21. Sharma, V. K.; Yngard, R. A.; Lin, Y. *Adv. Colloid Interface Sci.* **2009**, *145*, 83.
22. Sharma, N.; Bhatt, G.; Kothiyal, P. *Indian J. Pharm. Biol. Res.* **2015**, *3*, 13.
23. Thompson, D. T. *Nano Today* **2007**, *2*, 40.
24. (a) Lal, S.; Snape, T. J. *Curr. Med. Chem.* **2012**, *19*, 4828. (b) Sharma, V.; Kumar, P.; Pathak, D. *J. Heterocycl. Chem.* **2010**, *47*, 491.
25. Yamane, Y.; Liu, X.; Hamasaki, A.; Ishida, T.; Haruta, M.; Yokoyama, T.; Tokunaga, M. *Org. Lett.* **2009**, *11*, 5162.
26. Perea-Buceta, J. E.; Wirtanen, T.; Laukkanen, O.-V.; Mäkelä, M. K.; Nieger, M.; Melchionna, M.; Huittinen, N.; Lopez-Sanchez, J. A.; Helaja, J. *Angew. Chem., Int. Ed.* **2013**, *52*, 11835.
27. Savva, I.; Kalogirou, A. S.; Achilleos, M.; Vasile, E.; Koutentis, P. A.; Krasia-Christoforou, T. *Molecules* **2016**, *21*, 1218.
28. Schröder, F.; Erdmann, N.; Noël, T.; Luque, R.; Van der Eycken, E. V. *Adv. Synth. Catal.* **2015**, *357*, 3141.
29. (a) Xing, L.; McDonald, J. J.; Kolodziej, S. A.; Kurumbail, R. G.; Williams, J. M.; Warren, C. J.; O'Neal, J. M.; Skepner, J. E.; Roberds, S. L. *J. Med. Chem.* **2011**, *54*, 1211. (b) Siracusa, M. A.; Salerno, L.; Modica, M. N.; Pittalà, V.; Romeo, G.; Amato, M. E.; Nowak, M.; Bojarski, A. J.; Mereghetti, I.; Cagnotto, A.; Mennini, T. *J. Med. Chem.* **2008**, *51*, 4529. (c) Shah, K.; Chhabra, S.; Shrivastava, S. K.; Mishra, P. *Med. Chem. Res.* **2013**, *22*, 5077. (d) Jain, A. K.; Paul, A.; Maji, B.; Muniyappa, K.; Bhattacharya, S. *J. Med. Chem.* **2012**, *55*, 2981.
30. Tang, L.; Guo, X.; Yang, Y.; Zha, Z.; Wang, Z. *Chem. Commun.* **2014**, *50*, 6145.
31. Bonandi, E.; Christodoulou, M. S.; Fumagalli, G.; Perdicchia, D.; Rastelli, G.; Passarella, D. *Drug Discovery Today* **2017**, *22*, 1572.
32. Boominathan, M.; Pugazhentiran, N.; Nagaraj, M.; Muthusubramanian, S.; Murugesan, S.; Bhuvanesh, N. *ACS Sustainable Chem. Eng.* **2013**, *1*, 1405.
33. (a) Feng, L.-S.; Liu, M.-L.; Zhang, S.; Chai, Y.; Wang, B.; Zhang, Y.-B.; Lv, K.; Guan, Y.; Guo, H.-Y.; Xiao, C.-L. *Eur. J. Med. Chem.* **2011**, *46*, 341. (b) Jain, S.; Chandra, V.; Jain, P. K.; Pathak, K.; Pathak, D.; Vaidya, A. *Arabian J. Chem.* **2016**, <https://doi.org/10.1016/j.arabj.2016.10.009>. (c) Mandewale, M. C.; Patil, U. C.; Shedge, S. V.; Dappadwad, U. R.; Yamgar, R. S. *Beni-Suef Univ. J. Basic Appl. Sci.* **2017**, *6*, 354.
34. So, M.-H.; Liu, Y.; Ho, C.-M.; Lam, K.-Y.; Che, C.-M. *ChemCatChem* **2011**, *3*, 386.
35. (a) Wodka, D.; Bielanska, E.; Socha, R. P.; Elzbieciak, Wodka, M.; Gurgul, J.; Nowak, P.; Warszyński, P.; Kumakiri, I. *ACS Appl. Mater. Interfaces* **2010**, *2*, 1945. (b) Dinh, C.-T.; Nguyen, T.-D.; Kleitz, F.; Do, T.-O. *ACS Appl. Mater. Interfaces* **2011**, *3*, 2228. (c) Taşçı, Z.; Kunduracioğlu, A.; Kani, İ.; Çetinkaya, B. *ChemCatChem* **2012**, *4*, 831. (d) Nowack, B. *Science* **2010**, *330*, 1054.
36. (a) Herr, R. J. *Bioorg. Med. Chem.* **2002**, *10*, 3379. (b) Butler, R. N. *Comprehensive Heterocyclic Chemistry II*; Katritzky, A. R.; Rees, C. W.; Scriven, E. F. V., Eds.; Pergamon: Oxford, 1996, vol. 4, p. 621.
37. Mani, P.; Sharma, C.; Kumar, S.; Awasthi, S. K. *J. Mol. Catal. A: Chem.* **2014**, *392*, 150.
38. (a) Baraldi, P. G.; Tabrizi, M. A.; Preti, D.; Bovero, A.; Romagnoli, R.; Fruttarolo, F.; Zaid, N. A.; Moorman, A. R.; Varani, K.; Gessi, S.; Merghi, S.; Borea, P. A. *J. Med. Chem.* **2004**, *47*, 1434. (b) Lee, L. US Patent S4933471A. (c) Pfister, J. R.; Belardinelli, L.; Lee, G.; Lum, R. T.; Milner, P.; Stanley, W. C.; Linden, J.; Baker, S. P.; Schreiner, G. *J. Med. Chem.* **1997**, *40*, 1773.
39. Safaei-Ghomi, J.; Ghasemzadeh, M. A. *J. Saudi Chem. Soc.* **2015**, *19*, 642.
40. Schröder, F.; Sharma, U. K.; Mertens, M.; Devred, F.; Debecker, D. P.; Luque, R.; Van der Eycken, E. V. *ACS Catalysis* **2016**, *6*, 8156.
41. Maleki, A.; Movahed, H.; Ravaghi, P. *Carbohydr. Polym.* **2017**, *156*, 259.
42. Balwe, S. G.; Shinde, V. V.; Rokade, A. A.; Park, S. S.; Jeong, Y. T. *Catal. Commun.* **2017**, *99*, 121.
43. Hano, Y.; Yamanaka, J.; Nomura, T.; Momose, Y. *Heterocycles* **1995**, *41*, 1035.
44. Cong, H.; Porco, J. A., Jr. *Org. Lett.* **2012**, *14*, 2516.
45. (a) Trend, R. M.; Ramtohl, Y. K.; Ferreira, E. M.; Stoltz, B. M. *Angew. Chem., Int. Ed.* **2003**, *115*, 2998. (b) Stoltz, B. M. *Chem. Lett.* **2004**, *33*, 362. (c) Trend, R. M.; Ramtohl, Y. K.; Stoltz, B. M. *J. Am. Chem. Soc.* **2005**, *127*, 17778.