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Recent progress in copper nanomaterials: catalysis, energy, biomedicine, and environmental applications

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Copper-based nanocomposites have gained growing attention due to their high stability, reusability, biocompatibility, and antimicrobial properties, including antibacterial, antifungal, and antiviral properties. They serve as efficient and cost-effective alternatives to noble metal catalysts in a wide range of organic transformations, particularly in C–C, C–N, C–O, and C–S bond-forming reactions. In addition to coupling processes, these catalysts have shown strong potential in oxidation, reduction, and other related transformations, underlining their versatility and functional significance. This review presents a comprehensive overview of recent advances (2019–2024) in copper-based nanomaterials, with emphasis on their catalytic applications and broader roles in biomedical fields, environmental remediation, photocatalysis, sustainable energy, agriculture, and the food industry.

1. Introduction

Nanoparticles find extensive applications in numerous fields such as catalysis, biomedical uses, environmental remediation, energy conversion, sensing, imaging, and nanomedicine, all due to their diverse physical and chemical properties.[1] Copper plays a crucial role in organic synthesis for two main reasons.

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Anamika Brahma

Anamika Brahma, born in Assam, earned her BSc (Hons.) in Chemistry from Handique Girls' College, Gauhati University (2020) and an MSc from Ramjas College, University of Delhi (2022). She worked as a research trainee under Prof. Ramesh Chandra, focusing on fluorescent 8-hydroxyquinoline derivatives and noscapine optical studies. Since 2024, she has been pursuing her PhD under Dr Snigdha Singh at the University of Delhi on nanomaterials for catalysis, water remediation, and biomedical applications. She has qualified CSIR-NET JRF (AIR 140) and GATE and co-authored research papers and book chapters.

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Firstly, its ability to stabilize various oxidation states (from 0 to +3) enables it to facilitate both radical and polar pathways through one- and two-electron transfer processes. Secondly, the strong affinity of copper for binding with heteroatoms enhances both σ- and π-interactions with unsaturated functional groups.[2,3] The increasing interest in this area has resulted in the development of highly specialized nanoparticles, enhancing catalysis across a broad range of applications.[4] Copper nanoparticles serve as excellent alternatives to pricier noble metals such as platinum, palladium, gold, and silver, commonly used in conventional chemical processes.[5] Although copper plays a key role in cross-coupling reactions, its relatively low catalytic activity and tendency to promote side reactions such as homo-coupling limit its wider applicability.[6] The use of copper in heterogenized molecular catalytic systems, as well as in both supported and unsupported nanoparticle forms, enables efficient catalyst recovery and reuse. Due to their high activity, selectivity, large surface area, and stability under diverse conditions, copper-based nanomaterials are employed in a range of chemical transformations, including organocatalytic and photocatalytic reactions.[7] These nanoparticles have improved both the physicochemical properties of the particles and the interface between the metal and its support.[8] Each component of the nanocomposite plays a role in creating a synergistic effect, functioning as a Lewis acid and boosting catalytic efficiency.[9]

Cu-based nanocatalysts find widespread application in nanotechnology owing to their unique properties, particularly their efficiency in organic transformations, electrocatalysis, and photocatalysis.[10,11] These nanoparticles offer advantages such as low loading, high atom economy, cost effectiveness, and recyclability, making them ideal for sustainable chemical processes.[12] In recent years, copper-based nanocatalysts have played an important role in multicomponent reactions (MCRs), leading to rapid developments in synthetic methodologies.[13]

Nisha

Nisha is pursuing her PhD in Chemistry at the University of Delhi under Prof. Neera Sharma. Her research focuses on nanocatalysis and the synthesis of biologically active heterocycles. She has published several peer-reviewed articles, including studies on CuI/MnO_2 nanocatalyzed synthesis of benzimidazoles, Fe_3O_4/PANI/CuI nanocomposites for sustainable A^3 coupling reactions, and indole scaffolds as COX-2 inhibitors with anti-inflammatory potential. Her work demonstrates a strong commitment to eco-friendly catalytic methodologies and medicinal chemistry, effectively bridging nanomaterials, catalysis, and drug discovery.

Yashaswi Sharma

Yashaswi Sharma was born and brought up in Delhi, India. He completed his MSc and BSc (Hons.) in Chemistry at the University of Delhi, India. He is currently working as a Junior Research Fellow at the Department of Chemical Engineering, Indian Institute of Technology Roorkee, India. During his MSc, he worked in the Drug Discovery and Development Laboratory, Department of Chemistry, University of Delhi and his research work involved copper-based nanocatalysts for sustainable organic transformations. His current research interests include drug discovery, medicinal chemistry, nanomaterials, and transport phenomena in ion channels and synthetic nanopores.

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Bhoomi Sachdeva

Bhoomi Sachdeva, born and raised in Delhi, India, completed her BSc at Gargi College, University of Delhi, in 2021, and her MSc at the Netaji Subhas University of Technology, Delhi, in 2023. That same year, she joined the University of Delhi as a research trainee under Prof. Ramesh Chandra, gaining experience in nanomaterials research. In 2024, she received an Indo-France PhD fellowship and began her doctoral studies at the University of Lille, France. Her research focuses on borophene-based nanocatalysts for water remediation, with interests in heterogeneous catalysis, nanomaterials, and environmental applications.

Furthermore, the magnetically separable copper nanocatalysts have also gained interest in synthetic chemistry due to their easy recovery and reuse, contributing to the development of greener and more efficient synthetic protocols.[14] Supported copper-based nanocomposites, including CS–TDI–PMDA–TS–Cu(II),[15] Fe_3O_4@SiO_2–bis(aminopyridine)–Cu(II),[16] Cu^{2+}/mesoporous carbon nanocatalyst,[17] CuI nanoparticle-modified IRMOF-3/PSTA,[18] UiO-66-NH_2@SA-PS/CuI,[19] and Cu@TMU-16-NH_2-Gl,[20] have been utilized in a variety of organic transformations. A copper-based HKUST-1/TiO_2 composite has also been utilized for efficient photocatalytic hydrogen production using water and methanol, demonstrating remarkable activity and highlighting copper's potential as a noble metal-free alternative in photocatalysis.[21]

Additionally, copper-based nanoparticles have significant biomedical applications, including antifungal, antimicrobial, antibacterial, and anticancer applications, as well as roles in cancer imaging and therapy.[22] Due to their unique properties along with their compatibility with living tissue, copper nanoparticles are also employed in treatments such as photothermal and photodynamic therapy.[23] Nanoparticles are utilized in biosensing applications to detect biological components such as DNA strands, enzymes, antibodies, and even whole cells, primarily for medical and biological purposes.[24] The incorporation of nanoparticles into biosensors enables the connection of the bio-receptors and transducer at the nanoscale, thereby enhancing sensitivity and detection capabilities.[25] Pd–CuO/rGO has been synthesized by Dhara *et al.* using a single-step reduction process for glucose detection in blood serum.[26] Zou *et al.* have prepared CuO/g-C_3N_4 nanocomposites for electrochemical detection of dopamine with a 1.00×10^{-10} mol L^{-1} detection limit.[27] Furthermore, copper nanocatalysts are being investigated for a range of environmental remediation applications because of their catalytic activity, surface properties, and potential to improve the efficiency of pollutant degradation. For example, Kaboudin *et al.* synthesized Cu-NPs stabilized with β-cyclodextrin (Cu_2-β-CD), which have been effectively used for the reduction of nitroaromatic compounds and dye degradation, highlighting their potential in wastewater treatment and the removal of toxic pollutants from the environment.[28] Additionally, copper-based nanoparticles have attracted attention as potential fertilizers at lower concentrations, demonstrating their capacity to enhance plant growth and yield.[29] In the field of sustainable energy, they are essential for converting carbon dioxide into valuable chemicals and fuels, making a significant contribution to efforts aimed at combating climate change.[30] However, due to the chemical inertness of CO_2, its electrochemical reduction requires highly effective catalysts, and Cu-based systems have been widely explored for this purpose. Recent research highlights that tuning the crystallinity of Cu nanoparticles significantly influences their catalytic activity and selectivity in CO_2 reduction reactions.[31] Previous literature studies have highlighted the importance of understanding the effects of copper nanoparticles in exploring their potential for

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Ramesh Chandra

Prof. Ramesh Chandra, an eminent scientist, a teacher, and an administrator, served as a Head of the Department of Chemistry, University of Delhi, a Founder Director of Dr B. R. Ambedkar Center for Biomedical Research (ACBR) and the Institute of Nano Science & Materials (INMS), and a Vice-Chancellor of Maharaja Surajmal Brij University, Rajasthan. With over 38 years of research experience, he has worked at Cornell University Medical Center, Rockefeller University, SUNY Stony Brook, Harvard Medical School, and MIT. His work in drug discovery and metabolism has resulted in patents, 300+ publications, six books, and mentorship of over 100 PhD scholars worldwide.

Snigdha Singh

Dr Snigdha Singh, born in Delhi, earned her BSc from Hindu College (2013) and MTech in Chemical Synthesis and Process Technologies (2016) from the University of Delhi, where she also completed her PhD in Medicinal Chemistry (2021). She received the Indo-Italy PhD Exchange Scholarship (University of Siena, 2018) and the Indo-UK PhD Newton Bhabha Scholarship (University of Oxford, 2020). She has held postdoctoral research positions at Humboldt University and Rensselaer Polytechnic Institute. Currently an Assistant Professor at Delhi University, she has published one international patent, three books, book chapters, and more than 45 papers.

disease management while minimizing any negative impact on plant growth.[32] This encompasses their application in agrochemicals for the efficient delivery and controlled release of pesticides and fertilizers.[33] Further, the potential use of Cu-based nanoparticle-infused biopolymer films for preserving fresh food and the impact of nanoparticle migration on food safety were explored. The addition of Cu-based nanoparticles enhances the properties of the film and improves its functional performance.[34] Different types of Cu-based nanoparticles, such as copper oxide, copper sulfide, copper ions, and copper alloys, affect biopolymer films in distinct ways.

In the following sections of this review, we have examined applications of copper-based nanocatalysts in organic transformations, including reduction, oxidation, coupling reactions, and some miscellaneous reactions. We have also investigated their uses in biomedical, environmental, photocatalytic, energy, agriculture, and food industries. By reviewing the latest research findings, we aimed to offer a comprehensive overview of the progress and future potential of copper-based nanocatalysts in modern science and technology.

2. Synthesis of Cu-based nanomaterials

A lot of research has gone into making copper-based nanomaterials because they have great catalytic, electrical, and biological capabilities. Recent years have seen a considerable advancement in the synthesis of copper-based nanomaterials due to the need for versatile, affordable, and sustainable catalysts.[35] The two methods commonly used to produce these nanomaterials are top-down and bottom-up. While bottom-up methods, like chemical reduction, sol–gel, hydrothermal, co-precipitation, and green synthesis, allow for fine-grained control over particle size, shape, and surface functionality, top-down methods use physical or mechanical means to break down bulk materials into nanoscale structures.[36] Ball milling, laser ablation, electrochemical etching, and arc discharge are examples of popular top-down methods. Although these techniques are simple and scalable, they may have problems with surface imperfections and particle uniformity.[37] The synthesis strategy selected has a significant impact on the final copper-based nanomaterials' physicochemical properties, surface reactivity, and catalytic activity.[38] In catalytic systems, optimal activity and stability are ensured by a carefully selected technique that is adapted to the intended use.[39] Different synthesis routes of copper based nanocatalysts are illustrated in Fig. 1.

2.1. Physical methods

Copper-based nanomaterials are physically synthesized using methods such as arc discharge, chemical vapor deposition (CVD), sputtering, laser ablation, pulsed laser deposition (PLD), and electrodeposition. Because of its scalability, excellent purity, and capacity to create a consistent thin coating for electronics and sensors, CVD is frequently used. By depositing copper atoms onto substrates *via* sputtering and PVD, the thickness and composition of films may be precisely controlled. PLD and laser ablation create controlled crystallinity nanostructures by vaporizing copper targets with high-energy lasers. Reducing copper ions on electrode surfaces allows for the economic growth of nanowires and coatings through electrodeposition. For use in 3D printing and catalysis, bulk copper is mechanically reduced to nanoscale particles *via* ball milling.[40] Nanoparticles for conductive and antibacterial materials are produced by vaporizing copper in liquid media using spark and pulsed wire discharge techniques.[41] Arc discharge creates high-purity CuNPs with adjustable size and shape under an inert atmosphere, making them ideal for biomedical applications and catalysis. Due to their versatility and ability to control nanomaterial properties, CVD, sputtering, and laser ablation are among the most commonly used methods.[42] The required particle size, shape, crystallinity, and end-use application of the copper nanomaterial are taken into consideration while choosing these techniques.

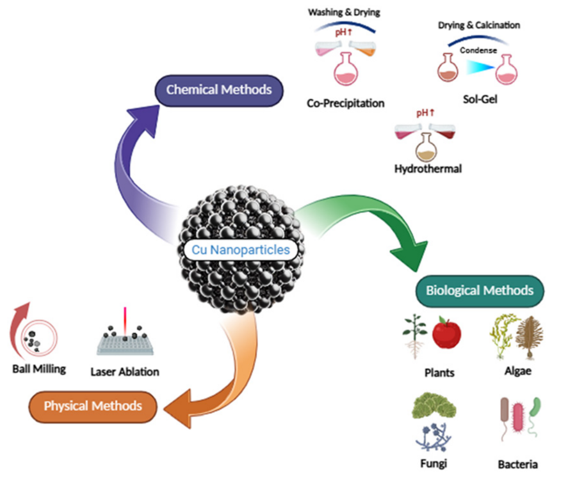


Fig. 1 General methods for the synthesis of Cu nanoparticles.

2.2. Chemical methods

Copper-based nanomaterials have been synthesized using a variety of chemical approaches, such as sol–gel, hydrothermal, chemical reduction, and electrochemical deposition. Among these, chemical reduction is still frequently employed to turn Cu^{2+} ions into nanoparticles by using reducing agents such as sodium borohydride or hydrazine.[43] The sol–gel technique is particularly suitable for specialized applications as it offers precise control over morphology through parameters like precursor concentration and gelation conditions.[44] Crystalline CuNPs with regulated growth and minimal agglomeration can be produced through hydrothermal synthesis, which is carried out at high temperatures and pressures. By varying the deposition potential, electrolyte composition, and duration, electrochemical deposition allows precise control over nanoparticle size and homogeneity.[45] Cu-based nanostructures with certain physicochemical characteristics that are appropriate for catalytic, electrical, and sensing applications can be synthesized using these techniques.[46] Excellent scalability and structural control are provided by the sol–gel and hydrothermal processes, whereas very uniform and surface-specific nanomaterials are produced by electrochemical techniques.[47] These methods are crucial for developing Cu-based functional materials because they allow for the fine-tuning of size, shape, and crystallinity.

2.3. Biological methods

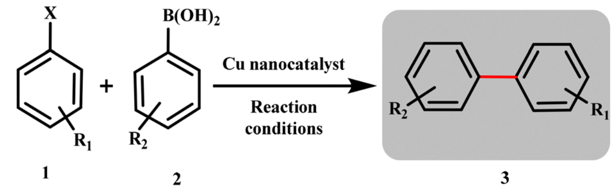
The production of copper-based nanomaterials using biological synthesis has drawn interest as an economical and environmentally beneficial method that provides exact control over the size, shape, and functionality of the particles.[48,49] Plant extract-based synthesis, enzyme-assisted techniques, microorganism-mediated synthesis, and biomimetic or bio-inspired approaches are some examples of biological pathways. Among these, microbial synthesis has been the most extensively investigated due to its adaptability, scalability, and biocompatibility.[50] Cu^{2+} ions can be converted to CuNPs through enzymatic action, primarily mediated by reductases, in bacteria like *Pseudomonas* and *Bacillus*, and fungi like *Fusarium* and *Aspergillus*.[51,52] Additionally, the proteins secreted by these bacteria serve as natural capping agents, improving the stability of the nanoparticles and inhibiting their aggregation. The microbes are cultivated in copper-rich media to initiate the reduction process, after which the resulting nanoparticles are harvested and purified *via* centrifugation and filtration. Protein secreted during growth, along with extracellular polymeric materials, aid in nanoparticle stabilization. TEM, SEM, and XRD are some of the methods used to characterize the biosynthesized CuNPs.[53] For specific uses in biomedicine,[54] catalysis, and environmental remediation, this green synthesis pathway is constantly being improved.

3. Copper-based nanocatalysed organic reactions

3.1. Coupling reactions including C–C, C–N, C–O, and C–S bond formation

Copper nanocatalysts are employed in coupling reactions because of their high surface area and cost-effectiveness, which enhance activity, selectivity, and stability compared to traditional catalysts. Their versatility and reusability make them suitable for various bond-forming reactions, including C–C, C–N, C–O, and C–S. Recent advancements in the synthesis and functionalization of copper nanoparticles have significantly improved their catalytic performance.[55]

3.1.1. Suzuki–Miyaura coupling reaction. The Suzuki–Miyaura cross-coupling is traditionally catalyzed by palladium.[56] However, due to the high cost and toxicity of palladium, researchers have investigated alternative copper-based catalysts, which are cost-effective and sustainable (Scheme 1).[57]



Scheme 1 Suzuki–Miyaura cross coupling reaction.

In 2019, Anuma *et al.* developed a heterogeneous copper Schiff base complex catalyst, which was used to synthesize a biphenyl product with 94% yield. The catalyst was recycled and the efficiency of its active metal centre was retained 87.5% even after 5 cycles[58] Akbarzadeh and colleagues prepared a non-toxic CNT–Fe$_3$O$_4$–PTh–Cu(I) catalyst in 2020 for catalyzing the Suzuki–Miyaura coupling reaction in a short time. In 2021, Metkazini *et al.* synthesized Ni$_4$Cu@CNO nanoparticles, achieving the first Pd-free Suzuki reaction under light irradiation, which resulted in a 98% yield within 6 hours.[59] Sun *et al.* reported the synergistic effect of a bimetallic catalyst with minimal precious metal loading by synthesising a Cu/C-700/Pd nanocomposite. This catalyst exhibited 99.73% activity and 98.87% selectivity in Suzuki reaction.[60]

Feng's research group synthesised the COF-based Cu catalyst (Cu–TAPB–BTDA–COF) by binding 4,4′-(benzothiadiazole-4,7-diyl)dibenzaldehyde(BTDA) with 1,3,5-tris-(4-aminophenyl)-benzene (TAPB) and evaluated its catalytic activity for Suzuki reaction, which was attributed to the ''single-atom'' catalytic sites and the unique porosity of the COF carrier, which allowed the reactant substrates to access the active sites.[61] In 2024, Abdullaev *et al.* employed Hummers' method to synthesise graphene oxide nanosheets, loaded with metallic copper, resulting in a cathode catalyst known as GO@Cu. This approach significantly enhanced catalytic activity, improving yields from 87% to 93%, while also notably increased the selectivity for electro-oxidation synthesis in Suzuki coupling reactions.[62,63]

In this coupling (Fig. 2), the cycle began with the oxidative addition of the aryl halide **1** to Cu(0), generating intermediate **I.** Next, *trans* metalation took place with the arylboronic acid derivative **2a**, which led to the formation of the diaryl–Cu species **II.** Finally, reductive elimination from intermediate **II**

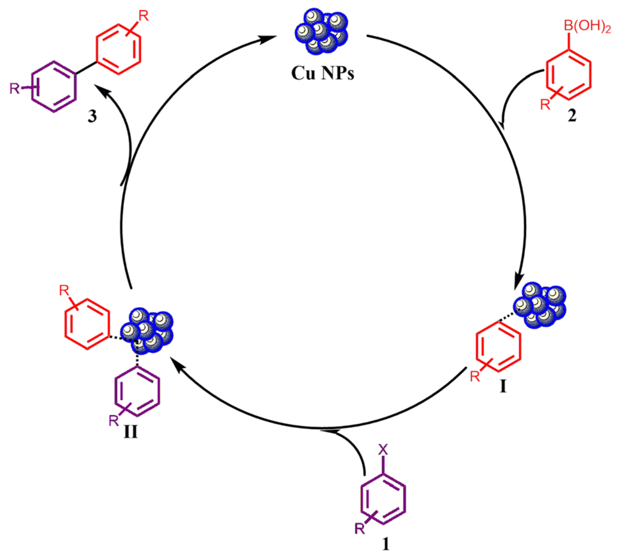
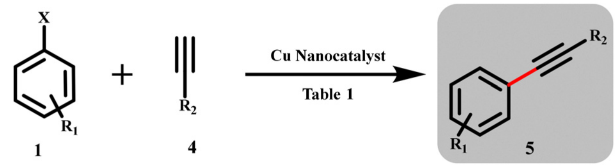


Fig. 2 Plausible mechanism for copper nanoparticle catalysed Suzuki–Miyaura coupling reaction.

afforded the desired biaryl product **3**, while regenerating the Cu NP catalyst. Throughout the process, Cu NPs not only mediated the oxidative addition–transmetalation–reductive elimination sequence but also enhanced electron transfer and stabilized the reaction intermediates under ligand-free or heterogeneous conditions. This contributed to higher reactivity and a broader substrate scope of Suzuki-type couplings in nanocatalysis.

3.1.2. Sonogashira coupling catalysed by a copper nanocomposite. The Sonogashira coupling is a widely used reaction in organic synthesis, involving the reaction of terminal alkynes with aryl or vinyl halides in the presence of a Pd(0) catalyst and a copper(I) salt (Scheme 2).[64] To minimize the use of expensive metals, researchers have focused on identifying cost-effective, eco-friendly, and sustainable alternatives. So, copper nanocatalysts have emerged as promising substitutes.[65]

In a 2019 study, Elazab and his team synthesized a Pd/CuO nanocatalyst by doping active Pd nanoparticles onto the surface of copper oxide using a straightforward and environmentally friendly one-pot method, and its catalytic activity was evaluated for Sonogashira coupling reaction.[66] In 2020, Olekszyszen *et al.* developed a bimetallic PdCu nanocatalyst, facilitating product formation in the coupling reaction *via* a quasi-homogeneous pathway.[67] In 2021, Yang *et al.* synthesized a copper-containing Au_{13} nanocomposite, $[Au_{13}Cu_2(PPh_3)_6(SC_2H_4Ph)_6]^+$ $[NO_3]^-$ ($Au_{13}Cu_2$), through an anti-galvanic reaction between Au_{25} and $Cu(PPh_3)_2NO_3$. This innovative system exhibited high selectivity and catalytic activity, achieving a 93% product yield under air.[68] Nasresfahani *et al.* successfully demonstrated that the Ni/Cu-MCM-41 nanocomposite is the most effective bimetallic catalyst for the Sonogashira coupling of various aryl halides with phenylacetylene, under Pd-free conditions.[69] Zhou and colleagues conducted a study highlighting the effective use of visible light to perform Sonogashira transformations employing a Cu_xO/CNT nanocomposite. They showed that the active species for the Sonogashira coupling under visible light is the copper(I) phenylacetylide intermediate. The interaction between Cu_xO and iodobenzene under light irradiation facilitates the coupling reaction. Both the light-activated aromatic iodide on Cu_xO nanoparticles and the light-excited copper phenylacetylide play key roles in achieving high selectivity for the Sonogashira product.[70] Another method reported by Sarmah *et al.* used an eco-friendly solvo-thermal approach to produce Cu_2O/Cu nanoparticles, which were found to serve as highly effective catalysts in the Sonogashira coupling reaction. The efficiency of the catalyst was due to the interaction between Cu(0) and Cu(I). Both copper species underwent reversible oxidation and reduction *via* electron transfer between Cu(0) and the Cu_2O surface, leading to a synergistic enhancement of catalytic activity within the reaction system.[71] The Fe_3O_4@SiO_2@Cyt-Ni/Cu system, designed by Nasseri and group, is the first example of a π-conjugated bridge between two metals supported on reusable magnetic materials. This interesting nanocatalyst showed high catalytic performance in Sonogashira cross-coupling reactions under solvent-free conditions. The Cu–Ni bimetallic system leveraged the cooperative interaction between the conjugated 4-ABPT ligand and the Cu/Ni centres, showcasing the synergistic effects inherent in the Fe_3O_4@SiO_2@Cyt-Ni/Cu structure.[72]



Scheme 2 Sonogashira cross-coupling reaction.

Table 1 summarises recent advancements in copper-based nanocatalysts for the Sonogashira coupling reaction. A variety of support materials, including magnetic nanoparticles, mesoporous clay, dendrimeric frameworks, and carbon nanofibers, have been explored to enhance catalyst stability, dispersibility, and reusability. The CuNPs/MK-10 catalyst reported by Stabile *et al.* showed 100% yield at 80 °C using triethylamine as base, while the Fe_3O_4@SiO_2@Cyt-Ni/Cu system offered a comparable 94% yield in just 2 hours with good recyclability over 7 cycles.[72] Catalysts functionalized with dendrimers and polyethylene glycol required minimal catalyst loading (as low as 0.8 mol%) while maintaining high activity and recyclability.[75] Fan *et al.* incorporated a bimetallic species Pd/Cu@MCC–PAMAM–PEI, which exhibited 96% yield in an inert environment at just 20 mg loading.[76]

In the Sonogashira coupling (Fig. 3), the reaction began with the activation of the terminal alkyne **4a**, where Cu NPs assisted in its deprotonation to generate the copper acetylide intermediate **III**. This intermediate then reacted with the aryl halide **1** to produce the organocopper species **IV**. Subsequent coupling yielded the $C(sp^2)$–C(sp) product **5** through reductive elimination, passing *via* intermediate **V**. Throughout the catalytic cycle, Cu NPs not only mediated the deprotonation and coupling steps but also stabilized the reactive intermediates, thereby enhancing the efficiency of the reaction under mild conditions. Regeneration of the active Cu species closed the catalytic cycle, enabling multiple turnovers.

Table 1 Sonogashira coupling reaction using copper-based nanocatalysts

S. no.	Catalyst	Reaction conditions	Time	Yield (%)	Catalyst loading (mol%)	Recyclability	Ref.
1	Fe_3O_4@SiO_2@Cyt-Ni/Cu	DMSO, K_2CO_3, 100 °C	2 h	94	0.1	7 cycles	Nasseri *et al.*[72]
2	CuNPs/MK-10	TEA, 80 °C	4 h	100	1.7	—	Stabile *et al.*[73]
3	MNPs-guanidine-bis(ethanol)-Cu	K_2CO_3, PEG, 120 °C	3 h	96	1.0	8 cycles	Patra *et al.*[74]
4	γ-Fe_2O_3@PEG@PAMAM G_0-Cu	NaOH, H_2O, 80 °C	3 h	94	0.8	6 cycles	Sheikh *et al.*[75]
5	Pd/Cu@MCC–PAMAM–PEI	K_2CO_3, DMSO, 80 °C, 4 h, under N_2	4 h	96	2.5	—	Fan *et al.*[76]
6	Fe_3O_4@CNF@Cu	H_2O, KOH, ultrasonic irradiation, 40 °C	6 h	98	0.2	6 cycles	Kargar *et al.*[77]

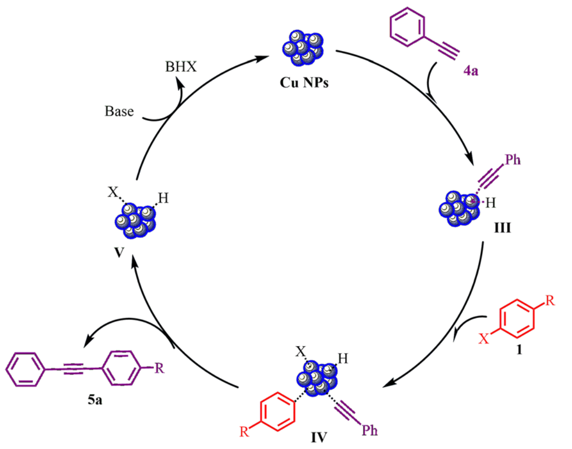
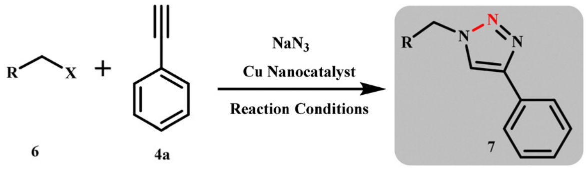


Fig. 3 Plausible mechanism for copper nanoparticle catalysed Sonogashira coupling reaction.

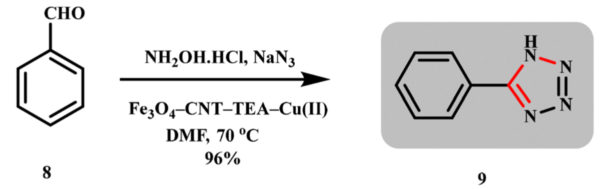
3.1.3. Click reaction for the synthesis of 1,2,3-triazole derivatives. A general reaction for click chemistry using a Cu nanocatalyst is shown in Scheme 3. Khalili *et al.* synthesized 1,4-disubstituted (*β*-hydroxy)-1,2,3-triazoles with 96% yield using $CuAl_2O_4$ nanoparticles. This green, additive-free process utilizes cost-effective sodium azide for *in situ* azide generation, avoiding hazardous intermediates, reducing waste, and simplifying reactions.[78] Pourhassan *et al.* synthesized triazole and tetrazole using a thioamide-based ligand mesoporous SBA-15 catalyst. The catalyst SBA15/thioamideCu(I) efficiently facilitated the synthesis of triazole and tetrazoles under mild aqueous conditions.[79]

Akbarzadeh *et al.* developed an affordable heterogeneous catalyst by incorporating Cu(II) nanoparticles onto triethylamine-functionalized magnetic carbon nanotubes (Fe_3O_4–CNT–TEA–Cu(II)). This catalyst efficiently promoted the one-pot synthesis of 5-substituted 1*H*-tetrazole derivatives, achieving high yields and accommodating a wide range of substrates. Key advantages include low catalyst loading, easy magnetic separation, and rapid reaction times (Scheme 4).[80]

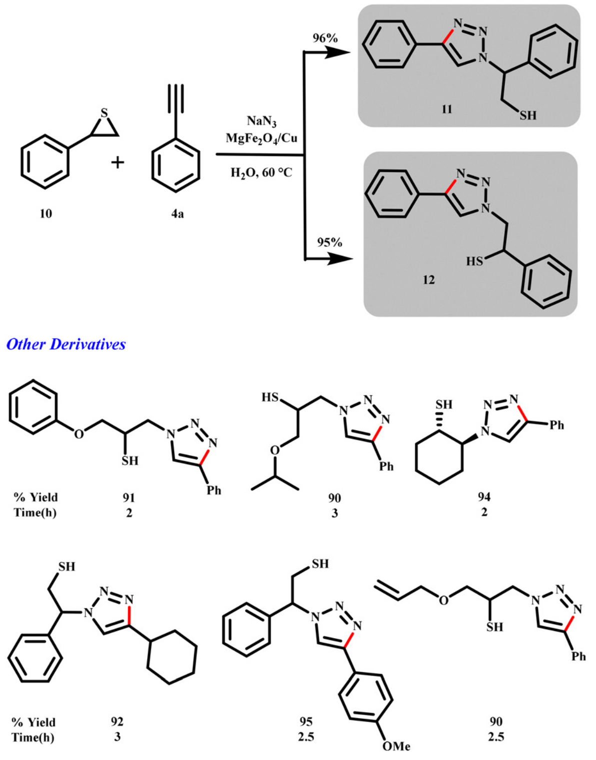
Eisavi *et al.* coated magnesium ferrite magnetic nanoparticles ($MgFe_2O_4$) on copper nanoparticles to prevent oxidation and aggregation. The $MgFe_2O_4$/Cu catalyst was employed for the regioselective synthesis of 1,2,3-triazoles from thiiranes, alkynes, and sodium azide in water, achieving high efficiency under optimized conditions. The procedure was tested with various thiiranes (bearing electron-donating/withdrawing groups and cyclic forms) and different alkynes using the Cu nanocomposite, affording triazoles in 80–96% yield within 2–4 h (Scheme 5).[81]



Scheme 3 General click reaction.



Scheme 4 Catalytic synthesis of heterocyclic derivatives using Fe_3O_4–CNT–TEA–Cu(II) nanoparticles (Akbarzadeh *et al.*).

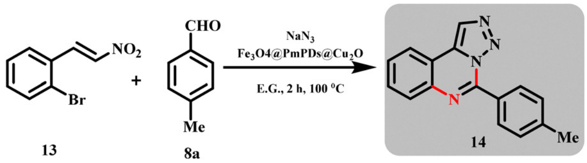


Scheme 5 $MgFe_2O_4$/Cu catalysed synthesis of *β*-thiol-1,4-disubstituted-1,2,3-triazoles from thiiranes (Eisavi *et al.*).

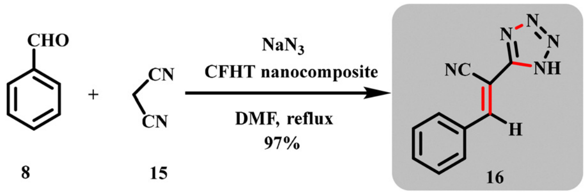
A magnetically separable Fe_3O_4@poly(*m*-phenylenediamine)@Cu_2O nanocatalyst was synthesized and characterized for efficient catalysis in the synthesis of 5-phenyl-[1,2,3]triazolo[1,5-*c*]quinazolines from (*E*)-1-bromo-2-(2-nitrovinyl)benzenes, aldehydes, and sodium azide under mild conditions. The nanocatalyst exhibited high catalytic activity and excellent recyclability over six runs with negligible loss, along with low metal ion leaching, and favourable green chemistry metrics, including a low *E*-factor, low process mass intensity, and high reaction mass efficiency. Under optimized conditions, Fe_3O_4@PmPDs@Cu_2O catalyzed the synthesis of 5-phenyl-[1,2,3]triazolo[1,5-*c*]quinazolines from various aldehydes and substituted (*E*)-1-bromo-2-(2-nitrovinyl)benzenes, affording good to excellent yields in most cases.

Electron-donating and halogen substituents were favourable, while electron-withdrawing groups on the phenyl ring hindered the reaction (Scheme 6).[82]

Hajizadeh *et al.* synthesized 5-substituted 1*H*-tetrazole derivatives using Cu(II) immobilized on an Fe_3O_4@HNTs–tetrazole (CFHT) nanocomposite. The nanocomposite efficiently catalyzed



Scheme 6 Fe_3O_4@poly(*m*-phenylenediamines)@Cu_2O catalysed synthesis of quinazolines (Rawat *et al.*).



Scheme 7 Catalytic synthesis of 5-substituted 1*H*-tetrazole derivatives (Hajizadeh *et al.*).

the multicomponent reactions of aromatic aldehydes, malononitrile, and sodium azide, yielding high productivity in short reaction times, and could be reused five times with maintained efficiency (Scheme 7).[83]

Sajjadi *et al.* prepared 5-amino-1*H*-tetrazole derivatives using a magnetic chitosan-supported Cu(II)-*N*-benzyl-amino-1*H*-tetrazole complex (MCS-BAT-Cu(II)) as the catalyst. The reaction involved C–N coupling of 5-amino-1*H*-tetrazole with various aryl iodides/bromides. The catalyst was efficiently separated using an external magnet and reused five times with minimal loss of activity.[84] Moghaddam *et al.* synthesized 1,2,3-triazole derivatives using copper(II)-coated magnetic core–shell nanoparticles (Fe_3O_4@SiO_2) modified with isatoic anhydride as a catalyst. The reactions were carried out under mild conditions. The catalyst exhibited high efficiency and could be reused for up to six consecutive cycles.[85] Arefi *et al.* synthesized 1,2,3-triazole derivatives using a core–shell magnetic metal organic framework (MOF) catalyst based on Fe_3O_4 magnetic nanoparticles coated with copper organic frameworks. The reactions were conducted in water as a green solvent, and the catalyst exhibited good to excellent yields and high reusability due to its superparamagnetic properties.[86] The Cu–Kojic acid complex on silica-MCM-41 was synthesized by Aghbash and his group and was found to be an efficient catalyst for the synthesis of 1,2,3-triazoles under green conditions. This catalyst offered easy synthesis, short reaction time, high stability, and simple purification.[87] Anvari *et al.* performed one-pot synthesis of 1,4-disubstituted 1,2,3-triazoles in water using a Cu@KCC-1-NH-CS_2 nanoreactor, which demonstrated high efficiency, very short reaction times (5–20 min), and excellent yields. The procedure involved an easy workup without toxic solvents and the catalyst could be reused up to five times with minimal activity loss.[88] Chetia *et al.* developed polyaniline-supported Cu (Cu/PANI) catalysts *via* interfacial polymerization, efficiently catalyzing regioselective triazole synthesis through azide–alkyne cycloaddition and click reactions in water at room temperature.[89] Wang *et al.* synthesised *in situ* copper nanoparticles/poly(ionic liquid) (CuNPs/poly-IL) composites, and their catalytic activity was investigated for click reaction.[90]

Valiey *et al.* synthesized the Cu@APS–TDU–PMO nanocomposite, which incorporates a urea-bridged periodic mesoporous organosilica. This composite exhibited high catalytic activity, thermal stability, and reusability for the synthesis of 2-(1*H*-tetrazol-5-yl)acrylonitrile derivatives under solvent-free conditions.[91] Kodasi and his group developed a green, one-pot synthesis of 1,2,3-triazoles using Cu microcrystals (CuMCs) *via* 1,3-dipolar cycloaddition. This method achieved high yields (87–90%) with excellent purity and regioselectivity.[92] Moeini *et al.* synthesized efficient $CuFe_{2-x}Y_xO_4$ nanoparticles (x = 0.00, 0.25, 0.50, 0.75, 1.00), which exhibited enhanced catalytic properties in click chemistry, yielding high amounts (82–97%) of triazole derivatives.[93] Cu anchored on poly[3-(carboxypropyl)thiophene-2,5-diyl]-modified multi-walled carbon nanotubes (Cu@PCT@CNT) efficiently catalyzed the synthesis of 1,4-disubstituted 1,2,3-triazoles in a three-component one-pot system. The process emphasized aqueous conditions, the use of non-hazardous azides, easy catalyst recovery, and high reusability.[94] The Fe_3O_4@SiO_2@BHA-Cu(II) nanocomposite, synthesized by Norouzi and his group, efficiently catalyzed the synthesis of tetrazoles and polyhydroquinolines with high yields under mild conditions in an ethanol/PEG mixture.[95] Singh *et al.* fabricated the CuO–NrGO nanoparticles, which exhibited high catalytic activity for synthesizing 5-substituted-1*H*-tetrazole and 1,2,3-triazole derivatives with 92% and 95% yield, respectively.[96] The Fe_3O_4@AG/AP-Cu(I) nanocatalyst was developed by Khaleghi *et al.* for efficient synthesis of 1,2,3-triazole derivatives *via* click chemistry, achieving 95% yield under mild conditions.[97]

Kwak *et al.* synthesized an Fe_3O_4@PDA@Cu nanocatalyst,-which effectively catalyzed the synthesis of 1,2,3-triazoles *via* three-component click reactions in water.[98] A novel rGO/PANI/Cu nanocomposite, synthesized *via* interfacial polymerization, is an efficient catalyst for 1,4-disubstituted-1,2,3-triazole synthesis *via* click chemistry.[99] A new Cu@NH_2GO nanocatalyst was synthesized by Sharma *et al. via* Schiff base functionalization of graphene oxide; it exhibited excellent stability and reusability (up to 5 cycles) with significant dye degradation (99% in 90 min), highlighting its potential for green chemistry applications.[100] Sahoo *et al.* prepared stable copper(I)-coordination polymers (CPs), [Cu(4-ABPT)Cl] (CP-1), [Cu(4-ABPT)Br] (CP-2), and [Cu_2(4-ABPT)$_{0.5}I_2$] (CP-3), and these were evaluated as catalysts for click reactions. CP-1 demonstrated quantitative conversion of phenylacetylene, benzyl bromide, and sodium azide into 1,4-cycloaddition products within 2 hours under neat conditions.[101] Cu(II)-loaded phosphorylated cellulose nanofibers (Cu-PCNFs) synthesised by Bahsis *et al.* serve as efficient and recyclable heterogeneous catalysts for click reactions. These bio-based catalysts enable the regioselective synthesis of 1,4-disubstituted-1,2,3-triazoles in water at room temperature, demonstrating high catalytic activity, stability over multiple cycles, and ease of separation, thereby contributing to sustainable click chemistry applications.[102] Fe_3O_4@CG/CPTMS/OL-Cu, a novel magnetic catalyst, investigated for the synthesis of 1,2,3-triazole attached phenylacetamides, offers several eco-friendly advantages like solvent-free conditions, high yields, rapid reactions, minimal waste generation, easy work-up, and convenient magnetic separation.[103]

Two novel heterogeneous copper catalysts based on dehydroacetic acid chitosan Schiff base (DCSB–Cu and DCSB–CuO nanoparticles) were synthesized and characterized by Asadi *et al.* The catalytic activity of these catalysts was evaluated for click reactions in water, showing that DCSB–Cu exhibits superior catalytic activity due to a smaller particle size and uniform distribution.[104]

The highly regioselective copper(I)-catalyzed azide–alkyne cycloaddition (CuAAC) reaction yields 1,4-disubstituted 1,2,3-triazoles. A copper acetylide is created when Cu(I) coordinates with the terminal alkyne. This copper acetylide then reacts with the azide to produce a metalacyclic intermediate **X** (Fig. 4).

The triazole product is efficiently produced by cyclization and reductive elimination. In this process, Cu(I) is frequently regenerated *in situ* from Cu(II) salts using reducing agents. This method is widely employed in materials chemistry, bioconjugation, and the surface functionalization of Cu-based nanomaterials.

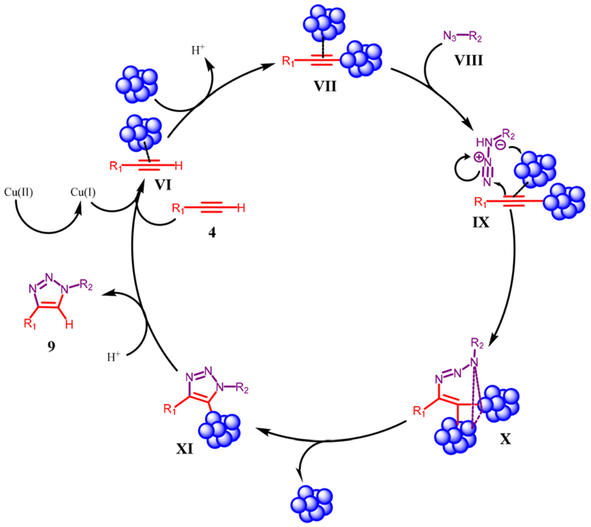
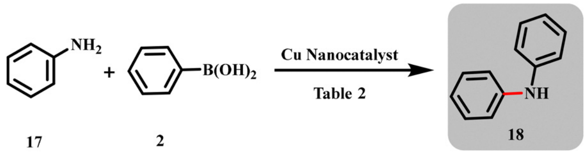


Fig. 4 Plausible mechanism for copper nanoparticle catalyzed Click reaction.



Scheme 8 General Chan–Lam cross-coupling reaction.

3.1.4. Chan–Lam coupling for C–N bond formation. Sanja Jeremic *et al.* synthesised a Cu/BNC nanocatalyst for Chan–Lam coupling, which involves the reaction between benzyl amine and phenyl boronic acid, resulting in the formation of *N*-benzylaniline.[105] A graphene oxide-supported Cu(II) ligand complex (GO@AP/L-Cu) was synthesized and employed as a heterogeneous catalyst for *N*-arylation and C–H activation reactions in aqueous medium, affording products in ~90% yields.[106] A general Chan–Lam cross-coupling reaction is illustrated in Scheme 8.

Table 2 concludes that Mobina Kouser *et al.* reported a PdCu@TiO_2–$NSiO_2$/Pt–TNS catalyst that achieved 88% yield in just 25 min with recyclability up to 6 cycles.[107] P. S. Pharande *et al.* reported a Cell–ThP–Cu(II) system, which gave 96% yield in water at room temperature with low catalyst loading (0.072 mol%) and 5-cycle reusability.[108] D. S. Kuliukhina *et al.* used CuI, delivering 85% yield over 24 h with high catalyst loading (20 mol%) and reusability.[109] Nastaran Ghasemi *et al.* demonstrated 89% yield at room temperature using Cu@Phen@MGO, while Manashi Sarmahal *et al.* employed Cu_2O/Cu, achieving 90% yield in 7 h with 3-cycle stability.[110,111] Masoumeh Shaker *et al.* reported an Fe_3O_4-supported system, which gave 97% yield under ambient conditions with 0.89 mol% loading and 7-cycle reuse.[112] Cu–TAPB–TFP reported by Ignacio Romero-Muñiz and peers also gave 97% yield in 18 h with 5-cycle recyclability.[113] Chenlu Zhang *et al.* reported $CuCl_2$@PAN-F, which showed excellent 98% yield in just 3 h with 8 mol% catalyst and 5-cycle use.[114] Lastly, Sharma *et al.* reported a catalyst, Cu@KF·C/$CoFe_2O_4$, which produced 85% yield in 2 h with 0.1 g loading and stable performance over 5 cycles.[115]

Cu@Ag–TiO_2–NGO offers high catalytic activity and reusability, demonstrating excellent performance in Chan–Lam coupling.[116] Kouser *et al.* have synthesized a PdCu@TiO_2–$NSiO_2$/PC–TNS catalyst and investigated its potential for the formation of a C–N bond *via* Chan–Lam coupling.[117] CuO/t-ZrO_2 and CuI nanoparticles have been prepared and used as catalysts in Chan–Lam coupling reactions to synthesize *N*-aryl imidazoles from imidazole and arylboronic acids under mild, additive-free conditions.[118] Yaduvanshi *et al.* synthesised an environmentally friendly Pd–Cu/KLR catalyst using KLE as a reducing agent, however, it exhibited poor performance in Suzuki C–C coupling

Table 2 Copper catalysed Chan–Lam coupling

S. no.	Catalyst	Reaction conditions	Time	Yield (%)	Catalyst loading (mol%)	Recyclability	Ref.
1	PdCu@TiO_2–$NSiO_2$/PC-TNS	K_2CO_3, EtOH: H_2O, 60 °C	25 min	88	19	6 cycles	Kouser *et al.*[107]
2	Cell–ThP–Cu(II)	Water, RT	6 h	96	0.07	5 cycles	Pharande *et al.*[108]
3	CuI	DMSO, 110 °C	24 h	85	20	—	Kuliukhina *et al.*[109]
4	Cu@Phen@MGO	MeOH, RT	20 h	89	2	6 cycles	Ghasemi *et al.*[110]
5	Cu_2O/Cu	MeOH, 60 °C	7 h	90	10	3 cycles	Sarmahl *et al.*[111]
6	Fe_3O_4@RF@void@PMO(IL)/Cu	K_2CO_3, EtOAc/H_2O (1 : 1), RT	5 h	97	0.9	7 cycles	Shaker *et al.*[112]
7	Cu–TAPB–TFP	CH_2Cl_2, 30 °C	18 h	97	2.6	5 cycles	Romero-Muñiz *et al.*[113]
8	$CuCl_2$@PAN-F	MeOH	3 h	98	8	5 cycles	Zhang[114] *et al.*
9	Cu@KF-C/$CoFe_2O_4$	Cs_2CO_3, EtOH 90 °C	2 h	85	2.2	5 cycles	Sharma *et al.*[115]

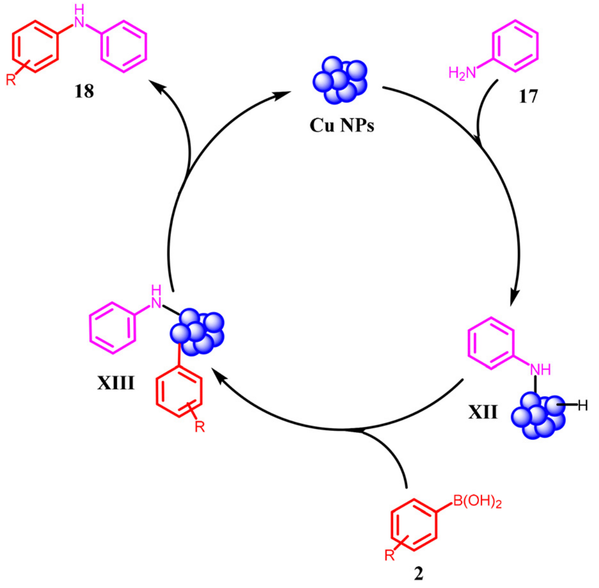
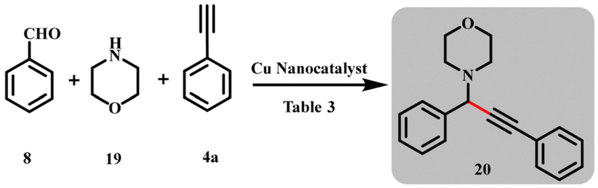


Fig. 5 Plausible mechanism for copper nanoparticle catalysed Chan–Lam coupling reaction.

reactions. Interestingly, the bioactive heterocycles synthesized with Pd–Cu/KLR showed promising antibacterial activity, with one compound displaying potency comparable to ciprofloxacin.[119]

In this Chan–Lam coupling (Fig. 5), the reaction began with the coordination of amine **17** to the Cu species, giving rise to the Cu–amine intermediate **XII**. In parallel, the arylboronic acid **2** underwent transmetalation with the Cu catalyst, transferring the aryl group and forming intermediate **XIII**. Subsequent reductive elimination from **XIII** produced the desired C–N coupled product **18**, while regenerating the active Cu catalyst. This pathway proceeded under mild and aerobic conditions, without requiring strong bases or additional ligands. The Cu NPs not only stabilized the intermediates but also enhanced electron transfer, thereby increasing the reaction's efficiency. As a result, the method tolerated a wide range of nucleophiles and proved suitable for biocompatible and environmentally friendly C–N bond formation.



Scheme 9 A^3 coupling using copper nanocatalysts.

3.1.5. A^3 coupling for the synthesis of propargyl amine derivatives. The aldehyde–alkyne–amine (A^3) coupling (Scheme 9) is a multicomponent reaction that yields propargylamines,[120] which are valuable intermediates in natural product synthesis and pharmaceuticals. Copper nanoparticles serve as highly effective catalysts for this reaction due to their large surface area and unique electrical properties, which facilitate the activation of both amine and alkyne substrates.[121] The process begins with the formation of a copper–acetylide intermediate, followed by nucleophilic addition of the amine to the activated aldehyde. Copper nanocatalysts offer significant advantages, including excellent atom economy, high selectivity, and mild reaction conditions, making them a promising choice for environmentally sustainable chemical synthesis.[122]

Table 3 summarises that Shahverdi *et al.* employed a $[Cu(BTA)_2]_n$ catalyst in dioxane at 80 °C, achieving 95% yield in 4 h using a 3 mol% catalyst.[124] Kohli *et al.* reported Fe_3O_4/PANI/CuI, which yielded 96% in just 10 minutes under neat conditions with only 10 mg of catalyst, and maintained recyclability over 7 cycles.[125] Cheng *et al.* used PANBis(Py)–Cu(I)DF under solvent-free conditions at 110 °C, obtaining >99% yield in 12 h with only 0.1 mol% catalyst.[128] Bagheri *et al.* synthesized a nanocomposite of MMT-K10/Fe_3O_4/CuO, obtaining 91% yield in 8 h using 30 mg of the catalyst, with high reusability.[130] Banda *et al.* used Fe_3O_4–NH_2–Cu at 80 °C (neat), achieving 97% yield in 5 h with 15 mg of the catalyst.[131] Tajbaksh *et al.* reported a starch-based copper nanocomposite Fe_3O_4@starch-Acr@Cu(II), producing 99% yield in 36 h using only 0.020 g of the catalyst.[132] Huang *et al.* applied Cu(BDC)@Cu(II)/CMC in a toluene reflux system to deliver 96% yield in 4 h using 7.5 mol% catalyst.[134] Jia *et al.* developed a CuI–

Table 3 A^3 coupling catalysed by copper nanocomposites

S. no.	Catalyst	Reaction conditions	Time	Yield (%)	Catalyst loading (mol%)	Recyclability	Ref.
1	[CuCl{k1 (P)-1b}$_2$]	Neat, 100 °C	1.5 h	99	0.5	—	Guaramato *et al.*[123]
2	$[Cu(BTA)_2]$n	Dioxane, 80 °C	4 h	95	3	6 cycles	Shahverdi *et al.*[124]
3	Fe_3O_4/PANI/CuI(10)	Neat, 80 °C	10 min	96	1.8	7 cycles	Kohli *et al.*[125]
4	Cu–L4	Chloroform, 90 °C	24	90	1	—	Pandey *et al.*[126]
5	$Cu(NO_3)_2 \cdot 3H_2O$	DMSO, 80 °C	2 h	81	10	—	Wang *et al.*[127]
6	PANbis(Py)–Cu(II)F	Solvent free, 110 °C	12 h	>99	0.1	6 cycles	Cheng *et al.*[128]
7	CuI/Zn dust	Neat, 60 °C	18 h	98	20	—	Agbo *et al.*[129]
8	MMT-K10/Fe_3O_4/CuO	Toluene, 80 °C	8 h	91	2	High	Bagheri *et al.*[130]
9	Fe_3O_4–NH_2–Cu	Neat, 80 °C	5 h	97	1.2	5 cycles	Banda *et al.*[131]
10	Fe_3O_4@starch-Acr@Cu(II)	H_2O, Reflux	36 min	99	39.3	5 cycles	Tajbakhsh *et al.*[132]
11.	CuI	DMSO, 60–65 °C	15 h	95	1.3	—	Grishchenko *et al.*[133]
12.	Cu(BDC)@Cu(II)/CMC	Toluene, reflux	4 h	96	7.5	6 cycles	Huang *et al.*[134]
13.	Cu_3NC(NHC)	DCM, RT	12 h	99	2.5	6 cycles	Jia *et al.*[135]
14.	Co^{2+}–Cu@SA(7.5)-600	Toluene, 110 °C	1 h	88	9.4	5 cycles	Kaur *et al.*[136]
15.	Fe_3O_4–BIm–Pyrim–CuI	H_2O, reflux	3 h	98	0.15	8 cycles	Li *et al.*[137]

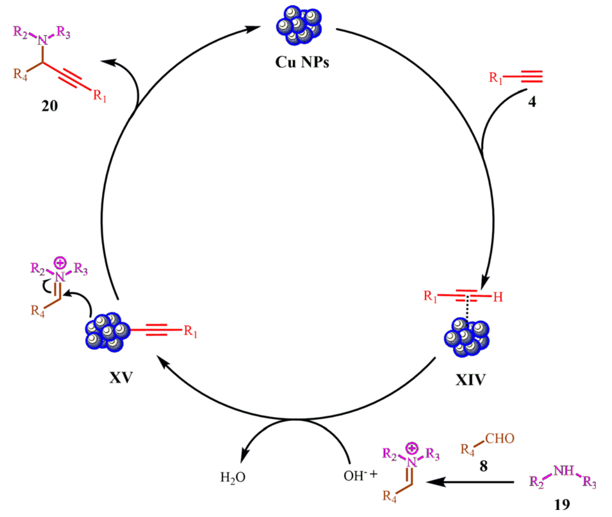
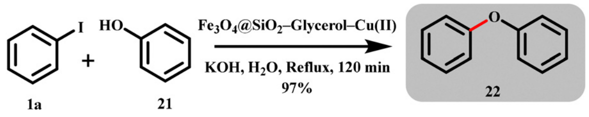


Fig. 6 Plausible mechanism for copper nanoparticle catalysed A^3 coupling reaction.

NC(NHC) catalyst in DCM at room temperature, obtaining 95% yield in 12 h with 2.5 mol% loading.[135] Kaur *et al.* used Co^{2+}–Cu@SBA-15–600 and obtained 88% yield in 8 h with 0.05 g of the catalyst.[136] Li *et al.* demonstrated Fe_3O_4-Blue-Burke-CuI achieving 98% yield in 3 h under reflux with 20 mg of the catalyst and recyclability up to 8 cycles.[137]

Cu(I) is used as a catalyst in the A^3 coupling reaction (Fig. 6); the process began with the activation of the terminal alkyne **4** by Cu, which generated the copper acetylide intermediate **XIV**. Simultaneously, the aldehyde **8** reacted with the amine **19** to form the iminium ion. The copper acetylide then combined with this iminium ion through nucleophilic addition, producing the Cu-bound propargylamine intermediate **XV**. Subsequent release from the Cu center yielded the desired propargylamine product **20**, while regenerating the Cu catalyst. Throughout the reaction, Cu NPs not only facilitated the formation of the copper acetylide but also stabilized the intermediates, thereby enhancing regioselectivity and overall efficiency. The method proved to be atom-economical and was widely employed in the synthesis of pharmacologically relevant scaffolds.

3.1.6 C–O coupling reactions. Diaryl ethers are crucial biologically active intermediates, and due to their significant biological activity, there is a strong demand for the development of practical and scalable synthetic methods. Over the past few decades, diaryl ethers have been synthesized through various protocols using copper and palladium catalysts under mild conditions. However, due to concerns over toxicity, metal contamination, and other drawbacks, copper nanoparticles have garnered attention as catalysts for C–O coupling reactions. This is because they offer low toxicity, excellent catalytic activity, and cost-effectiveness.



Scheme 10 Fe_3O_4@SiO_2–glycerol–Cu(II) catalysed synthesis of di-aryl ethers (Ashraf *et al.*).

Table 4 indicates that Yongsheng Zhou *et al.* reported *β*-CD-CuNPs, which delivered 91% yield in 12 h under basic conditions with 5-cycle recyclability.[138] Mohammad Eslami *et al.* employed CuO/mGO–TA–Me–BTA in aqueous reflux to achieve 89% yield in 6 h, also recyclable for 5 cycles.[139] Md Lutfor Rahman *et al.* developed a cellulose-supported Cu(II) catalyst that achieved 99% yield in just 1.5 h at 70 °C with excellent reusability (7 cycles).[140] Ahmed Talal Ali *et al.* used an Fe_3O_4-supported Cu(II) metallo-complex, which reached 98% yield in 1 h under aqueous reflux with 8-cycle stability.[141] Arida Jabbari *et al.* reported a Cu(II)-AMP@boehmite system that afforded a 98% yield in 1 h at 130 °C, reusable up to 6 cycles.[142] Forough Gorginpour *et al.* used CuNPs@O-POP, achieving 97% yield despite a long reaction time (48 h), while maintaining reusability over five cycles.[143]

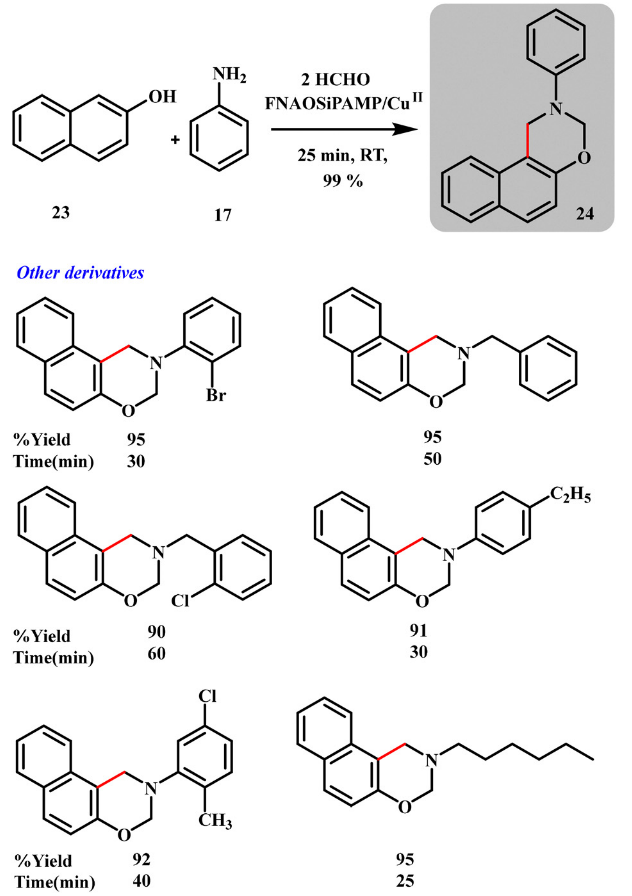
Forough Gorginpour *et al.* synthesized CuNPs@Q-POP nanoparticles and investigated their catalytic acitivity for C–O coupling reaction using iodobenzene and phenol.[144] Ashraf *et al.* prepared a copper(II) complex supported on surface-modified Fe_3O_4/SiO_2 nanoparticles (Fe_3O_4@SiO_2–glycerole–Cu(II)), employed as an effective catalyst for C–O cross-coupling reactions of aryl halides with phenol (Scheme 10).[145]

Keihanfar *et al.* developed a novel eco-friendly catalyst, Fe_3O_4@nanoalmond shell@Osi (CH_2)/$NHCH_2$pyridine/Cu^{II}(FNAOSiPAMP)/Cu^{II}; it efficiently catalyzed the synthesis of naphtho[1,2-*e*][1,3]oxazines (Scheme 11) under solvent-free conditions, with advantages including high yields, easy workup, and thermal stability. They synthesized a range of naphtho[1,2-*e*][1,3]oxazine derivatives from various amines, *β*-naphthol, and formaldehyde, achieving good to excellent yields within short reaction times.[146]

A remarkably recyclable Cu(II)-Schiff base-TCT-APTES@SiO_2@Fe_3O_4 core–shell magnetic nanocatalyst was synthesized by Kalantar *et al.*, which efficiently catalyzes the one-pot

Table 4 Copper catalysed reactions for C–O bond formation

S. no	Catalyst	Reaction conditions	Time	Yield (%)	Catalyst loading (mg)	Recyclability	Ref.
1	*β*-CD-CuNPs	DMF, 100 °C, Cs_2CO_3	12 h	91	—	5 cycles	Zhou *et al.*[138]
2	CuO/mGO-TA-Me-BTA	H_2O, Cs_2CO_3, reflux	6 h	89	20	5 cycles	Eslami *et al.*[139]
3	Cellulose-based NCL-Cu(II)@PA	MeCN, K_2CO_3, 70 °C	1.5 h	99	32	7 cycles	Rahman *et al.*[140]
4	Fe_3O_4 supported [Cu(II) met(II) $(Pro\text{-}H)_2$]	H_2O, Cs_2CO_3, reflux	1 h	98	8	8 cycles	Ali *et al.*[141]
5	Cu(II)-MP-bis(AMP)@boehmite	DMSO, KOH, 130 °C	1 h	98	30	6 cycles	Jabbari *et al.*[142]
6	CuNPs@Q-POP	K_2CO_3, DMF, 110 °C	48 h	97	75	5 cycles	Gorginpour *et al.*[143]



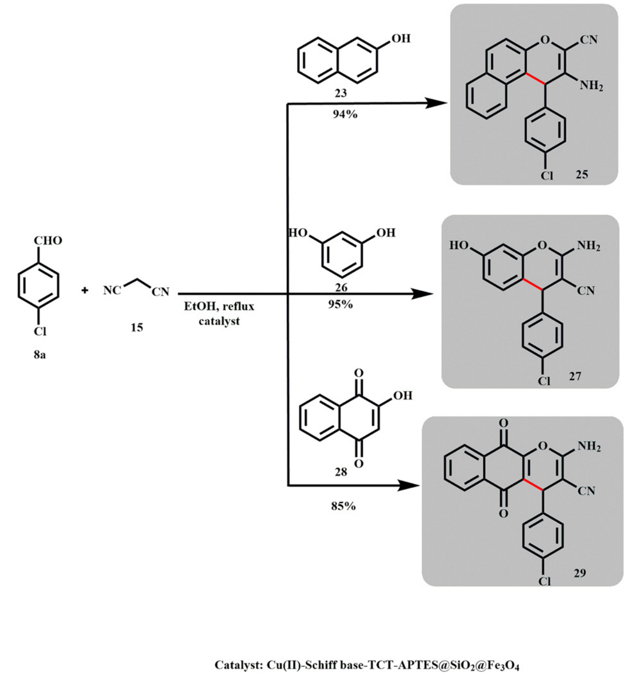
Scheme 11 FNAOSiPAMP/Cu^{II} catalysed synthesis of naphtho[1,2-e][1,3]oxazine (Keihanfar *et al.*).

synthesis of chromene derivatives, showing minimal copper leaching (Scheme 12).[147]

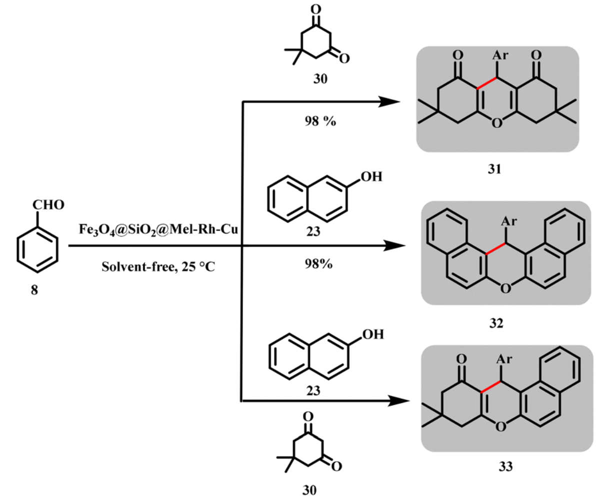
Peiman *et al.* carried out a one-pot synthesis of xanthene and spirooxindole-pyran derivatives under mild, solvent-free conditions, yielding excellent results in terms of both reaction speed and product yield (Scheme 13).[148]

Li *et al.* developed an efficient method for the synthesis of imidazo[1,2-*a*]pyridine and pyranopyrazole derivatives, catalyzed by a novel nanocatalyst, Fe$_3$O$_4$@Dop/amide-benzImid-CuBr$_2$. This nanocatalyst was synthesized by immobilizing copper on magnetic iron nanoparticles modified with dopamine and 1*H*-benzo[*d*]-imidazole-2-carboxylic acid (Scheme 14)[149]

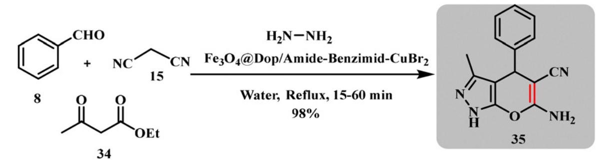
3.1.7 C–S coupling catalysed by a copper nanocomposite. Ashraf *et al.* synthesized an Fe$_3$O$_4$@SiO$_2$–glycerol–Cu(II) nanocomposite and effectively catalyzed C–S cross-coupling reactions between aryl halides with thiourea, achieving high yields and recyclability for six cycles using an external magnet. This magnetic nanocatalyst offered advantages such as short reaction times, simple work-up, and ease of separation. C–S coupling of various aryl halides with thiols using the catalyst in water under reflux gave di-aryl sulfides in 47–96% yields within 10 to 240 min. Aryl iodides and bromides generally gave higher yields and shorter reaction times than chlorides (Scheme 15).[150]



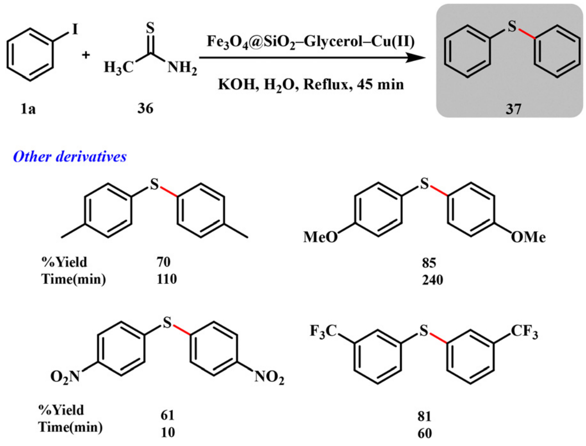
Scheme 12 Cu(II)-Schiff base-TCT-APTES@SiO$_2$@Fe$_3$O$_4$ catalysed synthesis of chromene derivatives (Kalantar *et al.*).



Scheme 13 Fe$_3$O$_4$@SiO$_2$@NTMPThio–Cu catalysed synthesis of xanthenes (Peiman *et al.*).



Scheme 14 Fe$_3$O$_4$@Dop/amide-benzimid-CuBr$_2$ catalysed synthesis of 6-amino-3-methyl-4-phenyl-1,4-dihydropyrano[2,3-c]pyrazole-5-carbonitrile (Li *et al.*).



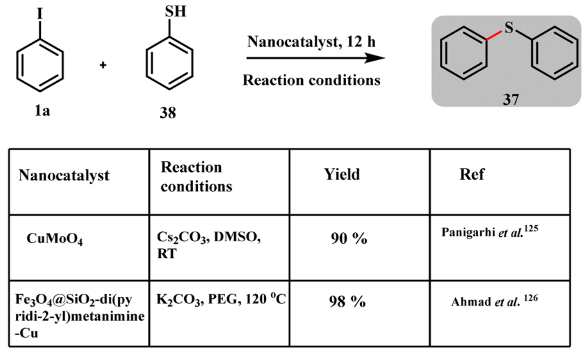
Scheme 15 $Fe_3O_4@SiO_2$–glycerol–Cu(II) catalysed synthesis of sulfides (Ashraf *et al.*).

A novel $CuMoO_4$ bimetallic nanocatalyst exhibits superior efficiency compared to Cu(II) catalysts at room temperature for C–S cross-coupling reactions. It achieves high yields and recyclability even in the absence of ligands, highlighting its potential for a wide range of thiols and haloarenes (Scheme 16).[151]

Ahmad *et al.* synthesised another well-dispersed, magnetically separable copper nanocatalyst $Fe_3O_4@SiO_2$-di(pyridin-2-yl) amine-Cu, and its catalytic activity was evaluated for the synthesis of diphenylsulfane as shown in Scheme 16.[152]

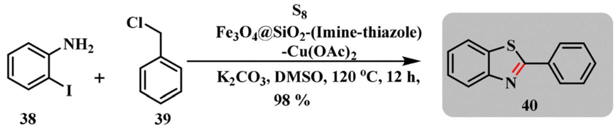
Feng *et al.* developed a similar catalyst, a copper complex supported on magnetic nanoparticles modified with an imine-thiazole ligand ($Fe_3O_4@SiO_2$–(imine-thiazole)–$Cu(OAc)_2$), which was employed in the synthesis of diaryl sulfides and benzothiophenes, achieving good to excellent yields. This catalyst could be easily recovered magnetically and reused for at least seven cycles without significant loss of activity (Scheme 17).[153]

Abdelbasset and his team developed a novel, magnetically recoverable copper catalyst, $Fe_3O_4@SiO_2$-imine/thio-Cu(II), which demonstrated high efficiency in synthesizing biologically active diaryl sulfones *via* sulfonylative Suzuki–Miyaura cross-coupling reactions and maintained reusability for seven cycles without significant loss of activity (Scheme 18).[154]

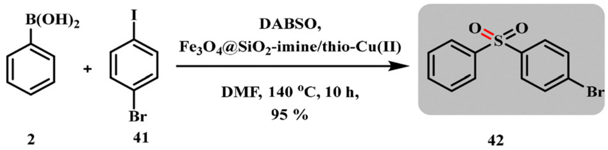


Nanocatalyst	Reaction conditions	Yield	Ref
$CuMoO_4$	Cs_2CO_3, DMSO, RT	90 %	Panigarhi *et al.*[125]
$Fe_3O_4@SiO_2$-di(pyridi-2-yl)metanimine-Cu	K_2CO_3, PEG, 120 °C	98 %	Ahmad *et al.* [126]

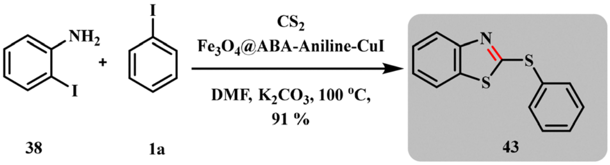
Scheme 16 $CuMoO_4$ catalysed synthesis of diphenylsulfane (Panigrahi *et al.* and Ahmed *et al.*).



Scheme 17 $Fe_3O_4@SiO_2$–(imine-thiazole)–$Cu(OAc)_2$ catalysed synthesis of 2-substituted benzothiazoles (Feng *et al.*).



Scheme 18 $Fe_3O_4@SiO_2$-imine/thio-Cu(II) catalysed synthesis of diaryl sulfones (Abdelbasset *et al.*).

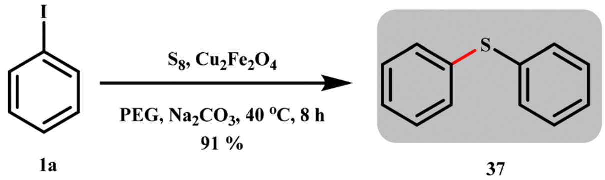


Scheme 19 $Fe_3O_4@ABA$–aniline–CuI catalysed synthesis of 2-(phenylthio)benzo[*d*]thiazole (Sun *et al.*).

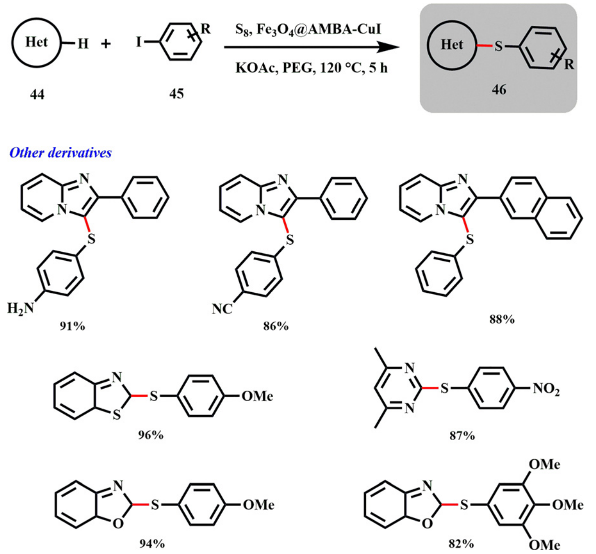
The $Fe_3O_4@ABA$–aniline–CuI nanocomposite was synthesized by Sun *et al.*, which catalyzed one-pot three-component reactions of 2-iodoaniline with carbon disulfide and aryl/heteroaryl iodide to furnish benzothiazole–sulfide aryls and heteroaryls. This catalyst, composed of cost-effective materials, can be easily separated magnetically and reused for at least seven cycles without a significant loss of activity (Scheme 19).[155]

Ichie *et al.* prepared a magnetically separable $CuFe_2O_4$ nanocatalyst, which exhibited high efficiency in C–S coupling reactions using S8 in PEG 400 at 40 °C. The catalyst, easily recovered *via* filtration, maintained catalytic activity over five cycles (Scheme 20).[156]

Fan *et al.* synthesised an eco-friendly $Fe_3O_4@AMBA$–CuI nanocatalyst for the synthesis of diaryl sulfides containing imidazo[1,2-*a*]pyridine, benzoazole, pyrimidine, and oxadiazole scaffolds through C–H bond sulfenylation of imidazopyridines. The $Fe_3O_4@AMBA$–CuI catalyst exhibited excellent reusability, maintaining its activity and magnetic properties for up to eight cycles. This method efficiently accommodated a wide variety of substituted iodobenzene derivatives, consistently affording the target products in good to high yields. Electron-donating



Scheme 20 $Cu_2Fe_2O_4$ catalysed synthesis of diphenylsulfane (Ichie *et al.*).



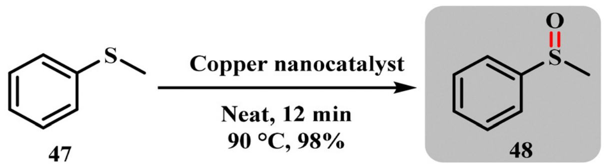
Scheme 21 Fe_3O_4@AMBA–CuI catalysed synthesis of 2-phenyl-3-(*p*-tolylthio)imidazo[1,2-*a*]pyridine (Fan *et al.*).

substituents on iodobenzene or heterocyclic derivatives notably enhanced the reaction efficiency, producing higher yields compared to electron-withdrawing groups. Demonstrating its scalability, the model three-component reaction of 2-phenylimidazo[1,2-*a*]pyridine, sulfur (S_8), and 4-methyl iodobenzene was successfully performed on a 50-fold scale under optimized conditions, delivering an impressive 88% yield (Scheme 21).[157]

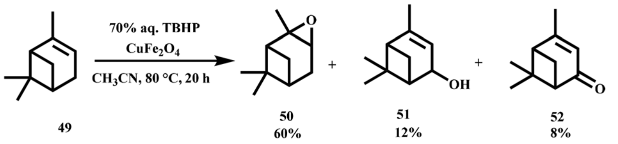
3.2. Oxidation reactions

Leili Heidari *et al.* developed $CoFe_2O_4$@SiO_2–CPTES–Guanidine–Cu(II), which offers an efficient method for the oxidation of sulphide, achieving 95% yield under solvent-free conditions at 40 °C (Scheme 22).[158] A magnetic nanocatalyst $ZnFe_2O_4$@SiO_2@APTES@DHBS-Cu was synthesised in a green and mild environment by Arash Ghorbani-Choghamarani *et al.* for the oxidation of sulfides under green conditions, exhibiting excellent catalytic activity.[159]

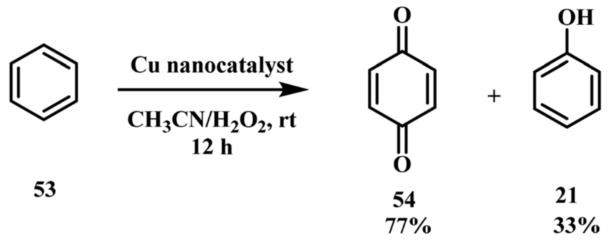
Mdletshe *et al.* synthesized spinel $CuFe_2O_4$ nanostructures using a surfactant-assisted method for the oxidation of pinene to renewable aroma oxygenates such as verbenone, verbenol, and pinene oxide. The prepared $CuFe_2O_4$ nanoparticles converted 80% of pinene to these renewable oxygenates in 20 h (Scheme 23).[160]



Scheme 22 Cu(II) catalysed oxidation of sulphides into sulphoxides (Heidari *et al.*).



Scheme 23 Oxidation of pinene catalysed by copper ferrite nanoparticles (Mdletshe *et al.*).



Scheme 24 Oxidation of benzene into phenol and benzoquinone catalysed by copper nanoparticles (Wanna *et al.*).

A recyclable and efficient Cu nanocatalyst has been used for the selective oxidation of benzene to *p*-benzoquinone. Notably, the addition of water to the reaction significantly increased the selectivity for *p*-benzoquinone, achieving 84% selectivity and increasing the conversion efficiency to 98% (Scheme 24).[161]

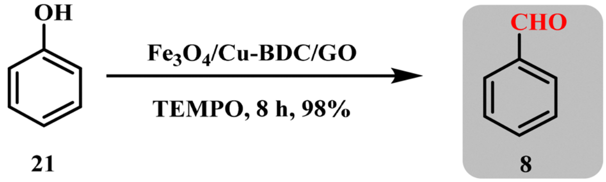
CuO_x–ZrO_2–CeO_2 composites with varying Cu/Zr ratios were easily and efficiently prepared using a simple solid-state chemical method for CO oxidation into CO_2 with 100% conversion.[162]

Alamgholiloo *et al.* synthesized Fe_3O_4/Cu-BDC/GO with TEMPO as a co-catalyst for the aerobic oxidation of alcohols. This catalyst achieved good conversion and excellent selectivity, regardless of whether the alcohols had electron-withdrawing or electron-donating substituents (Scheme 25).[163]

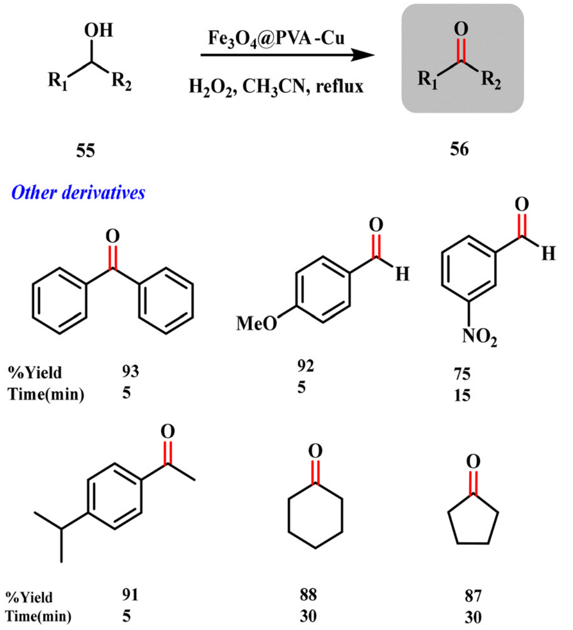
A highly magnetic nanocatalyst, Fe_3O_4@PVA–Cu, was synthesized by Jamal Rahimi *et al.* for the oxidation of alcohols to ketones. As seen in Scheme 26, the highest product yields were obtained from alcohols bearing electron-donating groups at the *ortho* or *meta* positions of the phenyl ring. These substituents increase the negative charge on the benzylic carbon, facilitating the hydrogen removal from the intermediate complex.[164]

Mir Saeed Esmaeili *et al.* employed raffinose, an oligosaccharide polymer, to synthesize Fe_3O_4@raffinose–Cu_2O, an efficient nanocatalyst for the oxidation of primary benzyl alcohols to benzaldehyde derivatives, enhancing both yields and reaction time.[165] Magnetic Fe_3O_4@SiO_2/Cu was synthesised *via* a co-precipitation method and exhibited excellent catalytic activity for the oxidation of benzyl alcohol to benzaldehyde (Scheme 27).[166]

Bimetallic Ni–Cu NPs supported on reduced quantum dots have been prepared *via* an electrochemical method for methanol



Scheme 25 Oxidation of phenol to benzaldehyde catalysed by an Fe_3O_4/Cu-BDC/GO catalyst (Alamgholiloo *et al.*).



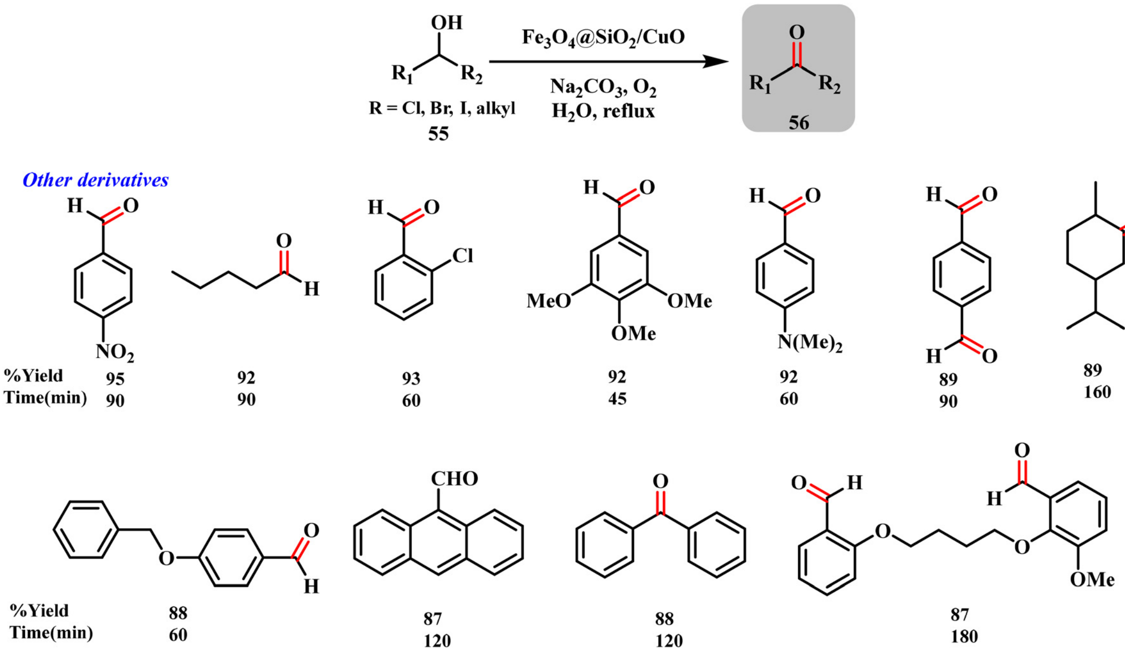
Scheme 26 Oxidation of alcohol to ketone catalysed by a copper-based nanocomposite (Rahimi *et al.*).

oxidation.[167] Bimetallic Pt_3Cu nano-dendrites (NDs) with a multi-branched structure on a W-modified TiO_2 support have been synthesized by Hau Quoc Pham *et al.* using a microwave-assisted technique, providing an efficient technique for methanol oxidation.[168] A Schiff base ligand immobilized on a magnetic-supported copper nanocatalyst (Fe_3O_4@SiO_2/Schiff base/Cu(II)) has been synthesized, and its catalytic activity for olefin oxidation has been investigated. The catalyst exhibited excellent activity, with advantages such as easy separation, short reaction times, and high conversion rates.[169] Pradyut Kumar Behera *et al.* have synthesized a bimetallic $CuMoO_4$ nanocatalyst that efficiently catalyzes the dehydrogenative oxidation of benzyl alcohol. A DFT study reveals that dehydrogenation predominantly occurs at the copper center rather than the molybdenum site.[170] Asma Ghazzy synthesized a trimetallic $Cu_{0.5}Zn_{0.5}$–Fe catalyst using an eco-friendly method with Tilia plant extract. This catalyst demonstrated excellent catalytic activity for the oxidation of various benzylic alcohols, achieving 99% yield and 98% selectivity toward aldehydes.[171] CuNPs@LDH was synthesized using a chemical reduction method and exhibited excellent catalytic activity in the liquid-phase oxidation of cyclohexane with *tert*-butyl hydroperoxide. It also demonstrated six cycles of recyclability without any loss in catalytic performance.[172]

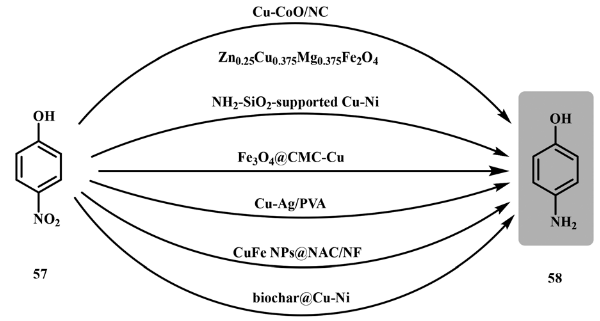
The CuO@GO nanocatalyst was synthesized using a wet chemical method by Maqsood Ahmad Malik *et al.*, while the Pt–Cu/C catalyst was prepared by Xiang Zhang *et al.* Both catalysts demonstrated excellent catalytic activity for the oxidation of alcohols.[173] Fe_3O_4@PectinImidazoleSO$_3$H–Cu(II) an efficient biopolymer based magnetic nanocatalyst has been reported for oxidation of benzyl free alcohol to aldehyde under neat conditions.[174]

3.3 Reduction reactions

Zeynizadeh *et al.* synthesized a copper nanoparticle-immobilized superparamagnetic montmorillonite (MMT@Fe_3O_4@Cu) composite, which catalysed reduction of nitroarenes to arylamines and acetanilide in water. The catalyst facilitated easy magnetic recovery and demonstrated good reusability, maintaining its activity over six cycles with minimal loss in activity.[175] Scheme 28 shows



Scheme 27 Oxidation of benzyl alcohol to benzaldehyde (Dehkordi *et al.*).



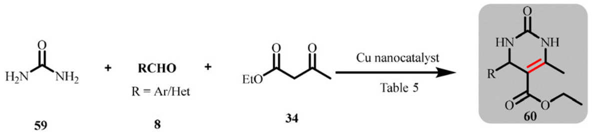
Scheme 28 Various copper-catalysts used in reduction reaction.

the different copper besed catalysts that are used for reduction reaction.

Dey *et al.* synthesized copper ferrite magnetic nanoparticles (CFNC) *via* a wet chemical method. This catalyst demonstrated high catalytic efficiency in reducing 4-nitrophenol to 4-aminophenol, with first-order kinetics. The catalyst also facilitated easy magnetic separation, allowing for reuse and making it highly cost-effective.[176] The DFNS/PEI/Cu nanocatalyst, which incorporated copper nanoparticles within fibrous silicate nanospheres, demonstrated high catalytic activity and reusability for reducing nitro-aromatic compounds in aqueous solutions. This design offered a sustainable and efficient solution for water pollution. Also immobilisation of Cu nanoparticles prevented nanocatalyst aggregation and improved the catalyst active sites. The catalyst remained effective for at least 10 reuse cycles without any loss in performance.[177] Patil *et al.* demonstrated that Cu–Mg substituted zinc ferrite ($Zn_{0.25}Cu_{0.375}Mg_{0.375}Fe_2O_4$) serves as an efficient photocatalyst under natural sunlight, achieving >99% efficiency in converting carcinogenic 4-nitrophenol into useful 4-aminophenol.[178] An NH_2–SiO_2-supported Cu–Ni nanocatalyst designed by Sarkar *et al.* achieved 98.5% conversion of 4-nitrophenol to 4-aminophenol within 15 minutes at pH 6, which followed a pseudo-first-order kinetic model.[179] An Fe_3O_4@CMC–Cu nanocatalyst, synthesized *via* hydrothermal and *in situ* deposition methods, was demonstrated as highly efficient for reduction of various organic pollutants such as *p*-nitrophenol, *o*-nitrophenol, methylene blue, and methyl orange with short reaction times (3–8 min), superior stability, reusability over six cycles, and magnetic retrievability.[180] Wang *et al.* designed a Cu–Ag bimetallic nano-catalyst anchored on polyvinyl alcohol sponge (Cu–Ag/PVA) *via* a two-step impregnation and reduction method. It exhibited excellent catalytic efficiency (a rate constant of 0.54 min^{-1}) and recyclability (>98% conversion of 4-nitrophenol maintained over twelve cycles).[181] Zarei *et al.* synthesized a biochar@Cu–Ni bimetallic nanocatalyst using pistachio shell biochar *via* a hydrothermal method, showing robust catalytic performance for the reduction of 4-NP and aldehydes using $NaBH_4$.[182] Shen *et al.* developed a Cu–CoO/NC nanocatalyst *via* a sol–gel method using EDTA and urea as carbon and nitrogen sources, retaining its catalytic activity over 5 cycles for 4-NP reduction.[183] He *et al.* designed a CuFe NPs@NAC/NF cathode, *via* sol–gel and *in situ* carbothermic reduction methods, featuring Cu and Fe nanoparticles enclosed in N-doped graphitized carbon on nickel foam. It exhibited high NO_3^- reduction efficiency (75.2%) and maintained stability over 15 cycles.[184]

3.4. Miscellaneous reactions

Multi-component reactions (MCRs) are especially efficient for synthesizing heterocyclic compounds because of their simplicity, high atom economy, and minimal by-product formation. These reactions allow the creation of complex molecules in a single step by combining three or more reactants, providing a streamlined and efficient synthetic method.[185] Kumari *et al.* described a simple synthesis of magnetically separable copper-loaded L-DOPA functionalized magnetite nanoparticles (Fe_3O_4–DOPA–CuNPs), which exhibited remarkable catalytic performance, especially in the Biginelli reaction under microwave irradiation. This catalyst demonstrated exceptional efficiency in four multicomponent reactions, including the synthesis of DHPMs, imidazoles, 2-amino-4*H*-chromenes, and 1,2,3-triazole derivatives.[186] CuNPs grafted on carbon microspheres catalyze an efficient one-pot synthesis of spirooxoindole derivatives from isatin, malononitrile, and enolizable ketones, offering high yields, easy separation, and reusable catalytic efficiency in an aqueous-alcoholic medium.[187] Alinezhad *et al.* reported the green synthesis of CuO nanoparticles using *Euphorbia maculata* extract, demonstrating high catalytic activity in the solvent-free Biginelli reaction and achieving the best yield of 95% at 90 °C for 90 minutes. The catalyst, effective with various aldehydes and active methylene compounds, maintained yields of 95% over three cycles.[188] Bendi *et al.* reported in their study a robust, efficient, and reusable cobalt ferrite magnetic nanocomposite [$CoFe_2O_4$/$Cu(OH)_2$] as a heterogeneous catalyst for synthesizing biologically active DHPMs *via* the Biginelli reaction, under thermal and solvent-free conditions, offering high yields, easy work-up, and excellent catalyst reusability, with DFT calculations conducted to analyze the molecular properties of the DHPM derivatives.[189] Nasseri *et al.* synthesised Fe_3O_4@Cu–Mn NPs, which served as an efficient and recyclable catalyst for the solvent-free, mild Biginelli reaction, yielding diverse dihydropyrimidinone derivatives with advantages including catalyst stability, low metal leaching, and maintained catalytic activity over five cycles, showing its potential for sustainable synthesis in green chemistry protocols.[190] Rezayati *et al.* developed Fe_3O_4@SiO_2@GP/picolylamine–Cu(II), which served as an efficient magnetically recoverable nanocatalyst for the Biginelli condensation, yielding 3,4-dihydropyrimidinones with high conversions under solvent-free conditions.[191] Azizi *et al.* reported the synthesis and characterization of $CuFe_2O_4$@PEO–SO_3H, an eco-friendly magnetically recoverable solid acid catalyst, which catalysed Biginelli condensation reaction to produce dihydropyrimidine derivatives with high yields.[192] Nazzar *et al.* reported a heterogeneous magnetic catalyst, Fe_3O_4 coated with silicate and modified with graphene quantum dot-copper (GQD/Cu); its catalytic activity was investigated for Biginelli and Hantzsch reactions, producing DHPM and DHP derivatives with high yields.[193] Patil *et al.* presented in their study utilization of cotton waste-derived lignin as a low-cost, recyclable, and environmentally friendly catalyst for the Biginelli reaction, which



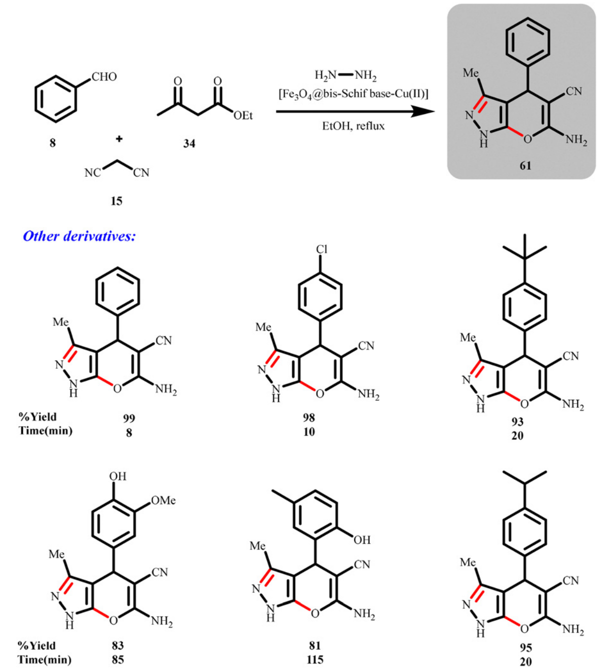
Scheme 29 Synthesis of DHPMs using copper based nanocatalysts.

furnished high yields of 3,4-dihydropyrimidinone derivatives in short reaction time.[194] Sharma *et al.* reported a new catalytic approach using $CuFe_2O_4/CuO–CeO_2$ nanoparticles under microwave irradiation, which efficiently catalysed the synthesis of dihydropyrimidinones (DHPMs) with high yields of 80–95%.[195] Scheme 29 depicts the synthesis of DHPMs using different copper nanocatalysts.

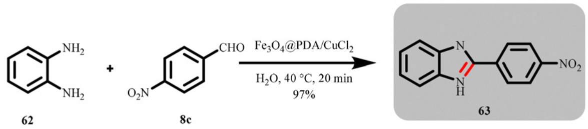
Table 5 summarises that Fajer *et al.* developed Fe_3O_4@AAPA-AP-$CuCl_2$, which gave 96% yield in 8 h at 180 °C using PEG, with 7-cycle reusability.[196] Jiang *et al.* used Fe_3O_4@Diol/Phen–$CuCl_2$ under milder conditions (100 °C, 2 h), achieving 94% yield and 7-cycle recyclability.[197] Peiman *et al.* reported Fe_3O_4@SiO_2@NTMPThio–Cu for solvent-free synthesis at room temperature, obtaining 97% yield in just 12 minutes with 8-cycle reuse.[198] Li *et al.* introduced a $CuBr_2$-based Fe_3O_4@Dop/amide-BenzImid system that yielded 98% in 90 min under reflux in water, while Kalantari *et al.* synthesized a Cu(II)-Schiff base@-SiO_2@Fe_3O_4 catalyst that reached 96% yield in 20 min in EtOH with 7-cycle stability.[199,200] Thrilokraj *et al.* used simple Fe_3O_4 NPs (30 mol%) for 91% yield in 50 min, and Mohassel Yazdi *et al.* reported SBA-15@ELA delivering 96% yield in 6 h with only 0.01 g of the catalyst and 6-cycle recyclability.[201,202]

The synthesis of a Schiff base-Cu(II) complex supported on Fe_3O_4 was reported to occur *via in situ* ligand generation and subsequent metal complexation. The catalyst was employed at 8 mol% loading. It exhibited high efficiency in facilitating multi-component cyclocondensation reactions for the synthesis of pyrano[2,3-*c*]pyrazoles and preserved its catalytic activity after eight cycles. The catalyst efficiently synthesized 2-amino-3-cyanopyridines from various aromatic and heteroaromatic aldehydes, with electron-withdrawing groups showing higher reactivity.

The method was also effective on a 50-fold scale, delivering a 93% yield under the same conditions (Scheme 30).[203]



Scheme 30 Synthesis of pyrano[2,3-c]pyrazoles using a copper-based nanocatalyst (Ali *et al.*).



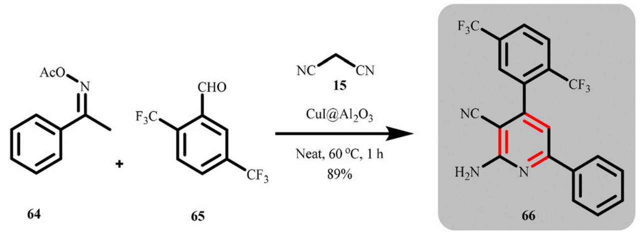
Scheme 31 Fe_3O_4@PDA/$CuCl_2$ for synthesis of benzimidazole (Badbedast *et al.*).

The study conducted by Badbedast and his peers developed magnetite polydopamine-supported copper nanoparticles for the efficient synthesis of benzimidazoles and benzothiazoles in an aqueous medium, offering high yields, short reaction times, and catalyst recyclability. The catalyst demonstrated excellent activity and stability, with a TON of up to 3233 and TOF of up to 38 800 h^{-1} under mild, green conditions. The catalyst loading was 0.03 g, and a marginal decline in catalyst activity was observed over the course of five consecutive reactions, with a yield of 94% (Scheme 31).[204]

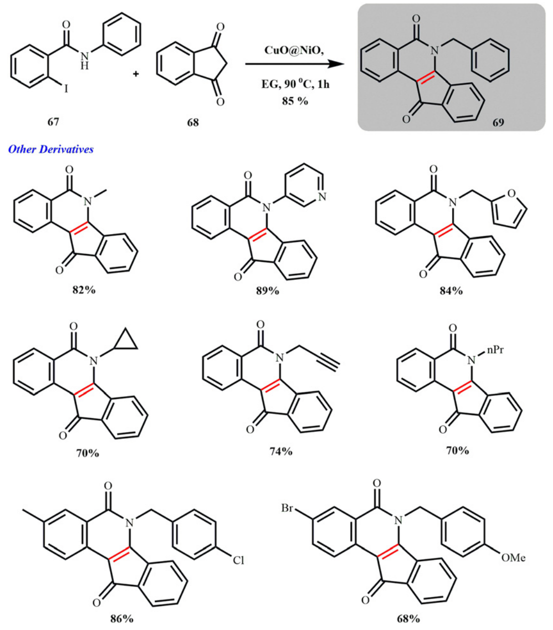
Rawat *et al.* presented a green, additive-free synthesis of 2-aminonicotinonitriles from oxime acetate, aldehyde, and malononitrile using 10 mg of a CuI@Al_2O_3 nanocatalyst under solvent-free conditions achieving high yields and superior green chemistry metrics. The catalyst was recovered using

Table 5 DHPMs catalysed by copper-based nanocomposites

S. no.	Catalyst	Reaction conditions	Time	Yield (%)	Catalyst loading (mol%)	Recyclability	Ref.
1	Fe_3O_4@AAPA-AP-$CuCl_2$	PEG, 180 °C	8 h	96	0.36	7 cycles	Fajer *et al.*[196]
2	Fe_3O_4@Diol/Phen-$CuCl_2$	PEG, 100 °C	2 h	94	5	7 cycles	Jiang *et al.*[197]
3	Fe_3O_4@SiO_2@NTMPThio-Cu	Solvent free, 25 °C	12 min	97	15	8 cycles	Peiman *et al.*[198]
4	Fe_3O_4@Dop/amide-BenzImid-$CuBr_2$	Water, Reflux	90 min	98	8	8 cycles	Li *et al.*[199]
5	Cu(II)-Schiff base-TCT-APTES@SiO_2@Fe_3O_4	EtOH, Reflux	20 min	96	6	7 cycles	Kalantari *et al.*[200]
6	Fe_3O_4 NPs	Neat, 80 °C	50 min	91	30	5 cycles	Thrilokraj *et al.*[201]
7	SBA-15@ELA	EtOH, Reflux	6 h	96	10	6 cycles	Yazdi *et al.*[202]



Scheme 32 $CuI@Al_2O_3$ catalysed synthesis of 2-aminonicotinonitrile (Rawat *et al.*).



Scheme 33 CuO@NiO catalysed synthesis of idenoisoquinoline (Rawat *et al.*).

ethanol followed by centrifugation and reused several times without loss of catalytic activity (Scheme 32).[205]

According to the proposed mechanism (Fig. 7), the $CuI@Al_2O_3$ nanocatalyst facilitated several crucial steps in the synthesis of 2-aminonicotinonitriles. In the presence of copper(I) species supported on alumina, the oxime acetate **64** became activated, which generated the copper-bound enamide intermediate **XVII** and promoted the elimination of acetic acid. Simultaneously, a Knoevenagel condensation between the aromatic aldehyde **8** and malononitrile **15** produced the α,β-unsaturated nitrile intermediate **XVI**. The copper-bound enamide intermediate then added to this activated alkene in a Michael-type fashion, forming the adduct **XVIII**. Subsequent intramolecular cyclization occurred when the enamide nitrogen attacked the nitrile group, leading to the formation of the dihydropyridine intermediate **XIX**. Finally, oxidation—most likely assisted by trace Cu(II) species or molecular oxygen—caused aromatization, yielding the desired 2-aminonicotinonitrile product **66**. Throughout the cycle, $CuI@Al_2O_3$ not only activated the substrates and stabilized the intermediates but also improved selectivity and efficiency under mild reaction conditions.

Also, a novel CuO@NiO nanocatalyst was developed and characterized by this group for the green synthesis of indenoisoquinolines, using 0.08 mol% of the catalyst and achieving high yields, wide substrate scope, excellent green chemistry metrics, and recyclability up to six cycles with minimal leaching. CuO@NiO-catalyzed synthesis of various indenoisoquinoline derivatives from 2-iodobenzamide and 1,3-indanedione at 90 °C, giving yields between 65 and 92%. A broad range of aromatic, heteroaromatic, and aliphatic substituents were tolerated, with many products obtained in yields above 80% (Scheme 33).[206]

Fig. 8 shows that the CuO@NiO nanocatalyst increases the electrophilicity of phthalic anhydride by activating it through surface coordination in this reaction. After that, the amine is nucleophilically added to form a monoamide intermediate that stays attached to the surface. After condensation at the active amide site, there is an intramolecular cyclization reaction with 2-acetylbenzoic acid. Following the creation of a fused

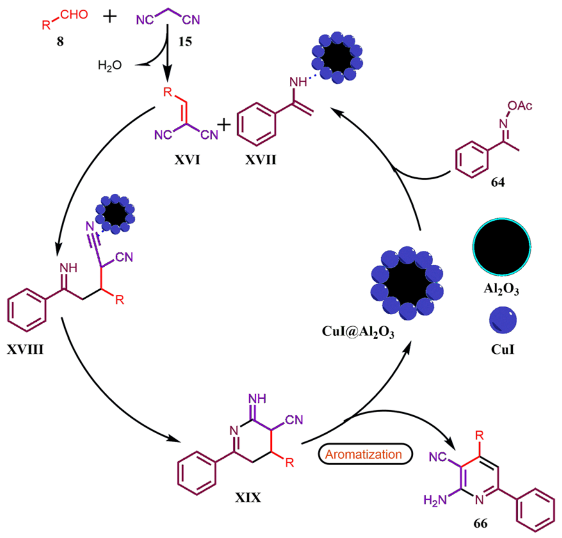


Fig. 7 Plausible mechanism for synthesis of 2-aminonicotinonitrile using a $CuI@Al_2O_3$ nanocatalyst.

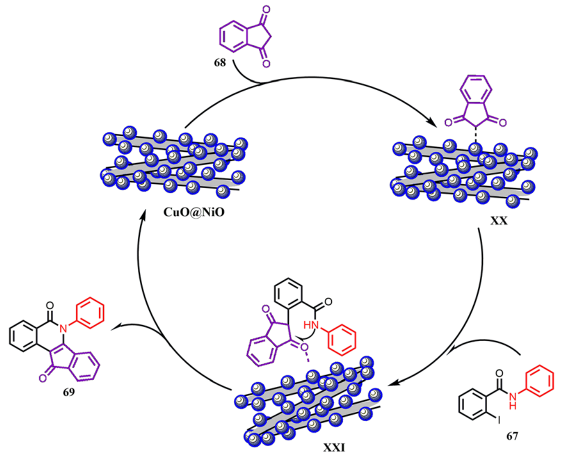
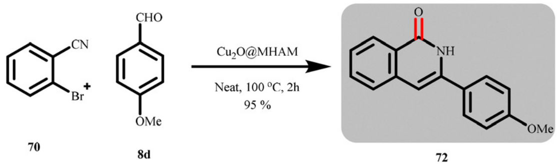


Fig. 8 Plausible mechanism for synthesis of indenoisoquinolines using a CuO@NiO nanocatalyst.



Scheme 34 Cu$_2$O@MHAM catalysed synthesis of isoquinolones (Rawat *et al.*).

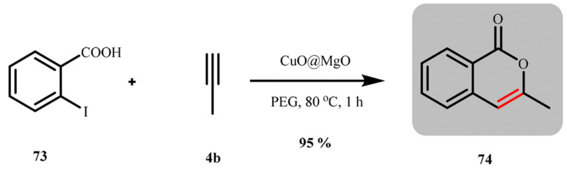
heterocyclic ring, the catalyst surface is renewed for more turnover and the final product is released.

A marigold hollow alumina microsphere nanocatalyst decorated with Cu$_2$O was developed and characterized for the efficient synthesis of isoquinolones from 2-bromobenzonitriles and ketones under solvent-free conditions using 5 mg of the catalyst for 3 mmol model reaction. The catalyst exhibited outstanding catalytic performance, showing high recyclability over five cycles while maintaining activity. It also demonstrated favourable green chemistry metrics, including a low *E*-factor and high reaction mass efficiency (Scheme 34).[207]

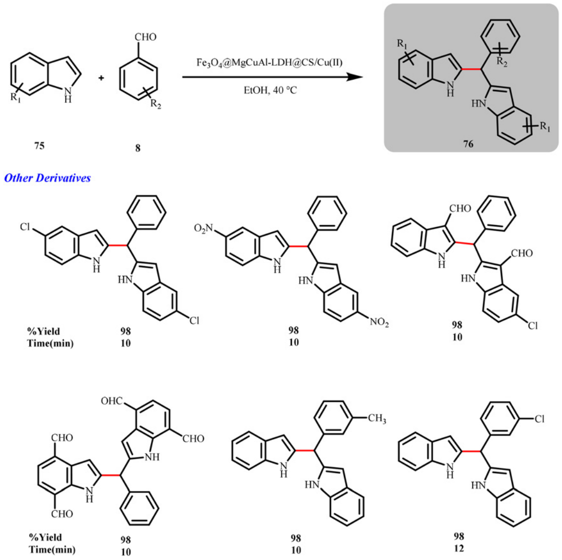
A mesoporous CuO@MgO nanocomposite synthesized *via* a sugar-blowing induced confined method demonstrated efficient catalysis for the synthesis of 3-substituted isocoumarins from 2-iodobenzoic acids and terminal alkynes using 10 mg of the catalyst for 4 mmol model reaction. The catalyst exhibited broad substrate scope, high yield under mild conditions, exceptional recyclability over five cycles with minimal activity loss, and favourable green chemistry metrics, highlighting its potential for sustainable synthetic applications in medicinal chemistry (Scheme 35).[208]

Rashtiani *et al.* developed a novel Fe$_3$O$_4$@MgCuAl–LDH@CS/Cu(II) nanocatalyst using chitosan as a non-toxic biopolymer, which was successfully applied for the high-yield synthesis of BIMs *via* ultrasonic-assisted condensation of aromatic aldehydes and indole. The catalyst was characterized by various techniques, showing enhanced performance with sonication. The catalyst used in the reaction was 25 mg and was easily recyclable up to nine times with maintained activity. Using Fe$_3$O$_4$@MgCuAl–LDH@CS/Cu(II) under ultrasonic conditions at 40 °C for 5 min gave the best yields of bis(indolyl)methanes from indoles and aromatic aldehydes. Electron-withdrawing substituents on aldehydes, such as nitro or halogen, led to higher conversions than electron-donating groups (Scheme 36).[209]

The Fe$_3$O$_4$@SiO$_2$–bis(aminopyridine)–Cu(II) nanocatalyst, developed by Mahmood and his team through a post-synthetic method, showed remarkable efficiency in synthesizing benzothiazoles and polyhydroquinolines, achieving excellent yields in environmentally friendly solvents using 1 mmol% of the catalyst. It also exhibited strong reusability, retaining its catalytic activity over six cycles, indicating its potential for wider use in metal-catalyzed reactions. The catalyst enabled the synthesis of diverse benzothiazoles from 2-aminobenzenethiol and various nitriles in ethanol under reflux, giving high isolated yields of 83–98%. A wide variety of aromatic, heteroaromatic, and aliphatic nitriles with electron-donating or electron-withdrawing groups were well tolerated (Scheme 37).[210]

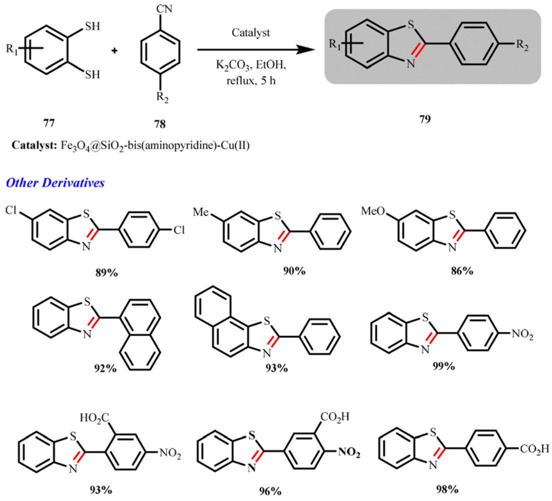


Scheme 35 CuO@MgO catalysed synthesis of isocumarins (Rawat *et al.*).

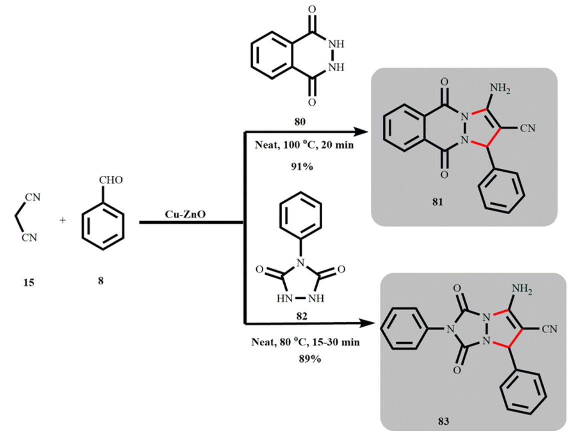


Scheme 36 Bis(indolyl)methane synthesis in the presence of Fe$_3$O$_4$@MgCuAl–LDH@CS/Cu(II) (Rashtiani *et al.*).

The Cu–ZnO hollow sphere nanostructures were used as catalysts to synthesize 1*H*-pyrazolo[1,2-*b*]phthalazine-5,10-diones and pyrazolo[1,2-*a*][1,2,3]triazole-1,3-diones. These reactions were optimized under solvent-free conditions at 100 °C and 80 °C, respectively using 0.02 g of the catalyst. The Cu–ZnO catalyst showed outstanding reusability and high efficiency over multiple cycles (Scheme 38).[211]



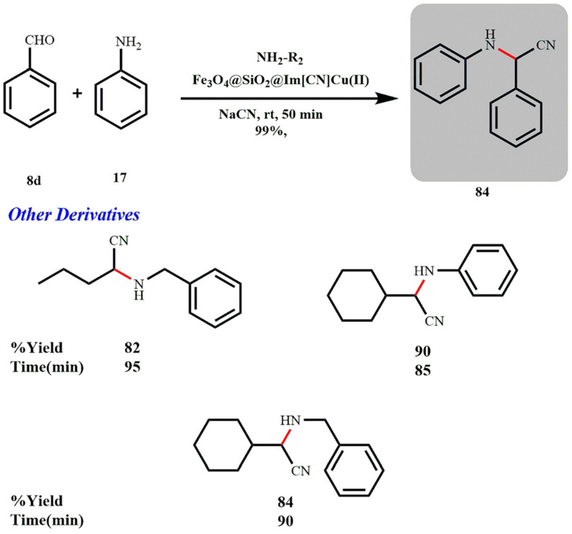
Scheme 37 Reaction between 2-aminobenzenethiol and benzonitrile catalyzed by an Fe$_3$O$_4$@SiO$_2$–bis(aminopyridine)–Cu(II) nanocomposite (Mahmood *et al.*).



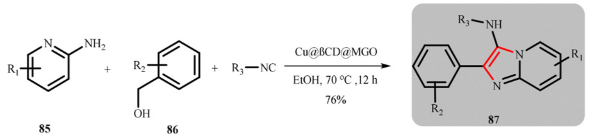
Scheme 38 Catalytic synthesis of heterocyclic derivatives using Cu–ZnO nanoparticles (Maleki *et al.*).

The one-pot synthesis of α-aminonitriles *via* the Stecker reaction was achieved using $Fe_3O_4@SiO_2@Im[CN]Cu(II)$ nanoparticles as a magnetic nanocatalyst. 10 mg of the catalyst was used in the model reaction, and it effectively promoted the reaction between aldehydes, aniline, or benzylamine, and NaCN in water, resulting in high to excellent yields. It demonstrated excellent activity, selectivity, and turnover frequency and could be easily recovered and reused for at least seven cycles with minimal loss of efficiency. The nanocomposite efficiently catalyzed the synthesis of α-amino nitriles from a wide range of aldehydes, including acid-sensitive, aromatic, and aliphatic types. Aromatic aldehydes gave higher yields and faster reactions, while aliphatic ones showed slightly lower conversions and longer times (Scheme 39).[212]

Bahadorikhalili *et al.* proposed a green and efficient approach for synthesizing *N*-(alkyl)-2-phenylimidazo[1,2-*a*]pyridin-3-amine derivatives *via* copper-catalyzed oxidative cyclization. They developed a novel copper nanocatalyst by immobilizing Cu onto β-cyclodextrin (βCD)-functionalized magnetic graphene oxide nanosheets (Cu@βCD@MGO). This catalyst effectively oxidizes benzylic alcohols to aldehydes, which then react with pyridine-2-amine and isocyanides to produce the desired derivatives. 25 mg of the catalyst was used for the model reaction. The catalyst shows excellent recyclability up to 10 times, and no loss in the reaction performance was observed (Scheme 40).[213]



Scheme 39 Catalytic synthesis of α-aminonitrile derivatives using $Fe_3O_4@SiO_2@Im[CN]Cu(II)$ nanoparticles (Kazemnejadi *et al.*).



Scheme 40 Catalytic synthesis of *N*-(alkyl)-2-phenylimidazo[1,2-*a*]pyridin-3-amine derivatives using Cu@β-CD@MGO nanoparticles (Bahadorikhalili *et al.*).

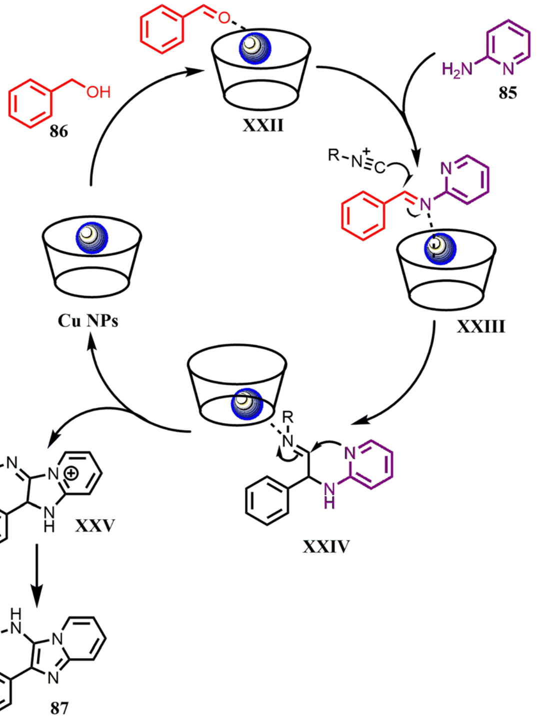
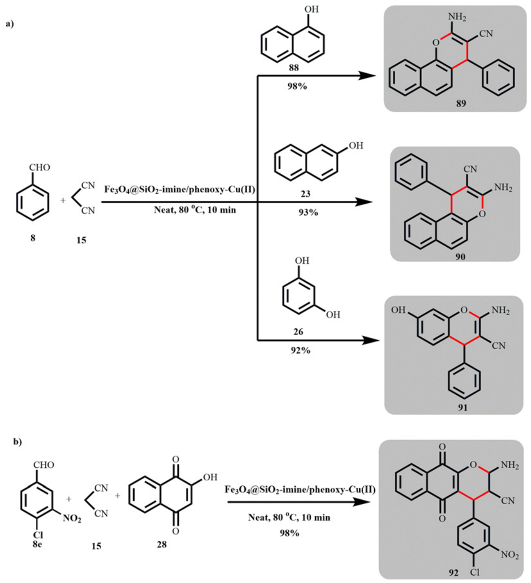


Fig. 9 Plausible mechanism for synthesis of *N*-(alkyl)-2-phenylimidazo[1,2-*a*]pyridin-3-amine derivatives using Cu@β-CD@MGO nanoparticles.

Fig. 9 illustrates that the Cu-based nanoparticles help activate benzyl alcohol **86** in this transition, forming a reactive benzylic intermediate most likely by the creation of a Cssu-alkoxide molecule **XXII**. Secondly, 2-aminopyridine nucleophilically attacks this intermediate, forming an imine **XXIII** that interacts with another aminopyridine equivalent. For a fused triazolopyridine derivative, intramolecular condensation and cyclization are required. Overall, the process is aided by moderate circumstances, and the catalyst surface controls its strong regioselectivity.

Ebrahimiasl *et al.* synthesized an Fe_3O_4-supported copper(II) Schiff base complex by modifying Fe_3O_4 with 1,3-phenylenediamine, followed by coordination with salicylaldehyde and Cu(II). The resulting $Fe_3O_4@SiO_2$-imine/phenoxy-Cu(II) nanoparticles proved to be an effective catalyst for the one-pot, three-component synthesis of 2-amino-4*H* chromene derivatives



Scheme 41 Catalytic synthesis of 2-amino-4*H* chromene (a) Benzaldehyde and (b) 4-chloro-3-nitrobenzaldehyde derivatives using Fe_3O_4@-SiO_2-imine/phenoxy-Cu(II) nanoparticles (Ebrahimiasl *et al.*).

using 0.02 g for the model reaction. The catalyst demonstrated excellent reusability over five cycles with minimal loss of efficiency (Scheme 41).[214]

As shown in Fig. 10, the process starts with ammonium acetate being converted to ammonia *in situ*, which then combines with a cyclic diketone to generate an amino-substituted intermediate. Meanwhile, an electrophilic alkene species is produced by a Knoevenagel condensation between the diketone and arylidene β-ketoester. Hydrogen bonds and catalyst stabilization propel these intermediates through a series of nucleophilic addition, condensation, and annulation processes. Through a sequence of carefully planned bond-forming processes, this results in a highly substituted polycyclic system.

The synthesis of 5-phenyl-5,10-dihydropyrido[2,3-*d*:6,5-*d*′]-dipyrimidine 2,4,6,8(1*H*,3*H*,7*H*,9*H*)tetraone derivatives was achieved using a Cu(II) catalyst immobilized on functionalized magnetic mesoporous MCM-41 (Fe_3O_4@MCM-41-GPTMS-Gu). The 4.45 mol% of catalyst was used, and it efficiently facilitated a one-pot, multicomponent condensation reaction under environmentally friendly conditions, yielding excellent results. It demonstrated high activity and could be effectively reused for at least five cycles with strong stability and minimal loss of efficiency (Scheme 42).[215]

M. Kamalzare *et al.* synthesized 4*H*-pyran derivatives using a bionanocatalyst derived from starch combined with magnetic nanoparticles. The catalyst (0.03 g) proved to be excellent in multicomponent reaction, offering advantages such as mild conditions, easy recovery, low cost, and non-toxicity. The catalyst maintained its high activity and reusability for at least six cycles without significant loss of performance (Scheme 43).[216]

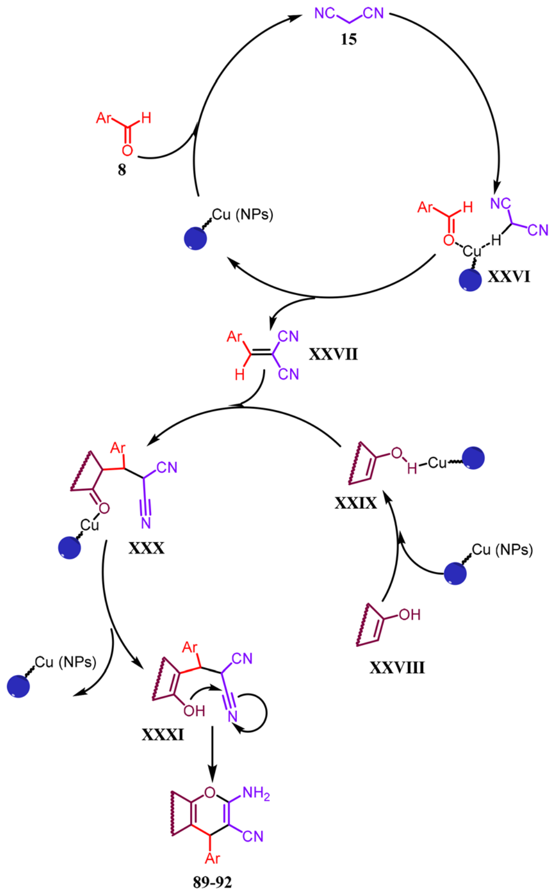
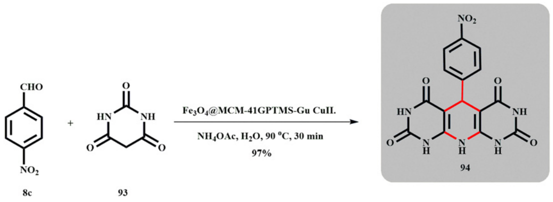
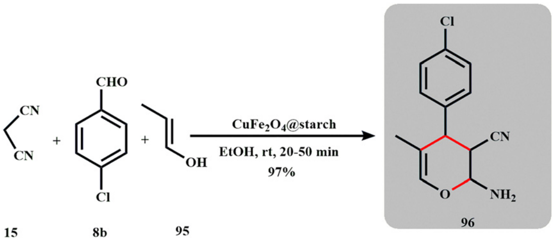


Fig. 10 Plausible mechanism for synthesis of 2-amino-4*H* chromene derivatives using Fe_3O_4@SiO_2-imine/phenoxy-Cu(II) nanoparticles (Ebrahimiasl *et al.*).

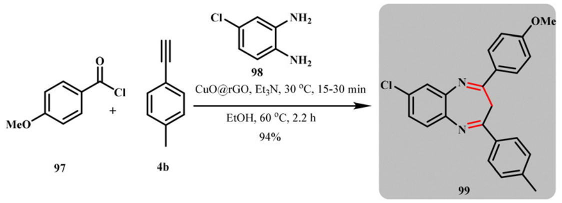


Scheme 42 Catalytic synthesis of heterocyclic derivatives using Fe_3O_4 @MCM-41-GPTMS-Gu-Cu nanoparticles (Farsi *et al.*).

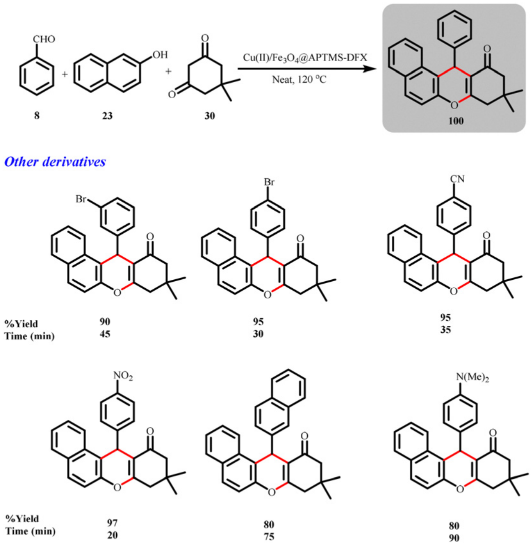


Scheme 43 Catalytic synthesis of 4*H*-pyran derivatives using $CuFe_2O_4$@starch nanoparticles (Kamalzare *et al.*).

Sarkar *et al.* synthesized biologically active 1,5-benzodiazepine *via* sequential addition of acyl chloride, terminal alkyne and *o*-phenylenediamines using CuO@rGO (0.8 mol%) under mild conditions. The process starts with the *in situ* formation of ynones, which then react with *o*-phenylenediamines in the presence of ethanol, yielding a variety of benzodiazepines with high product



Scheme 44 Catalytic synthesis of 1.5-benzodiazepine derivatives using a CuO@rGO nanocomposite (Sarkar *et al.*).

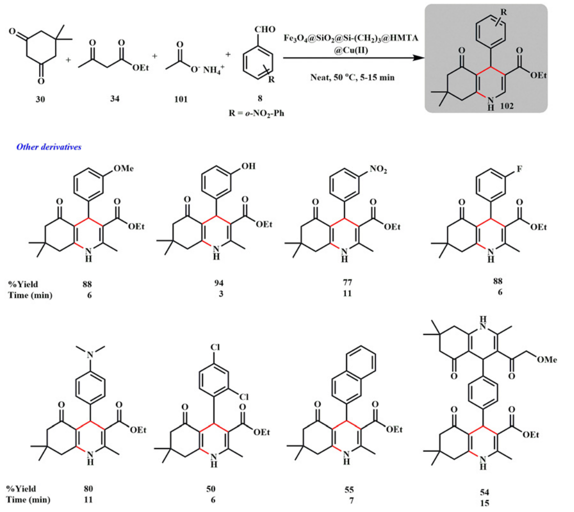


Scheme 45 Catalytic synthesis of heterocyclic derivatives using a Cu(II)/Fe$_3$O$_4$@APTMS-DFX nanocomposite (Sonei *et al.*).

yield. The catalyst showed excellent recyclability up to seven consecutive runs (Scheme 44).[217]

12-Aryl-8,9,10,12-tetrahydrobenzo[*a*] xanthene-11-one derivatives have been synthesized by Sonei *et al.* using a Cu(II)-immobilized Fe_3O_4@APTMS-DFX nanoparticle catalyst. The reaction has been efficiently carried out using 0.02 g of the catalyst, aromatic aldehyde, 2-naphthol, and dimedone under solvent-free conditions, offering high activity, easy separation with an external magnet, and the ability to be reused for six cycles without significant copper leaching. Various derivatives with Br, CN, NO_2, and $N(Me)_2$ substituents were obtained in high yields (80–97%) within short reaction times (20–90 min) (Scheme 45).[218]

Salem *et al.* prepared hexahydroquinoline derivatives using a nanomagnetic catalyst with a nano-Fe_3O_4 core. The reaction has been carried out under solvent-free conditions at 65 °C with 0.05 g of the catalyst, providing high efficiency, high yields, and short reaction times.[219] The catalyst was recovered using a magnet and reused up to 4 cycles with minimal loss in its catalytic activity. Under optimal conditions, various HHQ derivatives were synthesized in 50–96% yields within 3–15 min using dimedone, ethyl acetoacetate, ammonium acetate, and aryl aldehydes with the catalyst (Scheme 46).



Scheme 46 Catalytic synthesis of hexahydroquinoline derivatives using an Fe_3O_4@SiO_2@Si-(CH_2)@HMAT@Cu nanocomposite (Salem *et al.*).

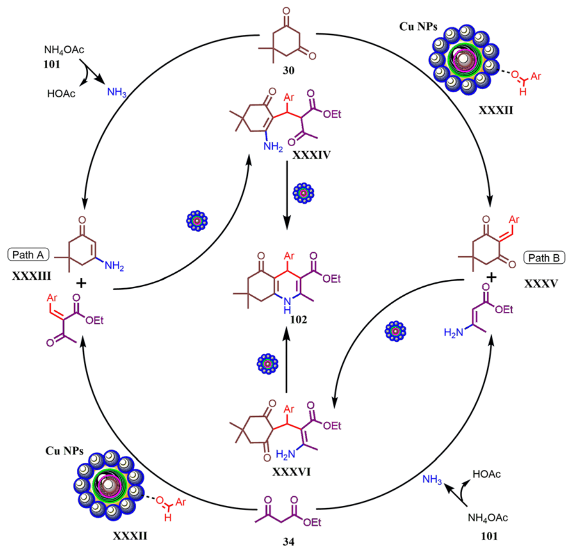
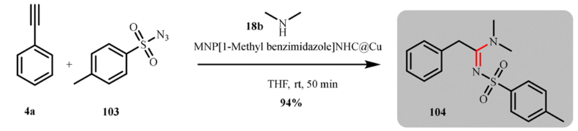


Fig. 11 Plausible mechanism for synthesis of hexahydroquinoline derivatives using an Fe_3O_4@SiO_2@Si-(CH_2)@HMAT@Cu nanocomposite (Salem *et al*).

The catalytic cycle, as represented in Fig. 11, started when the aldehyde **30** and malononitrile **101** were activated by Cu nanoparticles, which enabled their Knoevenagel condensation to form the α,β-unsaturated nitrile intermediate **XXXII**. This activated species was then subjected to conjugate addition by a nucleophile that had been coordinated and activated by Cu, producing intermediate **XXXIV**. Subsequently, the adduct underwent cyclization through tautomerization and nucleophilic attack on the cyano group, generating intermediate **XXXV** (Path B) or **XXXIII** (Path A). These intermediates converged *via* intramolecular transformations to yield **XXXVI**, which further rearranged to give the fused benzofuran derivative **102** with high selectivity. Throughout the process, Cu coordination not only activated the reactants but also stabilized the key intermediates and transition states, thereby improving the regioselectivity and efficiency of the overall transformation.



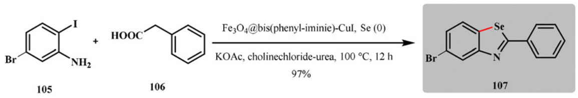
Scheme 47 Synthesis of *N*-sulfonyl amidine derivatives in the presence of the catalyst MNP [1-methylbenzimidazole]NHC@Cu (Pawar *et al.*).

Pawar *et al.* prepared *N*-sulfonyl amidines using a magnetically separable nanoparticle-decorated N-heterocyclic carbene complex with copper (MNP[1-methyl benzimidazole] NHC@Cu) as the catalyst. The synthesis of *N*-sulfonyl amidines has been conducted *via* a one-pot multicomponent reaction of phenylacetylene, tosyl azide-, and amines using 50 mg of the catalyst at room temperature. The catalyst was recovered and used for six cycles without a significant loss in the yield (Scheme 47).[220]

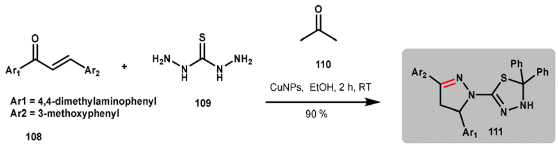
In a study conducted by Hu *et al.*, a novel Fe_3O_4@bis(phenylimine)–CuI nanocomposite was successfully fabricated and characterized, demonstrating high catalytic efficiency in the synthesis of 2-substituted benzoselenazoles. The one-pot, three-component reaction of 2-iodoanilines, selenium powder, and aryl acetic acids and 7 mmol% of the catalyst in CHCl–urea solvent provided products with good to excellent yields. The catalyst was recovered and reused up to 7 runs with minimal loss in its catalytic activity (Scheme 48)[221]

Zeebaree *et al.* have synthesised copper nanoparticles using *Trifolium resupinatum* leaf extract as both a reducing and capping agent, generating active catalysts. The 5 mol% catalyst was employed in a one-pot, three-component reaction at ambient temperature, condensing thiocarbohydrazide, acetophenone, and chalcone to produce 1,3,4-thiadiazole derivative compounds. The catalyst was recycled up to six cycles without significant loss in its catalytic activity (Scheme 49).[222]

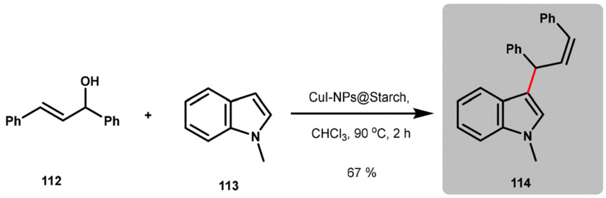
Mallick *et al.* synthesised copper(I) iodide nanoparticles supported on starch (CuI-NPs@starch) in an aqueous medium. The nanocatalyst proved to be effective for the regioselective 3-allylation of indoles including both *N*-substituted and ring-substituted variants using various allyl alcohols under conditions that are tolerant to air and moisture using 30 mg of the catalyst. However, the catalyst showed poor recyclability, with significant copper leaching (1.6% w/w) as confirmed by AAS, leading to a marked loss in activity after one use (Scheme 50).[223]



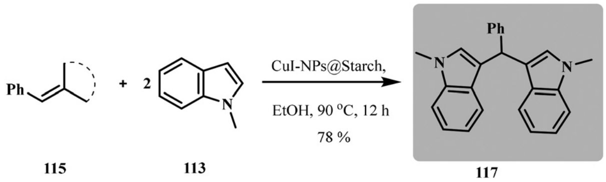
Scheme 48 Fe_3O_4@bis(phenyl-imine)–CuI catalysed synthesis of 2-phenylbenzo[*d*][1,3]selenazole (Hu *et al.*).



Scheme 49 Copper nanoparticle-catalysed synthesis of 1,3,4-thiadiazole derivative compounds (Zeebaree *et al.*).



Scheme 50 Copper nanoparticle-catalysed 3-allylation of indoles (Mallick *et al.*).

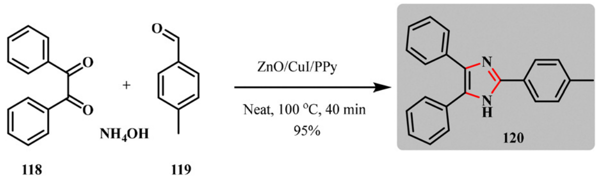


Scheme 51 Copper nanoparticle catalysed synthesis of bisindolylmethane (Suresh *et al.*).

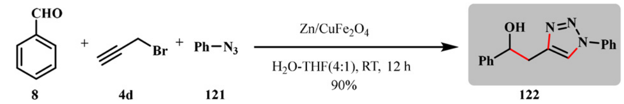
Suresh *et al.* used starch-supported cuprous iodide nanoparticles (CuI-NPs@starch) as an efficient heterogeneous catalyst for C–C bond cleavage reactions involving carbon-based leaving groups such as malononitrile, ethyl cyanoacetate, acetylacetone, and Meldrum's acid. The reaction was performed using 20 mol% of the heterogenous catalyst, enabling the synthesis of biologically important bisindolylmethanes in good yields (Scheme 51).[224]

A novel ZnO/CuI/PPy nanocomposite was synthesized and employed as a catalyst for the synthesis of 2,4,5-trisubstituted imidazole *via* a multicomponent reaction using benzil, aromatic aldehydes, and ammonium acetate under solvent-free (neat) conditions. The nanocatalyst exhibited excellent catalytic activity, providing high yields when using 10–30 mg of the catalyst. Notably, the ZnO/CuI/PPy catalyst demonstrated remarkable reusability, retaining high activity over six consecutive cycles with minimal loss in yield (Scheme 52).[225]

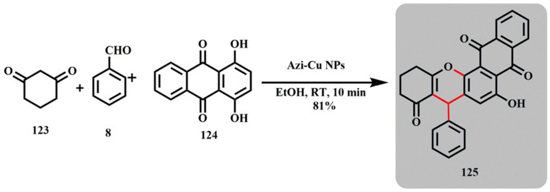
A copper-based magnetic nanocatalyst, combined with activated zinc dust, was utilized for the one-pot synthesis of novel *β*-hydroxy-1,4-disubstituted-1,2,3-triazole derivatives by Hazra and group, in high yields, using mild conditions. The catalyst employed in the reaction has demonstrated excellent catalytic activity when using 0.2 mmol of $CuFe_2O_4$ and 3 mmol of activated zinc dust, with recyclability observed up to five cycles, exhibiting minimal decline in catalytic efficacy (Scheme 53).[226]



Scheme 52 ZnO/CuI/PPy catalyzed synthesis of 2,4,5-trisubstituted imidazole (Kohli *et al.*).



Scheme 53 Copper nanoparticle catalysed one-pot synthesis of 1,4-disubstituted 1,2,3-triazole derivatives (Hazra *et al.*).



Scheme 54 Azi-Cu NP catalysed one-pot synthesis of xanthene (Selvaraj *et al.*).

Selvaraj *et al.* synthesized azithromycin-mediated copper nanoparticles (Azi-Cu NPs) and employed them as effective catalysts for the one-pot synthesis of anthraquinone-linked xanthene derivatives through a grindstone-assisted multicomponent reaction. The reaction, catalyzed using 30 mol%, yielded 81% to 92% of the product and the reusability of the Azi-Cu NPs catalyst was tested, which showed its catalytic activity over five consecutive cycles without notable performance loss after recovery and drying at 80 °C (Scheme 54).[227]

4. Biomedical applications of copper nanocatalysts

Copper-based nanocomposites have gained significant interest in biomedical applications due to their unique properties and potential benefits. Some key biomedical applications include antibacterial, antiviral, and anticancer applications and drug delivery (Fig. 12). Metal-based nanomaterials, including various metal ions, nanoparticles, and composites, offer a promising alternative. These materials can exhibit antibacterial properties through mechanisms such as the production of reactive oxygen species (ROS) like hydrogen peroxide (H_2O_2), hydroxyl radicals ($^\bullet$OH), and singlet oxygen, as well as ion leaching.[228–231] Among the most potent nanocatalysts for combating bacteria, fungi, and viruses when used at optimal concentrations, CuO is remarkably non-toxic and cost-effective.[232] Their various types include copper sulphide,[233] copper oxide, copper selenide-based compound nanomaterials,[234] copper coordination compound nanomaterials and nanocomposites.[235,236] Cu nanomaterials are cost-effective and easier to produce and can be biosynthesized, offering improved biocompatibility and lower cytotoxicity compared to gold or silver nanomaterials.[237]

4.1. Anticancer

Ganesan *et al.* developed GO–CuO nanocomposites by decorating graphene oxide over copper oxide nanoparticles. The nanoparticles exhibited a cytotoxic activity of 70% against HCT-116 human colon cancer cell lines at a concentration of 100 μg mL^{-1}.[238] They can act as catalysts for generating reactive oxygen species (ROS) under specific conditions, which can induce oxidative stress and selectively target cancer cells while sparing healthy tissue.[239] This approach is being explored for photodynamic therapy[240] and other forms of cancer treatment.[241] Huang *et al.* developed a customized ROS-activable prodrug nanomedicine, Cu-SK@DTC-PPB, designed for highly selective antitumor therapy. This nanocomposite was engineered to trigger a self-amplifying feedback loop in the tumor microenvironment, where a small amount of ROS initiates the formation of bioactive Cu(DTC)$_2$ and the release of shikonin (SK).[242] Mukherjee *et al.* synthesized a copper–plumbagin complex (Cu-PLN) and evaluated its antiproliferative effects on various cancer cell lines. Notably, Cu-PLN exhibited significantly higher toxicity towards breast carcinoma and skin melanoma cells compared to noncancerous breast epithelial and skin fibroblast cells, highlighting its selective cytotoxicity for cancer cells.[243]

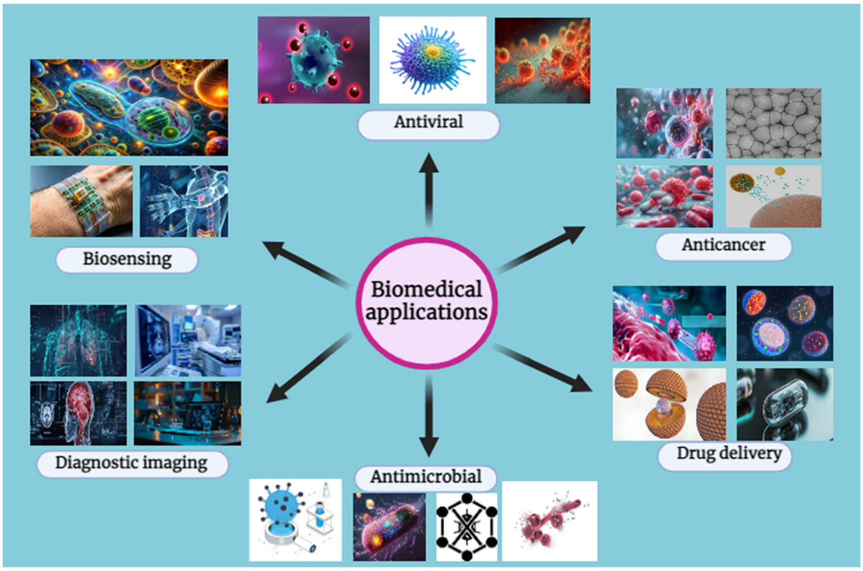


Fig. 12 Biomedical applications of copper nanocatalysts.

4.2. Antiviral

Mazukow *et al.* developed a spray using alumina granules coated with CuO nanoparticles for filtering viruses from water, and they studied the impact of copper oxidation states on virus removal efficiency. Similarly, Domagala *et al.* explored the antiviral efficacy of Cu_2O nanostructures encapsulated on multi-walled carbon nanotube (MWCNT) filters, focusing on their stability in removing viruses from water.[244] Ahmad Tavakoli *et al.* demonstrated that co-culturing CuO NPs with HSV-1-infected cells at a specific concentration resulted in significant anti-HSV-1 activity, achieving an 83% increase in cellular disinfection.[245] Hang *et al.* found that HCV also demonstrated resistance to Cu_2O NPs. The research indicated that Cu_2O NPs exerted inhibitory effects on virus infection in target cells by preventing virus attachment and entry stages.[246] For instance, Borkow *et al.* showed that CuO impregnated masks can effectively reduce the risk of pathogen transmission in the air without modifying the mask's standard filtration procedure. They proposed that these masks, containing CuO NPs, offer protection against a wide range of pathogens.[247]

4.2.1. Copper-based nanoparticles *vs.* SARS-CoV-2. During the covid pandemic, Hosseini *et al.* investigated the effects of a Cu_2O coating on a solution containing disseminated SARS-CoV-2 virus in aqueous droplets. This CuO coating effectively reduced SARS-CoV-2 infectivity by 99.8% within 30 minutes and by 99.9% within an hour.[248] Recently, Delumeau *et al.* showed that thin-film coatings of Cu and Cu_2O deposited on glass exhibited a potent antiviral effect against human coronavirus HCoV-229E.[249] Carabineiro *et al.* used the $CuFe_2O_4$ magnetic nanoparticles as a heterogenous catalyst in the Biginelli reaction to quickly and efficiently synthesize substituted dihydropyrimidinone (DHPM) derivatives. They investigated the potential of these DHPM derivatives as inhibitors of three key SARS-CoV-2 proteins and found that DHPM derivatives had better binding properties than hydroxychloroquine, taken as ref. 250.

4.3. Antimicrobial

Copper based nanocatalysts can be used to develop antimicrobial coatings for medical devices, surfaces in hospitals, and wound dressings. Nasrollahzadeh *et al.* reported the synthesis of an Fe_3O_4/SiO_2–Thiotet–Cu(II) nanocatalyst, which showed excellent antimicrobial activities against *E. coli* and *S. aureus*.[251] Ali *et al.* synthesized Cu–Ag bimetallic nanoparticles (BmNPs) using the extract of beetroot, which exhibited antimicrobial activity against *Salmonella typhimurium* and *Bacillus subtilis.*[252] Zhang *et al.* proposed a new approach to advancing the development of responsive biomaterials based on nanocatalysts for the treatment of bacterial infections by developing Cu-SA@BCNW/PNI hybrid nanogels incorporating high POD-mimicking activity and GSH-depleting functionality for antibacterial purposes.[253]

4.4. Drug delivery

Copper nanoparticles can be utilized as carriers for drug delivery due to their small size and surface properties. They can encapsulate drugs and deliver them to specific tissues or cells.[254,255] Recently, Zhang *et al.* developed a straightforward method to create a nanocatalyst with multiple enzyme-like activities using self-assembling peptides with ATCUN copper-binding motifs.[256] Wang *et al.* developed a self-assembled copper-based nanoplatform, TCCHA, for enhanced chemodynamic, photodynamic and antiangiogenic tritherapy against hepatocellular carcinoma. *In vivo*, TCCHA effectively inhibited tumor angiogenesis and growth with minimal systemic toxicity.[257] Wei *et al.* recently developed an advanced nanodrug delivery system, Cu/ZIF-8@GOx-DOX@HA (CZGDH), combining Cu-doped zeolite imidazolate framework-8, glucose oxidase, doxorubicin, and hyaluronic acid for targeted tumor therapy, targeting tumor cells through hyaluronic acid and degrading under acidic conditions, releasing GOx, DOX, and Cu^{2+} in the tumor microenvironment (TME).[258]

4.5. Diagnostic imaging

Diagnostic imaging encompasses various techniques, including ultrasound, X-ray, and computed tomography (CT).[259] Copper nanoparticles have potential applications in diagnostic imaging,[260,261] such as contrast agents for magnetic resonance imaging (MRI)[262] or computed tomography (CT) scans.[263] Their magnetic and optical properties can be tuned to improve imaging contrast and sensitivity.[264]

Zhang *et al.* developed ultrasmall PEGylated $Cu_{2-x}Se$ NPs with strong near-infrared absorption using a simple aqueous method. These water-soluble, biocompatible nanoparticles proved to be effective nanotheranostic agents for various imaging techniques, including deep-tissue photoacoustic imaging, computed tomography, and single-photon emission computed tomography.[265] Zhu *et al.* developed well-defined $Au@Cu_{2-x}E$ (E = S, Se) core@shell dual plasmonic supraparticles (SPs) using an aqueous fabrication method for multimodal imaging and tumor therapy. Using a modified self-limiting self-assembly strategy, they created monodisperse spherical and rod-like $Au@Cu_{2-x}S$ and $Au@Cu_{2-x}Se$ SPs.[266] Zhang *et al.* later adjusted the near-infrared absorption of $Cu_{2-x}Se$ NPs by doping them with magnetic ferric ions (Fe^{3+}), which also provided these semiconductors with magnetic resonance imaging (MRI) capabilities.[267] By adjusting the size and shape of Cu nanocrystals, their localized surface plasmon resonance (LSPR) peaks can be shifted to the near-infrared region, enhancing their potential for optical imaging and photodynamic therapy.[268]

4.6. Biosensing

Also, copper nanocatalysts can be employed in biosensors for the detection of biomolecules such as glucose,[269,270] proteins,[271,272] enzymes,[273,274] cholesterol[275,276] and DNA.[277] Surface modifications of copper nanoparticles can enhance their biocompatibility and enable specific binding to target biomolecules, improving the sensitivity and selectivity of biosensing platforms.[278] Zhang *et al.* described an easy method to prepare a Cu/Ni-CMWCNTs bimetallic electrocatalyst, deposited on carboxylated multi-walled carbon nanotubes (CMWCNTs) and mounted on an indium tin oxide glass sheet, for glucose sensing and electrooxidation. The sensor, based on an AuCu nanobramble, showed significant potential for glucose detection, featuring a linear working range from 0.25 to 10 mM, a sensitivity of 339.3 μA mM^{-1} cm^{-2}, and a limit of detection (LOD) of 16.62 μM.[279] Jain *et al.* investigated the multifunctional catalytic properties of $Cu_3V_2O_7(OH)_2{\cdot}2H_2O$ nanoribbons, examining their ability to mimic peroxidase, oxidase, and laccase activities.[280] Singh *et al.* developed a novel nanocatalyst, FeCu@2-DG, designed as a mimetic enzyme for detecting and treating cancer cells *in vitro*. The nanocatalyst's peroxidase activity was effectively used as a selective colorimetric sensor for liver cancer cells (HepG2), with a detection range of 50–1000 cell per mL and a limit of detection of 20 cells per mL.[281]

5. Other applications of copper based nanocatalysts

The advantageous characteristics of copper nanoparticles, including their affordability, low melting point, and excellent conductivity, position them for integration into emerging technologies like flexible electronics, including foldable and wearable devices.[282] Interestingly, copper nanoparticles also exhibit unique optical properties, such as localized surface plasmon resonance (LSPR),[283] which can be exploited in optical sensors. Changes in the LSPR spectrum due to the interactions of copper nanoparticles with analytes enable label-free detection with high sensitivity. This makes copper nanocatalysts valuable in developing optical sensing platforms for various applications.[284] Also, copper nanocatalysts can be integrated into smart materials and wearable sensors for real-time monitoring of environmental or physiological parameters.[285,286] Their catalytic and electronic properties allow them for the development of flexible, lightweight sensors capable of continuous monitoring in diverse settings.[287]

5.1. Environmental

Copper nanocatalysts have emerged as pivotal agents in numerous industrial and environmental applications due to their unique properties and catalytic efficiency. Their use in selective oxidation reactions enables the production of fine chemicals and pharmaceuticals with enhanced efficiency and reduced environmental impact.[288] Also, in the field of wastewater treatment, copper nanocatalysts exhibit remarkable capabilities in the degradation of organic pollutants, ensuring cleaner water resources.[289] Cu nanoparticles are effective in gas sensing because of their catalytic activity and surface reactivity. They are used in catalytic oxidation or reduction of gases such as hydrogen (H_2), carbon monoxide (CO),[290] nitrogen dioxide (NO_2),[291] and volatile organic compounds (VOCs).[292,293] For example, Zheng *et al.* developed Pd/Bi/Cu hierarchical nano-architectures (HNAs) for their use in H_2 sensing. The synthesized HNAs were capable of operating over a broad temperature range (approximately 156–418 K).[294] It was observed that Cu_2O shows higher activity for CO oxidation compared to CuO among the two stable copper oxides, Cu(I) and Cu(II). These catalysts were prepared by controlled heating of precipitated copper hydroxide following activation in a redox environment.[295] Xi *et al.* investigated the influence of CeO_2, MnO_2, and Fe_2O_3 on CuO/SiO_2 in CO oxidation reactions. CeO_2 exhibited the strongest promotional effects, enabling CuO/CeO_2–SiO_2 to achieve complete CO conversion at 150 °C, which was 120 °C lower than the reference catalyst CuO/SiO_2. This enhancement was attributed to CeO_2 facilitating the formation of Cu^+ species and mobile lattice oxygen species on the catalyst surface.[296] Cao *et al.* published a study for the synthesis of mesoporous CuO–Fe_2O_3 composite oxide catalysts with varying CuO contents. These catalysts demonstrated notable catalytic efficiency and durability in low-temperature CO oxidation.[297] Zou *et al.* synthesized CuO/$Ce_{1-x}Ti_xO_2$ catalysts for low-temperature CO oxidation using a surfactant-assisted co-precipitation method. These catalysts demonstrated significantly enhanced oxidation activity and thermal stability due to strong interactions between the dispersed Cu species and the $Ce_{1-x}Ti_xO_2$ support.[298] Similarly, Chen *et al.* synthesized a series of $Ce_{20}Cu_5Ni_yO_x$ catalysts with varying nickel contents using the reverse coprecipitation method for low-temperature CO oxidation.[299] Recently, Ziadi *et al.* developed a copper oxide nanowire (CuO NW) based CO sensing device fabricated with Pt nanoparticles. Upon heating the Pt NP–CuO NW system, the oxidation states of Pt increased, which slowed down the charge transfer processes.[300] Sundarapandi *et al.* developed core–shell nanostructures of AuNC@Cu_2O, stabilized with *N*-[3-(trimethoxysilyl)propyl] diethylenetriamine (TPDT), and studied their electrocatalytic properties for nitrite detection using cyclic voltammetry. Among the different Cu_2O shell thicknesses investigated, the TPDT-stabilized AuNC@Cu_2O nanostructure with a core–shell ratio of 1 : 10 exhibited the highest electrocatalytic activity. The estimated detection limit for nitrite concentration was remarkably low, measured at 14.7 nM.[301] Deng *et al.* reported a simple synthesis of a CuO nanocatalyst supported on nickel foam (CuO@NF) for electrochemical nitrite detection. The nanocatalyst exhibited a broad linear detection range from 0.5 to 4250 M and maintained a stable current response even at a nitrite concentration as low as 0.5 M.[302] Recently, Abbas *et al.* developed poly(3,4-ethylenedioxythiophene)-functionalized carbon matrix-supported copper nanoparticles (PEDOT-C@Cu NPs) using a straightforward green synthesis method. They also applied machine learning (ML) to optimize experimental parameters such as pH, drying time, and concentrations to predict the current response of the electrochemical sensor. It also showed enhanced electrochemical sensing performance for real-time monitoring of pickled vegetable extracts.[303] Zhang *et al.* examined the copper nanocatalyst (Cu_{19} cluster) for CO_2 hydrogenation, studying the impact of the copper particle size on the adsorption energies of reactants and intermediates, as well as on the activation barriers of fundamental reaction steps. Their investigation utilized DFT calculations and microkinetic simulations, concluding that medium sized Cu_{19} clusters demonstrated the greatest activity in CO_2 hydrogenation. This heightened activity was attributed to the moderate coverage of CO_2 and lower dissociation barriers facilitated by these clusters.[304] Recently, Yan *et al.* synthesized an atomically-ordered Cu_9Ga_4 intermetallic compound characterized by catalytically inert gallium atoms arranged in a square binding configuration around copper atoms.[305] Yang *et al.* introduced an active and selective single atom catalyst (SAC) for low-temperature

CO_2 hydrogenation. They synthesized a C_3N_4-suppported Cu SAC with a substantial loading of 12 wt% and demonstrated that by adjusting treatment parameters, such as those affecting Cu–N_4 and Cu–N_3 coordination structures, the coordination environment of Cu atoms in the SAC could be systematically modified, leading to significant variations in CO_2 hydrogenation efficiency. They concluded that the Cu–N_4 SAC exhibited a remarkable CH_3OH productivity with a selectivity of more than 95%.[306] Mao *et al.* engineered a highly stable nickel oxygenate/Cu electrocatalyst through *in situ* electrochemical reconstruction, creating abundant NiOOH/Cu interfaces.[307]

5.2. Energy

Cheng *et al.* developed an efficient conductive ink for flexible electronics by dispersing copper nanoparticles in diethylene glycol. The resulting copper film demonstrated electrical conductivity.[252] Liu *et al.* hydrothermally developed CuS/C-120@PANI nanocomposites for their application in supercapacitors. The optimal architecture of CuS/C-120@PANI enhances the interaction among its diverse components, offering many sites for electrochemical reactions that facilitate the diffusion and transfer of electrolyte ions during these reactions.[308] The incorporation of nanometal oxide significantly increased the band gap of the Cu–MOF/rGO composite, shifting its light absorption capabilities from primarily visible light to include near and far UV light. These materials hold promise for applications as coatings on devices operating under UV light conditions.[309]

5.2.1 Batteries. Li *et al.* were able to synthesize MOF-derived *N*,*S* co-doped carbon matrix-encapsulated Cu_2S nanoparticles for their application as anodes of Li ion batteries. They investigated the mechanisms of alkali metal ion storage using DFT calculations. The Cu_2S@NCS anode-based batteries exhibited enhanced long cycling stability and better rate capacities. Their work shows the potential for efficient and precise co-doping of nanomaterials, to enhance their application in batteries.[310] Dong *et al.* utilized Cu nanoclusters in activating Fe_3N nanoparticles for their application in zinc–air batteries. The nanoclusters activated the iron nanoparticles by the Mott–Schottky effect, exhibiting spontaneous transfer of electrons.[29]

5.2.2 Supercapacitors. Lately, Cu-based nanomaterials have found their applications in designing more efficient supercapacitors. Liu *et al.* hydrothermally developed CuS/C-120@PANI nanocomposites for their application in supercapacitors. The optimal architecture of CuS/C-120@PANI enhances the interaction among its diverse components, offering many sites for electrochemical reactions that facilitate the diffusion and transfer of electrolyte ions during these reactions.[311] Kamble *et al.* synthesized $CuCo_2O_4$ nanorods and further coated them with CuO nanoneedles, for their application in supercapacitors. The synthesized nanostructure showed a promising specific capacitance of 713 F g^{-1} at 11 mA cm^{-2}, $\sim$90% capacitance retention after 5000 cycles, indicating itself as a promising functional material for applications in capacitors and other energy devices.[312] Also, Yang and his co-workers synthesized Cu-based heterostructures starting from Cu_2O nanocubes, for their application in asymmetric supercapacitors. The synthesized CuS_2@Cu_7Se_4@NC heterostructures exhibited great performance as an electrode in supercapacitors, showing a high specific capacitance of 660 F g^{-1} at 1 A g^{-1}. They further coupled activated carbon (AC) with the designed heterostructures, showing excellent results in asymmetric supercapacitance and related energy applications.[313]

5.3. Photocatalysis

Dyes are some of the major pollutants of the environment, especially the water resources. Copper nanocomposites have been efficiently applied for their use in photocatalytic degradation of many dyes[314] like CV, rosaniline hydrochloride, acid brown 14, acid red 14, EBT, ECR dyes, *etc.* that are hazardous to the environment as well as to human beings.[315,316] For instance, Rehman *et al.* synthesized a CeZn–CuO nanocatalyst *via* a coprecipitation method. The nanocatalyst degraded the MO dye by approximately 81%.[317] Mani *et al.* developed CuO NPs with *Musa acuminata* free tepal crop (MAFT-CuO). The developed MAFT-CuO NPs showed applications in decolorization of Coomassie brilliant blue G-250 dye (CBB G-250) and aerobic oxidation and were non-toxic as well as biodegradable.[318]

5.4. Agriculture

Copper nanocatalysts are also utilized in environmental sensors to detect pollutants like heavy metals,[319,320] pesticides[321] or industrial chemicals[322] present in the air, water, and soil.[323] They catalyze the degradation of pollutants and participate in redox reactions, which produce measurable changes in sensor signals. This capability makes copper nanocatalysts suitable for monitoring the environmental contaminants[324]

Copper nanoparticles can be utilized for the removal of contaminants from water sources.[325] Manavi *et al.* synthesized a CuO–PP–MAH nanocomposite using environmentally friendly methods and evaluated its effectiveness in reducing chemical oxygen demand (COD) and biochemical oxygen demand (BOD) in industrial tannery wastewater and observed significant decrease in these parameters.[326] Guo *et al.* developed a hydrogel loaded with bimetallic peroxide ($CeCuO_x$) for disinfecting water. The $CeCuO_x$ material can undergo *in situ* decomposition to generate H_2O_2 and bimetallic oxide when exposed to weakly acidic water. This process is followed by the direct generation of hydroxyl radicals ($^{\bullet}OH$) through a synergistic-enhanced Fenton-like catalytic reaction involving cerium (Ce) and copper (Cu).[327,328] Copper nanocatalysts have shown promise in catalyzing the conversion of harmful gases like nitrogen oxides (NO_x) and volatile organic compounds (VOCs) into less harmful substances through oxidation or reduction reactions.[329] They can be integrated into catalytic converters for automobiles[330] or used in air purification systems[331] to mitigate urban air pollution.[332] Copper nanoparticles can be applied in soil remediation efforts to degrade organic pollutants or immobilize heavy metals.[333] They can catalyze the degradation of pesticides,[334,335] herbicides,[336] and petroleum-derived contaminants in soil,[337] thereby reducing environmental contamination[338] and improving soil quality.[339]

5.5. Food industry

Copper nanoparticles have been studied for their potential in catalyzing the conversion of carbon dioxide (CO_2) into value-added products, such as methane or methanol. Rossi *et al.* synthesized shape-controlled copper nanocrystals (Cu NCs) and investigated how the nanocatalyst's shape and size affect the CO_2 reduction reaction (CO_2RR).[340] Kim *et al.* also synthesized branched CuO nanoparticles, which were highly selective for the production of ethylene by the CO_2RR, achieving faradaic efficiency around 70%. Weng *et al.* reported a copper–porphyrin complex (copper(II)-5,10,15,20-tetrakis-(2,6-dihydroxyphenyl)porphyrin) as an electrocatalyst having high selectivity for CO_2 reduction to produce hydrocarbons like methane and ethylene.[341] In another study, Yang *et al.* synthesized novel $Cu_{2-x}Se_{(y)}$ nanocatalysts using the solvent coordination molecular template method. They conducted CO_2 reduction experiments, achieving methanol production with a faradaic efficiency (FE) of 77.6%.[342]

6. Toxicity of Cu nanoparticles

Although copper-based nanoparticles show more effectiveness and lower toxicity than some other metal-based nanoparticles,[343,344] the increase in accumulation and discharge of copper nanoparticles in the ecosystem can have adverse health effects on the lives of animals as well as humans, which makes it important to understand the toxicity mechanisms of metal-based nanoparticles. In 2020, Malhotra *et al.* reviewed the toxicity effects of copper and copper-based nanoparticles on fish of various water bodies. The study revealed that Cu and CuO NPs affected many species of fish by increasing toxicity and reducing Na^+/K^+-ATPase in gills, leading to necrosis of hepatocytes and an increase in oxidative stress markers in the liver and other organs.[345] A study conducted by Chen *et al.* showed that copper nanoparticles can have critical but sex-dependent toxicological effects on the liver, kidney, and spleen, affecting the male organs more severely than the female ones.[346] The homeostatic mechanisms that control copper metabolism are particularly vulnerable to disruption, especially in humans with genetic abnormalities. When toxicity arises, it leads to free-radical-induced oxidative damage, triggering a cascade of effects that commonly result in impaired liver function and reduced mitochondrial respiration.[347] Torres *et al.* studied the impact of copper oxide nanoparticles on Mediterranean mussels (*Mytilus galloprovincialis*), particularly when the mussels were simultaneously exposed to pathogenic bacteria. The researchers exposed the mussels to copper nanoparticle concentrations ranging from 100 to 450 $\mu g\ L^{-1}$ while also infecting them with the pathogenic bacterium *Vibrio tubiashii.*[348] Rajput *et al.* investigated the effects of copper oxide nanoparticles on spring barley (*Hordeum sativum*) and found that the barley grown in the presence of Cu NPs exhibited reduced size, morphological changes, diminished roots, lower germination rate, and decreased yield.[349] Due to the high toxicity of nanoparticles and the incomplete understanding of their mechanisms of action in the body, they should not be released into the environment or exposed to living organisms. Further investigations into the impact of copper nanoparticles on organisms are essential, given the potential for serious pathological processes they may initiate.[350]

7. Conclusion

The copper-based nanocomposites have shown exceptional versatility and made a substantial impact across various industries, leading to significant advancements in materials science. Their multifunctional characteristics, such as stability, reusability, and biocompatibility, combined with outstanding catalytic, antimicrobial, and environmental remediation abilities, make them essential for tackling modern challenges. Copper-based nanocomposites are expected to play a pivotal role in driving technological advancements, offering promising solutions in fields such as environmental protection and healthcare.

Conflicts of interest

There are no conflicts to declare.

Data availability

The authors confirm that the data supporting the findings of this study are available within the article.

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