



Cite this: *Mater. Adv.*, 2025,
6, 9296

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

Khushboo Aggarwal,^{†a} Anamika Brahma,^{†a} Nisha,^a Yashaswi Sharma,^{id}^a
Priyanshu Rajput,^a Bhoomi Sachdeva,^a Aarushi Singh,^{*b} Ramesh Chandra^{*cde} and
Snigdha Singh^{id}^{*ad}

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.

Received 13th May 2025,
Accepted 5th September 2025

DOI: 10.1039/d5ma00484e

rsc.li/materials-advances

^a Drug Discovery & Development Laboratory, Department of Chemistry, University of Delhi, Delhi-110007, India. E-mail: ssingh3@chemistry.du.ac.in

^b Ramjas College, Department of Chemistry, University of Delhi, Delhi-110007, India

^c Dr B. R. Ambedkar Centre for Biomedical Research (ACBR), University of Delhi, Delhi-110007, India

^d Institute of Nanomedical Science (INMS), University of Delhi, Delhi-110007, India

^e Maharaja Surajmal Brij University, Bharatpur 321201, Rajasthan, India

[†] Equal contribution.

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.



Khushboo Aggarwal

Khushboo Aggarwal completed her BSc (Hons.) Chemistry at Kalindi College, University of Delhi and MSc in Chemistry at the Netaji Subhas University of Technology. She then worked as a Research Trainee under Prof. Ramesh Chandra, focusing on the synthesis and applications of nanocatalysts in organic transformations. Currently, she is pursuing her PhD under the supervision of Dr Sarika Singh, Department of Chemistry, University of Delhi, on the topic of “Development of Surface Segregated Multi-metallic Perovskite Supported Catalyst for Different Applications.” She has co-authored papers in reputed journals and presented her research at national and international conferences.



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 nospapine 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.



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/MnO₂ nanocatalyzed synthesis of benzimidazoles, Fe₃O₄/PANI/CuI nanocomposites for sustainable A³ 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.



Priyanshu Rajput

Priyanshu Rajput was born and brought up in Bijnor, Uttar Pradesh, India. He completed his BSc degree from Gurukul Kangri, Uttarakhand in 2023, followed by an MSc degree in Chemistry from the University of Delhi, in 2025. He is currently working as a research trainee under the supervision of Dr Snigdha Singh at the Drug Discovery and Development Laboratory, Department of Chemistry, University of Delhi. His research interests include synthetic organic

chemistry, heterocyclic chemistry, medicinal chemistry, and nanoscience.



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 Fe₃O₄@SiO₂-bis(aminopyridine)-Cu(II),¹⁶ Cu²⁺/mesoporous carbon nanocatalyst,¹⁷ CuI nanoparticle-modified IRMOF-3/PSTA,¹⁸ UiO-66-NH₂@SA-PS/CuI,¹⁹ and Cu@TMU-16-NH₂-GI,²⁰ have been utilized in a variety of organic transformations. A copper-based HKUST-1/TiO₂ 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-C₃N₄ 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 (Cu₂- 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 CO₂, 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 CO₂ reduction reactions.³¹ Previous literature studies have highlighted the importance of understanding the effects of copper nanoparticles in exploring their potential for



Aarushi Singh

Dr. Aarushi Singh, Assistant Professor of Chemistry at Ramjas College, University of Delhi, earned her BSc (2011) and MSc (2013) from DU, completing her PhD in 2021 under Prof. Ramesh Chandra and Dr Rakeshwar Bandichhor on pyrazinoindoles. She has held research positions at the Max Planck Institute, University of Alberta, and Humboldt Universität, with international experience at JAIST, Japan, supported by Shastri and JASSO fellowships. The author of one book and 15+ papers, her research spans organic and heterocyclic synthesis, biologically active compounds, and advanced molecular design.



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



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

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.

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 Cu²⁺ 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



Scheme 1 Suzuki–Miyaura cross coupling reaction.

investigated alternative copper-based catalysts, which are cost-effective and sustainable (Scheme 1).⁵⁷

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–Fe₃O₄–PTh–Cu(I) catalyst in 2020 for catalyzing the Suzuki–Miyaura coupling reaction in a short time. In 2021, Metkazini *et al.* synthesized Ni₄Cu@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**

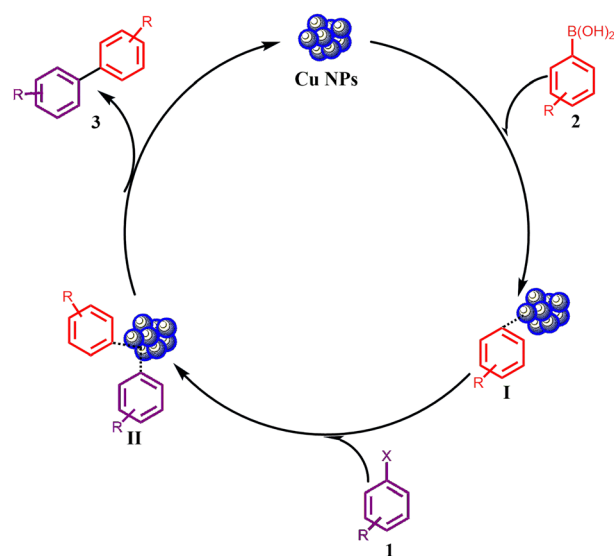


Fig. 2 Plausible mechanism for copper nanoparticle catalysed Suzuki–Miyaura coupling reaction.



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, Oleksyszyn *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 Au₁₃ nanocomposite, [Au₁₃Cu₂(PPh₃)₆(SC₂H₄Ph)₆]⁺ [NO₃]⁻ (Au₁₃Cu₂), through an anti-galvanic reaction between Au₂₅ and Cu(PPh₃)₂NO₃. 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 Cu₂O/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 Cu₂O surface, leading to a synergistic enhancement of catalytic activity within the reaction system.⁷¹ The Fe₃O₄@SiO₂@Cyt-Ni/Cu system, designed by Nasser 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 Fe₃O₄@SiO₂@Cyt-Ni/Cu structure.⁷²

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 Fe₃O₄@SiO₂@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(sp²)-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.



Scheme 2 Sonogashira cross-coupling reaction.

Table 1 Sonogashira coupling reaction using copper-based nanocatalysts

S. no.	Catalyst	Reaction conditions	Time	Yield (%)	Catalyst loading (mol%)	Recyclability	Ref.
1	Fe ₃ O ₄ @SiO ₂ @Cyt-Ni/Cu	DMSO, K ₂ CO ₃ , 100 °C	2 h	94	0.1	7 cycles	Nasser <i>et al.</i> ⁷²
2	CuNPs/MK-10	TEA, 80 °C	4 h	100	1.7	—	Stabile <i>et al.</i> ⁷³
3	MNPs-guanidine-bis(ethanol)-Cu	K ₂ CO ₃ , PEG, 120 °C	3 h	96	1.0	8 cycles	Patra <i>et al.</i> ⁷⁴
4	γ -Fe ₂ O ₃ @PEG@PAMAM G ₀ -Cu	NaOH, H ₂ O, 80 °C	3 h	94	0.8	6 cycles	Sheikh <i>et al.</i> ⁷⁵
5	Pd/Cu@MCC-PAMAM-PEI	K ₂ CO ₃ , DMSO, 80 °C, 4 h, under N ₂	4 h	96	2.5	—	Fan <i>et al.</i> ⁷⁶
6	Fe ₃ O ₄ @CNF@Cu	H ₂ O, KOH, ultrasonic irradiation, 40 °C	6 h	98	0.2	6 cycles	Kargar <i>et al.</i> 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 ($\text{Fe}_3\text{O}_4\text{-CNT-TEA-Cu(II)}$). 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 $\text{MgFe}_2\text{O}_4/\text{Cu}$ 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 $\text{Fe}_3\text{O}_4\text{-CNT-TEA-Cu(II)}$ nanoparticles (Akbarzadeh *et al.*).



Other Derivatives



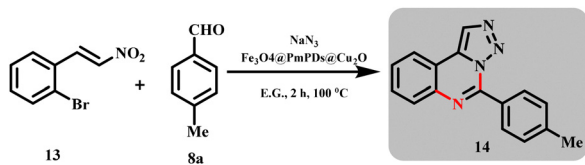
Scheme 5 $\text{MgFe}_2\text{O}_4/\text{Cu}$ catalysed synthesis of β -thiol-1,4-disubstituted-1,2,3-triazoles from thiiranes (Eisavi *et al.*).

A magnetically separable $\text{Fe}_3\text{O}_4@\text{poly}(m\text{-phenylenediamine})@\text{Cu}_2\text{O}$ 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, $\text{Fe}_3\text{O}_4@\text{PmPDs}@\text{Cu}_2\text{O}$ 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

Hajzadeh *et al.* synthesized 5-substituted 1*H*-tetrazole derivatives using Cu(II) immobilized on an $\text{Fe}_3\text{O}_4@\text{HNTs-tetrazole}$ (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 (Hajjizadeh *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

Valley *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 $\text{CuFe}_{2-x}\text{Y}_x\text{O}_4$ 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@NH₂GO 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 [Cu₂(4-ABPT)_{0.5}I₂] (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



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



Scheme 8 General Chan-Lam cross-coupling reaction.

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.

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@TiO₂-NSiO₂/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 Cu₂O/Cu, achieving 90% yield in 7 h with 3-cycle stability.^{110,111} Masoumeh Shaker *et al.* reported an Fe₃O₄-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 CuCl₂@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/CoFe₂O₄, which produced 85% yield in 2 h with 0.1 g loading and stable performance over 5 cycles.¹¹⁵

Cu@Ag-TiO₂-NGO offers high catalytic activity and reusability, demonstrating excellent performance in Chan-Lam coupling.¹¹⁶ Kouser *et al.* have synthesized a PdCu@TiO₂-NSiO₂/PC-TNS catalyst and investigated its potential for the formation of a C-N bond *via* Chan-Lam coupling.¹¹⁷ CuO/t-ZrO₂ 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 ₂ CO ₃ , EtOH: H ₂ O, 60 °C	25 min	88	19	6 cycles	Kouser <i>et al.</i> ¹⁰⁷
2	Cell-ThP-Cu(II)	Water, RT	6 h	96	0.07	5 cycles	Pharande <i>et al.</i> ¹⁰⁸
3	CuI	DMSO, 110 °C	24 h	85	20	—	Kuliukhina <i>et al.</i> ¹⁰⁹
4	Cu@Phen@MGO	MeOH, RT	20 h	89	2	6 cycles	Ghasemi <i>et al.</i> ¹¹⁰
5	Cu ₂ O/Cu	MeOH, 60 °C	7 h	90	10	3 cycles	Sarmahl <i>et al.</i> ¹¹¹
6	Fe ₃ O ₄ @RF@void@PMO(IL)/Cu	K ₂ CO ₃ , EtOAc/H ₂ O (1 : 1), RT	5 h	97	0.9	7 cycles	Shaker <i>et al.</i> ¹¹²
7	Cu-TAPB-TFP	CH ₂ Cl ₂ , 30 °C	18 h	97	2.6	5 cycles	Romero-Muñiz <i>et al.</i> ¹¹³
8	CuCl ₂ @PAN-F	MeOH	3 h	98	8	5 cycles	Zhang ¹¹⁴ <i>et al.</i>
9	Cu@KF-C/CoFe ₂ O ₄	CS ₂ CO ₃ , EtOH 90 °C	2 h	85	2.2	5 cycles	Sharma <i>et al.</i> 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.

3.1.5. A³ coupling for the synthesis of propargyl amine derivatives. The aldehyde-alkyne-amine (A³) 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 Fe₃O₄/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/Fe₃O₄/CuO, obtaining 91% yield in 8 h using 30 mg of the catalyst, with high reusability.¹³⁰ Banda *et al.* used Fe₃O₄-NH₂-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 Fe₃O₄@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-



Scheme 9 A³ coupling using copper nanocatalysts.

Table 3 A³ 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 <i>et al.</i> ¹²³
2	[Cu(BTA) ₂] _n	Dioxane, 80 °C	4 h	95	3	6 cycles	Shahverdi <i>et al.</i> ¹²⁴
3	Fe ₃ O ₄ /PANI/CuI(10)	Neat, 80 °C	10 min	96	1.8	7 cycles	Kohli <i>et al.</i> ¹²⁵
4	Cu-L4	Chloroform, 90 °C	24	90	1	—	Pandey <i>et al.</i> ¹²⁶
5	Cu(NO ₃) ₂ ·3H ₂ O	DMSO, 80 °C	2 h	81	10	—	Wang <i>et al.</i> ¹²⁷
6	PANbis(Py)-Cu(II)F	Solvent free, 110 °C	12 h	>99	0.1	6 cycles	Cheng <i>et al.</i> ¹²⁸
7	CuI/Zn dust	Neat, 60 °C	18 h	98	20	—	Agbo <i>et al.</i> ¹²⁹
8	MMT-K10/Fe ₃ O ₄ /CuO	Toluene, 80 °C	8 h	91	2	High	Bagheri <i>et al.</i> ¹³⁰
9	Fe ₃ O ₄ -NH ₂ -Cu	Neat, 80 °C	5 h	97	1.2	5 cycles	Banda <i>et al.</i> ¹³¹
10	Fe ₃ O ₄ @starch-Acr@Cu(II)	H ₂ O, Reflux	36 min	99	39.3	5 cycles	Tajbaksh <i>et al.</i> ¹³²
11	CuI	DMSO, 60–65 °C	15 h	95	1.3	—	Grishchenko <i>et al.</i> ¹³³
12	Cu(BDC)@Cu(II)/CMC	Toluene, reflux	4 h	96	7.5	6 cycles	Huang <i>et al.</i> ¹³⁴
13	Cu ₂ NC(NHC)	DCM, RT	12 h	99	2.5	6 cycles	Jia <i>et al.</i> ¹³⁵
14	Co ²⁺ -Cu@SA(7.5)-600	Toluene, 110 °C	1 h	88	9.4	5 cycles	Kaur <i>et al.</i> ¹³⁶
15	Fe ₃ O ₄ -BIm-Pyrim-CuI	H ₂ O, reflux	3 h	98	0.15	8 cycles	Li <i>et al.</i> ¹³⁷





Fig. 6 Plausible mechanism for copper nanoparticle catalysed A³ 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 Co²⁺-Cu@SBA-15-600 and obtained 88% yield in 8 h with 0.05 g of the catalyst.¹³⁶ Li *et al.* demonstrated Fe₃O₄-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 A³ 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



Scheme 10 Fe₃O₄@SiO₂-glycerol-Cu(II) catalysed synthesis of di-aryl ethers (Ashraf *et al.*).

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.

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 Fe₃O₄-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 activity for C–O coupling reaction using iodobenzene and phenol.¹⁴⁴ Ashraf *et al.* prepared a copper(II) complex supported on surface-modified Fe₃O₄/SiO₂ nanoparticles (Fe₃O₄@SiO₂-glycerol-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, Fe₃O₄@nanoalmond shell@Osi(CH₂)/NHCH₂pyridine/Cu^{II}(FNAO-SiPAMP)/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@SiO₂@Fe₃O₄ 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 ₂ CO ₃	12 h	91	—	5 cycles	Zhou <i>et al.</i> ¹³⁸
2	CuO/mGO-TA-Me-BTA	H ₂ O, Cs ₂ CO ₃ , reflux	6 h	89	20	5 cycles	Eslami <i>et al.</i> ¹³⁹
3	Cellulose-based NCL-Cu(II)@PA	MeCN, K ₂ CO ₃ , 70 °C	1.5 h	99	32	7 cycles	Rahman <i>et al.</i> ¹⁴⁰
4	Fe ₃ O ₄ supported [Cu(II) met(II) (Pro-H) ₂]	H ₂ O, Cs ₂ CO ₃ , reflux	1 h	98	8	8 cycles	Ali <i>et al.</i> ¹⁴¹
5	Cu(II)-MP-bis(AMP)@boehmite	DMSO, KOH, 130 °C	1 h	98	30	6 cycles	Jabbari <i>et al.</i> ¹⁴²
6	CuNPs@Q-POP	K ₂ CO ₃ , DMF, 110 °C	48 h	97	75	5 cycles	Gorginpour <i>et al.</i> ¹⁴³



**Other derivatives**

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, Fe₃O₄@Dop/amide-benzimid-CuBr₂. 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

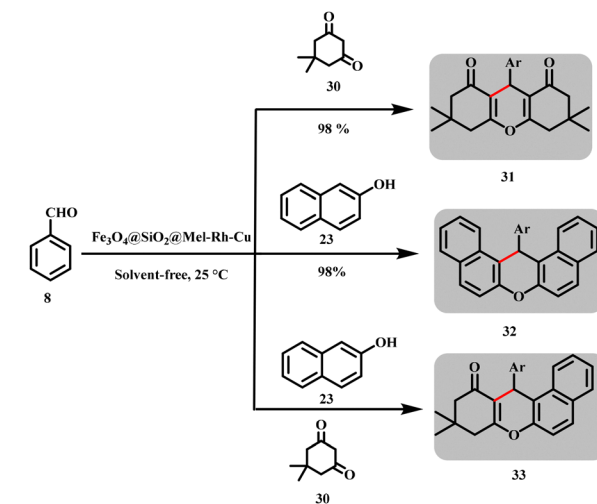
3.1.7 C–S coupling catalysed by a copper nanocomposite.

Ashraf *et al.* synthesized an Fe₃O₄@SiO₂-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

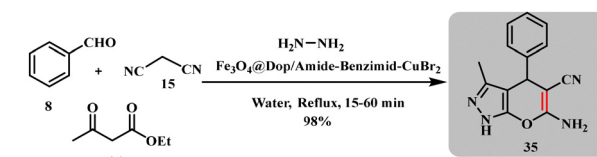


Catalyst: Cu(II)-Schiff base-TCT-APTES@SiO₂@Fe₃O₄

Scheme 12 Cu(II)-Schiff base-TCT-APTES@SiO₂@Fe₃O₄ catalysed synthesis of chromene derivatives (Kalantar *et al.*).

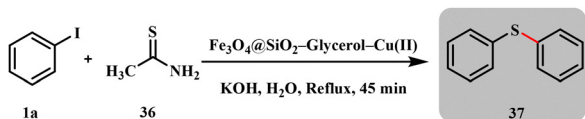


Scheme 13 Fe₃O₄@SiO₂@NTMPThio-Cu catalysed synthesis of xanthenes (Peiman *et al.*).

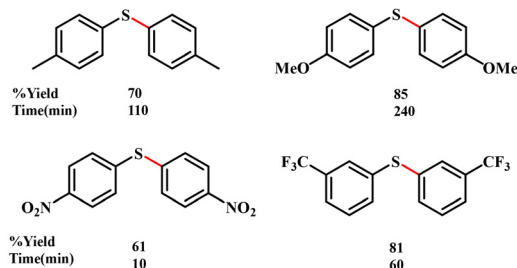


Scheme 14 Fe₃O₄@Dop/amide-benzimid-CuBr₂ catalysed synthesis of 6-amino-3-methyl-4-phenyl-1,4-dihydropyran[2,3-*c*]pyrazole-5-carbonitrile (Li *et al.*).





Other derivatives



Scheme 15 $\text{Fe}_3\text{O}_4@SiO_2$ -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 $\text{Fe}_3\text{O}_4@SiO_2$ -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 ($\text{Fe}_3\text{O}_4@SiO_2$ -(imine-thiazole)-Cu(OAc)₂), which was employed in the synthesis of diaryl sulfides and benzothio-phenes, 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, $\text{Fe}_3\text{O}_4@SiO_2$ -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 <i>et al.</i> ¹⁵⁵
$\text{Fe}_3\text{O}_4@SiO_2$ -di(pyridin-2-yl)metanimine-Cu	K_2CO_3 , PEG, 120 °C	98 %	Ahmad <i>et al.</i> ¹⁵⁶

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



Scheme 17 $\text{Fe}_3\text{O}_4@SiO_2$ -(imine-thiazole)-Cu(OAc)₂ catalysed synthesis of 2-substituted benzothiazoles (Feng *et al.*).



Scheme 18 $\text{Fe}_3\text{O}_4@SiO_2$ -imine/thio-Cu(II) catalysed synthesis of diaryl sulfones (Abdelbasset *et al.*).

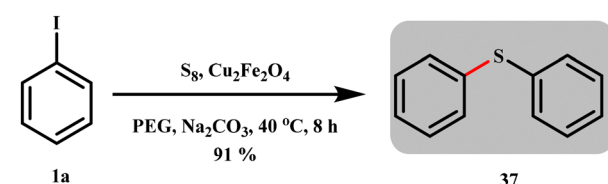


Scheme 19 $\text{Fe}_3\text{O}_4@ABA$ -aniline-CuI catalysed synthesis of 2-(phenylthio)benzothiazole (Sun *et al.*).

The $\text{Fe}_3\text{O}_4@ABA$ -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 heteroaryl. 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 S_8 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 $\text{Fe}_3\text{O}_4@AMBA$ -CuI nanocatalyst for the synthesis of diaryl sulfides containing imidazo[1,2-*a*]pyridine, benzazole, pyrimidine, and oxadiazole scaffolds through C-H bond sulfenylation of imidazopyridines. The $\text{Fe}_3\text{O}_4@AMBA$ -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 $\text{Cu}_2\text{Fe}_2\text{O}_4$ catalysed synthesis of diphenylsulfane (Ichie *et al.*).





Other derivatives



Scheme 21 $\text{Fe}_3\text{O}_4\text{@AMBA-CuI}$ 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 $\text{CoFe}_2\text{O}_4\text{@SiO}_2\text{-CPTES-Guani-dine-Cu(II)}$, 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 $\text{ZnFe}_2\text{O}_4\text{@SiO}_2\text{@APTES@DHBS-Cu}$ 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.* synthesised 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

A recyclable and efficient Cu nanocatalyst has been used for the selective oxidation of benzene to *p*-benzoquinone. Notably,



Scheme 22 Cu(II) catalysed oxidation of sulphides into sulfoxides (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.*).

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

$\text{CuO}_x\text{-ZrO}_2\text{-CeO}_2$ 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.* synthesised $\text{Fe}_3\text{O}_4\text{/Cu-BDC/GO}$ 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, $\text{Fe}_3\text{O}_4\text{@PVA-Cu}$, was synthesised 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 synthesise $\text{Fe}_3\text{O}_4\text{@raffinose-Cu}_2\text{O}$, an efficient nanocatalyst for the oxidation of primary benzyl alcohols to benzaldehyde derivatives, enhancing both yields and reaction time.¹⁶⁵ Magnetic $\text{Fe}_3\text{O}_4\text{@SiO}_2\text{/Cu}$ 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 $\text{Fe}_3\text{O}_4\text{/Cu-BDC/GO}$ catalyst (Alamgholiloo *et al.*).





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

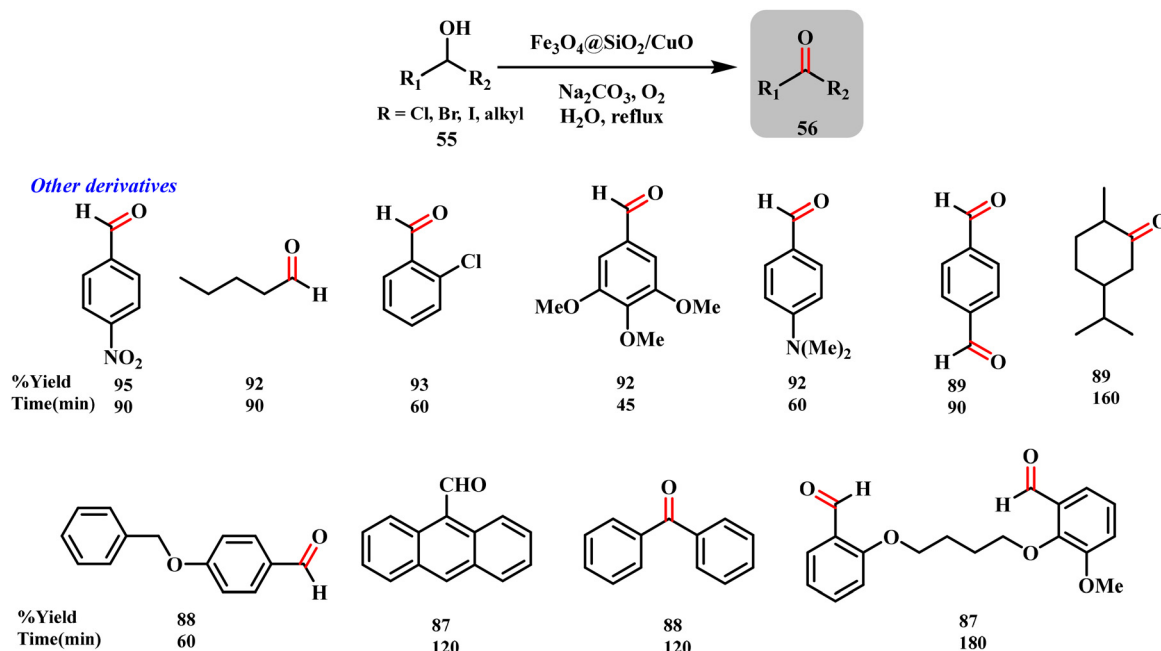
oxidation.¹⁶⁷ Bimetallic Pt₃Cu nano-dendrites (NDs) with a multi-branched structure on a W-modified TiO₂ support have been synthesized by Hau Quoc Pham *et al.* using a microwave-assisted technique, providing an efficient technique for methanol oxidation.¹⁶⁸ A Schiff base ligand immobilized on a magnetic-supported copper nanocatalyst (Fe₃O₄@SiO₂/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 CuMoO₄ 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 Fe₃O₄@PectinImidazoleSO₃H-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@Fe₃O₄@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 based 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 spirooxindole 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 Rezaayati *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 CuFe₂O₄/CuO–CeO₂ 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 Fe₃O₄@AAPA-AP-CuCl₂, which gave 96% yield in 8 h at 180 °C using PEG, with 7-cycle reusability.¹⁹⁶ Jiang *et al.* used Fe₃O₄@Diol/Phen–CuCl₂ under milder conditions (100 °C, 2 h), achieving 94% yield and 7-cycle recyclability.¹⁹⁷ Peiman *et al.* reported Fe₃O₄@SiO₂@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 CuBr₂-based Fe₃O₄@Dop/amide-BenzImid system that yielded 98% in 90 min under reflux in water, while Kalantari *et al.* synthesized a Cu(II)-Schiff base@SiO₂@Fe₃O₄ catalyst that reached 96% yield in 20 min in EtOH with 7-cycle stability.^{199,200} Thrilokraj *et al.* used simple Fe₃O₄ 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 Fe₃O₄ 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

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,



Other derivatives:

Scheme 30 Synthesis of pyrano[2,3-*c*]pyrazoles using a copper-based nanocatalyst (Ali *et al.*).Scheme 31 Fe₃O₄@PDA/CuCl₂ for synthesis of benzimidazole (Badbedast *et al.*).

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 malonitrile using 10 mg of a CuI@Al₂O₃ 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 ₃ O ₄ @AAPA-AP-CuCl ₂	PEG, 180 °C	8 h	96	0.36	7 cycles	Fajer <i>et al.</i> ¹⁹⁶
2	Fe ₃ O ₄ @Diol/Phen-CuCl ₂	PEG, 100 °C	2 h	94	5	7 cycles	Jiang <i>et al.</i> ¹⁹⁷
3	Fe ₃ O ₄ @SiO ₂ @NTMPThio-Cu	Solvent free, 25 °C	12 min	97	15	8 cycles	Peiman <i>et al.</i> ¹⁹⁸
4	Fe ₃ O ₄ @Dop/amide-BenzImid-CuBr ₂	Water, Reflux	90 min	98	8	8 cycles	Li <i>et al.</i> ¹⁹⁹
5	Cu(II)-Schiff base-TCT-APTES@SiO ₂ @Fe ₃ O ₄	EtOH, Reflux	20 min	96	6	7 cycles	Kalantari <i>et al.</i> ²⁰⁰
6	Fe ₃ O ₄ NPs	Neat, 80 °C	50 min	91	30	5 cycles	Thrilokraj <i>et al.</i> ²⁰¹
7	SBA-15@ELA	EtOH, Reflux	6 h	96	10	6 cycles	Yazdi <i>et al.</i> ²⁰²





Scheme 32 CuI@Al₂O₃ catalysed synthesis of 2-aminonicotinonitrile (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@Al₂O₃ 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@Al₂O₃ 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



Fig. 7 Plausible mechanism for synthesis of 2-aminonicotinonitrile using a CuI@Al₂O₃ nanocatalyst.



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

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, hetero-aromatic, 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

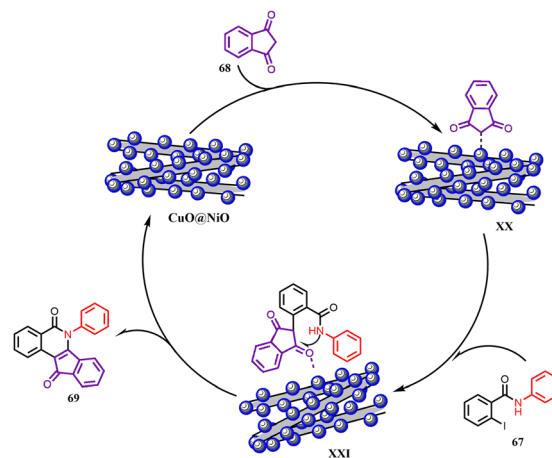


Fig. 8 Plausible mechanism for synthesis of indenoisoquinolines using a CuO@NiO nanocatalyst.



Scheme 34 $\text{Cu}_2\text{O}@\text{MHAM}$ 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_2O 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 $\text{CuO}@\text{MgO}$ 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 $\text{Fe}_3\text{O}_4@\text{MgCuAl-LDH}@CS/\text{Cu(II)}$ 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 $\text{Fe}_3\text{O}_4@\text{MgCuAl-LDH}@CS/\text{Cu(II)}$ 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 $\text{Fe}_3\text{O}_4@\text{SiO}_2\text{-bis(aminopyridine)-Cu(II)}$ 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

Scheme 35 $\text{CuO}@\text{MgO}$ catalysed synthesis of isocoumarins (Rawat *et al.*).

Other Derivatives

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

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

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

Catalyst: $\text{Fe}_3\text{O}_4@\text{SiO}_2\text{-bis(aminopyridine)-Cu(II)}$

Other Derivatives

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



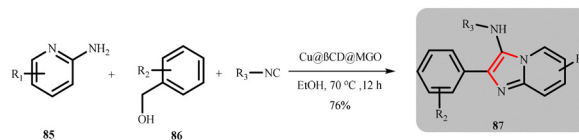
Scheme 38 Catalytic synthesis of heterocyclic derivatives using Cu-ZnO nanoparticles (Maleki *et al.*).

The one-pot synthesis of α -aminonitriles *via* the Stecker reaction was achieved using $\text{Fe}_3\text{O}_4@\text{SiO}_2@\text{Im}[\text{CN}]\text{Cu}(\text{II})$ 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 (β CD)-functionalized magnetic graphene oxide nanosheets ($\text{Cu}@\beta\text{CD}@\text{MGO}$). This catalyst effectively oxidizes



Scheme 39 Catalytic synthesis of α -aminonitrile derivatives using $\text{Fe}_3\text{O}_4@\text{SiO}_2@\text{Im}[\text{CN}]\text{Cu}(\text{II})$ nanoparticles (Kazemnejadi *et al.*).



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

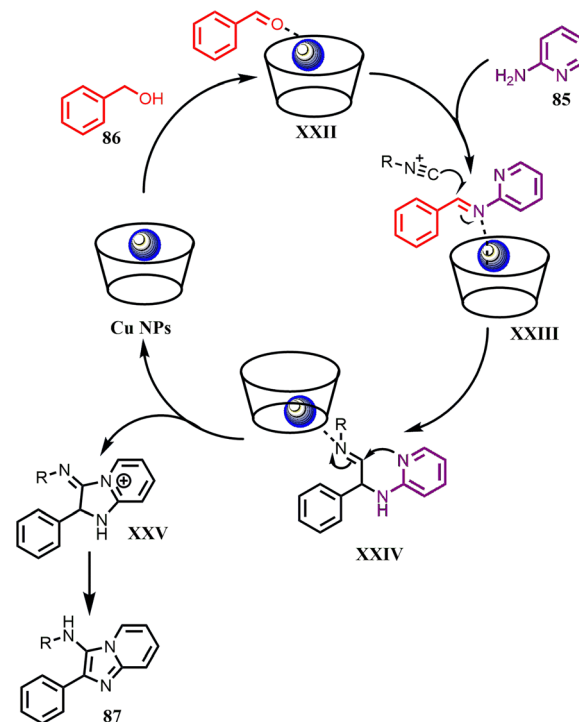


Fig. 9 Plausible mechanism for synthesis of *N*-(alkyl)-2-phenylimidazo[1,2-*a*]pyridin-3-amine derivatives using $\text{Cu}@\beta\text{-CD}@\text{MGO}$ nanoparticles.

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

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 Csu-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 $\text{Fe}_3\text{O}_4@\text{SiO}_2$ -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-4H chromene (a) Benzaldehyde and (b) 4-chloro-3-nitrobenzaldehyde derivatives using $\text{Fe}_3\text{O}_4\text{-@SiO}_2\text{-imine/phenoxy-Cu(II)}$ nanoparticles (Ebrahimiast *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.

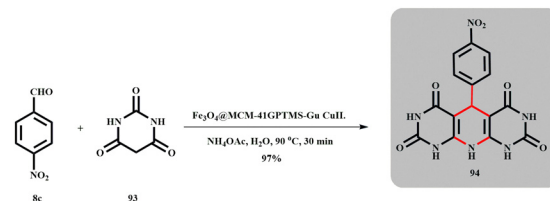
The synthesis of 5-phenyl-5,10-dihydropyrido[2,3-*d*:6,5-*d'*]-dipyrimidine 2,4,6,8(1*H*,3*H*,7*H*,9*H*)tetraone derivatives was achieved using a Cu(II) catalyst immobilized on functionalized magnetic mesoporous MCM-41 ($\text{Fe}_3\text{O}_4\text{-@MCM-41-GPTMS-Gu}$). The 4.45 mol% of catalyst was used, 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 4H-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

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



Fig. 10 Plausible mechanism for synthesis of 2-amino-4H chromene derivatives using $\text{Fe}_3\text{O}_4\text{-@SiO}_2\text{-imine/phenoxy-Cu(II)}$ nanoparticles (Ebrahimiast *et al.*).



Scheme 42 Catalytic synthesis of heterocyclic derivatives using $\text{Fe}_3\text{O}_4\text{-@MCM-41-GPTMS-Gu-Cu}$ nanoparticles (Farsi *et al.*).



Scheme 43 Catalytic synthesis of 4H-pyran derivatives using $\text{CuFe}_2\text{O}_4\text{-@starch}$ nanoparticles (Kamalzare *et al.*).

conditions. The process starts with the *in situ* formation of yrones, 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.*).



Other derivatives



Scheme 45 Catalytic synthesis of heterocyclic derivatives using a Cu(II)/Fe₃O₄@APTMS-DFX nanocomposite (Sonei *et al.*).

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

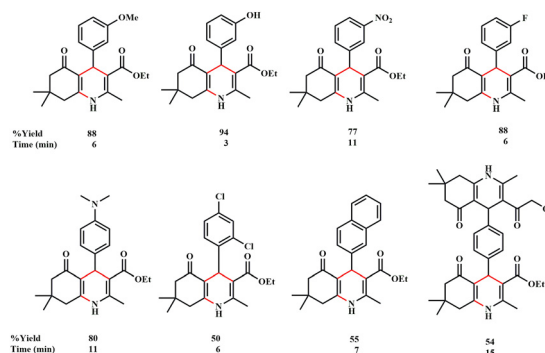
12-Aryl-8,9,10,12-tetrahydrobenzo[*a*] xanthene-11-one derivatives have been synthesized by Sonei *et al.* using a Cu(II)-immobilized Fe₃O₄@APTMS-DFX nanoparticle catalyst. The reaction has been efficiently carried out using 0.02 g of the catalyst, aromatic aldehyde, 2-naphthol, and dimedone under solvent-free 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, NO₂, 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-Fe₃O₄ 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).

The catalytic cycle, as represented in Fig. 11, started when the aldehyde **30** and malononitrile **101** were activated by Cu



Other derivatives



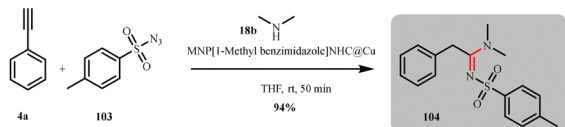
Scheme 46 Catalytic synthesis of hexahydroquinoline derivatives using an Fe₃O₄@SiO₂@Si-(CH₂)₂@HMAT@Cu nanocomposite (Salem *et al.*).



Fig. 11 Plausible mechanism for synthesis of hexahydroquinoline derivatives using an Fe₃O₄@SiO₂@Si-(CH₂)₂@HMAT@Cu nanocomposite (Salem *et al.*).

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 five cycles without a significant loss in the yield (Scheme 47).²²⁰

In a study conducted by Hu *et al.*, a novel Fe₃O₄@bis(phenyl-imine)-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 CHCl₃-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 thiocarbonylhydrazide, 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

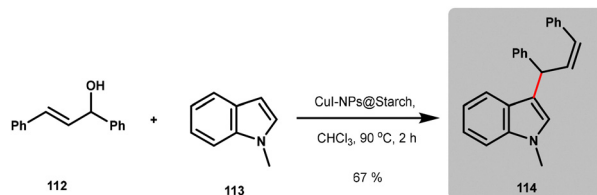
Mallick *et al.* synthesised copper(I) iodide nanoparticles supported on starch (CuI-NPs@starch) in an aqueous medium. The nanocatalyst proved to be effective for the regioselective 3-allylation of indoles including both *N*-substituted and ring-substituted variants using various allyl alcohols under conditions that are tolerant to air and moisture using 30 mg of the catalyst. However, the catalyst showed poor recyclability, with



Scheme 48 Fe₃O₄@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.*).

significant copper leaching (1.6% w/w) as confirmed by AAS, leading to a marked loss in activity after one use (Scheme 50).²²³

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 heterogeneous 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 CuFe₂O₄ 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 xanthenes (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 xanthenes 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 (H₂O₂), hydroxyl radicals ([•]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 therapy²⁴⁰ 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 Cu₂O 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 Cu₂O NPs. The research indicated that Cu₂O 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 Cu₂O 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 Cu₂O deposited on glass exhibited a potent antiviral effect against human coronavirus HCoV-229E.²⁴⁹ Carabineiro *et al.* used the CuFe₂O₄ 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 Fe₃O₄/SiO₂-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 nanopatform, 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 Cu²⁺ 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 (Fe³⁺), 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 $339.3 \mu\text{A mM}^{-1} \text{cm}^{-2}$, and a limit of detection (LOD) of $16.62 \mu\text{M}$.²⁷⁹ Jain *et al.* investigated the multifunctional catalytic properties of $\text{Cu}_3\text{V}_2\text{O}_7(\text{OH})_2 \cdot 2\text{H}_2\text{O}$ 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/ $\text{Ce}_{1-x}\text{Ti}_x\text{O}_2$ 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 $\text{Ce}_{1-x}\text{Ti}_x\text{O}_2$ support.²⁹⁸ Similarly, Chen *et al.* synthesized a series of $\text{Ce}_{20}\text{Cu}_5\text{Ni}_y\text{O}_x$ 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



CO₂ hydrogenation. They synthesized a C₃N₄-supported Cu SAC with a substantial loading of 12 wt% and demonstrated that by adjusting treatment parameters, such as those affecting Cu–N₄ and Cu–N₃ coordination structures, the coordination environment of Cu atoms in the SAC could be systematically modified, leading to significant variations in CO₂ hydrogenation efficiency. They concluded that the Cu–N₄ SAC exhibited a remarkable CH₃OH 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 Cu₂S nanoparticles for their application as anodes of Li ion batteries. They investigated the mechanisms of alkali metal ion storage using DFT calculations. The Cu₂S@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 Fe₃N 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 CuCo₂O₄ 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}, ~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 Cu₂O nanocubes, for their application in asymmetric

supercapacitors. The synthesized CuS₂@Cu₇Se₄@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 dyes³¹⁴ 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} pesticides³²¹ or industrial chemicals³²² 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 contaminants³²⁴

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 H₂O₂ and bimetallic oxide when exposed to weakly acidic water. This process is followed by the direct generation of hydroxyl radicals (•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 automobiles³³⁰ or used in air purification systems³³¹ 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 contamination³³⁸ and improving soil quality.³³⁹



5.5. Food industry

Copper nanoparticles have been studied for their potential in catalyzing the conversion of carbon dioxide (CO₂) 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 CO₂ reduction reaction (CO₂RR).³⁴⁰ Kim *et al.* also synthesized branched CuO nanoparticles, which were highly selective for the production of ethylene by the CO₂RR, 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 CO₂ 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 CO₂ 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 µg 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, anti-microbial, 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.

Acknowledgements

S. S. wishes to sincerely thank the Institution of Eminence at the University of Delhi and the Institute of Nanomedical Science (INMS) for their invaluable support. S. S., K. A., and A. B. are grateful to the University of Delhi for providing access to facilities. A. B. acknowledges UGC (231610191350) and Nisha acknowledges CSIR (09/045(1792)/2020-EMR-I) for awarding the Junior Research Fellowship.

References

- 1 L. Ouyang, V. Noël, A. Courty, J.-M. Campagne and A. Ouali, Copper nanoparticles with tunable size: implications for plasmonic catalysis, *ACS Appl. Nano Mater.*, 2022, **5**, 2839–2847, DOI: [10.1021/acsnm.2c00016](https://doi.org/10.1021/acsnm.2c00016).
- 2 P. K. Tandon and S. B. Singh, Catalytic applications of copper species in organic transformations: a review, *J. Catal.*, 2014, **1**, 21–34, DOI: [10.5958/2349-4344.2014.00002.0](https://doi.org/10.5958/2349-4344.2014.00002.0).
- 3 S. R. Khan, S. Ali, K. Zulfiqar, S. Jamil, S. Noreen, A. Raza and M. J. Latif, From nitroarenes to fuel efficiency: the dual impact of copper/polystyrene nanocomposite catalysts, *Inorg. Chem. Commun.*, 2025, **172**, 113690, DOI: [10.1016/j.inoche.2025.113690](https://doi.org/10.1016/j.inoche.2025.113690).
- 4 R. Pathak, V. D. Punetha, S. Bhatt and M. Punetha, A review on copper-based nanoparticles as a catalyst: synthesis and applications in coupling reactions, *J. Mater. Sci.*, 2024, **59**, 6169–6205, DOI: [10.1007/s10853-024-09546-z](https://doi.org/10.1007/s10853-024-09546-z).



- 5 M. B. Gawande, A. Goswami, F.-X. Felpin, T. A. M. B. Gawande, A. Goswami, F.-X. Felpin, T. Asefa, X. Huang, R. Silva, X. Zou, R. Zboril and R. S. Varma, Cu and Cu-based nanoparticles: synthesis and applications in catalysis, *Chem. Rev.*, 2016, **116**, 3722–3811, DOI: [10.1021/acs.chemrev.5b00482](https://doi.org/10.1021/acs.chemrev.5b00482).
- 6 S. Bhagat, S. Wahurwagh, A. Verma and U. Pratap, Harnessing synergy: immobilized Cu(II) and Pd(II) species on magnetic silica-coated copper ferrite for A³ and Sonogashira coupling reactions, *Appl. Surf. Sci.*, 2025, **687**, 162264, DOI: [10.1016/j.apsusc.2025.162264](https://doi.org/10.1016/j.apsusc.2025.162264).
- 7 A. M. Elgorban, N. Marraiki, S. A. Ansari and A. Syed, Green synthesis of Cu/Fe₃O₄ nanocomposite using Calendula extract and evaluation of its catalytic activity for chemoselective oxidation of sulfides to sulfoxides with aqueous hydrogen peroxide, *J. Organomet. Chem.*, 2021, **954**, 122077, DOI: [10.1016/j.jorganchem.2021.122077](https://doi.org/10.1016/j.jorganchem.2021.122077).
- 8 A. Boucherdoud, A. Seghier, D. E. Kherroub, O. Douinat, K. Dahmani, B. Bestani and N. Benderdouche, Autogenous deposition of copper oxide onto polyaniline nanocomposite catalysts for the photodegradation of methylene blue and Congo red: experimental inquiry, RSM optimization, and DFT calculation, *Mater. Sci. Eng., B*, 2025, **314**, 118015, DOI: [10.1016/j.mseb.2025.118015](https://doi.org/10.1016/j.mseb.2025.118015).
- 9 M. Fereydooni, R. Ghorbani-Vaghei and S. Alavinia, An economical synthesis of benzodiazepines using ACT@IRMOF core-shell as a potential eco-friendly catalyst through the activated carbon of Thymus plant (ACT), *Nanoscale Adv.*, 2025, **7**(4), 1091–1103, DOI: [10.1039/D4NA00907J](https://doi.org/10.1039/D4NA00907J).
- 10 M. Rawat and D. S. Rawat, CuO@NiO nanocomposite catalyzed synthesis of biologically active indenoisoquinoline derivatives, *ACS Sustainable Chem. Eng.*, 2020, **8**, 13701–13712, DOI: [10.1021/acssuschemeng.0c03898](https://doi.org/10.1021/acssuschemeng.0c03898).
- 11 N. K. Ojha, G. V. Zyryanov, A. Majee, V. N. Charushin, O. N. Chupakhin and S. Santra, Copper nanoparticles as inexpensive and efficient catalyst: a valuable contribution in organic synthesis, *Coord. Chem. Rev.*, 2017, **353**, 1–57, DOI: [10.1016/j.ccr.2017.07.012](https://doi.org/10.1016/j.ccr.2017.07.012).
- 12 N. K. Ojha, G. V. Zyryanov, A. Majee, V. N. Charushin, O. N. Chupakhin and S. Santra, Copper nanoparticles as inexpensive and efficient catalyst: a valuable contribution in organic synthesis, *Coord. Chem. Rev.*, 2017, **353**, 1–57, DOI: [10.1016/j.ccr.2017.10.004](https://doi.org/10.1016/j.ccr.2017.10.004).
- 13 D. Das, Multicomponent reactions in organic synthesis using copper-based nanocatalysts, *ChemistrySelect*, 2016, **1**, 1959–1980, DOI: [10.1002/slct.201600414](https://doi.org/10.1002/slct.201600414).
- 14 M. Kundu, B. Mondal, D. Das and U. K. Roy, Synthesis and reactivity of copper and copper containing magnetically separable catalysts, *ChemistrySelect*, 2022, **7**, e202104543, DOI: [10.1002/slct.202104543](https://doi.org/10.1002/slct.202104543).
- 15 S. Bondarian, M. G. Dekamin, E. Valiey and M. R. Naimi-Jamal, Supramolecular Cu(II) nanoparticles supported on a functionalized chitosan containing urea and thiourea bridges as a recoverable nanocatalyst for efficient synthesis of 1H-tetrazoles, *RSC Adv.*, 2023, **13**, 27088–27105, DOI: [10.1039/D3RA04964H](https://doi.org/10.1039/D3RA04964H).
- 16 Z. H. Mahmood, Y. Riadi, H. A. Hammoodi, A. F. Alkaim and Y. Fakri Mustafa, Magnetic nanoparticles supported copper nanocomposite: a highly active nanocatalyst for synthesis of benzothiazoles and polyhydroquinolines, *Polycycl. Aromat. Compd.*, 2023, **43**, 3687–3705, DOI: [10.1080/10406638.2022.2067866](https://doi.org/10.1080/10406638.2022.2067866).
- 17 H. Ghafuri, P. Hanifehnejad, A. Rashidzadeh, Z. Tajik and H. Dogari, Synthesis and characterization of nanocatalyst Cu²⁺/mesoporous carbon for amidation reactions of alcohols, *Sci. Rep.*, 2023, **13**, 10133, DOI: [10.1038/s41598-023-36936-2](https://doi.org/10.1038/s41598-023-36936-2).
- 18 H. Ghafuri, P. Hanifehnejad, A. Rashidzadeh, Z. Tajik and H. Dogari, Synthesis and characterization of nanocatalyst Cu²⁺/mesoporous carbon for amidation reactions of alcohols, *Sci. Rep.*, 2023, **13**, 10133, DOI: [10.1038/s41598-023-36521-6](https://doi.org/10.1038/s41598-023-36521-6).
- 19 S. Koosha, R. Ghorbani-Vaghei and S. Alavinia, Recyclable Nano-CuI immobilized on UiO-66-NH₂ coated with porous sodium alginate-polysulfonamide for synthesis of phenols, *Carbohydr. Polym. Technol. Appl.*, 2025, 100665, DOI: [10.1016/j.carpta.2024.100665](https://doi.org/10.1016/j.carpta.2024.100665).
- 20 S. Koosha, S. Alavinia and R. Ghorbani-Vaghei, CuI nanoparticles-immobilized on a hybrid material composed of IRMOF-3 and a sulfonamide-based porous organic polymer as an efficient nanocatalyst for one-pot synthesis of 2,3-disubstituted benzo[b]furans, *Arabian J. Chem.*, 2023, **16**, 104975, DOI: [10.1016/j.arabjc.2023.104975](https://doi.org/10.1016/j.arabjc.2023.104975).
- 21 A. Khan, M. Le Pivert, A. Ranjbari, D. Dragoë, D. Bahena-Urbe, C. Colbeau-Justin, C. Herrero, D. Rutkowska-Zbik, J. Deschamps and H. Remita, Cu-based MOF/TiO₂ composite nanomaterials for photocatalytic hydrogen generation and the role of copper, *Adv. Funct. Mater.*, 2025, 2501736, DOI: [10.1002/adfm.202501736](https://doi.org/10.1002/adfm.202501736).
- 22 M. Zhou, M. Tian and C. Li, Copper-Based Nanomaterials for Cancer Imaging and Therapy, *Bioconjugate Chem.*, 2016, **27**(5), 1188–1199, DOI: [10.1021/acs.bioconjchem.6b00156](https://doi.org/10.1021/acs.bioconjchem.6b00156).
- 23 X. Chen, Q. Cai, R. Liang, D. Zhang, X. Liu, M. Zhang, Y. Xiong, M. Xu, Q. Liu, P. Li, P. Yu and A. Shi, Copper Homeostasis and Copper-Induced Cell Death in the Pathogenesis of Cardiovascular Disease and Therapeutic Strategies, *Cell Death Dis.*, 2023, **14**, 105, DOI: [10.1038/s41419-023-05639-w](https://doi.org/10.1038/s41419-023-05639-w).
- 24 X. Huang, Y. Zhu and E. Kianfar, Nano Biosensors: Properties, Applications and Electrochemical Techniques, *J. Mater. Res. Technol.*, 2021, **12**, 1649–1672, DOI: [10.1016/j.jmrt.2021.03.048](https://doi.org/10.1016/j.jmrt.2021.03.048).
- 25 S. Malik, J. Singh, R. Goyat, Y. Saharan, V. Chaudhry, A. Umar, A. A. Ibrahim, S. Akbar, S. Ameen and S. Baskoutas, Nanomaterials-based biosensor and their applications: a review, *Heliyon*, 2023, **9**, e19929, DOI: [10.1016/j.heliyon.2023.e19929](https://doi.org/10.1016/j.heliyon.2023.e19929).
- 26 K. Dhara, R. Thiagarajan, B. G. Nair and S. B. T. Gopalakrishnan, Highly sensitive and wide-range non-enzymatic disposable glucose sensor based on a screen-printed carbon electrode modified with reduced graphene oxide and Pd–CuO nanoparticles, *Microchim. Acta*, 2015, **182**, 2183–2192, DOI: [10.1007/s00604-015-1549-x](https://doi.org/10.1007/s00604-015-1549-x).
- 27 J. Zou, S. Wu, Y. Liu, Y. Sun, Y. Cao, J. P. Hsu, A. T. S. Wee and J. Jiang, An ultra-sensitive electrochemical sensor



- based on 2D g-C₃N₄/CuO nanocomposites for dopamine detection, *Carbon*, 2018, **130**, 652–663, DOI: [10.1016/j.carbon.2018.01.060](https://doi.org/10.1016/j.carbon.2018.01.060).
- 28 B. Kaboudin, B. Burunli, M. Nazerian, T. Zhang and Y. Gu, A novel and green approach for the synthesis of copper nanoparticles and their applications in reduction of nitroaromatics and degradation of organic dyes, *J. Organomet. Chem.*, 2025, **1025**, 123477, DOI: [10.1016/j.jorganchem.2024.123477](https://doi.org/10.1016/j.jorganchem.2024.123477).
- 29 G. Tortella, O. Rubilar, P. Fincheira, J. Parada, H. C. de Oliveira, A. Benavides-Mendoza, S. Leiva, M. Fernandez-Baldo and A. B. Seabra, Copper nanoparticles as a potential emerging pollutant: divergent effects in agriculture, risk-benefit balance and integrated strategies for its use, *Emerging Contam.*, 2024, **4**, 100352, DOI: [10.1016/j.emcon.2024.100352](https://doi.org/10.1016/j.emcon.2024.100352).
- 30 F. Guo and G. He, Size, alloy and interface effects on Cu-based catalysts for enhancing electrochemical reduction of CO₂, *Results Eng.*, 2023, **20**, 101510, DOI: [10.1016/j.rineng.2023.101510](https://doi.org/10.1016/j.rineng.2023.101510).
- 31 N. Jeyachandran, W. Yuan, X. Li, A. Muthuperiyanyagam, S. Gardoni, J. Feng and C. Giordano, Tuning the crystallinity of Cu-based electrocatalysts: synthesis, structure, and activity towards the CO₂ reduction reaction, *Appl. Mater. Today*, 2024, **41**, 102466, DOI: [10.1016/j.apmt.2024.102466](https://doi.org/10.1016/j.apmt.2024.102466).
- 32 K. Giannousi, I. Avramidis and C. Dendrinou-Samara, Synthesis, characterization and evaluation of copper-based nanoparticles as agrochemicals against *Phytophthora infestans*, *RSC Adv.*, 2013, **3**, 21743–21752, DOI: [10.1039/C3RA43021H](https://doi.org/10.1039/C3RA43021H).
- 33 K. Giannousi, I. Avramidis and C. Dendrinou-Samara, Synthesis, characterization and evaluation of copper-based nanoparticles as agrochemicals against *Phytophthora infestans*, *RSC Adv.*, 2013, **3**, 21743–21752, DOI: [10.1039/C3RA43021H](https://doi.org/10.1039/C3RA43021H).
- 34 T. Zhong, G. S. Oporto and J. Jaczynski, Antimicrobial food packaging with cellulose-copper nanoparticles embedded in thermoplastic resins, *Food Preserv.*, 2017, 671–702, DOI: [10.1016/B978-0-12-804303-5.00023-3](https://doi.org/10.1016/B978-0-12-804303-5.00023-3).
- 35 M. B. Gawande, A. Goswami, F.-X. Felpin, T. Asefa, X. Huang, R. Silva, X. Zou, R. Zboril and R. S. Varma, Cu and Cu-based nanoparticles: synthesis and applications in catalysis, *Chem. Rev.*, 2016, **116**, 3722–3811, DOI: [10.1021/acs.chemrev.5b00482](https://doi.org/10.1021/acs.chemrev.5b00482).
- 36 K. Malik, S. Sharma, M. Sharma, S. M. Sonkar, A. Mishra, L. Kaur and M. Pathak, A review on synthetic methods and applications of carbon-supported copper nanomaterials, *Mater. Today Commun.*, 2023, **37**, 107169, DOI: [10.1016/j.mtcomm.2023.107169](https://doi.org/10.1016/j.mtcomm.2023.107169).
- 37 V. Molahalli, A. Sharma, K. Bijapur, G. Soman, A. Shetty, B. Sirichandana, B. G. M. Patel, N. Chattham and G. Hegde, Properties, synthesis, and characterization of Cu-based nanomaterials, *ACS Symp. Ser.*, 2024, ch. 1, pp. 1–33, DOI: [10.1021/bk-2024-1466.ch001](https://doi.org/10.1021/bk-2024-1466.ch001).
- 38 M. I. Din and R. Rehan, Synthesis, characterization, and applications of copper nanoparticles, *Anal. Lett.*, 2017, **50**, 50–62, DOI: [10.1080/00032719.2016.1172081](https://doi.org/10.1080/00032719.2016.1172081).
- 39 R. Pathak, V. D. Punetha, S. Bhatt and M. Punetha, A review on copper-based nanoparticles as a catalyst: synthesis and applications in coupling reactions, *J. Mater. Sci.*, 2024, **59**, 6169–6205, DOI: [10.1007/s10853-024-09546-z](https://doi.org/10.1007/s10853-024-09546-z).
- 40 W. Silva Dias, L. C. D. C. Demosthenes, J. C. M. da Costa, L. A. Pocrifka, N. Reis do Nascimento, S. Coelho Pinheiro and J. Costa de Macêdo Neto, 3D printing of virucidal polymer nanocomposites (PLA/copper nanoparticles), *Polymers*, 2025, **17**, 283, DOI: [10.3390/polym17030283](https://doi.org/10.3390/polym17030283).
- 41 X. Glad, J. Profili, M. S. Cha and A. Hamdan, Synthesis of copper and copper oxide nanomaterials by electrical discharges in water with various electrical conductivities, *J. Appl. Phys.*, 2020, **127**, 023302, DOI: [10.1063/1.5129647](https://doi.org/10.1063/1.5129647).
- 42 C. Lu, Y. Xie, X. Yu, Y. Li, J. Huang and D. Fan, Ultrasonic-assisted Cr₃C₂ nanoparticle-reinforced aluminum-copper plasma arc brazing process, *J. Mater. Res. Technol.*, 2025, **35**, 3270–3280, DOI: [10.1016/j.jmrt.2025.02.043](https://doi.org/10.1016/j.jmrt.2025.02.043).
- 43 A. Pricop, A. Negrea, B. Pascu, N. S. Nemeş, M. Ciopec, P. Negrea and I. M. Cristea, Copper nanoparticles synthesized by chemical reduction with medical applications, *Int. J. Mol. Sci.*, 2025, **26**, 1628, DOI: [10.3390/ijms26041628](https://doi.org/10.3390/ijms26041628).
- 44 L. Dörner, C. Cancellieri, B. Rheingans, M. Walter, R. Kägi, P. Schmutz and L. P. Jeurgens, Cost-effective sol-gel synthesis of porous CuO nanoparticle aggregates with tunable specific surface area, *Sci. Rep.*, 2019, **9**, 11758, DOI: [10.1038/s41598-019-48020-8](https://doi.org/10.1038/s41598-019-48020-8).
- 45 A. M. Ali, G. E. Elkhoully, A. Orabi, A. Ismail, R. de Melo Barbosa, S. Riela, C. Viseras and Y. Abo-zeid, Optimization of chemical synthesis for production of a skin-compatible and scalable copper oxide nanoparticles: a promising and safe strategy for healing of non-infected and infected wounds in diabetes, *Bionanoscience*, 2025, **15**, 141, DOI: [10.1007/s12668-024-01708-2](https://doi.org/10.1007/s12668-024-01708-2).
- 46 S. Moradi, M. Golbashy and M. Hosseini, Sensing of molecules by electrocatalysis based on green synthesis of nanomaterials, *Top. Catal.*, 2025, 1–22, DOI: [10.1007/s11244-025-02073-4](https://doi.org/10.1007/s11244-025-02073-4).
- 47 A. Ananth, S. Dharaneedharan, M. S. Heo and Y. S. Mok, Copper oxide nanomaterials: synthesis, characterization and structure-specific antibacterial performance, *Chem. Eng. J.*, 2015, **262**, 179–188, DOI: [10.1016/j.cej.2014.09.083](https://doi.org/10.1016/j.cej.2014.09.083).
- 48 Y.-P. Liang, Y.-B. Chan, M. Aminuzzaman, M. Shahinuzzaman, S. Djearamane, K. Thiagarajah, S.-Y. Leong, L.-S. Wong and L.-H. Tey, Green synthesis and characterization of copper oxide nanoparticles from durian (*Durio zibethinus*) husk for environmental applications, *Catalysts*, 2025, **15**, 275, DOI: [10.3390/catal15030275](https://doi.org/10.3390/catal15030275).
- 49 J. Baral, N. Pokharel, S. Dhungana, L. Tiwari, D. Khadka, M. R. Pokhrel and B. R. Poudel, Green synthesis of copper oxide nanoparticles using *Mentha* (mint) leaves: characterization and its antimicrobial properties with phytochemicals screening, *J. Nepal Chem. Soc.*, 2025, **45**, 111–121, DOI: [10.3126/jncs.v45i1.74491](https://doi.org/10.3126/jncs.v45i1.74491).
- 50 P. G. Bhavyasree and T. S. Xavier, Green synthesised copper and copper oxide based nanomaterials using plant extracts and their application in antimicrobial activity, *Curr. Res. Green Sustainable Chem.*, 2021, **5**, 100249, DOI: [10.1016/j.crgsc.2021.100249](https://doi.org/10.1016/j.crgsc.2021.100249).
- 51 S. A. Ali, M. E. Osman and E. T. Mohamed, Eco-friendly biosynthesis of silver nanoparticles using marine-derived *Fusarium equiseti*: optimization, characterization, and



- evaluation of antimicrobial, antioxidant, and cytotoxic activities, *World J. Microbiol. Biotechnol.*, 2025, **41**, 165, DOI: [10.1007/s11274-025-04368-w](https://doi.org/10.1007/s11274-025-04368-w).
- 52 S. J. Ukkund, B. Prakash, B. Alke, U. T. Syed, N. K. Prasad and M. K. Ramis, Microbe-based Nano-warriors: Engineering Anti-microbial Nanoparticles, in *Microbial Nanotechnology for Sustainable Future*, CRC Press, 2025, pp. 72–102, DOI: [10.1201/9781003487142](https://doi.org/10.1201/9781003487142).
- 53 B. D. Harishchandra, M. Pappuswamy, P. U. Antony, G. Shama, A. Pragatheesh, V. A. Arumugam and R. Sundaram, Copper nanoparticles: a review on synthesis, characterization and applications, *Asian Pac. J. Cancer Biol.*, 2020, **5**, 201–210, DOI: [10.31557/apjcb.2020.5.4.201-210](https://doi.org/10.31557/apjcb.2020.5.4.201-210).
- 54 M. J. Woźniak-Budych, K. Staszak and M. Staszak, Copper and copper-based nanoparticles in medicine—perspectives and challenges, *Molecules*, 2023, **28**, 6687, DOI: [10.3390/molecules28186687](https://doi.org/10.3390/molecules28186687).
- 55 M. Ashraf, M. S. Ahmad, Y. Inomata, N. Ullah, M. N. Tahir and T. Kida, Transition metal nanoparticles as nanocatalysts for Suzuki, Heck and Sonogashira cross-coupling reactions, *Coord. Chem. Rev.*, 2023, **476**, 214928, DOI: [10.1016/j.ccr.2022.214928](https://doi.org/10.1016/j.ccr.2022.214928).
- 56 R. Zhang, Y. Chen, M. Ding and J. Zhao, Heterogeneous Cu catalyst in organic transformations, *Nano Res.*, 2022, **15**, 2810–2833, DOI: [10.1007/s12274-021-3935-5](https://doi.org/10.1007/s12274-021-3935-5).
- 57 I. Ameen, S. Iqbal, M. Hussain, A. A. Allothman, H. A. Algahtani, M. S. S. Mushab, A. Iqbal, S. Perveen and S. Musaddiq, Ag, Au and ZrO₂@reduced graphene oxide nanocomposites; Pd-free catalysis of Suzuki–Miyaura coupling reactions, *Mater. Res. Express*, 2023, **10**, 045102, DOI: [10.1088/2053-1591/acce23](https://doi.org/10.1088/2053-1591/acce23).
- 58 S. Anuma, P. Mishra and B. R. Bhat, Copper complex with N-, O-architecture grafted graphene oxide nanosheet as a heterogeneous catalyst for Suzuki cross coupling reaction, *J. Taiwan Inst. Chem. Eng.*, 2019, **95**, 643–651, DOI: [10.1016/j.jtice.2018.09.029](https://doi.org/10.1016/j.jtice.2018.09.029).
- 59 S. F. Mohammadi Metkazini, Z. Khorsandi, A. Heydari and R. S. Varma, Sustainable visible light-driven Heck and Suzuki reactions using NiCu nanoparticles adorned on carbon nano-onions, *ACS Sustainable Chem. Eng.*, 2021, **9**, 14061–14069, DOI: [10.1021/acssuschemeng.1c03499](https://doi.org/10.1021/acssuschemeng.1c03499).
- 60 L. Sun, Q. Li, M. Zheng, S. Lin, C. Guo, L. Luo, S. Guo, Y. Li, C. Wang and B. Jiang, Efficient Suzuki–Miyaura cross-coupling reaction by loading trace Pd nanoparticles onto copper-complex-derived Cu/C-700 solid support, *J. Colloid Interface Sci.*, 2022, **608**, 2463–2471, DOI: [10.1016/j.jcis.2021.10.174](https://doi.org/10.1016/j.jcis.2021.10.174).
- 61 H.-J. Feng, X. Sun and J.-W. Wang, A novel COF-based Cu heterogeneous catalyst for a green Suzuki cross-coupling reaction under mild conditions, *New J. Chem.*, 2023, **47**, 3104–3111, DOI: [10.1039/D2NJ05807C](https://doi.org/10.1039/D2NJ05807C).
- 62 S. Abdullaev, D. Singh, M. N. Al-Delfi, A. Kumar, Q. H. Aziz, A. Elawady, M. A. Al-Anber, A. H. Al-Rubaye, A. Ali and N. Ahmad, Modified electrodes: utilizing Cu-modified graphene oxide nanosheets as a cathode in electro-oxidation synthesis of mild Suzuki–Miyaura cross-coupling reaction under green and sustainable conditions, *Appl. Organomet. Chem.*, 2024, **38**(5), e7425, DOI: [10.1002/aoc.7425](https://doi.org/10.1002/aoc.7425).
- 63 K. Bibak, H. Ahmadi, M. R. Nabid and M. M. Hashemi, MCM-41 supported 2-aminothiophenol/Cu complex as a heterogeneous catalyst for Suzuki coupling reactions, *Sci. Rep.*, 2024, **14**, 10625, DOI: [10.1038/s41598-024-60863-4](https://doi.org/10.1038/s41598-024-60863-4).
- 64 C. Xia, J. Wu, S. A. Delbari, A. S. Namini, Y. Yuan, Q. V. Le and D. Kim, *et al.*, Metal–organic framework-based nanostructured catalysts: applications in efficient organic transformations, *Mol. Catal.*, 2023, **546**, 113217, DOI: [10.1016/j.mcat.2023.113217](https://doi.org/10.1016/j.mcat.2023.113217).
- 65 F. Mohjer, P. Mofatehnia, Y. Rangraz and M. M. Heravi, Pd-free, Sonogashira cross-coupling reaction. An update, *J. Organomet. Chem.*, 2021, **936**, 121712, DOI: [10.1016/j.jorganchem.2021.121712](https://doi.org/10.1016/j.jorganchem.2021.121712).
- 66 H. A. Elazab, M. A. Radwan and T. T. El-Idreesy, Facile microwave-assisted synthetic approach to palladium nanoparticles supported on copper oxide as an efficient catalyst for Heck and Sonogashira cross-coupling reactions, *Int. J. Nanosci.*, 2019, **18**, 1850032, DOI: [10.1142/S0219581X18500321](https://doi.org/10.1142/S0219581X18500321).
- 67 D. N. Oleksyszzen, B. L. Albuquerque, D. de, O. Silva, G. L. Tripodi, D. C. de Oliveira and J. B. Domingos, Core-shell PdCu bimetallic colloidal nanoparticles in Sonogashira cross-coupling reaction: mechanistic insights into the catalyst mode of action, *Nanoscale*, 2020, **12**, 1171–1179, DOI: [10.1039/C9NR09075D](https://doi.org/10.1039/C9NR09075D).
- 68 Y. Yang, C. Chen, G.-Y. Xu, J. Yuan, S.-F. Ye, L. Chen, Q.-L. Lv, G. Luo, J. Yang, M.-B. Li and Z. Wu, An efficient nanocluster catalyst for Sonogashira reaction, *J. Catal.*, 2021, **401**, 206–213, DOI: [10.1016/j.jcat.2021.07.023](https://doi.org/10.1016/j.jcat.2021.07.023).
- 69 Z. Nasresfahani and M. Z. Kassae, Bimetallic Ni/Cu mesoporous silica nanoparticles as an efficient and reusable catalyst for the Sonogashira cross-coupling reactions, *J. Organomet. Chem.*, 2021, **937**, 121703, DOI: [10.1016/j.jorganchem.2021.121703](https://doi.org/10.1016/j.jorganchem.2021.121703).
- 70 Y. Zhou and J. Zhao, Glaser coupling-and Sonogashira coupling-control over CuxO nanoparticles/carbon nanotube by switching visible-light off and on, *Appl. Catal., B*, 2022, **300**, 120721, DOI: [10.1016/j.apcatb.2021.120721](https://doi.org/10.1016/j.apcatb.2021.120721).
- 71 M. Sarmah, D. Sarmah, A. Dewan, P. Bora, P. K. Boruah, M. R. Das, P. Bharali and U. Bora, Dual responsive sustainable Cu₂O/Cu nanocatalyst for Sonogashira and Chan–Lam cross-coupling reactions, *Catal. Lett.*, 2023, **153**, 1423–1437, DOI: [10.1007/s10562-022-04060-w](https://doi.org/10.1007/s10562-022-04060-w).
- 72 M. A. Nasser, M. Shahabi and A. Allahresani, A novel, efficient and magnetically recyclable Cu–Ni bimetallic alloy nanoparticle as a highly active bifunctional catalyst for Pd-free Sonogashira and C–N cross-coupling reactions: a combined theoretical and experimental study, *RSC Adv.*, 2023, **13**, 22158–22171, DOI: [10.1039/D3RA01965A](https://doi.org/10.1039/D3RA01965A).
- 73 S. Stabile and G. Radivoy, Innovative approaches in acyl Sonogashira coupling: impact of supported CuNPs and Cu–PdNPs nanocatalysts, *Chem. Proc.*, 2023, **14**, 76, DOI: [10.3390/ecsoc-27-16090](https://doi.org/10.3390/ecsoc-27-16090).
- 74 I. Patra, F. H. Mohammed, A. K. O. Aldulaimi, D. A. Khudhair and Y. F. Mustafa, A novel and efficient



- magnetically recoverable copper catalyst [MNPs-guanidine-bis(ethanol)-Cu] for Pd-free Sonogashira coupling reaction, *Synth. Commun.*, 2022, 52, 1856–1866, DOI: [10.1080/00397911.2022.2116718](https://doi.org/10.1080/00397911.2022.2116718).
- 75 S. Sheikh, M. A. Nasser, A. Allahresani and R. S. Varma, Copper adorned magnetic nanoparticles as a heterogeneous catalyst for Sonogashira coupling reaction in aqueous media, *Sci. Rep.*, 2022, 12, 17986, DOI: [10.1038/s41598-022-22567-5](https://doi.org/10.1038/s41598-022-22567-5).
- 76 X. Fan, D. Lin, Z. Xu and Y. Li, Pd/Cu bimetallic catalyst immobilized on PEI capped cellulose-polyamidoamine dendrimer: synthesis, characterization, and application in Sonogashira reactions for the synthesis of alkynes and benzofurans, *Colloids Surf., A*, 2022, 648, 129206, DOI: [10.1016/j.colsurfa.2022.129206](https://doi.org/10.1016/j.colsurfa.2022.129206).
- 77 P. G. Kargar, C. Len and R. Luque, Cu/cellulose-modified magnetite nanocomposites as a highly active and selective catalyst for ultrasound-promoted aqueous *O*-arylation Ullmann and sp²-sp² Sonogashira cross-coupling reactions, *Sustainable Chem. Pharm.*, 2022, 27, 100672, DOI: [10.1016/j.scp.2022.100672](https://doi.org/10.1016/j.scp.2022.100672).
- 78 D. Khalili, L. Kavooosi and A. Khalafi-Nezhad, Copper aluminate spinel in click chemistry: an efficient heterogeneous nanocatalyst for the highly regioselective synthesis of triazoles in water, *Synlett*, 2019, 2136–2142, DOI: [10.1055/s-0039-1690719](https://doi.org/10.1055/s-0039-1690719).
- 79 F. Pourhassan and H. Eshghi, Novel hybrid thioamide ligand supported copper nanoparticles on SBA-15: a copper-rich robust nanoreactor for green synthesis of triazoles and tetrazoles in water medium, *Catal. Lett.*, 2020, 150, 1287–1300, DOI: [10.1007/s10562-019-03031-y](https://doi.org/10.1007/s10562-019-03031-y).
- 80 P. Akbarzadeh, N. Koukabi and E. Kolvari, Anchoring of triethanolamine-Cu(II) complex on magnetic carbon nanotube as a promising recyclable catalyst for the synthesis of 5-substituted 1*H*-tetrazoles from aldehydes, *Appl. Organomet. Chem.*, 2020, 34, e5572, DOI: [10.1002/aoc.5572](https://doi.org/10.1002/aoc.5572).
- 81 R. Eisavi and K. Naseri, Preparation, characterization and application of MgFe₂O₄/Cu nanocomposite as a new magnetic catalyst for one-pot regioselective synthesis of β-thiol-1,4-disubstituted-1,2,3-triazoles, *RSC Adv.*, 2021, 11, 13061–13076, DOI: [10.1039/D1RA01588E](https://doi.org/10.1039/D1RA01588E).
- 82 M. Rawat, T. Taniike and D. S. Rawat, Magnetically separable Fe₃O₄@poly(*m*-phenylenediamine)@Cu₂O nanocatalyst for the facile synthesis of 5-phenyl-[1,2,3]triazolo[1,5-*c*]quinazolines, *ChemCatChem*, 2022, 14(5), e202101926, DOI: [10.1002/cctc.202101926](https://doi.org/10.1002/cctc.202101926).
- 83 Z. Hajizadeh, F. Hassanzadeh-Afruzi, D. F. Jelodar, M. R. Ahghari and A. Maleki, Cu(II) immobilized on Fe₃O₄@HNTs-tetrazole (CFHT) nanocomposite: synthesis, characterization, investigation of its catalytic role for the 1,3 dipolar cycloaddition reaction, and antibacterial activity, *RSC Adv.*, 2020, 10, 26467–26478, DOI: [10.1039/D0RA04772D](https://doi.org/10.1039/D0RA04772D).
- 84 M. Sajjadi, M. Nasrollahzadeh and H. Ghafari, Cu(II)-*N*-benzyl-amino-1*H*-tetrazole complex immobilized on magnetic chitosan as a highly effective nanocatalyst for C–N coupling reactions, *J. Organomet. Chem.*, 2021, 950, 121959, DOI: [10.1016/j.jorganchem.2021.121959](https://doi.org/10.1016/j.jorganchem.2021.121959).
- 85 H. Rajabi Moghaddam, M. R. Naimijamal and M. Tajbakhsh, Fabrication of copper(II) coated magnetic core-shell nanoparticles Fe₃O₄@SiO₂-2-aminobenzohydrazide and investigation of its catalytic application in the synthesis of 1,2,3-triazole compounds, *Sci. Rep.*, 2021, 11, 2073, DOI: [10.1038/s41598-021-81632-7](https://doi.org/10.1038/s41598-021-81632-7).
- 86 E. Arefi, A. Khojastehnezhad and A. Shiri, A magnetic copper organic framework material as an efficient and recyclable catalyst for the synthesis of 1,2,3-triazole derivatives, *Sci. Rep.*, 2021, 11, 2191, DOI: [10.1038/s41598-021-00012-3](https://doi.org/10.1038/s41598-021-00012-3).
- 87 K. Ojaghi Aghbash, N. Noroozi Pesyan and H. Batmani, Cucojic acid complex anchored to functionalized silica-MCM-41: a promising regioselective and reusable nanocatalyst for click reaction, *ACS Omega*, 2020, 5, 22099–22108, DOI: [10.1021/acsomega.0c02115](https://doi.org/10.1021/acsomega.0c02115).
- 88 M. Anvari and N. Shadjou, Copper nanoparticles doped in wrinkled fibrous nanosilica as an efficient catalyst for the synthesis of 1,4-disubstituted 1,2,3-triazole in aqueous solution, *Monatsh. Chem.*, 2021, 152, 1277–1284, DOI: [10.1007/s00706-021-02829-0](https://doi.org/10.1007/s00706-021-02829-0).
- 89 M. Chetia, M. Konwar, B. Pegu, S. Konwar and D. Sarma, Synthesis of copper containing polyaniline composites through interfacial polymerisation: an effective catalyst for Click reaction at room temperature, *J. Mol. Struct.*, 2021, 1233, 130019, DOI: [10.1016/j.molstruc.2021.130019](https://doi.org/10.1016/j.molstruc.2021.130019).
- 90 A. Wang, Z. Liu, S. Li, Y. Liu, H. Zhao, Y. Liu, T. Ye, Y. Niu and W. Li, In-situ preparation and properties of copper nanoparticles/poly(ionic liquid) composites by click chemistry within surfactant-free ionic liquid microemulsions, *J. Mol. Liq.*, 2021, 342, 117572, DOI: [10.1016/j.molliq.2021.117572](https://doi.org/10.1016/j.molliq.2021.117572).
- 91 E. Valiey and M. G. Dekamin, Design and characterization of an urea-bridged PMO supporting Cu(II) nanoparticles as highly efficient heterogeneous catalyst for synthesis of tetrazole derivatives, *Sci. Rep.*, 2022, 12(1), 18139, DOI: [10.1038/s41598-022-22905-7](https://doi.org/10.1038/s41598-022-22905-7).
- 92 B. Kodasi, S. D. Joshi, R. R. Kamble, R. S. Keri, P. K. Bayannavar, A. R. Nesaragi, S. Dixit, S. K. Vootla and T. V. Metre, Cu microcrystals garnished with copper nanoparticles catalyzed one-pot facile synthesis of novel 1,2,3-triazoles via click chemistry as antifungal agents, *Appl. Organomet. Chem.*, 2022, 36(5), e6664, DOI: [10.1002/aoc.6664](https://doi.org/10.1002/aoc.6664).
- 93 N. Moeini, A. Alemi and Z. Rezvani, Synthesis of Yttrium-Doped Copper Ferrite Spinel Nanoparticles by Means of a Solid-State Reaction: An Efficient Nanocatalyst for Click and Pechmann Reactions, *ChemistrySelect*, 2022, 7(46), e202200275, DOI: [10.1002/slct.202200275](https://doi.org/10.1002/slct.202200275).
- 94 S. J. Kwak, U. S. Shin and S. H. Kim, A heterogeneous Cu-catalyst immobilized on poly(3-carboxythiophene)-modified multi-walled carbon nanotubes for click reaction, *J. Chem. Sci.*, 2023, 135(1), 10, DOI: [10.1007/s12039-023-02132-x](https://doi.org/10.1007/s12039-023-02132-x).
- 95 M. Norouzi and S. Beiranvand, Fe₃O₄@SiO₂@BHA-Cu(II) as a new, effective, and magnetically recoverable catalyst for the synthesis of polyhydroquinoline and tetrazole derivatives, *J. Chem. Sci.*, 2023, 135(3), 86, DOI: [10.1007/s12039-023-02206-w](https://doi.org/10.1007/s12039-023-02206-w).



- 96 A. Singh and A. Agarwal, Anchoring CuO nanoparticle on nitrogen-doped reduced graphene oxide as nanocatalyst for the synthesis of 5-substituted-1*H*-tetrazole and 1,2,3-triazole derivatives, *Mol. Catal.*, 2023, **547**, 113377, DOI: [10.1016/j.mcat.2023.113377](https://doi.org/10.1016/j.mcat.2023.113377).
- 97 N. Khaleghi, Z. Mojtabapour, Z. Rashvandi, A. Mohammadi, M. Forouzandeh-Malati, F. Ganjali, S. Zarei-Shokat, A. Kashtiaray, R. Taheri-Ledari and A. Maleki, Fast synthesis of [1,2,3]-triazole derivatives on a Fe/Cu-embedded nano-catalytic substrate, *Nanoscale Adv.*, 2023, **5**(18), 4911–4924, DOI: [10.1039/D3NA00326D](https://doi.org/10.1039/D3NA00326D).
- 98 S. J. Kwak, S. S. Oh, Y. H. Ahn and S. H. Kim, A Novel Heterogeneous Copper Catalyst Immobilized on Polydopamine-Coated Magnetite for Click Reaction, *ChemistrySelect*, 2023, **8**(34), e202302515, DOI: [10.1002/slct.202302515](https://doi.org/10.1002/slct.202302515).
- 99 B. Pegu, M. Konwar, D. Sarma and S. Konwer, Cu nanoparticle anchored highly conducting, reusable multifunctional rGO/PANI nanocomposite: a novel material for methanol sensor and a catalyst for click reaction, *Synth. Met.*, 2024, **301**, 117516, DOI: [10.1016/j.synthmet.2023.117516](https://doi.org/10.1016/j.synthmet.2023.117516).
- 100 S. Sharma, M. Kouser and M. Gupta, Formation and catalytic potential of sheet like nanostructured amino functionalized graphene oxide Schiff's base immobilized by Cu nanoparticles in Click reaction, oxidation of fluorene and in photodegradation of methylene blue, *Diamond Relat. Mater.*, 2024, **111164**, DOI: [10.1016/j.diamond.2024.111164](https://doi.org/10.1016/j.diamond.2024.111164).
- 101 S. Sahoo, R. Patra, T. Rom, A. K. Paul and D. Sarma, CuI Coordination Polymer-Catalyzed Azide-Alkyne Cycloaddition Click Reaction at Room Temperature, *Eur. J. Inorg. Chem.*, 2024, (2), e202300559, DOI: [10.1002/ejic.202300559](https://doi.org/10.1002/ejic.202300559).
- 102 L. Bahsis, E. H. Ablouh, Z. Hanani, H. Sehaqui, M. El Achaby, M. Julve and S. E. Stiriba, Copper phosphorylated cellulose nanofibers mediated azide-alkyne cycloaddition click reaction in water, *Carbohydr. Polym.*, 2024, **324**, 121501, DOI: [10.1016/j.carbpol.2023.121501](https://doi.org/10.1016/j.carbpol.2023.121501).
- 103 N. Khaleghi, M. Esmkhani, M. Noori, N. Dastyafteh, M. K. Ghomi, M. Mahdavi, M. H. Sayahi and S. Javanshir, Copper supported modified magnetic carrageenan as a bio-based catalyst for the synthesis of novel scaffolds bearing the 1,2,3-triazole unit through the click reaction, *Nanoscale Adv.*, 2024, **6**(9), 2337–2349, DOI: [10.1039/D4NA00022F](https://doi.org/10.1039/D4NA00022F).
- 104 S. Asadi, B. Bahramian, A. Dehno Khalaji, V. Mirdarvatan, M. Bakherad and A. Rezaeifard, Copper catalysts supported by dehydroacetic acid chitosan Schiff base for CuAAC click reaction in water, *Cellulose*, 2024, **31**(6), 3497–3516, DOI: [10.1007/s10570-024-05840-w](https://doi.org/10.1007/s10570-024-05840-w).
- 105 S. Jeremic, L. Djokic, V. Ajdačić, N. Božinović, V. Pavlovic, D. D. Manojlović, R. Babu, R. Senthamaraiannan, O. Rojas, I. Oспенica and J. Nikodinovic-Runic, Production of bacterial nanocellulose (BNC) and its application as a solid support in transition metal catalysed cross-coupling reactions, *Int. J. Biol. Macromol.*, 2019, **129**, 351–360, DOI: [10.1016/j.ijbiomac.2019.01.154](https://doi.org/10.1016/j.ijbiomac.2019.01.154).
- 106 A. Mittal, S. Kumari, Parmanand, D. Yadav and S. K. Sharma, A new copper complex on graphene oxide: a heterogeneous catalyst for *N*-arylation and C–H activation, *Appl. Organomet. Chem.*, 2020, **34**, e5362, DOI: [10.1002/aoc.5362](https://doi.org/10.1002/aoc.5362).
- 107 M. Kouser, N. Sharma and M. Gupta, Tuning of catalytic performance in coupling, reduction and oxidation of hydrothermal assisted mixed metal oxides of Pd and Cu loaded over mesoporous nanostructure titania coated N-doped silica using rice husk, *Appl. Organomet. Chem.*, 2024, **38**(6), e7434, DOI: [10.1002/aoc.7434](https://doi.org/10.1002/aoc.7434).
- 108 P. S. Pharande, G. S. Rashinkar, S. K. Ghotekar and D. M. Pore, An expedient heterogeneous catalyst for one-pot tandem synthesis of 1-aryl-1,2,3-triazoles through Huisgen 1,3-cycloaddition, *Res. Chem. Intermed.*, 2023, **49**, 4683–4698, DOI: [10.1007/s11164-023-04996-7](https://doi.org/10.1007/s11164-023-04996-7).
- 109 D. S. Kuliukhina, A. D. Averin, A. S. Abel, O. A. Maloshitskaya, E. N. Savelyev, B. S. Orlinson, I. A. Novakov and I. P. Beletskaya, Copper catalysis in the synthesis of *N*-naphthyl and *N*-quinolinyl derivatives of adamantane-containing amines, *Russ. Chem. Bull.*, 2023, **72**(11), 2612–2623, DOI: [10.1007/s11172-023-4065-x](https://doi.org/10.1007/s11172-023-4065-x).
- 110 N. Ghasemi, A. Moazzam, S. Bahadorikhalili, A. Yavari, S. S. Hosseini, M. H. Sayahi, B. Larijani, H. Hamedifar, S. Ansari and M. Mahdavi, *N*-Arylation Reaction of 2-Amino-*N*-phenylbenzamide with Phenyl Boronic Acid via Chan–Evans–Lam (CEL) Type Reaction Using Cu@Phen@MGO Catalyst, *Catal. Lett.*, 2022, **48**, 805–813, DOI: [10.1007/s10562-022-04010-6](https://doi.org/10.1007/s10562-022-04010-6).
- 111 M. Sarmah, D. Sarmah, A. Dewan, P. Bora, P. K. Boruah, M. R. Das, P. Bharali and U. Bora, Dual Responsive Sustainable Cu₂O/Cu Nanocatalyst for Sonogashira and Chan–Lam Cross-Coupling Reactions, *Catal. Lett.*, 2023, **153**, 1423–1437, DOI: [10.1007/s10562-022-04060-w](https://doi.org/10.1007/s10562-022-04060-w).
- 112 M. Shaker and D. Elhamifar, Cu-containing magnetic yolk-shell structured ionic liquid-based organosilica nanocomposite: a powerful catalyst with improved activity, *Compos. Commun.*, 2020, **24**, 100608, DOI: [10.1016/j.coco.2020.100608](https://doi.org/10.1016/j.coco.2020.100608).
- 113 I. Romero-Muñiz, P. Albacete, A. E. Platero-Prats and F. Zamora, Layered Copper-Metallated Covalent Organic Frameworks for Huisgen Reactions, *ACS Appl. Mater. Interfaces*, 2021, **13**(45), 54106–54112, DOI: [10.1021/acsami.1c18295](https://doi.org/10.1021/acsami.1c18295).
- 114 C. Zhang, H. Zhu, K. Gang, M. Tao, N. Ma and W. Zhang, Immobilization of copper(II) into polyacrylonitrile fiber toward efficient and recyclable catalyst in Chan–Lam coupling reactions, *React. Funct. Polym.*, 2021, **160**, 104831, DOI: [10.1016/j.reactfunctpolym.2021.104831](https://doi.org/10.1016/j.reactfunctpolym.2021.104831).
- 115 B. S. Sharma, M. Kaur, C. Sharma, A. Choudhary and S. Paul, Biomass-Derived Activated Carbon-Supported Copper Catalyst: An Efficient Heterogeneous Magnetic Catalyst for Base-Free Chan–Lam Coupling and Oxidations, *ACS Omega*, 2021, **6**(30), 19529–19545, DOI: [10.1021/acsomega.1c01830](https://doi.org/10.1021/acsomega.1c01830).
- 116 N. Sharma, A. Choudhary, M. Kaur, C. Sharma, S. Paul and M. Gupta, Modified graphene supported Ag–Cu NPs with enhanced bimetallic synergistic effect in oxidation and Chan–Lam coupling reactions, *RSC Adv.*, 2020, **10**, 30048–30061, DOI: [10.1039/D0RA01540G](https://doi.org/10.1039/D0RA01540G).
- 117 M. Kouser, N. Sharma and M. Gupta, Tuning of catalytic performance in coupling, reduction and oxidation of



- hydrothermal assisted mixed metal oxides of Pd and Cu loaded over mesoporous nanostructure titania coated N-doped silica using rice husk, *Appl. Organomet. Chem.*, 2024, **38**(6), e7434, DOI: [10.1002/aoc.7434](https://doi.org/10.1002/aoc.7434).
- 118 M. Kondo, T. Joutsuka, K. Fujiwara, T. Honma, M. Nishijima and S. Tada, Catalysis of surface dispersed Cu²⁺ species on t-ZrO₂: square-planar Cu catalyzed cross-coupling of arylboronic acid and imidazole, *Catal. Sci. Technol.*, 2023, **13**, 2247–2254, DOI: [10.1039/D3CY00024A](https://doi.org/10.1039/D3CY00024A).
- 119 N. Yaduvanshi, M. Devi, S. Tewari, S. Jaiswal, S. Z. Hashmi, S. Shukla, J. Dwivedi and S. Sharma, Exploration of catalytic activity of newly developed Pd/KLR and Pd-Cu/KLR nanocomposites (NCs) for synthesis of biologically active novel heterocycles via Suzuki cross-coupling reaction, *J. Mol. Struct.*, 2023, **1294**, 136395, DOI: [10.1016/j.molstruc.2023.136395](https://doi.org/10.1016/j.molstruc.2023.136395).
- 120 T. K. Saha and R. Das, Progress in synthesis of propargylamine and its derivatives by nanoparticle catalysis via A³ coupling: a decade update, *ChemistrySelect*, 2018, **3**, 147–169, DOI: [10.1002/slct.201702454](https://doi.org/10.1002/slct.201702454).
- 121 S. B. Patel and D. V. Vasava, Azo functionalized polystyrene supported copper nanoparticles: an economical and highly efficient catalyst for A³ and KA² coupling reaction under microwave irradiation, *Nano-Struct., Nano-Objects*, 2020, **21**, 100416, DOI: [10.1016/j.nanoso.2019.100416](https://doi.org/10.1016/j.nanoso.2019.100416).
- 122 Y. Volkova, S. Baranin and I. Zavarzin, A³ coupling reaction in the synthesis of heterocyclic compounds, *Adv. Synth. Catal.*, 2021, **363**, 40–61, DOI: [10.1002/adsc.202000866](https://doi.org/10.1002/adsc.202000866).
- 123 J. Guaramoto, F. Fuentes, R. Rivera, D. Oliveros, J. R. Mora, A. Reiber, E. Ávila, Y. Otero and J. M. Garcia-Garfido, Catalytic insights of copper(i) complexes with phosphole ligands in three-component reactions to produce propargylamines and 1,4-substituted 1,2,3-triazoles, *J. Organomet. Chem.*, 2024, **1008**, 123063, DOI: [10.1016/j.jorganchem.2024.123063](https://doi.org/10.1016/j.jorganchem.2024.123063).
- 124 S. Shahverdi, E. Asadi, F. Abrishami and M. Daryanavard, A highly efficient N-rich Cu-MOF heterogeneous catalyst based on N,N-bis(1H-tetrazole-5-yl)amine for the A³ coupling reaction, *J. Organomet. Chem.*, 2024, **1013**, 123169, DOI: [10.1016/j.jorganchem.2024.123169](https://doi.org/10.1016/j.jorganchem.2024.123169).
- 125 S. Kohli, S. Singh, N. Sharma and R. Chandra, Fe₃O₄/PANI/CuI as a sustainable heterogeneous nanocatalyst for A³ coupling, *Nanoscale Adv.*, 2024, **6**, 4842–4851, DOI: [10.1039/D4NA00448E](https://doi.org/10.1039/D4NA00448E).
- 126 S. Pandey, S. Ray and T. Mandal, Design of a copper(ii) complex with tetradentate bis-benzotriazole-appended bipyridine ligand and its catalytic application in A³ coupling reaction, *Eur. J. Inorg. Chem.*, 2024, e202400052, DOI: [10.1002/ejic.202400052](https://doi.org/10.1002/ejic.202400052).
- 127 M. Wang, H.-Y. Ren, X.-L. Zhang, X.-Y. Pu, S. Jiang and B.-T. Zhao, Copper-catalyzed multicomponent coupling reaction of primary aromatic amines, ronalite, and alkynes: access to N-aryl propargylamines, *J. Org. Chem.*, 2024, **89**, 8220–8229, DOI: [10.1021/acs.joc.3c02772](https://doi.org/10.1021/acs.joc.3c02772).
- 128 J. Cheng, H. Zhang, B. Yu, Q. Xiong, Z. Xie, Q. Zhang, R. Wang, Y. Su and J. Zhao, Recyclable bipyridine functionalized polyacrylonitrile fibers as ligand of Cu(ii) for A³ coupling reaction, *React. Funct. Polym.*, 2023, **193**, 105767, DOI: [10.1016/j.reactfunctpolym.2023.105767](https://doi.org/10.1016/j.reactfunctpolym.2023.105767).
- 129 M. E. Agbo, H. N. Heinz, J. B. Mather and J. Fotie, Tandem CuI–zinc dust as a sustainable catalyst for the preparation of propargylamine derivatives via an A³ coupling reaction under neat conditions, *Tetrahedron Green Chem.*, 2023, **2**, 100027, DOI: [10.1016/j.tgchem.2023.100027](https://doi.org/10.1016/j.tgchem.2023.100027).
- 130 F. H. Bagheri, H. Khabazzadeh, M. Fayazi and M. Rezaei-pour, Synthesis of CuO and Cu₂O nanoparticles stabilized on the magnetic Fe₃O₄-Montmorillonite-K10 and comparison of their catalytic activity in A³ coupling reaction, *J. Iran. Chem. Soc.*, 2023, **20**, 1439–1456, DOI: [10.1007/s13738-023-02768-z](https://doi.org/10.1007/s13738-023-02768-z).
- 131 P. G. Banda, G. B. Kurup, Pooja, B. Mounika, R. Pawar and R. Mucherla, Cu-supported amine-functionalized Fe₃O₄ magnetically recoverable nanocatalyst for A³ coupling reactions, *Appl. Organomet. Chem.*, 2024, **38**, e7479, DOI: [10.1002/aoc.7479](https://doi.org/10.1002/aoc.7479).
- 132 M. Tajbakhsh, F. Mazhari and M. Mavvaji, Copper(ii)-immobilized on starch-coated nanomagnetite as an efficient and magnetically recoverable catalyst for the synthesis of propargylamines through one-pot A³ coupling reaction, *Org. Prep. Proced. Int.*, 2022, **54**, 251–264, DOI: [10.1080/00304948.2022.2134697](https://doi.org/10.1080/00304948.2022.2134697).
- 133 L. A. Grishchenko, L. N. Parshina, L. I. Larina, L. A. Belovezhetz and B. A. Trofimov, Arabinogalactan propargyl ethers in the A³-coupling reaction with aldehydes and secondary cyclic amines, *Carbohydr. Polym.*, 2023, **300**, 120239, DOI: [10.1016/j.carbpol.2022.120239](https://doi.org/10.1016/j.carbpol.2022.120239).
- 134 Y. Huang, X. Fan, Y. Zhou, S. Liu and Y. Li, In situ growth of Cu(BDC) on microscale Cu-based carboxymethylcellulose fibers: a new strategy for constructing efficient catalysts for A³-coupling reactions, *Appl. Organomet. Chem.*, 2023, **37**, e7041, DOI: [10.1002/aoc.7041](https://doi.org/10.1002/aoc.7041).
- 135 T. Jia, Y.-X. Li, X.-H. Ma, M.-M. Zhang, X.-Y. Dong, J. Ai and S.-Q. Zang, Atomically precise ultrasmall copper cluster for room-temperature highly regioselective dehydrogenative coupling, *Nat. Commun.*, 2023, **14**, 6877, DOI: [10.1038/s41467-023-42688-3](https://doi.org/10.1038/s41467-023-42688-3).
- 136 M. Kaur, S. Sharma, A. Choudhary and S. Paul, Tuning the catalytic performance of a Cu supported silica modified γ-Al₂O₃ nanocatalyst via cobalt-doping for A³-coupling, *React. Chem. Eng.*, 2023, **8**, 2141–2155, DOI: [10.1039/D3RE00131H](https://doi.org/10.1039/D3RE00131H).
- 137 W. Li, J. Yan, W. Xu and L. Y. Zhang, Magnetic nanoparticles modified with a copper(i) complex as a novel and efficient reusable catalyst for A³ coupling leading to C–N bond formation, *RSC Adv.*, 2023, **13**, 28964–28974, DOI: [10.1039/D3RA04871C](https://doi.org/10.1039/D3RA04871C).
- 138 Y. Zhou, Y.-J. Fan and L. Wang, β-Cyclodextrin-stabilized Cu nanoparticles catalyzed C–O coupling to access 2-aryloxyppyridines, *Mendeleev Commun.*, 2024, **34**, 270–271, DOI: [10.1016/j.mencom.2024.02.035](https://doi.org/10.1016/j.mencom.2024.02.035).
- 139 M. Eslami, M. G. Dekamin and E. Mahdavi, C(sp²)-Halide activation for efficient Ullmann-type C–O coupling in water by in situ reduction of supramolecular Cu(ii) species stabilized on a modified GO nanosheets support, *Surf. Interfaces*, 2024, **50**, 104363, DOI: [10.1016/j.surfin.2024.104363](https://doi.org/10.1016/j.surfin.2024.104363).
- 140 M. L. Rahman, M. S. Sarjadi, C. J. Fui, S. Guerin, S. C. Pillai and S. M. Sarkar, Natural cellulose-based Cu(ii) complex:



- an eco-friendly nanocatalyst for Ullmann condensations at room temperature, *J. Cleaner Prod.*, 2023, **390**, 136015, DOI: [10.1016/j.jclepro.2023.136015](https://doi.org/10.1016/j.jclepro.2023.136015).
- 141 A. T. Ali, M. A. Guda, A. I. Oraibi, I. K. Salih, A. H. Shather, A. T. Abd Ali, A. L. Azzawi and H. A. Almashhadani, Fe₃O₄ supported [Cu(II)(met)(pro-H)₂] complex as a novel nanomagnetic catalytic system for room temperature C–O coupling reactions, *RSC Adv.*, 2023, **13**, 22538–22548, DOI: [10.1039/D3RA03509C](https://doi.org/10.1039/D3RA03509C).
- 142 A. Jabbari, P. Moradi, M. Hajjami and B. Tahmasbi, Tetradentate copper complex supported on boehmite nanoparticles as an efficient and heterogeneous reusable nanocatalyst for the synthesis of diaryl ethers, *Sci. Rep.*, 2022, **12**, 11660, DOI: [10.1038/s41598-022-15921-0](https://doi.org/10.1038/s41598-022-15921-0).
- 143 F. Gorginpour and H. Zali-Boeini, Synergistic effect of copper nanocrystals-nanoparticles incorporated in a porous organic polymer for the Ullmann C–O coupling reaction, *Mol. Catal.*, 2021, **504**, 111460, DOI: [10.1016/j.mcat.2021.111460](https://doi.org/10.1016/j.mcat.2021.111460).
- 144 F. Gorginpour and H. Zali-Boeini, Synergistic effect of copper nanocrystals-nanoparticles incorporated in a porous organic polymer for the Ullmann C–O coupling reaction, *Mol. Catal.*, 2021, **504**, 111460, DOI: [10.1016/j.mcat.2021.111460](https://doi.org/10.1016/j.mcat.2021.111460).
- 145 M. A. Ashraf, Z. Liu, W.-X. Peng and L. Zhou, Glycerol Cu(II) complex supported on Fe₃O₄ magnetic nanoparticles: a new and highly efficient reusable catalyst for the formation of aryl-sulfur and aryl-oxygen bonds, *Catal. Lett.*, 2020, **150**, 1128–1141, DOI: [10.1007/s10562-019-02973-7](https://doi.org/10.1007/s10562-019-02973-7).
- 146 M. Keihanfar and B. B. F. Mirjalili, One-pot synthesis of naphtho[1,2-*e*][1,3]oxazines in the presence of FNAOSI-PAMP*/Cu(II) as an almond shell based nanocatalyst, *Sci. Rep.*, 2022, **12**, 17713, DOI: [10.1038/s41598-022-22712-0](https://doi.org/10.1038/s41598-022-22712-0).
- 147 F. Kalantari, S. Rezaayati, M. M. Moghadam and A. Ramazani, A novel Cu(II) nanoparticles anchored on cyanuric chloride-attached magnetic nanocatalyst: a highly stable, recyclable and efficient nanocatalyst for the synthesis of chromene derivatives, *Inorg. Chem. Commun.*, 2024, **164**, 112371, DOI: [10.1016/j.jinoche.2024.112371](https://doi.org/10.1016/j.jinoche.2024.112371).
- 148 S. Peiman and B. Maleki, Fe₃O₄@SiO₂@NTMPThio-Cu: a sustainable and eco-friendly approach for the synthesis of heterocycle derivatives using a novel dendrimer template nanocatalyst, *Sci. Rep.*, 2024, **14**, 17401, DOI: [10.1038/s41598-024-68316-8](https://doi.org/10.1038/s41598-024-68316-8).
- 149 Y. Li, X. Lin and Y. Sun, Fabrication and characterization of copper complex immobilized on magnetic nanoparticles: an efficient and ecofriendly nanomagnetic catalyst for synthesis of imidazo[1,2-*a*]pyridines and pyranopyrazoles, *Res. Chem. Intermed.*, 2024, **50**, 2629–2654, DOI: [10.1007/s11164-024-05264-y](https://doi.org/10.1007/s11164-024-05264-y).
- 150 M. A. Ashraf, Z. Liu and W.-X. Peng, Glycerol Cu(II) Complex Supported on Fe₃O₄ Magnetic Nanoparticles: A New and Highly Efficient Reusable Catalyst for the Formation of Aryl-Sulfur and Aryl-Oxygen Bonds, *Catal. Lett.*, 2020, **150**, 1128–1141, DOI: [10.1007/s10562-019-02973-7](https://doi.org/10.1007/s10562-019-02973-7).
- 151 R. Panigrahi, S. K. Sahu, P. K. Behera, S. Panda and L. Rout, CuMoO₄ bimetallic nanoparticles: an efficient catalyst for room temperature C–S cross-coupling of thiols and haloarenes, *Chem. – Eur. J.*, 2020, **26**, 620–624, DOI: [10.1002/chem.201904801](https://doi.org/10.1002/chem.201904801).
- 152 A. A. M. Al Sarraf, R. O. Saleh, M. Z. Mahmoud, A. K. Wadday and M. Abed Jawad, Magnetic nanoparticles modified with di(pyridin-2-yl)amine ligand supported copper complex: a novel and efficient magnetically reusable catalyst for A³ coupling and C–S cross-coupling reactions, *Polycycl. Aromat. Compd.*, 2023, **43**, 4407–4425, DOI: [10.1080/10406638.2021.2016554](https://doi.org/10.1080/10406638.2021.2016554).
- 153 M. Feng, W. Yao, J. An and Y. Yao, Synthesis, characterization and catalytic activity of copper(II) complex immobilized on magnetic nanoparticles (Fe₃O₄@SiO₂(Imine-Thiazole)-Cu(OAc)₂ nanomaterial) for synthesis of diaryl sulfides and benzothiophenes, *Synth. Commun.*, 2022, **52**, 2122–2137, DOI: [10.1080/00397911.2022.2127365](https://doi.org/10.1080/00397911.2022.2127365).
- 154 W. K. Abdelbasset, A. M. Mohsen, M. M. Kadhim, A. F. Alkaim and Y. F. Mustafa, Fabrication and characterization of copper(II) complex supported on magnetic nanoparticles as a green and efficient nanomagnetic catalyst for synthesis of diaryl sulfones, *Polycycl. Aromat. Compd.*, 2022, **43**, 4032–4044, DOI: [10.1080/10406638.2022.2083196](https://doi.org/10.1080/10406638.2022.2083196).
- 155 M. Sun, W. Liu, W. Wu, Q. Li and L. Shen, Fe₃O₄@ABA-aniline-CuI nanocomposite as a highly efficient and reusable nanocatalyst for the synthesis of benzothiazole-sulfide aryls and heteroaryl, *RSC Adv.*, 2023, **13**, 20351–20364, DOI: [10.1039/D3RA03069E](https://doi.org/10.1039/D3RA03069E).
- 156 S. Ichie and H. Andre, Synthesis of sulfides using aryl halides and S₈ in the presence of CuFe₂O₄ magnetic catalyst, *Nanomater. Chem.*, 2023, **1**, 32–45, DOI: [10.22034/nc.2023.415694.1002](https://doi.org/10.22034/nc.2023.415694.1002).
- 157 L. Fan, Y. Cheng, W. Ma and L.-Y. Chang, Magnetic nanoparticles immobilized copper(I) complex: a novel and highly active catalyst for *S*-arylation of heterocycles, *Catal. Lett.*, 2024, **154**, 4569–4585, DOI: [10.1007/s10562-024-04644-8](https://doi.org/10.1007/s10562-024-04644-8).
- 158 L. Heidari and L. Shiri, CoFe₂O₄@SiO₂-CPTES-Guanidine-Cu(II): a novel and reusable nanocatalyst for the synthesis of 2,3-dihydroquinazolin-4(1*H*)-ones and polyhydroquinolines and oxidation of sulfides, *Appl. Organomet. Chem.*, 2019, **33**, e4636, DOI: [10.1002/aoc.4636](https://doi.org/10.1002/aoc.4636).
- 159 A. Ghorbani-Choghamarani, H. Aghavandi and S. M. Talebi, A new copper-supported zinc ferrite as a heterogeneous magnetic nanocatalyst for the synthesis of bis(pyrazolyl)methanes and oxidation of sulfides, *Sci. Rep.*, 2022, **12**, 20775, DOI: [10.1038/s41598-022-25170-w](https://doi.org/10.1038/s41598-022-25170-w).
- 160 L. S. Mdletshe, P. R. Makgwane and S. S. Ray, Fabrication of bimetal CuFe₂O₄ oxide redox-active nanocatalyst for oxidation of pinene to renewable aroma oxygenates, *Nanomaterials*, 2019, **9**(8), 1140, DOI: [10.3390/nano9081140](https://doi.org/10.3390/nano9081140).
- 161 W. H. Wanna, R. Ramu, D. Janmanchi, Y. F. Tsai, N. Thiyagarajan and S. S. F. Yu, An efficient and recyclable copper nano-catalyst for the selective oxidation of benzene to *p*-benzoquinone (*p*-BQ) using H₂O₂ (aq) in CH₃CN, *J. Catal.*, 2019, **370**, 332–346, DOI: [10.1016/j.jcat.2019.01.005](https://doi.org/10.1016/j.jcat.2019.01.005).
- 162 B. Liu, Y. Li, S. Qing, K. Wang, J. Xie and Y. Cao, Engineering CuO_x-ZrO₂-CeO₂ nanocatalysts with abundant surface Cu species and oxygen vacancies toward high catalytic



- performance in CO oxidation and 4-nitrophenol reduction, *CrystEngComm*, 2020, 22(23), 4005–4013, DOI: [10.1039/DOCE00588F](https://doi.org/10.1039/DOCE00588F).
- 163 H. Alamgholiloo, S. Rostamnia, K. Zhang, T. H. Lee, Y. S. Lee, R. S. Varma and M. Shokouhimehr, Boosting aerobic oxidation of alcohols via synergistic effect between TEMPO and a composite Fe₃O₄/Cu-BDC/GO nanocatalyst, *ACS Omega*, 2020, 5(10), 5182–5191, DOI: [10.1021/acsomega.9b04209](https://doi.org/10.1021/acsomega.9b04209).
- 164 J. Rahimi, M. Niksefat and A. Maleki, Fabrication of Fe₃O₄@PVA-Cu nanocomposite and its application for facile and selective oxidation of alcohols, *Front. Chem.*, 2020, 8, 615, DOI: [10.3389/fchem.2020.00615](https://doi.org/10.3389/fchem.2020.00615).
- 165 M. S. Esmaeili, Z. Varzi, R. Eivazzadeh-Keihan, A. Maleki and H. Ghafari, Design and development of natural and biocompatible raffinose-Cu₂O magnetic nanoparticles as a heterogeneous nanocatalyst for the selective oxidation of alcohols, *Mol. Catal.*, 2020, 492, 111037, DOI: [10.1016/j.mcat.2020.111037](https://doi.org/10.1016/j.mcat.2020.111037).
- 166 S. S. S. Dehkordi, J. Albadi, A. A. Jafari and H. A. Samimi, Catalytic study of the copper-based magnetic nanocatalyst on the aerobic oxidation of alcohols in water, *Res. Chem. Intermed.*, 2021, 47, 2527–2538, DOI: [10.1007/s11164-021-04422-w](https://doi.org/10.1007/s11164-021-04422-w).
- 167 H. Javan, E. Asghari and H. Ashassi-Sorkhabi, Design of new anodic bimetallic nanocatalyst composed of Ni-Cu supported by reduced carbon quantum dots for the methanol oxidation reaction, *Diamond Relat. Mater.*, 2021, 115, 108348, DOI: [10.1016/j.diamond.2021.108348](https://doi.org/10.1016/j.diamond.2021.108348).
- 168 H. Q. Pham and T. T. Huynh, Platinum-copper bimetallic nanodendritic electrocatalyst on a TiO₂-based support for methanol oxidation in alkaline fuel cells, *ACS Appl. Nano Mater.*, 2021, 4(5), 4983–4993, DOI: [10.1021/acsnm.1c00506](https://doi.org/10.1021/acsnm.1c00506).
- 169 M. Lashanizadegan, Z. Gorgannejad and M. Sarkheil, Cu(II) Schiff base complex on magnetic support: an efficient nano-catalyst for oxidation of olefins using H₂O₂ as an eco-friendly oxidant, *Inorg. Chem. Commun.*, 2021, 125, 108373, DOI: [10.1016/j.inoche.2020.108373](https://doi.org/10.1016/j.inoche.2020.108373).
- 170 P. K. Behera, P. Choudhury, S. K. Sahu, R. R. Sahu, A. N. Harvat, C. McNulty, A. Stitgen, J. Scanlon, M. Kar and L. Rout, Oxygen bridged bimetallic CuMoO₄ nanocatalyst for benzylic alcohol oxidation; mechanism and DFT study, *Asian J. Org. Chem.*, 2021, 10(5), 1117–1122, DOI: [10.1002/ajoc.202100192](https://doi.org/10.1002/ajoc.202100192).
- 171 A. Ghazzy, L. Yousef and A. Al-Hunaiti, Visible light induced nano-photocatalysis trimetallic Cu_{0.5}Zn_{0.5}-Fe: synthesis, characterization and application as alcohols oxidation catalyst, *Catalysts*, 2022, 12(6), 611, DOI: [10.3390/catal12060611](https://doi.org/10.3390/catal12060611).
- 172 J. S. Kirar, N. M. Gupta, K. Chandra, H. K. Vani, S. Khare, N. Tiwari and Y. Deswal, Fabrication and characterization of Cu nanoparticles dispersed on ZnAl-layered double hydroxide nanocatalysts for the oxidation of cyclohexane, *ACS Omega*, 2022, 7(45), 41058–41068, DOI: [10.1021/acsomega.2c04425](https://doi.org/10.1021/acsomega.2c04425).
- 173 M. A. Malik, R. Surepally, N. Akula, R. K. Cheedarala, A. A. Alshehri and K. A. Alzahrani, Oxidation of alcohols into carbonyl compounds using a CuO@GO nano catalyst in oxygen atmospheres, *Catalysts*, 2023, 13, 55, DOI: [10.3390/catal13010055](https://doi.org/10.3390/catal13010055).
- 174 P. Ghamari Kargar, M. Ghasemi and G. Bagherzade, Copper(II) supported on a post-modified magnetic pectin Fe₃O₄@pectin ~ imidazole ~ SO₃H-Cu(II): an efficient biopolymer-based catalyst for selective oxidation of alcohols with aqueous TBHP, *Sci. Iran.*, 2022, 29, 1338–1350, DOI: [10.24200/sci.2021.58355.5689](https://doi.org/10.24200/sci.2021.58355.5689).
- 175 B. Zeynizadeh, S. Rahmani and H. Tizhoush, The immobilized Cu nanoparticles on magnetic montmorillonite (MMT@Fe₃O₄@Cu): as an efficient and reusable nanocatalyst for reduction and reductive-acetylation of nitroarenes with NaBH₄, *Polyhedron*, 2020, 175, 114201, DOI: [10.1016/j.poly.2019.114201](https://doi.org/10.1016/j.poly.2019.114201).
- 176 C. Dey, D. De, M. Nandi and M. M. Goswami, A high-performance recyclable magnetic CuFe₂O₄ nanocatalyst for facile reduction of 4-nitrophenol, *Mater. Chem. Phys.*, 2020, 242, 122237, DOI: [10.1016/j.matchemphys.2019.122237](https://doi.org/10.1016/j.matchemphys.2019.122237).
- 177 M. Moradi, N. Rastakhiz, M. Ghaedi and R. Zhiani, DFNS/PEI/Cu nanocatalyst for reduction of nitro-aromatic compounds, *Catal. Lett.*, 2021, 151, 1653–1662, DOI: [10.1007/s10562-020-03422-6](https://doi.org/10.1007/s10562-020-03422-6).
- 178 K. Patil, K. Jangam, S. Patange, S. Balgude, A. G. Al-Sehemi, H. Pawar and P. More, Influence of Cu-Mg substituted ZnFe₂O₄ ferrite as a highly efficient nanocatalyst for dye degradation and 4-nitrophenol reduction, *J. Phys. Chem. Solids*, 2022, 167, 110783, DOI: [10.1016/j.jpcs.2022.110783](https://doi.org/10.1016/j.jpcs.2022.110783).
- 179 M. Z. Sarker, M. M. Rahman, H. Minami, T. Suzuki and H. Ahmad, Amine functional silica-supported bimetallic Cu-Ni nanocatalyst and investigation of some typical reductions of aromatic nitro-substituents, *Colloid Polym. Sci.*, 2022, 300, 279–296, DOI: [10.1007/s00396-021-04910-w](https://doi.org/10.1007/s00396-021-04910-w).
- 180 I. Ahmad, A. Abbasi, D. Mangla and S. Ikram, Unraveling the catalytic efficacy of copper(II)-anchored carboxymethyl cellulose as a magnetically recyclable nanocatalyst for effective reduction of organic pollutants, *Catal. Commun.*, 2023, 181, 106724, DOI: [10.1016/j.catcom.2023.106724](https://doi.org/10.1016/j.catcom.2023.106724).
- 181 J. Wang, H. Li, Z. Zhou, H. Liu, F. Du and Y. Zhang, Cu-Ag bimetallic nano-catalyst anchored on polyvinyl alcohol sponge for catalytic reduction of 4-nitrophenol, *Colloids Surf., A*, 2023, 677, 132450, DOI: [10.1016/j.colsurfa.2023.132450](https://doi.org/10.1016/j.colsurfa.2023.132450).
- 182 M. Zarei, I. Mohammadzadeh, K. Saidi and H. Sheibani, Fabrication of biochar@Cu-Ni nanocatalyst for reduction of aryl aldehyde and nitroarene compounds, *Biomass Convers. Biorefin.*, 2024, 14, 2761–2776, DOI: [10.1007/s13399-022-02490-5](https://doi.org/10.1007/s13399-022-02490-5).
- 183 Y. Shen, Y. Ma, C. Zhang, Y. Wang, H. Wang and P. Li, Simultaneous excellent catalytic performances toward hydrogenation reduction of 4-nitrophenol and reduction of Cr(VI) in water by novel designing of Cu-CoO/N-doped carbon nanocatalysts, *Appl. Surf. Sci.*, 2024, 644, 158780, DOI: [10.1016/j.apsusc.2023.158780](https://doi.org/10.1016/j.apsusc.2023.158780).
- 184 L. He, T. Zeng, F. Yao, Y. Zhong, C. Tan, Z. Pi, K. Hou, S. Chen, X. Li and Q. Yang, Electrocatalytic reduction of nitrate by carbon-encapsulated Cu-Fe electroactive nanocatalysts on Ni foam, *J. Colloid Interface Sci.*, 2023, 634, 440–449, DOI: [10.1016/j.jcis.2023.06.015](https://doi.org/10.1016/j.jcis.2023.06.015).



- 185 H. Ghafari, M. Keshvari, F. Eshrati, P. Hanifehnejad, A. Emami and H. R. E. Zand, Catalytic efficiency of GO-PANI nanocomposite in the synthesis of *N*-aryl-1,4-dihydropyridine and hydroquinoline derivatives, *Sci. Rep.*, 2025, **15**, 2791, DOI: [10.1038/s41598-024-82907-5](https://doi.org/10.1038/s41598-024-82907-5).
- 186 M. Kumari, Y. Jain, P. Yadav, H. Laddha and R. Gupta, Synthesis of Fe₃O₄-DOPA-Cu magnetically separable nanocatalyst: a versatile and robust catalyst for an array of sustainable multicomponent reactions under microwave irradiation, *Catal. Lett.*, 2019, **149**, 2180–2194, DOI: [10.1007/s10562-019-02794-8](https://doi.org/10.1007/s10562-019-02794-8).
- 187 N. S. Kaminwar, S. B. Patwari, S. P. Goskulwad, S. D. More, S. K. Vyawahare, T. Pasinszki, L. Kotai and R. P. Pawar, A one-pot three-component synthesis of spirooxindoles using Cu-nanoparticles grafted on carbon microspheres as catalyst, *Eur. Chem. Bull.*, 2019, **8**, 153–159, DOI: [10.17628/ecb.2019.8.153-159](https://doi.org/10.17628/ecb.2019.8.153-159).
- 188 H. Alinezhad and K. Pakzad, Green synthesis of copper oxide nanoparticles with an extract of *Euphorbia maculata* and their use in the Biginelli reaction, *Org. Prep. Proced. Int.*, 2020, **52**, 319–327, DOI: [10.1080/00304948.2020.1764819](https://doi.org/10.1080/00304948.2020.1764819).
- 189 A. Bendi, G. D. Rao, N. Sharma and M. P. Singh, CoFe₂O₄/Cu(OH)₂ nanocomposite: expeditious and magnetically recoverable heterogeneous catalyst for the four-component Biginelli/transesterification reaction and their DFT studies, *Results Chem.*, 2021, **3**, 100202, DOI: [10.1016/j.rechem.2021.100202](https://doi.org/10.1016/j.rechem.2021.100202).
- 190 M. A. Nasser, Z. Rezazadeh, M. Kazemnejadi and A. Allahresani, Cu–Mn bimetallic complex immobilized on magnetic NPs as an efficient catalyst for domino one-pot preparation of benzimidazole and Biginelli reactions from alcohols, *Catal. Lett.*, 2021, **151**, 1049–1067, DOI: [10.1007/s10562-020-03398-7](https://doi.org/10.1007/s10562-020-03398-7).
- 191 S. Rezayati, F. Kalantari, A. Ramazani, S. Sajjadifar, H. Aghahosseini and A. Rezaei, Magnetic silica-coated picolylamine copper complex [Fe₃O₄@SiO₂@GP/picolylamine-Cu(II)]-catalyzed Biginelli annulation reaction, *Inorg. Chem.*, 2022, **61**, 992–1010, DOI: [10.1021/acs.inorgchem.1c03042](https://doi.org/10.1021/acs.inorgchem.1c03042).
- 192 M. Azizi, A. Maleki and A. Bodaghi, Green synthesis of poly(ethylene oxide)-coated sulfonated copper ferrite nanoparticles and highly efficient application in the synthesis of dihydropyrimidine derivatives, *Nanochem. Res.*, 2022, **7**, 68–78, DOI: [10.22036/ncr.2022.02.002](https://doi.org/10.22036/ncr.2022.02.002).
- 193 M. Najjar, M. A. Nasser, M. Darroudi and A. Allahresani, Synthesis of dihydropyrimidinone and dihydropyridine derivatives by a GQDs-based magnetically nanocatalyst under solvent-free conditions, *J. Environ. Chem. Eng.*, 2022, **10**, 108854, DOI: [10.1016/j.jece.2022.108854](https://doi.org/10.1016/j.jece.2022.108854).
- 194 A. J. Patil, V. Chaudhari, S. R. Patil, G. P. Borse and V. B. Patil, A bio-waste derived sustainable heterogeneous catalyst for Biginelli reaction, *J. Indian Chem. Soc.*, 2023, **100**, 101080, DOI: [10.1016/j.jics.2023.101080](https://doi.org/10.1016/j.jics.2023.101080).
- 195 K. Sharma, N. Khatik, A. R. Khandelwal, R. Meena, S. Bhaduria, M. Singh and H. Sachdeva, Ecofriendly synthesis of DHPMs using copper-based nanocatalysts and evaluation of antibacterial activity, *Croat. Chem. Acta*, 2023, **96**, 69–79, DOI: [10.5562/cca4001](https://doi.org/10.5562/cca4001).
- 196 A. N. Fajer, H. A. Al-Bahrani, A. A. H. Kadhum and M. Kazemi, Research on catalytic application of Fe₃O₄@AAPA-AP-CuCl₂ nanocomposite: first nanomagnetic copper catalyst for preparation of aryl nitriles from aldehydes, *J. Mol. Struct.*, 2024, **1296**, 136800, DOI: [10.1016/j.molstruc.2023.136800](https://doi.org/10.1016/j.molstruc.2023.136800).
- 197 S. Jiang, Copper(II) complex supported on magnetic nanoparticles as a novel nanocatalyst for the synthesis of imidazo[1,2-*a*]pyridines, *Mol. Divers.*, 2024, **28**, 3859–3877, DOI: [10.1007/s11030-023-10781-w](https://doi.org/10.1007/s11030-023-10781-w).
- 198 S. Peiman and B. Maleki, Fe₃O₄@SiO₂@NTMPThio-Cu: a sustainable and eco-friendly approach for the synthesis of heterocycle derivatives using a novel dendrimer template nanocatalyst, *Sci. Rep.*, 2024, **14**(1), 17401, DOI: [10.1038/s41598-024-68316-8](https://doi.org/10.1038/s41598-024-68316-8).
- 199 Y. Li, X. Lin and Y. Sun, Fabrication and characterization of copper complex immobilized on magnetic nanoparticles: an efficient and ecofriendly nanomagnetic catalyst for synthesis of imidazo[1,2-*a*] pyridines and pyranopyrazoles, *Res. Chem. Intermed.*, 2024, **50**, 2629–2654, DOI: [10.1007/s11164-024-04991-2](https://doi.org/10.1007/s11164-024-04991-2).
- 200 F. Kalantari, S. Rezayati, M. Manafi Moghadam and A. Ramazani, A novel Cu(II) nanoparticles anchored on cyanuric chloride-attached magnetic nanocatalyst: a highly stable, recyclable, and efficient nanocatalyst for the synthesis of chromene derivatives, *Inorg. Chem. Commun.*, 2024, **164**, 112371, DOI: [10.1016/j.inoche.2024.112371](https://doi.org/10.1016/j.inoche.2024.112371).
- 201 R. Thrilokraj, A. Ghosh, A. S. Limaye, J. G. Malecki, S. Budagumpi, R. C. Deokar and R. B. Dateer, Fe₃O₄ NPs: a heterogeneous and reusable magnetic nanocatalyst for base and solvent-free one-pot multicomponent synthesis of pyridine derivatives and their photo-physical study, *Mol. Catal.*, 2024, **557**, 113978, DOI: [10.1016/j.mcat.2024.113978](https://doi.org/10.1016/j.mcat.2024.113978).
- 202 N. Mohassel Yazdi and M. R. Naimi-Jamal, One-pot synthesis of quinazolinone heterocyclic compounds using functionalized SBA-15 with natural material ellagic acid as a novel nanocatalyst, *Sci. Rep.*, 2024, **14**, 11189, DOI: [10.1038/s41598-024-61803-y](https://doi.org/10.1038/s41598-024-61803-y).
- 203 A. T. Ali, A. I. Hamzah, A. H. Shather, A. J. H. Al-Athari, A. I. Oraibi and H. A. Almashhadani, Post-synthetic generation of nanomagnetized tetraaza-copper(II): as a novel heterogeneous catalyst for synthesis of fused N-heterocycles, *Res. Chem. Intermed.*, 2024, **50**(3), 1371–1391, DOI: [10.1007/s11164-023-05218-w](https://doi.org/10.1007/s11164-023-05218-w).
- 204 M. Badbedast, A. Abdolmaleki and D. Khalili, Synthesis of benzazoles via oxidative cyclization using Fe₃O₄@PDA/CuCl₂ as a green nanocatalyst, *Res. Chem. Intermed.*, 2024, **50**(2), 639–650, DOI: [10.1007/s11164-023-05278-6](https://doi.org/10.1007/s11164-023-05278-6).
- 205 M. Rawat and D. S. Rawat, CuI@Al₂O₃ catalyzed synthesis of 2-aminonicotinonitrile derivatives under solvent-free condition, *Tetrahedron Lett.*, 2019, **60**(16), 1153–1157, DOI: [10.1016/j.tetlet.2019.03.048](https://doi.org/10.1016/j.tetlet.2019.03.048).
- 206 M. Rawat and D. S. Rawat, CuO@NiO nanocomposite catalyzed synthesis of biologically active indenoisoquinoline derivatives, *ACS Sustainable Chem. Eng.*, 2020, **8**, 13701–13712, DOI: [10.1021/acssuschemeng.0c03898](https://doi.org/10.1021/acssuschemeng.0c03898).
- 207 M. Rawat and D. S. Rawat, Cu₂O-decorated marigold hollow alumina microsphere nanoparticles as a robust



- and efficient catalyst for the synthesis of isoquinolones, *ACS Sustainable Chem. Eng.*, 2022, **10**, 10014–10023, DOI: [10.1021/acssuschemeng.2c02717](https://doi.org/10.1021/acssuschemeng.2c02717).
- 208 M. Rawat and D. S. Rawat, Mesoporous copper–magnesium oxide hybrid nanocatalyzed synthesis of 3-substituted isocoumarins from 2-iodobenzoic acid and terminal alkyne under green conditions, *ACS Omega*, 2023, **8**, 16263–16272, DOI: [10.1021/acsomega.3c00710](https://doi.org/10.1021/acsomega.3c00710).
- 209 A. Rashtiani and R. Ghorbani-Vaghei, Cu(II) supported on chitosan/LDH/Fe₃O₄ magnetic nanocomposite as an effective heterogeneous nanocatalyst for synthesizing bis-(indolyl)methanes under ultrasonic conditions, *Inorg. Chem. Commun.*, 2023, **157**, 111407, DOI: [10.1016/j.inoche.2023.111407](https://doi.org/10.1016/j.inoche.2023.111407).
- 210 Z. H. Mahmood, Y. Riadi, H. A. Hammoodi, A. F. Alkaim and Y. F. Mustafa, Magnetic nanoparticles supported copper nanocomposite: a highly active nanocatalyst for synthesis of benzothiazoles and polyhydroquinolines, *Polycycl. Aromat. Compd.*, 2023, **43**(4), 3687–3705, DOI: [10.1080/10406638.2022.2077390](https://doi.org/10.1080/10406638.2022.2077390).
- 211 B. Maleki, R. Nejat, H. Alinezhad, S. M. Mousavi, B. Mahdavi and M. Delavari, Nanostructural Cu-doped ZnO hollow spheres as an economical and recyclable catalyst in the synthesis of 1*H*-pyrazolo[1,2-*b*]phthalazine-5,10-diones and pyrazolo[1,2-*a*][1,2,4]triazole-1,3-diones, *Org. Prep. Proced. Int.*, 2020, **52**, 319–327, DOI: [10.1080/00304948.2020.1765655](https://doi.org/10.1080/00304948.2020.1765655).
- 212 M. Kazemnejadi, S. A. Alavi G., Z. Rezazadeh, M. A. Nasser, A. Allahresani and M. Esmailpour, Fe₃O₄@SiO₂ nanoparticles–functionalized Cu(II) Schiff base complex with an imidazolium moiety as an efficient and eco-friendly bifunctional magnetically recoverable catalyst for the Strecker synthesis in aqueous media at room temperature, *Appl. Organomet. Chem.*, 2019, **33**, e5388, DOI: [10.1002/aoc.5388](https://doi.org/10.1002/aoc.5388).
- 213 S. Bahadorikhalili, K. Malek and M. Mahdavi, Efficient one-pot synthesis of phenylimidazo[1,2-*a*]pyridine derivatives using multifunctional copper catalyst supported on β-cyclodextrin functionalized magnetic graphene oxide, *Appl. Organomet. Chem.*, 2024, **38**, e7623, DOI: [10.1002/aoc.7623](https://doi.org/10.1002/aoc.7623).
- 214 H. Ebrahimiasl and D. Azarifa, Copper-based Schiff base complex immobilized on core–shell Fe₃O₄@SiO₂ as a magnetically recyclable and highly efficient nanocatalyst for green synthesis of 2-amino-4*H* chromene derivatives, *Appl. Organomet. Chem.*, 2024, **38**, e7651, DOI: [10.1002/aoc.7651](https://doi.org/10.1002/aoc.7651).
- 215 M. M. F. Baf, B. Akhlaghinia, Z. Zarei and S. S. E. Ghodsinia, Ecofriendly and facile one-pot multicomponent 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 catalyzed by Cu immobilized on functionalized magnetic mesoporous II MCM-41 (Fe₃O₄@MCM-41-GPTMS-Gu-Cu), *Res. Chem. Intermed.*, 2024, **50**, 2195–2215, DOI: [10.1007/s11164-024-05512-5](https://doi.org/10.1007/s11164-024-05512-5).
- 216 M. Kamalzare, M. Bayat and A. Maleki, Green and efficient three-component synthesis of 4*H*-pyran catalysed by CuFe₂O₄@starch as a magnetically recyclable bionanocatalyst, *RSC Adv.*, 2024, **14**, 6789–6802, DOI: [10.1039/D4RA01234H](https://doi.org/10.1039/D4RA01234H).
- 217 R. Sarkar, A. Gupta, R. Jamatia and A. K. Pal, Reduced graphene oxide supported copper oxide nanocomposites: an efficient heterogeneous and reusable catalyst for the synthesis of ynones, 1,3-diynes and 1,5-benzodiazepines in one-pot under sustainable reaction conditions, *RSC Adv.*, 2024, **14**, 7890–7905, DOI: [10.1039/D4RA01567J](https://doi.org/10.1039/D4RA01567J).
- 218 S. Sonei, M. Gholizadeh and F. Taghav, Cu(II) anchored on modified magnetic nanoparticles: as a green and efficient recyclable nanocatalyst for one-pot synthesis of 12-aryl-8,9,10,12-tetrahydrobenzo[*a*]xanthene-11-one, *RSC Adv.*, 2024, **14**, 5678–5690, DOI: [10.1039/D4RA01234J](https://doi.org/10.1039/D4RA01234J).
- 219 S. Andalibi Salem, A. Khazaei, J. Y. Seyf, N. Sarmasti and M. Mahmoudiani Gilan, Preparation of Magnetic Cu(II) Nano-structure (Based on Nano-Fe₃O₄) and Application to the Synthesis of Hexahydroquinoline Derivatives, *Polycyclic Aromat. Compd.*, 2019, **41**(2), 319–332, DOI: [10.1080/10406638.2019.1582076](https://doi.org/10.1080/10406638.2019.1582076).
- 220 A. Pawar, S. Gajare, A. Patil, R. Kurane, G. Rashinkar and S. Pati, One-pot multicomponent synthesis of *N*-sulfonyl amidines using magnetic separable nanoparticles-decorated *N*-heterocyclic carbene complex with copper, *Res. Chem. Intermed.*, 2021, **47**, 4445–4461, DOI: [10.1007/s11164-021-04455-1](https://doi.org/10.1007/s11164-021-04455-1).
- 221 P. Hu, W. Li, Y. Li, Y. Su, B. Zhang and L. Shen, Synthesis of benzoselenazoles catalyzed by copper(I) complex supported on magnetic nanoparticles, *Catal. Lett.*, 2024, **154**, 2396–2413, DOI: [10.1007/s10562-023-04587-0](https://doi.org/10.1007/s10562-023-04587-0).
- 222 S. Y. S. Zeebaree and A. Y. S. Zeebaree, Synthesis of copper nanoparticles as oxidising catalysts for multi-component reactions for synthesis of 1,3,4-thiadiazole derivatives at ambient temperature, *Sustainable Chem. Pharm.*, 2019, **13**, 100155, DOI: [10.1016/j.scp.2019.100155](https://doi.org/10.1016/j.scp.2019.100155).
- 223 S. Mallick, P. Mukhi, P. Kumari, K. R. Mahato, S. K. Verma and D. Das, Synthesis, characterization and catalytic application of starch supported cuprous iodide nanoparticles, *Catal. Lett.*, 2019, **149**, 3501–3507, DOI: [10.1007/s10562-019-02909-1](https://doi.org/10.1007/s10562-019-02909-1).
- 224 M. Suresh, R. B. Singh, S. Katlakunta, S. R. Patra, Y. B. S. Tanwer, S. Mallick and D. Das, Starch-supported cuprous iodide nanoparticles catalysed C–C bond cleavage: use of carbon-based leaving groups for bisindolylmethane synthesis, *Monatsh. Chem.*, 2024, **155**(7), 739–745, DOI: [10.1007/s00706-024-03215-2](https://doi.org/10.1007/s00706-024-03215-2).
- 225 S. Kohli, G. Rathee, S. Hooda and R. Chandra, Exploring the untapped catalytic application of a ZnO/CuI/PPy nanocomposite for the green synthesis of biologically active 2,4,5-trisubstituted imidazole scaffolds, *Nanoscale Adv.*, 2023, **5**(8), 2352–2360, DOI: [10.1039/d3na00077j](https://doi.org/10.1039/d3na00077j).
- 226 P. P. Hazra, B. Mondal, D. Das, P. Majhi, U. Pradhan, S. Mallick, A. K. Shukla, R. K. Das and U. K. Roy, Multi-component consecutive Barbier propargylation and CuAAC click reactions using Zn/CuFe₂O₄ reagent: entry to anti-fungal triazole compounds, *Tetrahedron*, 2023, **139**, 133442, DOI: [10.1016/j.tet.2023.133442](https://doi.org/10.1016/j.tet.2023.133442).



- 227 K. Selvaraj, V. Loganathan, A. Ahamed, A. A. Hatamleh, A. Manilal and I. Akbar, Azithromycin mediated copper nanocatalysis (Azi-Cu-Nps): synthesis of anthraquinone connected xanthenes derivatives and their antioxidant, antityrosinase, and cytotoxic activities, *J. Mol. Struct.*, 2025, **1329**, 141447, DOI: [10.1016/j.molstruc.2025.141447](https://doi.org/10.1016/j.molstruc.2025.141447).
- 228 T. Bruna, F. Maldonado-Bravo, P. Jara and N. Caro, Silver nanoparticles and their antibacterial applications, *Int. J. Mol. Sci.*, 2021, **22**, 7202, DOI: [10.3390/ijms22137202](https://doi.org/10.3390/ijms22137202).
- 229 D. Franco, G. Calabrese, S. P. P. Guglielmino and S. Conoci, Metal-based nanoparticles: antibacterial mechanisms and biomedical application, *Microorganisms*, 2022, **10**, 1778, DOI: [10.3390/microorganisms10091778](https://doi.org/10.3390/microorganisms10091778).
- 230 X. Zhao, H. Tang and X. Jiang, Deploying gold nano-materials in combating multi-drug-resistant bacteria, *ACS Nano*, 2022, **16**, 10066–10087, DOI: [10.1021/acsnano.2c02778](https://doi.org/10.1021/acsnano.2c02778).
- 231 M. Godoy-Gallardo, U. Eckhard, L. M. Delgado, Y. J. de Roo Puente, M. Hoyos-Nogués, F. J. Gil and R. A. Perez, Antibacterial approaches in tissue engineering using metal ions and nanoparticles: from mechanisms to applications, *Bioact. Mater.*, 2021, **6**, 4470–4490, DOI: [10.1016/j.bioactmat.2021.04.035](https://doi.org/10.1016/j.bioactmat.2021.04.035).
- 232 A. Pugazhendhi, S. S. Kumar, M. Manikandan and M. Saravanan, Photocatalytic properties and antimicrobial efficacy of Fe-doped CuO nanoparticles against the pathogenic bacteria and fungi, *Microb. Pathog.*, 2018, **122**, 84–89, DOI: [10.1016/j.micpath.2018.06.008](https://doi.org/10.1016/j.micpath.2018.06.008).
- 233 Z. Zhang, J. Wen, J. Zhang, D. Guo and Q. Zhang, Vacancy-modulated of CuS for highly antibacterial efficiency via photothermal/photodynamic synergetic therapy, *Adv. Healthcare Mater.*, 2023, **12**(1), 2201746, DOI: [10.1002/adhm.202201746](https://doi.org/10.1002/adhm.202201746).
- 234 Y. Yang, C. Wang, N. Wang, J. Li, Y. Zhu and J. Zai, *et al.*, Photogenerated reactive oxygen species and hyperthermia by Cu₃SnS₄ nanoflakes for advanced photocatalytic and photothermal antibacterial therapy, *J. Nanobiotechnol.*, 2022, **20**(1), 195, DOI: [10.1186/s12951-022-01403-y](https://doi.org/10.1186/s12951-022-01403-y).
- 235 L. Wang, R. Peng, X. Liu, C. Heng, Y. Miao and W. Wang, *et al.*, Nitrite-enhanced copper-based Fenton reactions for biofilm removal, *Chem. Commun.*, 2021, **57**(45), 5514–5517, DOI: [10.1039/D1CC01647K](https://doi.org/10.1039/D1CC01647K).
- 236 J. Zeng, C. Gu, X. Geng, Z. Y. Wang, Z. C. Xiong and Y. J. Zhu, *et al.*, Engineering copper-containing nanoparticles-loaded silicene nanosheets with triple enzyme mimicry activities and photothermal effect for promoting bacteria-infected wound healing, *Small*, 2024, **20**(15), 2307096, DOI: [10.1002/smll.202307096](https://doi.org/10.1002/smll.202307096).
- 237 M. Pohanka, Copper and copper nanoparticles toxicity and their impact on basic functions in the body, *Bratisl. Lek. Listy*, 2019, **120**(6), 397–409, DOI: [10.4149/BLL_2019_064](https://doi.org/10.4149/BLL_2019_064).
- 238 K. Ganesan, V. K. Jothi, A. Natarajan, A. Rajaram, S. Ravichandran and S. Ramalingam, Green synthesis of Copper oxide nanoparticles decorated with graphene oxide for anticancer activity and catalytic applications, *Arabian J. Chem.*, 2020, **13**(8), 6802–6814, DOI: [10.1016/j.arabjc.2020.06.004](https://doi.org/10.1016/j.arabjc.2020.06.004).
- 239 H. Tian, S. Zhao, E. C. Nice, C. Huang, W. He, B. Zou and J. Lin, A cascaded copper-based nanocatalyst by modulating glutathione and cyclooxygenase-2 for hepatocellular carcinoma therapy, *J. Colloid Interface Sci.*, 2022, **607**, 1516–1526, DOI: [10.1016/j.jcis.2021.09.186](https://doi.org/10.1016/j.jcis.2021.09.186).
- 240 Y. Wang, X. Zhang, Y. Ma, X. Zhou, W. Xu, S. Qin and C. Yang, Self-assembled copper-based nanoparticles for enzyme catalysis-enhanced chemodynamic/photodynamic/antiangiogenic tritherapy against hepatocellular carcinoma, *J. Nanobiotechnol.*, 2024, **22**, 375, DOI: [10.1186/s12951-024-02276-4](https://doi.org/10.1186/s12951-024-02276-4).
- 241 W. Zuo, Z. Fan, L. Chen, J. Liu, Z. Wan, Z. Xiao and X. Zhu, Copper-based theranostic nanocatalysts for synergetic photothermal-chemodynamic therapy, *Acta Biomater.*, 2022, **147**, 258–269, DOI: [10.1016/j.actbio.2022.07.025](https://doi.org/10.1016/j.actbio.2022.07.025).
- 242 Z. Huang, Y. Ding, Y. Luo, M. Chen, Z. Zeng, T. Zhang and C. Zhao, ROS-triggered cycle amplification effect: a prodrug activation nanoamplifier for tumor-specific therapy, *Acta Biomater.*, 2022, **152**, 367–379, DOI: [10.1016/j.actbio.2022.08.072](https://doi.org/10.1016/j.actbio.2022.08.072).
- 243 S. Mukherjee, A. V. Sawant, S. S. Prassanawar and D. Panda, Copper-plumbagin complex produces potent anticancer effects by depolymerizing microtubules and inducing reactive oxygen species and DNA damage, *ACS Omega*, 2023, **8**, 3221–3235, DOI: [10.1021/acsomega.2c06691](https://doi.org/10.1021/acsomega.2c06691).
- 244 K. Domagała, C. Jacquin, M. Borlaf, B. Sinnet, T. Julian, D. Kata and T. Graule, Efficiency and stability evaluation of Cu₂O/MWCNTs filters for virus removal from water, *Water Res.*, 2020, **179**, 115879, DOI: [10.1016/j.watres.2020.115879](https://doi.org/10.1016/j.watres.2020.115879).
- 245 A. Tavakoli and M. S. Hashemzadeh, Inhibition of herpes simplex virus type 1 by copper oxide nanoparticles, *J. Virol. Methods*, 2020, **275**, 113688, DOI: [10.1016/j.jviromet.2019.113688](https://doi.org/10.1016/j.jviromet.2019.113688).
- 246 X. Hang, H. Peng, H. Song, Z. Qi, X. Miao and W. Xu, Antiviral activity of cuprous oxide nanoparticles against Hepatitis C Virus in vitro, *J. Virol. Methods*, 2015, **222**, 150–157, DOI: [10.1016/j.jviromet.2015.06.013](https://doi.org/10.1016/j.jviromet.2015.06.013).
- 247 G. Borkow, S. S. Zhou, T. Page and J. Gabbay, A novel anti-influenza copper oxide containing respiratory face mask, *PLoS One*, 2010, **5**(6), e11295, DOI: [10.1371/journal.pone.0011295](https://doi.org/10.1371/journal.pone.0011295).
- 248 M. Hosseini, A. W. Chin, S. Behzadinasab, L. L. Poon and W. A. Ducker, Cupric oxide coating that rapidly reduces infection by SARS-CoV-2 via solids, *ACS Appl. Mater. Interfaces*, 2021, **13**(5), 5919–5928, DOI: [10.1021/acsaami.0c27023](https://doi.org/10.1021/acsaami.0c27023).
- 249 L. V. Delumeau, H. Asgarimoghaddam, T. Alkie, A. J. B. Jones, S. Lum and K. Mistry, *et al.*, Effectiveness of antiviral metal and metal oxide thin-film coatings against human coronavirus 229E, *APL Mater.*, 2021, **9**(11), 111114, DOI: [10.1063/5.0056138](https://doi.org/10.1063/5.0056138).
- 250 S. A. Carabineiro, G. B. Dharma Rao, L. Singh, B. Anjaneyulu and M. Afshari, CuFe₂O₄ magnetic nanoparticles as heterogeneous catalysts for synthesis of dihydropyrimidinones as inhibitors of SARS-CoV-2 surface proteins—insights from molecular docking studies, *Processes*, 2023, **11**(8), 2294, DOI: [10.3390/pr11082294](https://doi.org/10.3390/pr11082294).
- 251 M. Nasrollahzadeh, M. Sajjadi and M. R. Tahsili, High efficiency treatment of organic/inorganic pollutants using recyclable magnetic N-heterocyclic copper(II) complex and



- its antimicrobial applications, *Sep. Purif. Technol.*, 2020, **238**, 116403, DOI: [10.1016/j.seppur.2019.116403](https://doi.org/10.1016/j.seppur.2019.116403).
- 252 F. Ali, S. Akbar, M. Sillanpää, U. Younas, A. Ashraf, M. Pervaiz and M. Ouladsmene, Recyclable Cu–Ag bimetallic nanocatalyst for radical scavenging, dyes removal and antimicrobial applications, *Chemosphere*, 2023, **313**, 137321, DOI: [10.1016/j.chemosphere.2022.137321](https://doi.org/10.1016/j.chemosphere.2022.137321).
- 253 S. Zhang, J. Hao, F. Ding and X. Ren, Nanocatalyst doped bacterial cellulose-based thermosensitive nanogel with biocatalytic function for antibacterial application, *Int. J. Biol. Macromol.*, 2022, **195**, 294–301, DOI: [10.1016/j.ijbiomac.2021.12.107](https://doi.org/10.1016/j.ijbiomac.2021.12.107).
- 254 H. Chen, X. Li, M. Huo, L. Wang, Y. Chen, W. Chen and B. Wang, Tumor-responsive copper-activated disulfiram for synergetic nanocatalytic tumor therapy, *Nano Res.*, 2021, **14**, 205–211, DOI: [10.1007/s12274-020-3062-5](https://doi.org/10.1007/s12274-020-3062-5).
- 255 M. Mirzaei, M. B. Zarch, M. Darroudi, K. Sayyadi, S. T. Keshavarz, J. Sayyadi and H. Maleki, Silica mesoporous structures: effective nanocarriers in drug delivery and nanocatalysts, *Appl. Sci.*, 2020, **10**(21), 7533, DOI: [10.3390/app10217533](https://doi.org/10.3390/app10217533).
- 256 W. Zhang, X. Tian and X. Li, Fabrication of nanocatalytic medicine from self-assembling peptides containing an ATCUN-like copper-binding motif for anticancer therapy, *ChemBioChem*, 2024, e202400216, DOI: [10.1002/cbic.202400216](https://doi.org/10.1002/cbic.202400216).
- 257 Y. Wang, X. Zhang, Y. Ma, X. Zhou, W. Xu, S. Qin and C. Yang, Self-assembled copper-based nanoparticles for enzyme catalysis-enhanced chemodynamic/photodynamic/antiangiogenic tritherapy against hepatocellular carcinoma, *J. Nanobiotechnol.*, 2024, **22**, 375, DOI: [10.1186/s12951-024-02274-9](https://doi.org/10.1186/s12951-024-02274-9).
- 258 F. Wei, L. Hou, Y. Yao, Y. Lai, T. Lin, S. Zhao and D. Tang, An intelligent Cu/ZIF-8-based nanodrug delivery system for tumor-specific and synergistic therapy via tumor microenvironment-responsive cascade reaction, *Microchim. Acta*, 2024, **191**, 447, DOI: [10.1007/s00604-024-05836-6](https://doi.org/10.1007/s00604-024-05836-6).
- 259 X. He, S. Liu, X. Hu, X. Huang, H. Zhang and X. Mao, Precious metal clusters as fundamental agents in bioimaging usability, *Front. Chem.*, 2023, **11**, 1296036, DOI: [10.3389/fchem.2023.1296036](https://doi.org/10.3389/fchem.2023.1296036).
- 260 C. Dong, W. Feng, W. Xu, L. Yu, H. Xiang, Y. Chen and J. Zhou, The copper age: copper (Cu)-involved nanotheranostics, *Adv. Sci.*, 2020, **7**, 2001549, DOI: [10.1002/advs.202001549](https://doi.org/10.1002/advs.202001549).
- 261 H. D. Lu, L. Z. Wang, B. K. Wilson, S. A. McManus, J. Jumai'an, P. K. Padakanti and R. K. Prud'homme, Copper loading of preformed nanoparticles for PET-imaging applications, *ACS Appl. Mater. Interfaces*, 2018, **10**, 3191–3199, DOI: [10.1021/acsami.7b17640](https://doi.org/10.1021/acsami.7b17640).
- 262 H. Yuan, Y. Zhao, C. Yang, C. Zhang, Y. Yang, H. Meng and X. Zhang, Copper-thioguanine metallodrug with self-reinforcing circular catalysis for activatable MRI imaging and amplifying specificity of cancer therapy, *Sci. China: Chem.*, 2020, **63**, 924–935, DOI: [10.1007/s11426-019-9690-0](https://doi.org/10.1007/s11426-019-9690-0).
- 263 L. Zhang, C. Jiang, B. Li, Z. Liu, B. Gu, S. He and S. Song, A core-shell Au@Cu_{2-x}Se heterogeneous metal nanocomposite for photoacoustic and computed tomography dual-imaging-guided photothermal boosted chemodynamic therapy, *J. Nanobiotechnol.*, 2021, **19**, 1–18, DOI: [10.1186/s12951-021-00874-5](https://doi.org/10.1186/s12951-021-00874-5).
- 264 S. Kim, J. H. Kim, W. Y. Kwon, S. H. Hwang, B. S. Cha, J. M. Kim and K. S. Park, Synthesis of DNA-templated copper nanoparticles with enhanced fluorescence stability for cellular imaging, *Microchim. Acta*, 2019, **186**, 1–5, DOI: [10.1007/s00604-019-3457-2](https://doi.org/10.1007/s00604-019-3457-2).
- 265 S. Zhang, C. Sun, J. Zeng, Q. Sun, G. Wang, Y. Wang and Z. Li, Ambient aqueous synthesis of ultrasmall PEGylated Cu_{2-x}Se nanoparticles as a multifunctional theranostic agent for multimodal imaging guided photothermal therapy of cancer, *Adv. Mater.*, 2016, **28**, 8927–8936, DOI: [10.1002/adma.201602193](https://doi.org/10.1002/adma.201602193).
- 266 H. Zhu, Y. Wang, C. Chen, M. Ma, J. Zeng, S. Li and M. Gao, Monodisperse dual plasmonic Au@Cu_{2-x}E (E = S, Se) core@shell supraparticles: aqueous fabrication, multimodal imaging, and tumor therapy at in vivo level, *ACS Nano*, 2017, **11**, 8273–8281, DOI: [10.1021/acsnano.7b03674](https://doi.org/10.1021/acsnano.7b03674).
- 267 S. Zhang, Q. Huang, L. Zhang, H. Zhang, Y. Han, Q. Sun and Z. Li, Vacancy engineering of Cu_{2-x}Se nanoparticles with tunable LSPR and magnetism for dual-modal imaging guided photothermal therapy of cancer, *Nanoscale*, 2018, **10**, 3130–3143, DOI: [10.1039/C7NR08622D](https://doi.org/10.1039/C7NR08622D).
- 268 Z. Lyu, Y. Shang and Y. Xia, Shape-controlled synthesis of copper nanocrystals for plasmonic, biomedical, and electrocatalytic applications, *Acc. Mater. Res.*, 2022, **3**, 1137–1148, DOI: [10.1021/accountsmr.2c00148](https://doi.org/10.1021/accountsmr.2c00148).
- 269 N. Myung, S. Kim, C. Lee, T. Kim and K. Rajeshwar, Facile synthesis of Pt–CuO nanocomposite films for non-enzymatic glucose sensor application, *J. Electrochem. Soc.*, 2016, **163**, B180, DOI: [10.1149/2.0881605jes](https://doi.org/10.1149/2.0881605jes).
- 270 C. Zhang, F. Li, S. Huang, M. Li, T. Guo, C. Mo and X. Li, In situ facile preparation of highly efficient copper/nickel bimetallic nanocatalyst on chemically grafted carbon nanotubes for nonenzymatic sensing of glucose, *J. Colloid Interface Sci.*, 2019, **557**, 825–836, DOI: [10.1016/j.jcis.2019.09.055](https://doi.org/10.1016/j.jcis.2019.09.055).
- 271 N. Losada-Garcia, A. Jimenez-Alesanco, A. Velazquez-Campoy, O. Abian and J. M. Palomo, Enzyme/nanocopper hybrid nanozymes: modulating enzyme-like activity by the protein structure for biosensing and tumor catalytic therapy, *ACS Appl. Mater. Interfaces*, 2021, **13**, 5111–5124, DOI: [10.1021/acsami.0c20523](https://doi.org/10.1021/acsami.0c20523).
- 272 Y. Chen, Y. Xianyu, J. Wu, B. Yin and X. Jiang, Click chemistry-mediated nanosensors for biochemical assays, *Theranostics*, 2016, **6**, 969–985, DOI: [10.7150/thno.14495](https://doi.org/10.7150/thno.14495).
- 273 N. Stasyuk, O. Smutok, O. Demkiv, T. Prokopiv, G. Gayda, M. Nisnevitch and M. Gonchar, Synthesis, catalytic properties and application in biosensorics of nanozymes and electronanocatalysts: a review, *Sensors*, 2020, **20**, 4509, DOI: [10.3390/s20164509](https://doi.org/10.3390/s20164509).
- 274 S. Jain, B. Sharma, N. Thakur, S. Mishra and T. K. Sarma, Copper pyrovanadate nanoribbons as efficient multi-enzyme mimicking nanozyme for biosensing applications, *ACS Appl. Nano Mater.*, 2020, **3**, 7917–7929, DOI: [10.1021/acsanm.0c01494](https://doi.org/10.1021/acsanm.0c01494).



- 275 Q. Wu, L. He, Z. W. Jiang, Y. Li, Z. M. Cao, C. Z. Huang and Y. F. Li, CuO nanoparticles derived from metal–organic gel with excellent electrocatalytic and peroxidase-mimicking activities for glucose and cholesterol detection, *Biosens. Bioelectron.*, 2019, **145**, 111704, DOI: [10.1016/j.bios.2019.111704](https://doi.org/10.1016/j.bios.2019.111704).
- 276 Y. Mao, L. Wang, K. Zhang, H. Zhang and J. Yang, Polydopamine on copper-doped cerium dioxide nanosheets as peroxidase mimics for the intelligent detection of cholesterol, *Langmuir*, 2023, **39**, 17286–17294, DOI: [10.1021/acs.langmuir.3c02468](https://doi.org/10.1021/acs.langmuir.3c02468).
- 277 D. Deng, L. Liu, Y. Bu, X. Liu, X. Wang and B. Zhang, Electrochemical sensing devices using ATCUN-Cu(II) complexes as electrocatalysts for water oxidation, *Sens. Actuators, B*, 2018, **269**, 189–194, DOI: [10.1016/j.snb.2018.04.105](https://doi.org/10.1016/j.snb.2018.04.105).
- 278 N. Stasyuk, O. Smutok, O. Demkiv, T. Prokopiv, G. Gayda, M. Nisnevitch and M. Gonchar, Synthesis, catalytic properties and application in biosensors of nanozymes and electronanocatalysts: a review, *Sensors*, 2020, **20**, 4509, DOI: [10.3390/s20164509](https://doi.org/10.3390/s20164509).
- 279 A. Ngamaroonchote, Y. Sanguansap, T. Wutikhun and K. Karn-Orachai, Highly branched gold–copper nanostructures for non-enzymatic specific detection of glucose and hydrogen peroxide, *Microchim. Acta*, 2020, **187**, 1–12, DOI: [10.1007/s00604-020-04284-2](https://doi.org/10.1007/s00604-020-04284-2).
- 280 S. Jain, B. Sharma, N. Thakur, S. Mishra and T. K. Sarma, Copper pyrovanadate nanoribbons as efficient multi-enzyme mimicking nanozyme for biosensing applications, *ACS Appl. Nano Mater.*, 2020, **3**, 7917–7929, DOI: [10.1021/acsanm.0c01589](https://doi.org/10.1021/acsanm.0c01589).
- 281 R. Singh, Q. Zeng, S. Cheng and S. Kumar, Selective colorimetric detection of cancer cells based on iron/copper nanocatalyst peroxidase activity, *IEEE Sens. J.*, 2022, **22**, 10492–10499, DOI: [10.1109/JSEN.2022.3163004](https://doi.org/10.1109/JSEN.2022.3163004).
- 282 C. Cheng, J. Li, T. Shi, X. Yu, J. Fan, G. Liao and Z. Tang, A novel method of synthesizing antioxidative copper nanoparticles for high-performance conductive ink, *J. Mater. Sci.: Mater. Electron.*, 2017, **28**, 13556–13564, DOI: [10.1007/s10854-017-7158-2](https://doi.org/10.1007/s10854-017-7158-2).
- 283 Z. Lyu, Y. Shang and Y. Xia, Shape-controlled synthesis of copper nanocrystals for plasmonic, biomedical, and electrocatalytic applications, *Acc. Mater. Res.*, 2022, **3**(11), 1137–1148, DOI: [10.1021/accountsmr.2c00190](https://doi.org/10.1021/accountsmr.2c00190).
- 284 M. Kamali, F. Samari and F. Sedaghati, Low-temperature phyto-synthesis of copper oxide nanosheets: its catalytic effect and application for colorimetric sensing, *Mater. Sci. Eng., C*, 2019, **103**, 109744, DOI: [10.1016/j.msec.2019.109744](https://doi.org/10.1016/j.msec.2019.109744).
- 285 S. A. El-Safty and M. A. Shenashen, Advanced nanoscale build-up sensors for daily life monitoring of diabetics, *Adv. Mater. Interfaces*, 2020, **7**, 2000153, DOI: [10.1002/admi.202000153](https://doi.org/10.1002/admi.202000153).
- 286 Y. Huang, Y. Han, J. Sun, Y. Zhang and L. Han, Dual nanocatalysts co-decorated three-dimensional, laser-induced graphene hybrid nanomaterials integrated with a smartphone portable electrochemical system for point-of-care non-enzymatic glucose diagnosis, *Mater. Today Chem.*, 2022, **24**, 100895, DOI: [10.1016/j.mtchem.2022.100895](https://doi.org/10.1016/j.mtchem.2022.100895).
- 287 X. Tong, L. Ga, L. G. Bi and J. Ai, Wearable electrochemical sensors based on nanomaterials for healthcare applications, *Electroanalysis*, 2023, **35**(2), e202200228, DOI: [10.1002/elan.202200228](https://doi.org/10.1002/elan.202200228).
- 288 H. Guo, L. J. Pei, S. L. Xie, M. Q. Shen, Y. Yang and H. Liu, Copper-based nanocatalysts toward chemoselective hydrogenation reaction, *cMat*, 2024, **1**(1), e9, DOI: [10.1002/cmt2.9](https://doi.org/10.1002/cmt2.9).
- 289 X. Li, J. You, J. Li, Z. Wang, Y. Zhao, J. Xu and H. Zhang, Progress of Copper-based Nanocatalysts in Advanced Oxidation Degraded Organic Pollutants, *ChemCatChem*, 2024, **16**(6), e202301108, DOI: [10.1002/cctc.202301108](https://doi.org/10.1002/cctc.202301108).
- 290 G. G. Xanthopoulou, A. V. Novikov, Y. A. Knysh and A. P. Amosov, Nanocatalysts for low-temperature oxidation of CO, *Eurasian Chem. – Technol. J.*, 2015, **17**(1), 17–31, DOI: [10.18321/ectj17](https://doi.org/10.18321/ectj17).
- 291 J. Wang, T. Feng, J. Chen, V. Ramalingam, Z. Li, D. M. Kabtamu and X. Fang, Electrocatalytic nitrate/nitrite reduction to ammonia synthesis using metal nanocatalysts and bio-inspired metalloenzymes, *Nano Energy*, 2021, **86**, 106088, DOI: [10.1016/j.nanoen.2021.106088](https://doi.org/10.1016/j.nanoen.2021.106088).
- 292 X. Shen, G. Shi, Y. Zhang and S. Weng, Wireless volatile organic compound detection for restricted internet of things environments based on cataluminescence sensors, *Chemosensors*, 2022, **10**(5), 179, DOI: [10.3390/chemosensors10050179](https://doi.org/10.3390/chemosensors10050179).
- 293 P. J. Maake, T. P. Mokoena, A. S. Bolokang, N. Hintshombita, J. Tshilongo, F. R. Cummings, H. C. Swart, E. I. Iwuoha and D. E. Motaung, Fabrication of AgCu/TiO₂ nanoparticle-based sensors for selective detection of xylene vapor, *Mater. Adv.*, 2022, **3**, 7302–7318, DOI: [10.1039/D2MA00597A](https://doi.org/10.1039/D2MA00597A).
- 294 L. Zheng, S. Zheng, H. Wei, L. Du, Z. Zhu, J. Chen and D. Yang, Palladium/bismuth/copper hierarchical nano-architectures for efficient hydrogen evolution and stable hydrogen detection, *ACS Appl. Mater. Interfaces*, 2019, **11**, 6248–6256, DOI: [10.1021/acsmi.8b19770](https://doi.org/10.1021/acsmi.8b19770).
- 295 U. R. Pillai and S. Deevi, Room temperature oxidation of carbon monoxide over copper oxide catalyst, *Appl. Catal., B*, 2006, **64**, 146–151, DOI: [10.1016/j.apcatb.2005.11.008](https://doi.org/10.1016/j.apcatb.2005.11.008).
- 296 X. Xi, S. Ma, J. F. Chen and Y. Zhang, Promotional effects of Ce, Mn and Fe oxides on CuO/SiO₂ catalysts for CO oxidation, *J. Environ. Chem. Eng.*, 2014, **2**, 1011–1017, DOI: [10.1016/j.jece.2014.03.012](https://doi.org/10.1016/j.jece.2014.03.012).
- 297 J. L. Cao, Y. Wang, X. L. Yu, S. R. Wang, S. H. Wu and Z. Y. Yuan, Mesoporous CuO–Fe₂O₃ composite catalysts for low-temperature carbon monoxide oxidation, *Appl. Catal., B*, 2008, **79**, 26–34, DOI: [10.1016/j.apcatb.2007.09.033](https://doi.org/10.1016/j.apcatb.2007.09.033).
- 298 Z. Q. Zou, M. Meng, L. H. Guo and Y. Q. Zha, Synthesis and characterization of CuO/Ce_{1-x}Ti_xO₂ catalysts used for low-temperature CO oxidation, *J. Hazard. Mater.*, 2009, **163**, 835–842, DOI: [10.1016/j.jhazmat.2008.07.039](https://doi.org/10.1016/j.jhazmat.2008.07.039).
- 299 G. Chen, Q. Li, Y. Wei, W. Fang and Y. Yang, Low temperature CO oxidation on Ni-promoted CuO–CeO₂ catalysts, *Chin. J. Catal.*, 2013, **34**, 322–329, DOI: [10.1016/S1872-2067\(11\)60453-3](https://doi.org/10.1016/S1872-2067(11)60453-3).



- 300 Z. Ziadi, A. J. Porkovich, P. Kumar, A. Datta, E. Danielson, V. Singh and M. Sowwan, Electronic metal-support interactions at the catalytic interfaces of CuO nanowires decorated with Pt nanoparticles for methanol oxidation and CO sensing, *ACS Appl. Nano Mater.*, 2020, 3, 8257–8267, DOI: [10.1021/acsanm.0c01685](https://doi.org/10.1021/acsanm.0c01685).
- 301 M. Sundarapandi, S. Shanmugam and R. Ramaraj, Tuning Cu₂O shell on gold nanocube core employing amine-functionalized silane for electrocatalytic nitrite detection, *ACS Appl. Nano Mater.*, 2022, 5, 1674–1682, DOI: [10.1021/acsanm.1c04214](https://doi.org/10.1021/acsanm.1c04214).
- 302 J. Deng, X. Ren, H. Yang, T. Qiu, Z. Wang and Y. Zhang, *et al.*, Vacuum-solvent thermal synthesis of nickel foam-supported CuO-based sensor electrode for good electrochemical detection of nitrite, *Microchem. J.*, 2024, 200, 110337, DOI: [10.1016/j.microc.2023.110337](https://doi.org/10.1016/j.microc.2023.110337).
- 303 W. Abbas, F. Zafar, M. F. Abou Taleb, M. Ameen, A. Sami and M. E. Mazhar, *et al.*, Machine learning trained poly(3,4-ethylenedioxythiophene) functionalized carbon matrix suspended Cu nanoparticles for precise monitoring of nitrite from pickled vegetables, *Food Chem.*, 2024, 460, 140395, DOI: [10.1016/j.foodchem.2024.140395](https://doi.org/10.1016/j.foodchem.2024.140395).
- 304 X. Zhang, J. X. Liu, B. Zijlstra, I. A. W. Filot, Z. Zhou, S. Sun and E. J. M. Hensen, Optimum Cu nanoparticle catalysts for CO₂ hydrogenation towards methanol, *Nano Energy*, 2018, 43, 200–209, DOI: [10.1016/j.nanoen.2017.11.021](https://doi.org/10.1016/j.nanoen.2017.11.021).
- 305 S. Yan, Z. Chen, Y. Chen, C. Peng, X. Ma, X. Lv, Z. Qiu, Y. Yang, Y. Yang, M. Kuang, X. Xu and G. Zheng, High-power CO₂-to-C₂ electroreduction on Ga-spaced, square-like Cu sites, *J. Am. Chem. Soc.*, 2023, 145, 26374–26382, DOI: [10.1021/jacs.3c10202](https://doi.org/10.1021/jacs.3c10202).
- 306 T. Yang, X. Mao, Y. Zhang, X. Wu, L. Wang, M. Chu, C. W. Pao, L. Xie, S. Wang, J. Liu, D. Ma, J. Zhang and B. Han, Coordination tailoring of Cu single sites on C₃N₄ realizes selective CO₂ hydrogenation at low temperature, *Nat. Commun.*, 2021, 12, 6022, DOI: [10.1038/s41467-021-26316-6](https://doi.org/10.1038/s41467-021-26316-6).
- 307 X. Mao, C. W. Chang, Z. Li, Z. Han, J. Gao, M. Lyons, J. M. Gregoire, B. Xu and Z. Weng, Sustainably high-rate electroreduction of CO₂ to multi-carbon products on nickel oxygenate/copper interfacial catalysts, *Adv. Energy Mater.*, 2024, 2400827, DOI: [10.1002/aenm.202400827](https://doi.org/10.1002/aenm.202400827).
- 308 Q. Liu, S. Zhang and Y. Xu, Two-step synthesis of CuS/C@PANI nanocomposite as advanced electrode materials for supercapacitor applications, *Nanomaterials*, 2020, 10(6), 1034, DOI: [10.3390/nano10061034](https://doi.org/10.3390/nano10061034).
- 309 M. Challa, M. R. Ambika, S. R. Usharani, B. C. Yallur and V. Adimule, Enhancement of band gap energy and crystallinity of Cu-MOFs due to doping of nano metal oxide, *Adv. Mater. Res.*, 2022, 1173, 13–22, DOI: [10.4028/p-f9yx5h](https://doi.org/10.4028/p-f9yx5h).
- 310 T. Li, D. Zhao, M. Shi, T. Wang, Q. Yin, Y. Li and Y. Sui, MOF-derived N, S co-doped carbon matrix-encapsulated Cu₂S nanoparticles as high-performance lithium-ion battery anodes: a joint theoretical and experimental study, *J. Mater. Chem. A*, 2023, 11(3), 1461–1472, DOI: [10.1039/D2TA08540A](https://doi.org/10.1039/D2TA08540A).
- 311 Q. Liu, S. Zhang and Y. Xu, Two-step synthesis of CuS/C@PANI nanocomposite as advanced electrode materials for supercapacitor applications, *Nanomaterials*, 2020, 10(6), 1034, DOI: [10.3390/nano10061034](https://doi.org/10.3390/nano10061034).
- 312 G. P. Kamble, A. S. Rasal, S. B. Gaikwad, V. S. Gurav, J. Y. Chang, S. S. Kolekar and A. V. Ghule, CuCo₂O₄ nanorods coated with CuO nanoneedles for supercapacitor applications, *ACS Appl. Nano Mater.*, 2021, 4(11), 12702–12711, DOI: [10.1021/acsanm.1c02784](https://doi.org/10.1021/acsanm.1c02784).
- 313 Y. Yang, L. Liu, S. Li and M. Zhu, Cu-based ternary heterostructures for high-performance asymmetric supercapacitors, *ACS Appl. Energy Mater.*, 2024, 7(17), 7307–7315, DOI: [10.1021/acsaem.3c03186](https://doi.org/10.1021/acsaem.3c03186).
- 314 X. Li, J. You, J. Li, Z. Wang, Y. Zhao, J. Xu, M. Duan and H. Zhang, Progress of copper-based nanocatalysts in advanced oxidation degraded organic pollutants, *ChemCatChem*, 2024, 16(6), e202301108, DOI: [10.1002/cctc.202301108](https://doi.org/10.1002/cctc.202301108).
- 315 R. S. Shinde, S. D. Khairnar, M. R. Patil, V. A. Adole, P. B. Koli, V. V. Deshmane, P. N. Bhosale, S. H. Pawar and A. V. Patil, Synthesis and characterization of ZnO/CuO nanocomposites as an effective photocatalyst and gas sensor for environmental remediation, *J. Inorg. Organomet. Polym. Mater.*, 2022, 32, 4370–4391, DOI: [10.1007/s10904-022-02422-x](https://doi.org/10.1007/s10904-022-02422-x).
- 316 Mandeep and P. Shukla, Microbial nanotechnology for bioremediation of industrial wastewater, *Front. Microbiol.*, 2020, 11, 590631, DOI: [10.3389/fmicb.2020.590631](https://doi.org/10.3389/fmicb.2020.590631).
- 317 A. ur Rehman, M. Aadil, S. Zulfiqar, P. O. Agboola, I. Shakir, M. F. A. Aboud and M. F. Warsi, Fabrication of binary metal doped CuO nanocatalyst and their application for the industrial effluents treatment, *Ceram. Int.*, 2021, 47(5), 5929–5937, DOI: [10.1016/j.ceramint.2020.10.243](https://doi.org/10.1016/j.ceramint.2020.10.243).
- 318 A. Mani, V. Loganathan, I. Akbar, A. Ahamed, B. K. Alnafisi and R. Gurusamy, Musa acuminata free tepal (MAFT) crop-mediated synthesis of copper oxide nanocatalyst (MAFT-CuO nanocatalyst): investigation of aerobic oxidation and dye decolourization via eco-friendly approach, *Ind. Crops Prod.*, 2024, 216, 118715, DOI: [10.1016/j.indcrop.2023.118715](https://doi.org/10.1016/j.indcrop.2023.118715).
- 319 H. W. Haso, A. A. Dubale, M. A. Chimdesa and M. Atlabachew, High performance copper based metal organic framework for removal of heavy metals from wastewater, *Front. Mater.*, 2022, 9, 840806, DOI: [10.3389/fmats.2022.840806](https://doi.org/10.3389/fmats.2022.840806).
- 320 T. L. Soundarya, H. S. Divyashree, C. Ranjini, B. Nirmala and G. Nagaraju, Artemisia pallens-mediated synthesis of second-generation CuO/ZnO nanophotocatalyst for rose bengal dye removal and simultaneous detection of heavy metals, *Biomass Convers. Biorefin.*, 2024, 1–22, DOI: [10.1007/s13399-024-05769-x](https://doi.org/10.1007/s13399-024-05769-x).
- 321 J. Bhatt, M. Jangid, N. Kapoor, R. Ameta and S. C. Ameta, Detection and Degradation of Pesticides Using Nanomaterials, *Biogenic Nano-Particles and their Use in Agro-ecosystems*, 2020, pp. 431–455, DOI: [10.1007/978-981-15-2985-6_23](https://doi.org/10.1007/978-981-15-2985-6_23).
- 322 K. S. Varma, A. D. Shukla, R. J. Tayade, P. A. Joshi, A. K. Das, K. B. Modi and V. G. Gandhi, Photocatalytic performance and interaction mechanism of reverse micelle synthesized Cu-TiO₂ nanomaterials towards levofloxacin under visible LED light, *Photochem. Photobiol. Sci.*, 2022, 21, 77–89, DOI: [10.1007/s43630-021-00141-8](https://doi.org/10.1007/s43630-021-00141-8).



- 323 S. Singh, V. Kumar, S. Datta, D. Bhatia, V. Dhaka and J. Singh, Novel Strategies for Environmental Remediation of Pesticides Using Nanocatalysts, *Biobased Nanotechnology for Green Applications*, 2021, pp. 543–556, DOI: [10.1007/978-3-030-61985-5_19](https://doi.org/10.1007/978-3-030-61985-5_19).
- 324 S. B. Khan, F. Ali and K. Akhtar, Chitosan nanocomposite fibers supported copper nanoparticles based perceptive sensor and active catalyst for nitrophenol in real water, *Carbohydr. Polym.*, 2019, **207**, 650–662, DOI: [10.1016/j.carbpol.2018.12.032](https://doi.org/10.1016/j.carbpol.2018.12.032).
- 325 D. Gašparovičová, M. Králik and M. Hronec, Pd–Cu supported on anionic polymers—promising catalysts for removal of nitrates from drinking water, *Collect. Czech. Chem. Commun.*, 1999, **64**, 502–514, DOI: [10.1135/cccc19990502](https://doi.org/10.1135/cccc19990502).
- 326 F. Manavi, M. R. A. Ghasri, S. Ahmadi and S. Habibi, In situ green synthesis of copper(II) oxide (CuO) and maleic anhydride grafted polypropylene (PP-MAH) for highly efficient nanocatalysis in tannery wastewater treatment, *Environ. Sci.: Water Res. Technol.*, 2024, **10**, 288–295, DOI: [10.1039/D3EW00795B](https://doi.org/10.1039/D3EW00795B).
- 327 Y. Guo, Z. Niu, J. Huang, Y. Ding, X. Li, Y. Song, G. Wen and X. Li, Bimetallic peroxide nanocatalytic gel for water disinfection, *J. Environ. Chem. Eng.*, 2024, **12**, 113015, DOI: [10.1016/j.jece.2024.113015](https://doi.org/10.1016/j.jece.2024.113015).
- 328 S. Eskandarinezhad, R. Khosravi, M. Amarzadeh, P. Mondal and F. J. C. Magalhães Filho, Application of different nanocatalysts in industrial effluent treatment: a review, *J. Compos. Compd.*, 2021, **3**, 43–56, DOI: [10.29252/jcc.3.1.5](https://doi.org/10.29252/jcc.3.1.5).
- 329 R. Ningthoujam, Y. D. Singh, P. J. Babu, A. Tirkey, S. Pradhan and M. Sarma, Nanocatalyst in remediating environmental pollutants, *Chem. Phys. Impact*, 2022, **4**, 100064, DOI: [10.1016/j.chphi.2022.100064](https://doi.org/10.1016/j.chphi.2022.100064).
- 330 S. Dey and G. C. Dhal, Controlling carbon monoxide emissions from automobile vehicle exhaust using copper oxide catalysts in a catalytic converter, *Mater. Today Chem.*, 2020, **17**, 100282, DOI: [10.1016/j.mtchem.2020.100282](https://doi.org/10.1016/j.mtchem.2020.100282).
- 331 A. Bathla, D. Kukkar, P. M. Heynderickx, S. A. Younis and K.-H. Kim, Removal of gaseous formaldehyde by portable photocatalytic air purifier equipped with bimetallic Pt@Cu–TiO₂ filter, *Chem. Eng. J.*, 2023, **469**, 143718, DOI: [10.1016/j.cej.2023.143718](https://doi.org/10.1016/j.cej.2023.143718).
- 332 Q. Li, X. Yan, M. Shi, Q. Wang, H. Liu, Z. Lin and X. Huang, Recent advances in metal/ceria catalysts for air pollution control: mechanism insight and application, *Environ. Sci.: Nano*, 2021, **8**(10), 2760–2779, DOI: [10.1039/D1EN00552H](https://doi.org/10.1039/D1EN00552H).
- 333 T. T. Nguyen, G. H. Le, C. H. Le, M. B. Nguyen, T. T. Quan, T. T. Pham and T. A. Vu, Atomic implantation synthesis of Fe–Cu/SBA-15 nanocomposite as a heterogeneous Fenton-like catalyst for enhanced degradation of DDT, *Mater. Res. Express*, 2018, **5**(11), 115005, DOI: [10.1088/2053-1591/aadffc](https://doi.org/10.1088/2053-1591/aadffc).
- 334 S. A. Ghoto, M. Y. Khuhawar, T. M. Jahangir and J. U. D. Mangi, Applications of copper nanoparticles for colorimetric detection of dithiocarbamate pesticides, *J. Nanostruct. Chem.*, 2019, **9**, 77–93, DOI: [10.1007/s40097-019-0299-4](https://doi.org/10.1007/s40097-019-0299-4).
- 335 D. Mittal, G. Kaur, P. Singh, K. Yadav and S. A. Ali, Nanoparticle-Based Sustainable Agriculture and Food Science: Recent Advances and Future Outlook, *Front. Nanotechnol.*, 2020, **2**, 579954, DOI: [10.3389/fnano.2020.579954](https://doi.org/10.3389/fnano.2020.579954).
- 336 D. Yang, J. Huo, Z. Zhang, Z. An, H. Dong, Y. Wang and J. Zhang, Citric acid modified ultrasmall copper peroxide nanozyme for in situ remediation of environmental sulfonylurea herbicide contamination, *J. Hazard. Mater.*, 2023, **443**, 130265, DOI: [10.1016/j.jhazmat.2023.130265](https://doi.org/10.1016/j.jhazmat.2023.130265).
- 337 Q. Diao, X. Chen, Z. Tang, S. Li, Q. Tian, Z. Bu, H. Liu, J. Liu and X. Niu, Nanozymes: powerful catalytic materials for environmental pollutant detection and degradation, *Environ. Sci.: Nano*, 2024, **11**, 766–796, DOI: [10.1039/D3EN00844D](https://doi.org/10.1039/D3EN00844D).
- 338 J. P. Fernandes, C. M. R. Almeida, F. Andreotti, L. Barros, T. Almeida and A. P. Mucha, Response of microbial communities colonizing salt marsh plants rhizosphere to copper oxide nanoparticles contamination and its implications for phytoremediation processes, *Sci. Total Environ.*, 2017, **581–582**, 801–810, DOI: [10.1016/j.scitotenv.2017.01.015](https://doi.org/10.1016/j.scitotenv.2017.01.015).
- 339 J. A. Buledi, P. A. Buledi, M. Batool, A. R. Solangi, A. Mallah, S. Ameen and H. K. Maleh, Exploring electrocatalytic proficiencies of CuO nanostructure for simultaneous determination of bentazone and mexacarbate pesticides, *Appl. Nanosci.*, 2021, **11**(6), 1889–1902, DOI: [10.1007/s13204-021-01864-x](https://doi.org/10.1007/s13204-021-01864-x).
- 340 K. Rossi and R. Buonsanti, Shaping copper nanocatalysts to steer selectivity in the electrochemical CO₂ reduction reaction, *Acc. Chem. Res.*, 2022, **55**(5), 629–637, DOI: [10.1021/acs.accounts.1c00663](https://doi.org/10.1021/acs.accounts.1c00663).
- 341 Z. Weng, J. Jiang, Y. Wu, Z. Wu, X. Guo, K. L. Materna and H. Wang, Electrochemical CO₂ reduction to hydrocarbons on a heterogeneous molecular Cu catalyst in aqueous solution, *J. Am. Chem. Soc.*, 2016, **138**(26), 8076–8079, DOI: [10.1021/jacs.6b04015](https://doi.org/10.1021/jacs.6b04015).
- 342 D. Yang, Q. Zhu, C. Chen, H. Liu, Z. Liu, Z. Zhao and B. Han, Selective electroreduction of carbon dioxide to methanol on copper selenide nanocatalysts, *Nat. Commun.*, 2019, **10**(1), 677, DOI: [10.1038/s41467-019-08646-7](https://doi.org/10.1038/s41467-019-08646-7).
- 343 G. C. Leite and M. C. Padoveze, Copper as an antimicrobial agent in healthcare: an integrative literature review, *J. Infect. Control.*, 2012, **1**, 33–36.
- 344 H. T. Michels and C. A. Michels, Copper alloys—the new ‘old’ weapon in the fight against infectious disease, *Curr. Trends Microbiol.*, 2016, **10**, 23–45.
- 345 N. Malhotra, T.-R. Ger, B. Uapipatanakul, J.-C. Huang, K. H.-C. Chen and C.-D. Hsiao, Review of copper and copper nanoparticle toxicity in fish, *Nanomaterials*, 2020, **10**(6), 1126, DOI: [10.3390/nano10061126](https://doi.org/10.3390/nano10061126).
- 346 Z. Chen, H. Meng, G. Xing, C. Chen, Y. Zhao, G. Jia and L. Wan, Acute toxicological effects of copper nanoparticles in vivo, *Toxicol. Lett.*, 2006, **163**(2), 109–120, DOI: [10.1016/j.toxlet.2005.10.003](https://doi.org/10.1016/j.toxlet.2005.10.003).
- 347 T. Ameh and C. M. Sayes, The potential exposure and hazards of copper nanoparticles: a review, *Environ. Toxicol. Pharmacol.*, 2019, **71**, 103220, DOI: [10.1016/j.etap.2019.103220](https://doi.org/10.1016/j.etap.2019.103220).
- 348 C. Torres-Duarte, S. Hutton, C. Vines, J. Moore and G. N. Cherr, Effects of soluble copper and copper oxide nanoparticle exposure on the immune system of mussels, *Mytilus galloprovincialis*, *Environ. Toxicol.*, 2018, **33**(10), 1085–1095, DOI: [10.1002/tox.22684](https://doi.org/10.1002/tox.22684).



- 349 V. D. Rajput, T. Minkina, A. G. Fedorenko, S. N. Sushkova, V. Tsitsuashvili, S. S. Mandzhieva, G. M. Fedorenko, M. V. Burachevskaya, A. A. Fedorov and K. S. Ghazaryan, Toxicity of copper oxide nanoparticles on spring barley (*Hordeum sativum distichum*), *Sci. Total Environ.*, 2018, **645**, 1103–1113, DOI: [10.1016/j.scitotenv.2018.07.211](https://doi.org/10.1016/j.scitotenv.2018.07.211).
- 350 M. Pohanka, Copper and copper nanoparticles toxicity and their impact on basic functions in the body, *Bratisl. Lek. Listy*, 2019, **120**(6), 397–409, DOI: [10.4149/BLL_2019_065](https://doi.org/10.4149/BLL_2019_065).

