IJARSCT
International Journal of Advanced Research in Science, Communication and Technology
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
ISSN: 2581-9429
Volume 6, Issue 8, April 2026
Impact Factor: 8.2

Application of Copper Oxide Nanoparticles in Organic Transformation: An Overview

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Abstract: *Copper-catalyzed organic transformations have gained significant importance in modern synthetic organic chemistry due to their efficiency, cost-effectiveness, and environmental friendliness. Copper, being the most abundant and inexpensive transition metal, serves as an excellent catalyst for a wide range of organic reactions. These transformations include C–C, C–N, C–O, and C–S bond-formation reactions, which are essential in the synthesis of pharmaceuticals, agrochemicals, and functional materials. Copper catalysts show remarkable versatility by operating under mild reaction conditions and showing good functional group tolerance. Various oxidation states of copper (Cu^0, Cu^+, and Cu^{2+}) play an important role in facilitating different reaction pathways. Recent advances focus on ligand-assisted catalysis, green solvents, and sustainable reaction protocols to improve selectivity and yield while minimizing environmental impact. This study highlights the mechanistic aspects, scope, and applications of copper-catalyzed organic transformations, emphasizing their role in developing eco-friendly and economically viable synthetic methodologies. The growing interest in copper catalysis reflects its potential as a powerful alternative to precious metal catalysts in organic synthesis.*

Keywords: Copper oxide Nanoparticles, organic transformation, C–C, C–N, C–O, and C–S bond-formation. Copper-Catalysed Organic Transformations: Mechanistic Insights, Applications, and Sustainable Approaches

1. Introduction

Transition metal catalysis play an important and central role in modern organic synthesis. Conventionally ,noble metals such as palladium ,platinum ,and rhodium have been widely as a catalyst in organic transformation. However, their limited availability and high cost have promoted to search for economical and sustainable alternatives. Copper has emerged as a versatile catalyst in organic transformation because of its abundance ,low cost, low toxicity and diverse oxidation states. Copper catalysed organic reaction have been extensively explored for formation of carbon-carbon single bond and carbon hetroatom such as (C-C, C-N,C-S & C-O)(Monnier & Taillefer, 2009) ,which are fundamental steps in organic synthesis of biological active compounds and industrial chemicals.(Guo et al., 2015) The development of copper -based catalytic system has significantly contributed to green chemistry by minizing waste generation and reducing energy consumption.

2. Properties and Oxidation States of Copper

Copper exihibits variable oxidation states (Allen et al., 2013)
Cu(0) metallic Copper
Cu(l) Cuprous state
Cu(ll) cupric states
Cyclic mechanism of copper base catalysed reaction are as follows (Punniyamurthy et al., 2005)
Electron transfer
Redox reaction

Radical mechanism
This versatility is a key to its effectiveness in organic transformations

3. Types of Copper Catalysed Organic Transformation

3.1 C-C Bond formation

Cu Catalyst are used in :

Ullmann reaction : it is used to synthesise biary compound or other Coupled product (Monnier & Taillefer, 2009)

Glaser Coupling : Alkyne homocoupling (to form carbon-carbon bonds between terminal alkynes)

Copper catalysts are used in:
Ullmann-type coupling reactions
Glaser coupling (alkyne homocoupling)
These reactions are essential for constructing complex carbon framework

3.2 C-N Bond Formation

Copper catalysis plays a vital role in amination reactions:
Cu Catalysis plays a vital role in amination reactions :
Ullmann amination (Davis et al., 2024)
Chan- Lam coupling
Applications :
Synthetis of aryl amines
Pharmaceutical intermediates

3.3 C-O Bond Formation

Copper-catalyzed etherification reactions:
Etherfication reaction can be carried out in the presence of Cu catalyst
Aryl halide + alcohol -----------→ Ethers
Applications :
Drug Synthesis
Polymer Chemistry

3.4 C-S Bond Formation

Thiolation reactions:
Thiolation reaction
Aryl Halide + thiols → Thioether
Application:
Agrochemicals (Evano et al., 2008)
Sulfur- containing drugs

4. Mechanicstics Aspect of Copper Catalysis

Copper Catalysed organic reactions proceeds through different mechanism depending on oxidation states.(Hoover, 2025)

4.1 Oxidative Addition – Reductive Ellimination

Common in Cu (l) / Cu (III) cycles
Form new bonds efficiently

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4.2 Single Electron Transfer (SET) Mechanism

Involves radical intermediates

Common in Cu(II) systems

4.3 Ligands- Assisted Catalysis

Ligand Stabilize Copper Intermediates

Improve Selectivity and reaction rate

5. Role of ligands in Cu Catalysis :

Ligands enhance catalytic performance by:

Ligands increase catalytic performance by :

Stabilizing oxidation states

Increasing Solubility

Improving selectivity

Common ligands

Amino Acid

Diamines

Phosphines

6. Green Chemistry and Sustainable Approaches (Li & Trost, 2008)

Recent developments emphasize eco-friendly synthesis:

6.1 Green Solvents

Water

Ethanol

Ionic Liquids

6.2 Solvent- Free Reaction

Minimize environmental pollution

Improve efficiency

6.3 recyclable catalyst

Heterogeneous copper catalyst

Nanoparticle -based System

7. Applications

7.1 Pharmaceutical Industry

7.1 Pharmaceutical Industry

Synthesis of antibiotics

Synthesis of Antibiotics

Anti-inflammatory Drugs

Anticancer Agents

7.2 Agrochemicals

Pesticides

Herbicides

7.3 Material Science

Polymers

Functional Materials

Electronic Materials

DOI: 10.48175/IJARSCT-33153

ISSN: 2581-9429 Volume 6, Issue 8, April 2026 Impact Factor: 8.2

8. Advantages of Copper Catalysis

Low cost and abundance

Mild reaction conditions

High Functional Group Tolerance

Environmentally friendly

9. Limitation :

Lower reactivity compared to noble metals in some cases

Sensitivity to air /moisture in certain system

Side reactions in radical pathways

10. Recent Advances

Development of Copper nanoparticle as catalyst

Photoredox Cu Catalysis

Bio-inspired Catalytic System

Bio-inspired catalytic systems

11. Future Perspective :

Future research directions include:

Future research direction include :

Designing more efficient ligand system

Improving Catalyst recyclability

Expanding industrial applications

Developing greener and safer protocols

12. Conclusion

Copper-catalysed organic transformations have revolutionised synthetic chemistry by providing cost-effective, sustainable and versatile alternatives to conventional catalysts. Their ability to facilitates a brode range of bond formation reaction under mild conditions make them indispensable in modern organic synthesis. Continued advancement in Copper catalyst will further strengthen its role in green and industrial chemistry.

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