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REVIEW

Green Synthesis of Copper Nanoparticles, Characterization, Recent Progress and Applications: An Overview

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Sustainable and environmentally friendly nanomaterials are in greater demand, which has sparked interest in green synthesis of metal nanoparticles. In recent years, copper nanoparticles (CuNPs) have emerged as promising materials owing to their outstanding physico-chemical and biological attributes and economic viability. To promote safer and more sustainable synthesis approaches, green synthesis methods have been developed using plant extracts and other biological resources as natural reducing and capping agents. The structural and morphological characteristics of the synthesized CuNPs are generally analyzed with various techniques like X-ray diffraction (XRD), scanning electron microscopy (SEM), transmission electron microscopy (TEM) and ultraviolet–visible (UV-Vis) spectroscopy. The wide range of uses of copper nanoparticles is also covered in this review, with special attention paid to their antibacterial, antifungal, antiviral and anticancer activity. Standardizing green synthesis procedures and increasing production while preserving the stability, homogeneity and reproducibility of nanoparticles is a crucial research need, despite the fact that numerous studies have shown. Future studies should also look into long-term environmental effects and synergistic processes in biomedical applications. By encompassing these perspectives, the present review aims to offer an in-depth understanding of green synthesis strategies for CuNPs and their role in fostering sustainable nanotechnological innovations.

Keywords: Sustainable synthesis, Plant extracts, Copper nanoparticles, Anticancer, Antimicrobial.

INTRODUCTION

Nanomaterials, characterized by their nanoscale dimensions, possess unique physico-chemical properties that distinguish them from their bulk counterparts and enable a wide range of advanced applications. Nanoparticles have a wide variety of applications, including medicinal treatments, the manufacturing of solar as well as oxide fuel battery for storing energy and their widespread integration into many daily products like clothing and cosmetics [1]. The creation of these environmentally acceptable techniques for nanoparticle synthesis is becoming into a significant area of nanotechnology, particularly for metallic nanoparticles, which have numerous uses [2]. The majority of nanoparticle manufacturing methods use chemical, biological and physical processes, which are costly and emit dangerous substances that seriously pollute the environment [3].

A number of classification schemes have been developed to arrange materials with a nanoscale size [4]. Based on the properties like size, shape, activity or the kind of material the nanoparticles can be categorised [5]. According to their constituent materials, nanoparticles are categorized as inorganic nanoparticles and organic nanoparticles [6]. The inorganic nanoparticles are sub-divided into carbon-based nanoparticles, metal and metal oxide nanoparticles, semiconducting nanoparticles, quantum dots and ceramic nanoparticles [7]. The organic nanoparticles are classified into polymeric nanoparticles and biomolecule derived nanoparticles [8].

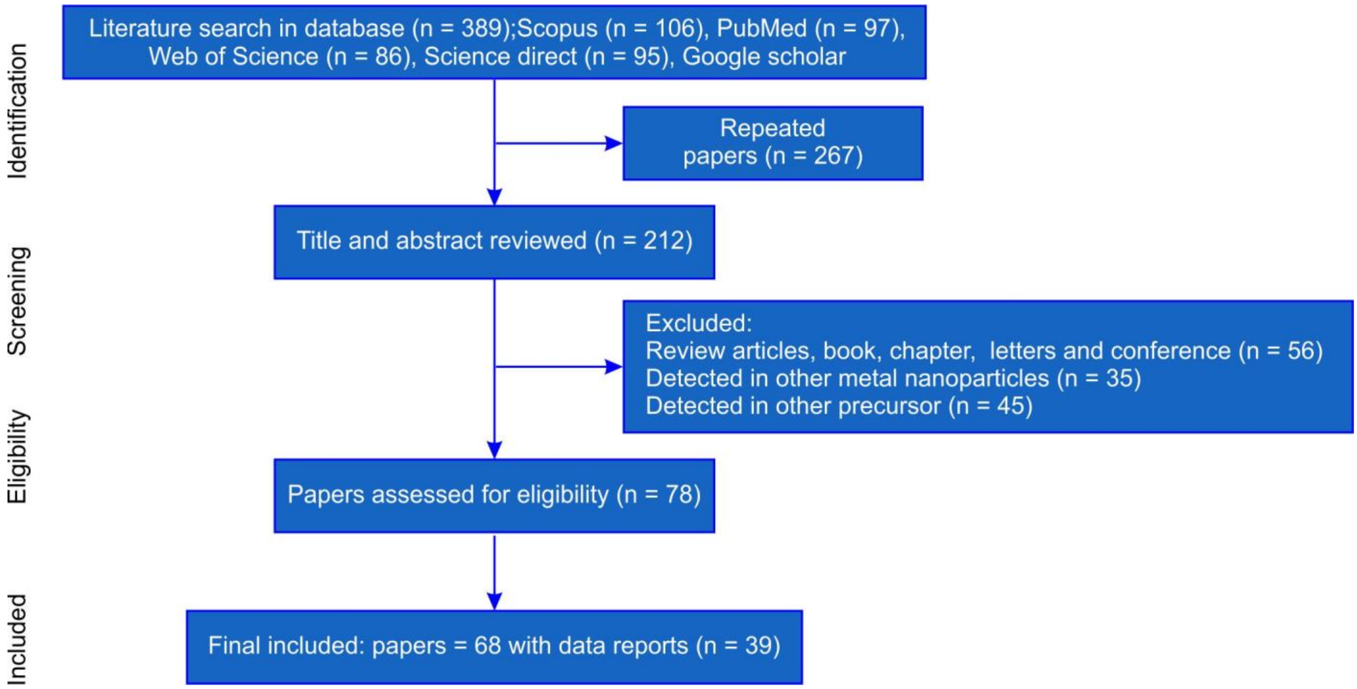

Fig. 1. Selection process of papers based on PRISMA

Based on their physical properties, shape, size and synthesis technique, researchers are actively developing the metal nanoparticles with distinct architectures and functional characteristics. Such efforts underscore the importance of sustainable nanotechnology as a solution to the limitations and environmental concerns associated with conventional nanoparticle synthesis methods [9]. In this review, copper nanoparticles (CuNPs) are highlighted due to their remarkable applications and inherent challenges [10]. Plant-based synthesis methods are emphasized as a sustainable approach to advance nanotechnology in an eco-friendly manner [11]. The synthesis of CuNPs can be broadly classified into physical and chemical techniques. In physical synthesis, bulk materials are broken down through pulverization or acidic treatments [12]. While this approach successfully produces nanoparticles, it requires continuous energy input and typically generates particles larger than 100 nm, which may disrupt system equilibrium [13].

Monoclinic semiconducting copper nanoparticles (CuNPs) have a variety of uses. These nanoparticles, characterized by a broad and direct band gap of 1.2-2.1 eV [14], are widely utilized in solar-powered devices, batteries and gas sensors due to their excellent optoelectronic properties. Moreover, their strong photocatalytic and antimicrobial activities make them effective in water purification systems, as well as in the formulation of antimicrobial agents, algaecides, weed killers and anti-fouling coatings [15-17]. Encouraging efforts toward this goal include the investigation and use of biological possessions that exist in the production of eco-friendly metal nanoparticles [18]. Plants, fungi, viruses and bacteria have become increasingly key sources for the cost-effective and ecologically friendly production of non-toxic nanoparticles in recent years. The development of nanomedicines has recently involved the use of a variety of nanostructures, including neocrystalline, liposomes, carbon nanotubes, metals and metal oxides and nanobiomolecules [19].

The selection methodology for the relevant studies was conducted using specific keywords such as copper nanoparticles (CuNPs), green synthesis, plant extract, *etc*. The flowchart based on PRISMA is given in Fig. 1. This review encompasses findings from 107 research papers on copper nanoparticles, with their trends and distribution visually summarized in Fig. 2, highlighting the breadth of current research in the field.

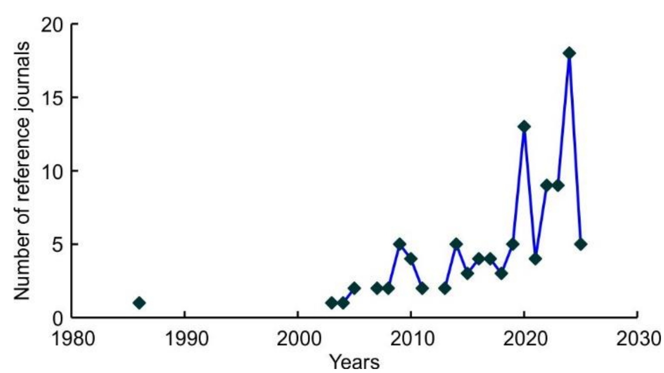

Fig. 2. Graphical representation of reviewed copper nanoparticles research papers

Importance of copper nanoparticles: Copper nanoparticles (CuNPs) are highly valued for their strong antibacterial and antifungal properties, making them indispensable in biological and healthcare applications [20,21]. Their antimicrobial efficacy is largely attributed to the generation of reactive oxygen species and the disruption of microbial cell membranes [22]. Beyond their biological role, CuNPs have shown promising activity against tumor cells, highlighting their potential in anticancer therapy [23]. In addition to biomedical applications, CuNPs play a crucial role in catalysis, facilitating reduction, oxidation and coupling reactions. Their high catalytic efficiency is a direct result of their large surface-area-to-volume ratio [24]. Furthermore, the intrinsic stability and excellent electrical conductivity of CuNPs make them attractive candidates for advanced sensor technologies and supercapacitors [25].

Limitations of conventional method of synthesis: The development of nanotechnology has been greatly aided by the traditional processes for creating CuNPs, including chemical reduction, electrochemical procedures and physical methods (such as laser ablation and evaporation-condensation). However, the cost, operational complexity and environmental impact of these methods are drawing more and more criticism [26]. Green synthesis is less effective for mass production since it frequently takes longer than chemical processes [27]. The final product may also aggregate or need further purification [28]. Moreover, a lot of plant-based pathways have issues with standardization, reproducibility and scalability [29]. Despite its potential, microbial synthesis, sterile conditions and labour-intensive culture was maintained [30]. These challenges highlight the need for deeper mechanistic studies and improved control strategies.

Factors affecting synthesis: The durability, shape and efficiency of CuNPs produced using green technologies are influenced by a number of parameters [31]. The nature and concentration of the biological reducing agent (plant extract or microbe) are the most important factors [32]. The amounts of proteins, flavonoids and polyphenols, which function as stabilizing and reducing agents will vary among plants. The size and shape of the particles are also greatly influenced by the pH of the reaction media. The smaller and more homogeneous nanoparticles are frequently preferred at higher pH values [33].

Green synthesis of CuNPs assisted by plants: Different plant parts, including the fruit, seed, stem, callus, leaves, bark and flowers are used in plant-mediated green synthesis processes to produce metal nanoparticles of various sizes and forms [34-37]. When extracts from various plant species and components are combined with metal salts, nanoparticles of various sizes, shapes, compositions and activities are produced [38-40].

Numerous factors such as pH, temperature, length, concentration of metal salts and photochemical composition of plant leaf particles, affect the quality, stability, quantity and yield rate of nanoparticles. Due to the existence of water-soluble phytochemicals, plants reduce metal ions more quickly [41]. In the synthesis of nanoparticles, ketones, terpenoids, amides, flavones, carboxylic acids and aldehydes are the key phytochemicals [42]. The quinones and plastohydroquinone molecules found in plant leaf extract may assistance in the metal ion reduction process. This suggests that heterocyclic compounds and biomolecules in plants are capable of carrying out the extracellular MNP synthesis [43].

From leaf extract: The gel of *Aloe vera* leaves was used to synthesize CuNPs [44]. Table-1 summarizes various plant leaf extracts used for the green synthesis of copper CuNPs and their corresponding applications. Different precursors such as copper nitrate, copper sulphate and copper chloride were employed, yielding nanoparticles of diverse shapes and sizes as observed through SEM/TEM analysis. The particle morphology ranges from spherical to cubic and rod-like structures, typically within the nanometer scale. It also emphasizes the multifunctional nature of CuNPs including antibacterial, antioxidant, photocatalytic and biomedical activities. These findings highlight the pivotal influence of plant species and synthesis parameters on the resultant physico-chemical attributes, structural morphology and functional performance of CuNPs.

From fruit extract: Various fruit-derived biomolecules acted as natural reducing and stabilizing agents, influencing the morphology and functionality of the synthesized nanoparticles. The CuNPs made from *Phyllanthus embilica* or goose berry, exhibit a crystalline shape and SEM and XRD analyses revealed that the CuNPs possessed an FCC structure with an average size ranging from 15 to 30 nm [56]. Table-2 presents a summary of fruit extracts utilized for the green synthesis of CuNPs and their corresponding applications. The CuNPs exhibited diverse structures such as spherical and rod-shaped forms with sizes typically ranging from 23 to 31 nm. These nanoparticles demonstrated significant biological activities, including antioxidant, antimicrobial, cytotoxic and photocatalytic properties. The data collectively emphasize the poten-

TABLE-1
LIST OF LEAF EXTRACTS USED FOR SYNTHESIS OF COPPER NANOPARTICLES AND THEIR APPLICATIONS

Name of the plant	Precursor	Application	SEM/TEM	Ref.
Azadirachta indica	Cupric chloride dihydrate	Antibacterial activity	Crystalline, cubical shape, size (48 nm)	[2]
Celastrus paniculatus	Copper(II) sulphate pentahydrate	Antibacterial activity	Spherical shape, size (2-10 nm), diameter (5 nm)	[45]
Arundinariagigantea	Cupric nitrate trihydrate	Photocatalytic applications	Monoclinic structure, size (36 nm)	[46]
Cupressocyparis leylandii	Copper sulphate pentahydrate	Antibacterial activity	Small spherical shape, size (17.08 nm)	[47]
Rubus glaucus Benth	Copper nitrate	Antioxidant	Spherical and of partial crystalline nature, size (13-25 nm)	[48]
Cissus vitiginea	Copper sulphate pentahydrate	Antioxidant activity	Spherical shape, size (5-20 nm)	[49]
Syzygium Cumin	Copper sulphate pentahydrate	Control the growth of human pathogens	Rod shape, size (10 µm)	[50]
Rosmarinus officinalis	Copper(II) Nitrate trihydrate	Antimicrobial activity	Spherical in shape, size (18 to 26 nm)	[51]
Alstoniascholaris	Copper sulphate	Antimicrobial activity	Irregular shapes, size (22-34 nm)	[52]
Jatropha Curcas	Copper chloride	Antibacterial activity	Spherical shape, size (12 1 nm)	[53]
Euphorbia serpens	Copper(II) acetate	Biomedical applications	Cube shape, size (20.39 nm)	[54]
Ecliptaprostrata	Copper acetate	Therapeutic application	Spherical shape, size (23-57 nm)	[55]

TABLE-2
LIST OF FRUIT EXTRACTS USED FOR SYNTHESIS OF COPPER NANOPARTICLES WITH THEIR APPLICATIONS

Name of the plant (fruit)	Precursor	Application	Morphology	Ref.
Rubus glaucus Benth	Copper nitrate	Antioxidant efficacy CuO-NPs showed 89.02%	Spherical shape, size (23-31 nm)	[48]
Punica granatum juice	Copper sulphate	Biomedical field	56 to 59 nm	[57]
Solanum macrocarpon	Copper acetate	Highly electroactive,	Spherical shape, size (~30 nm)	[58]
Citrus limon	Copper sulphate pentahydrate	antimicrobial activity	Rod shape, (~30 nm)	[59]
Abelmoschus esculentus	Copper(II) nitrate tri hydrate	Cytotoxicity and photocatalytic applications	Spherical shape, size (25 nm)	[60]
Amomum subulatum	Copper(II) sulphate	Cancer therapy	Rod shape, size (26.04 nm)	[61]

tial of fruit-based synthesis as an eco-friendly and efficient approach for producing functionally diverse CuNPs.

From seed extract: Seed extracts have emerged as an efficient alternative to conventional chemical stabilizers and reducing agents, offering a simple, single-step route for the green synthesis of metal nanoparticles (MNPs). They present a cost-effective and sustainable option compared to other biological approaches, owing to their low maintenance requirements, independence from controlled cultivation and rich diversity of phytochemicals that act as natural reducing and capping agents [62]. With *Caesalpinia bonducella* seed extract and a green synthesis method, CuNPs were produced. The presence of several components, such as flavonoids citrulline, phytosterinin and β-carotene, which act as reducing, stabilizing and capping agents [63]. Table-3 summarizes the use of various seed extracts for the biosynthesis of CuNPs, detailing their precursors, applications and morphological characteristics. The phytochemicals present in the seed extracts serve as effective reducing and capping agents, facilitating a green and sustainable synthesis approach. The resultant CuNPs exhibit a range of morphologies including spherical, rod, and cubic shapes with particle sizes spanning from approximately 6.5 to 98 nm. These biosynthesized nanoparticles demonstrate prominent functional properties such as antibacterial, antioxidant, catalytic degradation and antimicrobial activities.

Characterization techniques: In green synthesis, the bioactive compounds such as flavonoids, alkaloids and polyphenols facilitate the reduction of copper ions (Cu^{2+}) to elemental copper nanoparticles (Cu^0). These phytochemicals function as both reducing and stabilizing agents, preventing nanoparticle agglomeration by capping the particle surfaces. The mechanism typically involves the transfer of electrons from these biomolecules to the metal ions, promoting nucleation and growth of copper nanoparticles [67,68]. Table-4 presents various characterization techniques used for detecting CuNPs. Each method serves a specific purpose in confirming synthesis, identifying the characteristic functional groups, determining crystal structure and examining morphology. UV–Vis spectroscopy verifies nanoparticle formation through surface plasmon resonance peaks, while FTIR spectroscopy identifies the functional groups responsible for reduction and stabilization. XRD analysis provides insights into crystallinity and phase purity and SEM/TEM analyses reveal the CuNPs' size, shape and surface distribution. Collectively, these techniques ensure a comprehensive understanding of CuNPs properties and quality.

Applications: CuNPs possess significant antibacterial properties; however, their aerosolized delivery can cause cellular damage and provoke severe inflammatory responses. Surface modification of metal nanoparticles with biocompatible polysaccharides, such as chitosan, which also exhibits antibacterial activity, has been shown to reduce this toxicity [69]. Coating CuNPs with mucoadhesive polysaccharides like chitosan can enhance their potential for controlled copper ion release, although inhalation exposure may still exacerbate inflammatory effects [70]. In agricultural applications, trace

TABLE-3
LIST OF SEED EXTRACTS USED FOR SYNTHESIS OF COPPER NANOPARTICLES WITH THEIR APPLICATIONS

Name of the plant (seed)	Precursor	Application	SEM/TEM	Ref.
Caesalpinia bonducella	Copper sulphate	Electrochemical and biological field	13 nm	[63]
Nigella sativa	Copper(II) sulphate	High antibacterial activity	Rod shape, size (98.23 nm)	[64]
Persea americana	Copper(II) sulphate	Antioxidant activity	Spherical shape, size (62.25 nm)	[65]
Moringa stenopetala	Copper(II) nitrate trihydrate	Catalytic degradation	spherical shape, size (6.556 nm)	[66]
Tamarindus Indica	Copper sulphate	Antimicrobial activities	Cube shape, size (67 nm to 90 nm)	[66]

TABLE-4
CHARACTERISTICS TECHNIQUES FOR COPPER NANOPARTICLES DETECTION

Technique	Purpose	Key features/indicators
UV-Vis spectroscopy	Confirms nanoparticles synthesis (SPK peak)	Peak at 560-580 nm shows CuNPs; sharp peak = stable; broad = aggregation
FTIR spectroscopy	Identifies functional groups from plant extracts	Peaks at ≈ 3400 cm^{-1} (OH), ≈ 1600 cm^{-1} (C=O or C=C); confirms capping and reduction agents
XRD analysis	Determination of crystalline structure	Shows specific diffraction peaks; confirms the purity and phase
SEM analysis an TEM analysis	Surface morphology & aggregation	Reveals particle shape, texture, distribution

amounts of nanocrystalline iron, cobalt, and copper powders have been reported to improve seed germination, increase chlorophyll content, nodule formation, and overall crop yield [71]. The high natural abundance, low cost, and versatile synthesis routes of copper-based nanomaterials make CuNPs particularly attractive for such uses [72,73].

Medicinal and pharmaceutical applications: CuNPs, characterized by their nanoscale dimensions and high surface-area-to-volume ratio, can efficiently interact with and disrupt microbial membranes, rendering them highly effective in the biomedical applications such as surgical instruments, anti-microbial surface coatings and wound dressings [74]. In addition to their intrinsic antimicrobial activity, CuNPs have shown considerable promise as nanocarriers for drug delivery, enabling the targeted transport and controlled release of therapeutic agents, which can enhance efficacy while minimizing systemic side effects [75,76].

Antimicrobial activity: Strong antibacterial properties are demonstrated by CuNPs against a variety of bacteria, fungi and viruses [77]. The antimicrobial efficacy of CuNPs is influenced by various factors such as particle size, shape, concentration and surface functionalization, which can modulate their interaction with microbial cells [78]. They can readily pass through microbial membranes due to their small size, which causes cellular components to be disupted and ultimately results in cell death. Reactive oxygen species (ROS) produced by CuNPs harm lipids, proteins and DNA in microbial cells [79-81]. Furthermore, CuNPs can synergize with the conventional antibiotics, enhancing their bactericidal effects and potentially reducing the development of antimicrobial resistance [82].

Anticancer activity: The cytotoxic effects of CuNPs on tumour cells have demonstrated their promising potential in cancer therapy [83]. Due to their small size, CuNPs allows efficient cellular uptake and accumulation in tumor tissues, enhancing therapeutic efficacy [84]. CuNPs can induce reactive oxygen species (ROS) generation, causing oxidative stress, DNA damage, and apoptosis in cancer cells while sparing normal cells at controlled doses [85-87]. Furthermore, CuNPs can be functionalized with targeting ligands or drugs to enable selective delivery, improving the specificity and efficiency of anticancer therapy [88]. Their ability to act as photothermal and photodynamic agents further broadens their application in non-invasive cancer treatments [89]. Research has indicated that CuNPs have broad relevance as they have demonstrated efficacy against cell lines of liver, colon and breast cancer [90-92].

Antifungal activity: The copper nanoparticles have effective antifungal properties against variety of plant and human infectious fungi [93,94]. Moreover, CuNPs generate reactive oxygen species (ROS), which harm fungal proteins and DNA and ultimately result in cells death [95,96]. Research has demonstrated its efficacy against fungi such as *Aspergillus niger*, *Candida albicans* and *Fusarium oxysporum* [97-99].

Future perspectives of copper nanoparticles: CuNPs are increasingly recognized for their multifunctional potential in medicine, agriculture and environmental sustainability. Their broad-spectrum antibacterial, antifungal and antiviral properties position them as promising alternatives to traditional medications, particularly in addressing rising antibiotic resistance. In agriculture, CuNPs can serve as nanopesticides or nanofertilizers, improving plant health while reducing chemical inputs and environmental burden [100]. In biomedical applications, CuNPs show potential for targeted drug delivery, anticancer therapy and antimicrobial coatings, with ongoing efforts focused on enhancing biocompatibility and reducing cytotoxicity. Environmentally, their catalytic activity supports water purification, pollutant degradation and heavy metal removal, contributing to sustainable remediation strategies [101-103]. Green and eco-friendly synthesis methods remain a priority to ensure minimal ecological impact. The development of multifunctional CuNPs-based composites and controlled-release systems can further expand their applications across agriculture, medicine and environmental sectors. Future research will need to balance efficacy, safety and sustainability to fully harness the benefits of CuNPs [104].

Conclusion

Copper nanoparticles (CuNPs) have emerged as highly versatile nanomaterials with applications in medicine, agriculture and environmental sustainability. Their potent antibacterial, antifungal and antiviral properties make them strong candidates for replacing or complementing conventional treatments, particularly against antibiotic-resistant microorganisms. In agriculture, CuNPs can improve plant growth and productivity as nano-fertilizers and nano-pesticides while minimizing the use of chemical inputs. Environmentally, they serve as effective agents for water purification, pollutant breakdown, and removal of heavy metals, promoting sustainable remediation. Plant-, fruit- and seed-based green synthesis methods offer environmentally friendly and cost-effective routes to produce CuNPs, though issues such as scalability, reproducibility and standardization need to be addressed. Future studies should aim to refine synthesis techniques, enhance biocompatibility, and develop multifunctional CuNPs-based systems for controlled release. Ensuring a balance between efficiency, safety and environmental sustainability will be essential for the successful integration of CuNPs across diverse scientific and industrial fields.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this article.

REFERENCES

1. A. Abbasi, K. Ghorban, F. Nojoomi and M. Dadmanesh, *Asian Pac. J. Cancer Prev.*, **22**, 893 (2021); https://doi.org/10.31557/APJCP.2021.22.3.893
2. N. Nagar and V. Devra, *Mater. Chem. Phys.*, **213**, 44 (2018); https://doi.org/10.1016/j.matchemphys.2018.04.007
3. A. Curcio, A. Van de Walle, C. Péchoux, A. Abou-Hassan and C. Wilhelm, *Pharmaceutics*, **14**, 179 (2022); https://doi.org/10.3390/pharmaceutics14010179

4. S. Bayda, M. Adeel, T. Tuccinardi, M. Cordani and F. Rizzolio, *Molecules*, **25**, 112 (2019); https://doi.org/10.3390/molecules25010112
5. V. Chandrakala, V. Aruna and G. Angajala, *Emergent Mater.*, **5**, 1593 (2022); https://doi.org/10.1007/s42247-021-00335-x
6. J. Jeevanandam, A. Barhoum, Y.S. Chan, A. Dufresne and M.K. Danquah, *Beilstein J. Nanotechnol.*, **9**, 1050 (2018); https://doi.org/10.3762/bjnano.9.98
7. C. Buzea and I. Pacheco, in eds.: M. Ghorbanpour, K. Manika and A. Varma, Nanomaterial and Nanoparticle: Origin and Activity, In: Nanoscience and Plant–Soil Systems, Cham: Springer International Publishing, pp. 71–112 (2017).
8. H.L. Kagdada, A.K. Bhojani and D.K. Singh, in eds.: D.K. Singh, S. Singh and P. Singh, An Overview of Nanomaterials: History, Fundamentals and Applications, In: Nanomaterials: Advances and Applications, Singapore: Springer Nature, pp. 1–26 (2023).
9. E.N. Gecer, R. Erenler, C. Temiz, N. Genc and I. Yildiz, *Particul. Sci. Technol.*, **40**, 50 (2022); https://doi.org/10.1080/02726351.2021.1904309
10. L. Leon, E.J. Chung and C. Rinaldi, A Brief History of Nanotechnology and Introduction to Nanoparticles for Biomedical Applications, In: Nanoparticles for Biomedical Applications, Elsevier, pp. 1–4 (2020).
11. B.A. Abbasi, J. Iqbal, J.A. Nasir, S.A. Zahra, A. Shahbaz, S. Uddin, S. Hameed, F. Gul, S. Kanwal and T. Mahmood, *Microsc. Res. Tech.*, **83**, 1308 (2020); https://doi.org/10.1002/jemt.23522
12. M. Rafique, M.B. Tahir, M.S. Rafique and M. Hamza, in eds.: M.B. Tahir, M. Rafique and M. S. Rafique, History and Fundamentals of Nanoscience and Nanotechnology, In: Nanotechnology and Photocatalysis for Environmental Applications in Micro and Nano Technologies., Elsevier, Chap. 1, pp. 1–25 (2020).
13. N. Chakraborty, J. Banerjee, P. Chakraborty, A. Banerjee, S. Chanda, K. Ray, K. Acharya and J. Sarkar, *Green Chem. Lett. Rev.*, **15**, 187 (2022); https://doi.org/10.1080/17518253.2022.2025916
14. A.M.E. Shafey, *Green Process. Synth.*, **9**, 304 (2020); https://doi.org/10.1515/gps-2020-0031
15. S. Naz, A. Gul and M. Zia, *IET Nanobiotechnol.*, **14**, 1 (2019); https://doi.org/10.1049/iet-nbt.2019.0176
16. X. Ma, S. Zhou, X. Xu and Q. Du, *Front Surg.*, **5**, 905892 (2022); https://doi.org/10.3389/fsurg.2022.905892
17. K. Dulta, G.K. Ağçeli, P. Chauhan, R. Jasrotia, P.K. Chauhan and J.O. Ighalo, *Sustain. Environ. Res.*, **32**, 2 (2022); https://doi.org/10.1186/s42834-021-00111-w
18. I. Ijaz, E. Gilani, A. Nazir and A. Bukhari, *Green Chem. Lett. Rev.*, **13**, 223 (2020); https://doi.org/10.1080/17518253.2020.1802517
19. C. Wang, W. Tian, Y. Ding, Y. Ma, Z.L. Wang, N.M. Markovic, V.R. Stamenkovic, H. Daimon and S. Sun, *J. Am. Chem. Soc.*, **132**, 6524 (2010); https://doi.org/10.1021/ja101305x
20. P.K. Tyagi, A. Kumar, A. Mazumder and S. Tyagi, *Precis. Nanomed.*, **6**, 1048 (2023); https://doi.org/10.33218/001c.83932
21. M.C. Crisan, M. Teodora and M. Lucian, *Appl. Sci.*, **12**, 141 (2022); https://doi.org/10.3390/app12010141
22. M. Kushwaha, S. Shankar, D. Goel, S. Singh, J. Rahul, K. Rachna and J. Singh, *Mar. Pollut. Bull.*, **209**, 117109 (2024); https://doi.org/10.1016/j.marpolbul.2024.117109
23. X. Zhang, Y. Li, D. Ouyang, J. Lei, Q. Tan, L. Xie, Z. Li, T. Liu, Y. Xiao, T.H. Farooq, X. Wu, L. Chen and W. Yan, *J. Hazard. Mater.*, **418**, 126288 (2021); https://doi.org/10.1016/j.jhazmat.2021.126288
24. M. Nasrollahzadeh, S.M. Sajadi and M. Maham, *J. Mol. Catal. Chem.*, **396**, 297 (2015); https://doi.org/10.1016/j.molcata.2014.10.019
25. G. Ren, D. Hu, E.W.C. Cheng, M.A. Vargas-Reus, P. Reip and R.P. Allaker, *Int. J. Antimicrob. Agents*, **33**, 587 (2009); https://doi.org/10.1016/j.ijantimicag.2008.12.004
26. O.V. Kharissova, H.V.R. Dias, B.I. Kharisov, B.O. Pérez and V.M.J. Pérez, *Trends Biotechnol.*, **31**, 240 (2013); https://doi.org/10.1016/j.tibtech.2013.01.003
27. K.B. Narayanan and N. Sakthivel, *Adv. Colloid Interface Sci.*, **156**, 1 (2010); https://doi.org/10.1016/j.cis.2010.02.001
28. J. Huang, Q. Li, D. Sun, Y. Lu, Y. Su, X. Yang, H. Wang, Y. Wang, W. Shao, N. He, J. Hong and C. Chen, *Nanotechnology*, **18**, 105104 (2007); https://doi.org/10.1088/0957-4484/18/10/105104
29. H. Bar, D.K. Bhui, G.P. Sahoo, P. Sarkar, S. Pyne and A. Misra, *Colloids Surf. A Physicochem. Eng. Asp.*, **348**, 212 (2009); https://doi.org/10.1016/j.colsurfa.2009.07.021
30. B. Graca, A. Zgrundo, D. Zakrzewska, M. Rzodkiewicz and J. Karczewski, *Curr. Sci.*, **85**, 162 (2003); https://doi.org/10.1016/j.chemosphere.2018.05.022
31. S. Iravani, *Green Chem.*, **13**, 2638 (2011); https://doi.org/10.1039/c1gc15386b
32. V.K. Sharma, R.A. Yngard and Y. Lin, *Adv. Colloid Interface Sci.*, **145**, 83 (2009); https://doi.org/10.1016/j.cis.2008.09.002
33. T.J. Jeetkar, S.P. Khataokar, A.R. Indurkar, A. Pandit and M.S. Nimbalkar, *Adv. Nat. Sci. Nanosci. Nanotechnol.*, **13**, 033004 (2022); https://doi.org/10.1088/2043-6262/ac865d
34. P. Kuppusamy, M.M. Yusoff, G.P. Maniam and N. Govindan, *Saudi Pharm. J.*, **24**, 473 (2016); https://doi.org/10.1016/j.jsps.2014.11.013
35. R.A. Banjara, A. Kumar, R.K. Aneshwari, M.L. Satnami and S.K. Sinha, *Environ. Nanotechnol. Monit. Manag.*, **22**, 100988 (2024); https://doi.org/10.1016/j.enmm.2024.100988
36. S. Panigrahi, S. Kundu, S. Ghosh, S. Nath and T. Pal, *J. Nanopart. Res.*, **6**, 411 (2004); https://doi.org/10.1007/s11051-004-6575-2
37. M. Mohammadi Dargah, P. Pedram, G. Cabrera-Barjas, C. Delattre, A. Nesic, G. Santagata, P. Cerruti and A. Moeini, *Adv. Colloid Interface Sci.*, **332**, 103277 (2024); https://doi.org/10.1016/j.cis.2024.103277
38. N. El Messaoudi, S. Boukhris, A. El Messaoudi, A. Kumar, M. Bilal, and L.F.R. Ferreira, in eds.: A. Kumar, M. Bilal and L.F.R. Ferreira, Green Synthesis of Nanoparticles for Remediation Organic Pollutants in Wastewater By Adsorption; In: Advances in Chemical Pollution, Environmental Management and Protection, Elsevier, vol. 10, Chap. 14, pp. 305–345 (2024).
39. M.K. Sah, B.S. Thakuri, J. Pant, R.L. Gardas and A. Bhattarai, *Sustain. Chem.*, **5**, 40 (2024); https://doi.org/10.3390/suschem5020004
40. M. Pourmadadi, R. Holghoomi, A. shamsabadipour, R. Maleki-baladi, A. Rahdar and S. Pandey, *Plant Nano Biol.*, **8**, 100070 (2024); https://doi.org/10.1016/j.plana.2024.100070
41. O.V. Mikhailov and E.O. Mikhailova, *Materials*, **12**, 3177 (2019); https://doi.org/10.3390/ma12193177
42. A.K. Mittal, Y. Chisti and U.C. Banerjee, *Biotechnol. Adv.*, **31**, 346 (2013); https://doi.org/10.1016/j.biotechadv.2013.01.003
43. J. Kesharwani, K.Y. Yoon, J. Hwang and M. Rai, *J. Bionanoscience*, **3**, 39 (2009); https://doi.org/10.1166/jbns.2009.1008
44. V. Khanna, S. Singh, K. Sudhakar, D.S. Baghel, B. Kumar, S. Wadhawa and N.K. Pandey, *Rasayan J. Chem.*, **17**, 957 (2024); https://doi.org/10.31788/RJC.2024.1738801
45. S.C. Mali, A. Dhaka, C.K. Githala and R. Trivedi, *Biotechnol. Rep.*, **27**, e00518 (2020); https://doi.org/10.1016/j.btre.2020.e00518
46. H.N. Jayasimha, K.G. Chandrappa, P.F. Sanaulla and V.G. Dileepkumar, *Sens. Int.*, **5**, 100254 (2024); https://doi.org/10.1016/j.sintl.2023.100254
47. A. Halfadji, M. Naous, S. Rajendrachari, Y. Ceylan, K.B. Ceylan and P.V.R. Shekar, *J. Mol. Struct.*, **1301**, 137318 (2024); https://doi.org/10.1016/j.molstruc.2023.137318
48. B. Kumar, K. Smita, L. Cumbal, A. Debut and Y. Angulo, *J. Saudi Chem. Soc.*, **21**, S475 (2017); https://doi.org/10.1016/j.jscs.2015.01.009
49. S. Wu, S. Rajeshkumar, M. Madasamy and V. Mahendran, *Artif. Cells Nanomed. Biotechnol.*, **48**, 1153 (2020); https://doi.org/10.1080/21691401.2020.1817053
50. H.R. Aher, S. Vikhe, A. Han and S.R. Kuchekar, *Chem. Sci. Trans.*, **8**, 1 (2019).

51. M.D. Moroda, T. Leta Deressa, A.H. Tiwikrama and T.F. Chala, *Mater.*, **7**, 100337 (2025); https://doi.org/10.1016/j.nxmate.2024.100337
52. A.N. Labaran, Z.U. Zango, G. Tailor, A. Alsadig, F. Usman, M.T. Mukhtar, A.M. Garba, R. Alhathlool, K.H. Ibnaouf and O.A. Aldaghri, *Sci. Rep.*, **14**, 5589 (2024); https://doi.org/10.1038/s41598-024-56052-y
53. M.K. Ghosh, S. Sahu, I. Gupta and T.K. Ghorai, *RSC Advances*, **10**, 22027 (2020); https://doi.org/10.1039/D0RA03186K
54. S. Idrees, B.A. Abbasi, J. Iqbal and M. Kazi, *Heliyon*, **11**, e41397 (2025); https://doi.org/10.1016/j.heliyon.2024.e41397
55. I. Chung, A. Abdul Rahuman, S. Marimuthu, A. Vishnu Kirthi, K. Anbarasan, P. Padmini and G. Rajakumar, *Exp. Ther. Med.*, (2017); https://doi.org/10.3892/etm.2017.4466
56. B. Graca, A. Zgrundo, D. Zakrzewska, M. Rzodkiewicz and J. Karczewski, *Chemtech*, **9**, 498 (2018); https://doi.org/10.1016/j.chemosphere.2018.05.022
57. N. Padma, S. Banu and S. Kumari, *Annu. Res. Rev. Biol.*, **23**, 1 (2018); https://doi.org/10.9734/ARRB/2018/38894
58. E.C. Okpara, O.E. Ogunjinmi, O.A. Oyewo, O.E. Fayemi and D.C. Onwudiwe, *Heliyon*, **7**, e08571 (2021); https://doi.org/10.1016/j.heliyon.2021.e08571
59. M. Akl Awaad, *ResearchGate*, **7**, 1 (2025); https://doi.org/10.5281/zenodo.4017993
60. M.J. Javid-Naderi, Z. Sabouri, A. Jalili, H. Zarrinfar, S. Samarghandian and M. Darroudi, *Environ. Technol. Innov.*, **32**, 103300 (2023); https://doi.org/10.1016/j.eti.2023.103300
61. S. Dhir, R. Dutt, R.P. Singh, M. Chauhan, T. Virmani, G. Kumar, A. Alhalmi, M.S. Aleissa, H.A. Rudayni and M. Al-Zahrani, *Processes*, **11**, 2698 (2023); https://doi.org/10.3390/pr11092698
62. K. Bhardwaj, C. Chopra, P. Bhardwaj, D.S. Dhanjal, R. Singh, A. Najda, N. Cruz-Martins, S. Singh, R. Sharma, K. Kuča and S. Manickam, *J. Nanotechnol.*, **2022**, 2271278 (2022); https://doi.org/10.1155/2022/2271278
63. S. Sukumar, A. Rudrasenan and D. Padmanabhan Nambiar, *ACS Omega*, **5**, 1040 (2020); https://doi.org/10.1021/acsomega.9b02857
64. M. Kumar, D. Kaushik, A. Kumar, P. Gupta, C. Proestos, E. Oz, E. Orhan, J. Kaur, M.R. Khan, T. Elobeid, M. Bordiga and F. Oz, *Int. J. Food Sci. Technol.*, **58**, 2883 (2023); https://doi.org/10.1111/ijfs.16359
65. F.M. Ibrahim, D.A. Najeeb and H. ThamerSadeq, *Mater. Sci. Energy Technol.*, **6**, 130 (2023); https://doi.org/10.1016/j.mset.2022.12.006
66. H. Majeed, K. Ahmad, S. Bibi, T. Iftikhar, M.M. Ibrahim, T. Ruby, G.A.M. Mersal, Z.M. El-Bahy, K. Qureshi, M. Arif, K. Naseem, S. Shaheen and H.N. Bhatti, *Heliyon*, **10**, e30927 (2024); https://doi.org/10.1016/j.heliyon.2024.e30927
67. D. Paramelle, A. Sadovoy, S. Gorelik, P. Free, J. Hobley and D.G. Fernig, *Analyst (Lond.)*, **139**, 4855 (2014); https://doi.org/10.1039/C4AN00978A
68. N. Kulkarni and U. Muddapur, *J. Nanotechnol.*, **2014**, 510246 (2014); https://doi.org/10.1155/2014/510246
69. J.P. Ruparelia, A.K. Chatterjee, S.P. Duttagupta and S. Mukherji, *Acta Biomater.*, **4**, 707 (2008); https://doi.org/10.1016/j.actbio.2007.11.006
70. T. Kruk, K. Szczepanowicz, J. Stefańska, R.P. Socha and P. Warszyński, *Colloids Surf. B Biointerfaces*, **128**, 17 (2015); https://doi.org/10.1016/j.colsurfb.2015.02.009
71. N. Cioffi, L. Torsi, N. Ditaranto, G. Tantillo, L. Ghibelli, L. Sabbatini, T. Bleve-Zacheo, M. D'Alessio, P.G. Zambonin and E. Traversa, *Chem. Mater.*, **17**, 5255 (2005); https://doi.org/10.1021/cm0505244
72. A. Jafari, L. Pourakbar, K. Farhadi, L. Mohamadgolizad and Y. Goosta,, *Turk. J. Biol.*, **39**, 556 (2015); https://doi.org/10.3906/biy-1406-81
73. M.X. Zhang, F. Verhoeven, P. Ravensbergen, S. Kooij, R. Geoffrion, D. Bonn and C.J.M. van Rijn, *Pharmaceuticals*, **16**, 2 (2023); https://doi.org/10.3390/pharmaceutics16010002
74. R. Sankar, R. Maheswari, S. Karthik, K.S. Shivashangari and V. Ravikumar, *Mater. Sci. Eng. C*, **44**, 234 (2014); https://doi.org/10.1016/j.msec.2014.08.030
75. M. Pourmadadi, R. Holghoomi, A. Shamsabadipour, R. Maleki-baladi, A. Rahdar and S. Pandey, *Plant Nano Biol.*, **8**, 100070 (2024); https://doi.org/10.1016/j.plana.2024.100070
76. M.J. Woźniak-Budych, K. Staszak and M. Staszak, *Molecules*, **28**, 6687 (2023); https://doi.org/10.3390/molecules28186687
77. D. Xu, E. Li, B. Karmakar, N.S. Awwad, H.A. Ibrahium, H.-E.H. Osman, A.F. El-kott and M.M. Abdel-Daim, *Arab. J. Chem.*, **15**, 103638 (2022); https://doi.org/10.1016/j.arabjc.2021.103638
78. Z. Edis, S. Haj Bloukh, A. Ashames and M. Ibrahim, in eds.: P. Ramasami, M. Gupta Bhowon, S. Jhaumeer Laulloo, and H. Li Kam Wah, Copper-Based Nanoparticles, Their Chemistry and Antibacterial Properties: A Review. In: Chemistry for a Clean and Healthy Planet. ICPAC 2018. Springer, Cham (2019).
79. M. Maliki, I.H. Ifijen, E.U. Ikhuoria, E.M. Jonathan, G.E. Onaiwu, U.D. Archibong and A. Ighodaro, *Int. Nano Lett.*, **12**, 379 (2022); https://doi.org/10.1007/s40089-022-00380-2
80. P. Ghasemi, G. Shafiee, N. Ziamajidi and R. Abbasalipourkabir, *Biol. Trace Elem. Res.*, **201**, 3746 (2023); https://doi.org/10.1007/s12011-022-03458-2
81. P. Ponmurugan, K. Manjukarunambika, V. Elango and B.M. Gnanamangai, *J. Exp. Nanosci.*, **11**, 1019 (2016); https://doi.org/10.1080/17458080.2016.1184766
82. M. Selvarani, *Int. J. Pharm. Pharmaceut. Sci.*, **10**, 83 (2018).
83. P. Kanhed, S. Birla, S. Gaikwad, A. Gade, A.B. Seabra, O. Rubilar, N. Duran and M. Rai, *Mater. Lett.*, **115**, 13 (2014); https://doi.org/10.1016/j.matlet.2013.10.011
84. A.G. Krishna, S. Sahana, H. Venkatesan and V. Arul, *J. Egypt. Natl. Canc. Inst.*, **36**, 44 (2024); https://doi.org/10.1186/s43046-024-00254-y
85. Y. Wei, S. Chen, B. Kowalczyk, S. Huda, T.P. Gray and B.A. Grzybowski, *J. Phys. Chem. C*, **114**, 15612 (2010); https://doi.org/10.1021/jp1055683
86. W. Huang, H. Fang, S. Zhang and H. Yu, *Micro & Nano Lett.*, **16**, 374 (2021); https://doi.org/10.1049/mna2.12060
87. N.-D. Pham, M.-M. Duong, M.-V. Le, H.A. Hoang and L.-K.-O. Pham, *C. R. Chim.*, **22**, 786 (2019); https://doi.org/10.1016/j.crci.2019.10.007
88. M. Zhou, M. Tian and C. Li, *Bioconjugate Chem.*, **27**, 1188 (2016); https://doi.org/10.1021/acs.bioconjchem.6b00156
89. F. Qi, Y. Chang, R. Zheng, X. Wu, Y. Wu, B. Li, T. Sun, P. Wang, H. Zhang and H. Zhang, *ACS Biomater. Sci. Eng.*, **7**, 2745 (2021); https://doi.org/10.1021/acsbiomaterials.1c00189
90. M.F. Al-Hakkani, *SN Appl. Sci.*, **2**, 505 (2020); https://doi.org/10.1007/s42452-020-2279-1
91. M.J. Woźniak-Budych, K. Staszak and M. Staszak, *Molecules*, **28**, 6687 (2023); https://doi.org/10.3390/molecules28186687
92. M. Al-zharani, A.A. Qurtam, W.M. Daoush, M.H. Eisa, N.H. Aljarba, S. Alkahtani and F.A. Nasr, *Environ. Sci. Pollut. Res*., **28**, 1587 (2021); https://doi.org/10. 1007/s11356-020-09843-5
93. M.C. Crisan, M. Teodora and M. Lucian, *Appl. Sci*., **12**, 141 (2022); https://doi.org/10.3390/app12010141
94. A.R.M. Al-Qaissi, S.H. Fouzi and A.J. Al-Baytay, *IOP Conf. Ser. Earth Environ. Sci*., **1214**, 012010 (2023); https://doi.org/10.1088/1755-1315/1214/1/012010
95. A. Martínez, C. Apip, M.F. Meléndrez, M. Domínguez, G. Sánchez-Sanhueza, T. Marzialetti and A. Catalán, *J. Appl. Microbiol.*, **130**, 1883 (2021); https://doi.org/10.1111/jam.14859
96. K.A. Mosa, M. El-Naggar, K. Ramamoorthy, H. Alawadhi, A. Elnaggar, S. Wartanian, E. Ibrahim and H. Hani, *Front. Plant Sci*., **9**, 872 (2018); https://doi.org/10.3389/fpls.2018.00872
97. D. Devipriya and S.M. Roopan, *Mater. Sci. Eng. C*, **80**, 38 (2017); https://doi.org/10.1016/j.msec.2017.05.130
98. S.E.-D. Hassan, S.S. Salem, A. Fouda, M.A. Awad, M.S. El-Gamal and A.M. Abdo, *J. Radiat. Res. Appl. Sci.*, 11, 262 (2018); https://doi.org/10.1016/j.jrras.2018.05.003

99. S.Y. Ramy and F.A. Osama, *Afr. J. Microbiol. Res*., **7**, 1917 (2013).
100. A.P. Ingle and M. Rai, *IET Nanobiotechnol*., **11**, 546 (2017); https://doi.org/10.1049/iet-nbt.2016.0170
101. J.O. Ighalo, P.A. Sagboye, G. Umenweke, O.J. Ajala, F.O. Omoarukhe, C.A. Adeyanju, S. Ogunniyi and A.G. Adeniyi, *Environ. Nanotechnol., Monit. Manag.*, **15**, 100443 (2021); https://doi.org/10.1016/j.enmm.2021.100443
102. S. Bonthula, S.R. Bonthula, R. Pothu, R.K. Srivastava, R. Boddula, A.B. Radwan and N. Al-Qahtani, *Sustain. Chem.*, **4**, 246 (2023); https://doi.org/10.3390/suschem4030019
103. A. El Din Mahmoud, K.M. Al-Qahtani, S.O. Alflaij, S.F. Al-Qahtani and F.A. Alsamhan, *Sci. Rep.*, **11**, 12547 (2021); https://doi.org/10.1038/s41598-021-91093-7
104. L. Dorjee, R. Gogoi, D. Kamil, R. Kumar, T.K. Mondal, S. Pattanayak and B. Gurung, *Front. Microbiol*., 14, 1204512 (2023); https://doi.org/10.3389/fmicb.2023.1204512