Asian Journal of Chemistry; Vol. 36, No. 2 (2024), 263-274

ASIAN JOURNAL OF CHEMISTRY

https://doi.org/10.14233/ajchem.2024.28417

REVIEW

Synthesis and Nanotechnological Applications of Multi-Efficient Zinc Oxide Nanoparticles-A Review

AZAD YADAV[1], SHIVANI NARWAL[1], TAMANNA DESWAL[1], ANKIT SINDHU[1], RAHUL LANGYAN[1], NARENDER KUMAR[2], SASHI YADAV[3], RENU BALA[3] and RAJESH DHANKHAR[1,*]

[1]Department of Environmental Sciences, Maharshi Dayanand University, Rohtak-124001, India
[2]Ministry of Environment Forest and Climate Change, New Delhi-110003, India
[3]Department of Applied Science, University Institute of Engineering and Technology, Maharshi Dayanand University, Rohtak-124001, India

*Corresponding author: E-mail: rajeshdhankhar669@gmail.com

Received: 9 August 2023; *Accepted*: 2 December 2023; *Published online*: 31 January 2024; AJC-21512

Nanotechnology focuses on the development and application of materials with nanoscale dimensions. Zinc oxide nanoparticles are the ones that have the potential to play an important role in different fields like antimicrobial, antioxidant, photocatalysis, agriculture, rubber, textile and environmental remediation because of their cost-effectiveness, easy to use and environmentally safe nature. ZnO nanoparticles have recently been the subject of research due to their broad band width and strong excitation-binding energy. ZnO nanoparticles are synthesized using a variety of physical, chemical and biological processes. Green techniques involving plants, fungi, bacteria and algae have evolved to avoid the rapid release of toxic substances and use of extreme environments for the physical and chemical production of ZnO nanoparticles. This review article aims to summarize the recent work on the formation of ZnO nanoparticles and their applications in various fields.

Keywords: Zinc oxide nanoparticles, Applications, Green synthesis, ZnO applications, Ecofriendly, Large bandgap.

INTRODUCTION

Nanotechnology is the development, characterization and study of materials with a size between 1 and 100 nm and differs significantly from bulk materials based on size-related features. It is a fast-evolving technique with a promising future to completely transform all research fields [1-5]. Nanoparticles are variants of fundamental constituents developed after altering their atomic properties and become vital because of their distinct physical, chemical and magnetic characteristics [6]. The rapidly developing discipline of nanotechnology has the potential to revolutionize every area of study in the near future. [7]. At the nanoscale, materials can undergo transformations in their optical, structural, chemical, electrical, and mechanical properties [8,9]. Metal oxide-based nanoparticles, in particular zinc oxide, copper oxide, titanium oxide and nickel oxide, have received considerable attention due to their non-toxic nature, large quantity, exceptional surface area and thermal and chemical stability [10]. Also, these metal oxides have been utilized in different industrial operations. The large-scale manufacturing of glass and ceramics, rubber and tyres, pharmaceuticals, cosmetics, farming practices, paint and coating used more than 1.4×10^6 tonnes of zinc oxide in 2021. The market of ZnO is expected to attain 6.26 billion USD by 2026, which used to be 4.75 billion USD in 2019 [11]. The worldwide ZnO industry is growing at a 4.03% yearly growth. Zinc oxide nanoparticles is currently the most common kind of zinc nanoparticle (in both research and practice). Each year, an estimated 550 tonnes of ZnO nanoparticls produced in the global market [12,13].

Zinc oxide nanoparticles: ZnO is an inorganic, insoluble and white material present as a zincite mineral in the earth's crust. The majority of manufactured ZnO used for the industrial applications [14,15]. In materials science, ZnO is frequently referred to as an II-VI semiconductor because Zn and O are in 2nd and 6th group of the periodic table, respectively [16]. ZnO is an n-type semiconductor material with a 3.02-3.30 eV band gap, high melting temperature (1975 ºC) and higher binding potential (60 meV) [17]. Despite having a strong piezoelectric effect, ZnO also has a lot of luminescent properties as well as high electron mobility, electrochemical stability and mechanical energy. Its three crystallographic phases are cubic rock salt, hexagonal wurtzite and cubic Zn blend. Wurtzite (a = 3.25 Å, c = 5.12 Å) is the simplest and most prevalent of these phases in which the atom of zinc is bonded with four oxygen atoms tetrahedrally [14].

ZnO has a variety of uses because of its particular chemical, physical and biological characteristics. It is better suited for the advance-level water purification processes because of its cost effectiveness, environmental friendliness and biocompatibility [18,19]. ZnO has been declared safe for use in industries that deal with food by the Food and Drug Administration [20]. Materials such as plastic, glass, ceramic, cement, rubber, dietary supplements, electronics and non-flammable items commonly incorporate them due to their broad range of useful qualities. These qualities include moderate antibacterial activity, excellent electrical and thermal conductivity, exceptional temperature stability and stable pH level [21].

Methods for synthesis of nanoparticles: Usually for the production of nanoparticles, bottom-up and top-down strategies have been considered. Top-down strategies include etching, electro-explosion, sputtering and mechanical milling, whereas bottom-up strategies include three fundamental techniques for generating nanoparticles *viz*. physical, chemical and biological methods [22-24]. In a top-down strategy, large particles are broken into smaller particles with the help of milling or any other instrument. It requires the initial development of large-size particles, which are downsized to a nanoscale level using plastic deformation. This method cannot be used to produce nanoparticles at an industrial scale because it is costly and time consuming [25]. In the bottom-up approach, conventional techniques (physical and chemical methods) are used to synthesize noble, good quality nanoparticles. Still, the procedure is costly and frequently produces harmful byproducts that can have negative effects when used for biological purposes. In these procedures, extracapping and stabilizing agents are also required [26]; this issue is resolved when nanoparticles are synthesized through green approach, a bottom-up plan causing an oxidation/reduction process [27,28]. Large amounts of pure ZnO nanoparticles can be synthesized by adopting green synthesis method, which includes plants, bacteria, fungus, algae, *etc*. [29].

Conventional methods for the synthesis of ZnO nanomaterials: Mechanochemical and chemical processes are the conventional methods for synthesizing metallic nanoparticles, such as ZnO NPs. Classic approaches for the chemical synthesis include hydrothermal, sol-gel, co-precipitation and microemulsion techniques. High-energy ball milling and laser ablation are the examples of mechanochemical synthesis [30]. So there are various methods which are used for the fabrication of ZnO NPs (Table-1). In the following sub-sections, this study briefly discusses the advantages and disadvantages of the conventional ZnO NPs synthesis method as well as some unique and remarkable examples.

Sol gel technique: It is the most typical technique for synthesizing metal oxide nanoparticles as it involves gradual transformation of sol into a solid "gel" phase through hydrolysis and polymerization steps. The gel is then heated to evaporate solvents to obtain the resultant particle [31]. Shrinkage, breakage while drying and a failure to control porosity are a few additional fundamental drawbacks of this method. Despite its drawbacks, this approach remains one of the most popular because the material generated is homogenous; the processing temperature is low and cost effective [32,33].

Abarna *et al.* [34] used the sol-gel approach to produce mesoporous ZnO. The impact of jute fibers on ZnO characteristics was examined. To enhance gelation, $ZnC_4H_6O_4$, oxalic acid, jute fibres, alcohol and ethanol were combined and left overnight. The size of the crystals of the mesoporous ZnO was reduced from 33 to 24 nm by altering the amount of jute fibres from 0 to 1.5 g. As a result, the band gap shrinks to 2.91 eV from 3.02 eV. Davis *et al.* [35] synthesized ZnO using a combination of sol-gel and solvothermal methods. The solvents utilized in the solvothermal production of ZnO nanorods were water, DMF, acetonitrile, dimethyl sulfoxide, toluene, hydroquinone and xylene. The length (1-5 m) and width (50-180 nm) of the nanorods improved when a DMF/water mixture was applied. The diversity in the structure of produced ZnO can be explained by the differing solubilities of various solvents in water. Some of these may have hampered nanorods growth. The DMSO-water mixture produced improper slates with normal lengths ranging from 500 nm to 2 m. Finally, when hydroquinone was used, globular-shaped particles with a mean diameter range of 100-500 nm were created.

Hydrothermal method: Sir R. Murchison coined the term "hydrothermal" to explain the impact of hot water on the Earth's crust [36]. It represents a wet synthesis technique that kept compounds in vessels at temperature above the boiling point of water and under high pressure. The diffusion process can be controlled using this energy-efficient approach, which uses temperature lesser than those used for traditional synthesis processes [37]. The necessary metal oxide is created by the metal precursor in double phase. The metal ions first produce a metal hydroxide, then, the metal oxide is created by dehydrating the metal hydroxide [38]. A subtype of the hydrothermal process called solvothermal synthesis use solvents other than water. The synthesis of ZnO with adjustable crystallite size is found to be simple, affordable and low-temperature by using hydrothermal and solvothermal processes. It is fascinating and effective to use hydrothermal and solvothermal methods to produce various nanogeometries of materials, such as nanorods, nanowires, nanosheets and nanospheres [39]. The pH of the precursor Zn^{2+} solution, the ion concentration, the reaction temperature and the reaction time are just few of the parameters that may be adjusted for synthesis of ZnO through hydrothermal method [40]. These variables have a significant impact on the nucleation and growth rates, which in response affect morphology of resulting ZnO crystal [41-44]. Biron *et al.* [45] used this process to synthesis ZnO NPs with crystallite size of 20 nm. The crystal structure of the synthesized ZnO was hexagonal wurtzite. In addition, the obtained ZnO NPs showed a UV-Vis

TABLE-1
SYNTHESIS OF ZINC OXIDE NANOPARTICLES BY CONVENTIONAL METHODS

Name of method	Precursors used	Precursor conditions	Size (nm)	Shape	Ref.
Sol-gel	$Zn(CH_3COO)_2$, oxalic acid, ethanol and sodium hydroxide, sulphuric acid	Reaction temperature: 60 °C; drying: 100 °C; calcination: 5 h, 500 °C	33-24	Rod-shaped, spherical shaped	[34]
Sol-gel and solvothermal combined	Zinc(II) chloride, NaOH	Reaction: 15 min., room temperature; drying: 100 °C; calcination: 5 h, 500 °C	3-500	Spherical, nanoroads and nanoslates	[35]
Sol-gel	$Zn(CH_3COO)_2$, diethanolamine, ethanol	Reaction: room temperature; annealed of sol: 2 h, 500 °C	70	Nanotubes	[79]
Sol-gel	Zinc acetate dehydrates sodium hydroxide, polyethylene glycol, ethanol	Reaction: 300 °C; Centrifugation: 5000 rpm for 15 min drying: 70 °C	73-395	Nanorods	[80]
Hydrothermal	$Zn(CH_3COO)_2{\cdot}2H_2O$, NaOH	Autoclaving: 200 °C for 24 h, drying: 80 °C for 6 h	9-15	Rod-like, plate-like	[81]
Solvothermal	Zinc nitrate hexahydrate, ethylene glycol, polyvinyl alcohol, NaOH, $Zn(OH)_2$	Heated in reflux at 140 °C for 4 h, centrifugation: 8000 rpm for 15 min, drying: 80 °C for 24 h	20	Hexagonal wurtzite	[45]
Precipitation	Method 1-Zinc acetate dihydrate, KOH, methanol Method 2-Zinc nitrate hexahydrate, N,N-dimethylformamide	Conditions 1 – Reaction: room temperature for 2 h, calcination: 450 °C for 12 h Conditions 2 – drying: 150 °C, calcination: 450 °C for 8 h	19-34	Hexagonal wurtzite	[51]
Precipitation	$ZnCl_2$, NaOH, double distilled water	Reaction – room temperature, pH – 7-8, drying – room temperature for few days, calcination: 350 °C for 30 min	8.1	Hexagonal	[52]
Chemical vapour deposition	Dimethylzinc, oxygen, Nitrogen, acetone, ethanol	Temperature-450 to 500 °C, pressure-25 to 75 Torr, Growth time-25 min	50-250 and 300-500	Nanorods, nanotubes	[82]
Chemical vapour deposition	Zinc acetate & aluminum nitrate, ethanol solvent and nitrogen as carrier gas	Reaction: 400 °C, constant carrier gas (N_2) rate-30 L/h, time of atomization-10 min	39.2-47.3	Irregular, spherical	[83]
Microemulsion	$Zn(NO_3)_2$, $ZnSO_4$, $ZnCl_2$, NaOH	Centrifugation-4000 r/min for 10 min, drying-130 °C for 2 h, calcination-550 °C for 3 h	16	Hexagonal	[57]
Microemulsion	$Zn(NO_3)_2$, NaOH, hexanol, heptane	Hydrothermal treatment-140 °C for 15 h, Centrifugation-5000 rpm, drying-60 °C	Less than 100	Columnar, spherical	[58]
Laser ablation	Laser, NaOH	Wavelength – 532, pulse duration – 10 ns, pulses number-50, pulsed repetition rate-6 Hz	80.76-102.54	Spherical	[63]
Laser ablation	Laser-Q-switched Nd-YAG LASER, distilled water, methanol	Wavelength-1064 nm and pulse duration-6 ns, repetition rate-10 Hz	1-30	Hexagonal wurtzite	[64]
High energy ball milling	ZnO Powder, Zirconia balls	Process temperature – room temperature, milling speed-200 to 600 rpm	200-400	Hexagonal	[68]
Sputtering	Cleaned glass/Si substrates	Base pressure: 9 µTorr, operating pressure: 5 mTorr, argon flow rate-20 sccm, oxygen gas flow rate: 15 sccm	59.90 to 83.95	Hexagonal and cubic ZnO thin films	[71]
Thermal decomposition	$Zn_4(SO_4)(OH)_6{\cdot}H_2O$, ZnO, $NH_3{\cdot}H_2O$ solution, $ZnCl_2$ solution	pH-6 and 11, room temperature for 2 h, dried at 70 °C overnight, calcinated in a muffle furnace at 875 °C for 1 h	80-117	Rod-like, spherical shape	[73]
Lithography	$Zn(CH_3COO)_2{\cdot}2H_2O$, ethanol amine	Reaction – room temperature, Annealing – 300 °C for 10 min	190	Nanorods	[78]

absorption band and a band gap at 344 nm and 3.23 eV, respectively.

Precipitation method: In this process, the interaction of precipitating agent with soluble metal precursor leads to precipitate formation. The KOH, NaOH and NH_4OH are three most often used precipitating agents, as a result, metal hydroxides are frequently generated as precipitates. Several factors influence the precipitate formation, including the nature and amount of the metal salt, precipitating agent, reaction temperature, molar ratio of the precursor salt and base and pH of the solution.

Furthermore, the sequence of reactants in which they are used significantly impacts the morphology of the obtained particle. For example, fewer nuclei of large size are formed when salt is added to the base and more nuclei of smaller size are formed when the base is combined with metal salt. The formation of white $Zn(OH)_2$ precipitates on addition of base to a solution of clear Zn precursor; ZnO nuclei are formed by dehydrating the two -OH groups of $Zn(OH)_2$ [46,47]. This process has a number of advantages, such as ease of use, speed, a low requirement for temperatures and simplified power management [48]. As an aside, this method has one major limitation: it generates nanoparticles with a large number of water molecules tied to them. Furthermore, batch-to-batch repeatability problems, particles of different sizes and high agglomeration are disadvantages [49,50]. Bodke *et al.* [51] formed ZnO by precipitating it with $Zn(CH_3CO_2)_2 \cdot H_2O$ and KOH having a crystallite size of 20 nm [51]. In a different work, Gnanasekaran *et al.* [52] use anhydrous $ZnCl_2$ and NaOH to synthesize ZnO. The obtained ZnO had a hexagonal shape and 8.1 nm crystallite size with surface area of roughly 66 $m^2 g^{-1}$.

Chemical vapour deposition: Chemical vapour deposition (CVD) is the technique of applying a fine layer of reactant species to a substrate. Deposition occurs in a reaction chamber at room temperature by incorporating different gases. A chemical reaction takes place through interaction of a heated substrate and combined gas [53]. This reaction produces a thin layer of product on the surface of substrate, which is regenerated and used again. In CVD, the factor that majorly impacts is substrate temperature. CVD generates very pure, homogeneous, complicated and strong nanoparticles. The difficulties of CVD cover the necessity for specialized equipment and the very hazardous gaseous byproducts [54]. Saravade *et al.* [55] used chemical vapour deposition to develop Mn-doped ZnO. About, 6% Mn can be adjusted inside the lattice of ZnO.

Microemulsion technique: Collisions of water droplets in a microemulsion medium caused reaction of precipitation, which ultimately ended in the creation of nanoparticles having surfactant-stabilized nucleation. The advantages include its ease, high thermal stability and lower aggregation. This approach has various limitations, including the effect of pH and temperature on microemulsion longevity and also the continuous requirement for extremely concentrated surfactants or cosurfactants that may irritate [56]. Wang *et al.* [57] synthesized ZnO NPs of 16 nm in microchannel reactor systems. Following a 2 h drying period at 130 ºC, the calcination of ZnO NPs was performed for 3 h at 550 ºC. Li *et al.* [58] used microemulsion procedure to synthesize ZnO NPs with various morphologies, including columnar and spherical.

Laser ablation technique: This technique removes the surface metallic ions from metal with a beam of laser, a small fraction of ethanol, liquid methanol and pure H_2O. This method can produce a broad range of nanomaterials, such as carbon nanomaterials, metal nanoparticles, ceramics and oxide composites [59,60]. This approach is easy to carry out and also environmentally safe [61], however, pyrolysis residues are still unclear and must be addressed [62]. Al-Dahash *et al.* [63] synthesize ZnO NPs of sizes varying from 80.76 to 102.54 nm by applying laser ablation in NaOH aqueous medium. Farahani *et al.* [64] used the laser ablation method to fabricate ZnO NPs of nearly spherical shape and size varying from 1 to 30 nm in a methanol and distilled water suspension from a zinc source.

High-energy ball milling: It is defined as a technology that generates metal nanoparticles of fine size inside an elevated shaker mill [65]. Its main benefit is the capacity to simultaneously produce an enormous amount of material. The disadvantages of this technique include the odd-shaped nanoparticles and pollutants generated from milling balls [66,67]. Prommalikit *et al.* [68] synthesized ZnO NPs, suggesting that ZnO NPs may be synthesized from ZnO powder present in the market with an average size of 0.8 nm. The milling procedure yielded particles ranging in size from 200 to 400 nm.

Sputtering: Sputtering is the technique of depositing nanoparticles on a surface by ejecting colliding particles [69]. Sputtering is typically characterized by depositing a fine coating of nanoparticles followed by annealing. The morphology and dimensions of the nanoparticles are evaluated by sheet thickness, temperature, time period of annealing, substrate type, *etc.* [70]. Gholami *et al.* [71] prepared Ni-doped nanocomposite by radio-frequency sputtering method and observed that Ni doping declines the optical bandgap of ZnO from ~3.37 eV to ~3.18 eV.

Thermal decomposition: The process involves the release of heat, which disrupts the chemical bonds of the substance, resulting in an endothermic chemical decomposition. The decomposition temperature is the precise temperature at which a substance breakdown chemically. The metal is decomposed at particular temperatures in a chemical reaction that yields the nanoparticles [72]. Darezereshki *et al.* [73] produced ZnO nanoparticles in air for 60 min at 875 ºC by direct thermal decomposition of the source. The pH of the precursor solution was adjusted by the addition of ammonium hydroxide solution at 6 and 11.

Lithography: It uses a focused beam of light or electrons for nanoparticle development and capable of producing 1D and 2D nanoparticles. It typically combines two significant processes *viz.* deposition and etching [74,75]. The two most common types of lithography are masked and maskless lithography. Masked nanolithography employs a particular mask or template to transfer nanopatterns across a broad area. Masked lithography techniques include photo, soft and nanoimprint lithography [76,77]. Chalangar *et al.* [78] used colloidal lithography to control the morphology and density of ZnO nanorods because the synthesized ZnO structure using low-cost chemical baths is randomly arranged and difficult to manage in terms of uniformity and surface density. The results showed that vertically oriented ZnO nanorods with adjustable diameter and thickness were successfully grown in the prescribed gaps in the patterned resist mask placed on the layer formed. The method is capable of producing optimized devices based on vertically arranged ZnO nanorods of exceptional crystalline grade.

Green approaches for synthesis of nanoparticles: The green route includes various methods, such as plant-mediated, fungi-mediated, algae-mediated, bacteria-mediated, yeast-mediated, *etc.* [79-85]. Nanoparticle production by a biogenic process are more advanced than those produced by chemical methods in different aspects [86]. Most researchers focused on producing metal oxide nanoparticles using the biogenic processes as it is quicker, cheaper, sustainable and without effecting humans [87].

Plant extract: The particular phytosubstances found in plant components like leaves, stems, roots, fruits and seeds are used for synthesis of ZnO NPs (Table-2) [6]. The phytochemicals secreted by various plants are utilized to convert metal ions to zero valence metal nanoparticles [88,89]. In recent years, ZnO NPs synthesis by a variety of organically recyclable residues from food, such as fruit flesh and rind and also waste from agriculture, such as fruit peel, bran from rice, bran from sorghum, bran from wheat, maize cob, *etc*. have been deployed as green sources [90-92]. Singh *et al.* [93] used watermelon rind, a typically agricultural waste, to produce flower-shaped ZnO NPs. Large number of phytochemicals like carotenoids, alkaloids, flavonoids, proteins, pectin, saponins, citrulline and cellulose are present in watermelon rind and may serve as a reducing agent for the production of ZnO NPs. Abdelmigid *et al.* [94] generate ZnO NPs using *Punica granatum* peel and coffee ground extracts. Coffee ground extracts and punica peel are efficient green ZnO NPs reducers with less cytotoxicity on Vero cells than chemical ZnO NPs.

Microorganisms: Nanoparticles fabrication from microorganisms like bacteria and fungi is increased due to the relative ease of handling and genetic manipulation (Table-3). Bacteria have few amounts of organic functional groups that can reduce Zn^{2+} ions [124,125]. Examples of Gram-positive and Gram-negative bacteria utilized in the biosynthesis of ZnO NPs are *Rhodococcus pyridinivorans* [126] and *Serratia ureilytica* [127] respectively. However, nanoparticles synthesis by microorganisms is challenging due to the time-consuming method of keeping cell cultures, cellular synthesis and numerous processing stages. Raliya *et al.* [128] utilized *Bacillus licheniformis*, a pathogenic bacteria, to produce ZnO NPs. These nanoflower-shaped ZnO have high efficiency of degradation for methylene blue dye. Fungi are widely suggested for the extracellular synthesis of ZnO NPs because of their high yield rate, simple downstream treatment and competitive prices [124]. Due to their higher tolerance levels and greater metal bioaccumulation, various fungi are preferred compared to bacteria [129]. Broadly, *Aspergillus* species and *Candida albicans* fungi [130] were utilized to produce ZnO NPs and most of these nanoparticles were reported to be spherical in shape. *Actinomycetes* are less utilized microorganisms for producing metal nanoparticles [131]. On the other hand, *Actinomycetes* appear to be viable candidates for the intracellular and extracellular synthesis of metal nanoparticles [132]. *Actinomycetes* generate nanoparticles with high polydispersity, stability and high biocidal activity against a wide range of diseases [133,134].

Algae: Algae from *Sargassaceae* family like *Sargassum muticum* and *S. myriocystum* are also exploited for ZnO NPs synthesis. Nanoparticles synthesized from *Sargassum muticum* were investigated with the help of XRD and FESEM [139]. ZnO NPs derived from *S. myriocystum* were compared using DLS and AFM techniques, which revealed distinct range of size as well as the presence of carbonyl and hydroxyl stretching in nanoparticles with a wide range of shapes like spherical, radial, triangle, hexagonal and rod [140] (Table-4).

Applications of ZnO NPs: ZnO NPs are prioritized among many different metal oxide nanoparticles because of their diverse applications, which include different types of sensors, cosmetics, solar cells, tyre industry, ceramics, paints, storage, agriculture, water treatment and pharmaceuticals. In order to emphasize their outstanding findings and act as a roadmap for future researchers, several applications of ZnO NPs have been thoroughly investigated and presented under the following sub-headings.

Photocatalysis: During this process, the surface of the catalyst undergoes oxidation or reduction processes, resulting in the generation of an electron-hole pair that emits light with reduced intensity. Organic pollutants can be oxidized either directly by a photogenerated hole or indirectly by a reaction with distinctive reactive groups, like hydroxyl radical formed in solution as a result of a photocatalyst [141]. Alvi *et al.* [142] used hydrothermal procedure to fabricate ZnO nano chips. The obtained ZnO nanochips were efficient in degrading crystal violet, which decayed entirely in 90 min. Suwanboon *et al.* [143] synthesized ZnO by utilizing a surface-directing agent in the form of tartaric acid through a simple precipitation route. Under the visible light, methylene blue degradation efficiencies with the help of ZnO photocatalyst fabricated with a TA/$Zn(NO_3)_2$ mol ratio of 0, 1, 2 and 5 were 42, 37, 72 and 98%, respectively. The methylene blue degradation results were improved by surface irradiation to 81, 74, 100 and 100%, accordingly. The photocatalytic activity was enhanced by UV irradiation because ZnO has excellent UV light-absorbing capabilities. Hypothesized effects of the synthesis variables on cationic and anionic dye removal efficiency, point-of-zero charges (pHz), hydrodynamic diameter (Dh), time, temperature and concentration are the subject of an additional investigation. The conditions of fabrication had a significant impact on the removal efficiency [144].

Antimicrobial activity: The ability of ZnO to withstand high temperatures and to be biocompatible has made it a well-known antibacterial agent. ZnO NPs have been used in dental composite resins for their antibacterial properties [145]. There are two pathways that potentially explain the antibacterial effect of zinc oxide. Damage to the bacterial cell wall is connected with the second pathway, while the first pathway is associated with the release of reactive oxygen species [146,147]. ZnO has been applied as an antibacterial agent against various bacterial strains (*Escherichia coli*, *Salmonella enterica*, *Salmonella paratyph*, *Staphylococcus aureus*, *Klebsiella pneumoniae*, *Bacillus subtilis*, *Serratia marcescens*, *Proteus mirabilis* and *Citrobacter freundii*) and fungal strains (*Aspergillus flavus*, *Aspergillus nidulans*, *Trichoderma harzianum* and *Rhizopus stolonifer*) [147-152]. Chennimalai *et al.* [153] utilized green path to fabricate the ZnO nanorods and studied antibacterial efficiency. According to the findings of this study, antibacterial capabilities of ZnO nanorods against Gram-positive bacterial strain such as *Staphylococcus aureus* and *Bacillus subtilis* as well as Gram-negative strains such as *Salmonella paratyphi* and *Escherichia coli* were influenced by *Ricinus communis* leaf extract. The antibacterial activity of ZnO NPs is caused

TABLE-2
PLANTS BASED SYNTHESIS OF ZINC OXIDE NANOPARTICLES

Plant name	Plant part used	Reducing or functional group	Size and shape	Ref.
Conyza canadensis	Leaves	O-H, carbonyl	Spherical	[95]
Solanum tuberosum	Potato extract	–	20 ± 1.2, hexagonal	[96]
Solanum nigrum	Leaf extract	Carboxylate group, O-H and NH	2.07-2.20 spherical	[97]
Coptidis rhizoma	Dried rhizome	Primary and secondary, amine, aromatic, aliphatic amine, alcohol, carboxylic acid, alkyl, halide and alkynes	Spherical, rod-shaped, 2.9-25.2	[98]
Azadirachta indica	Fresh leaves	Amine, alcohol, ketone, carboxylic acid	Spherical, 18	[99]
Pongamia pinnata	Fresh leaves	O-H stretching, C=O, spreading carboxylic acid or their ester, C-O-H bending mode	Spherical, hexagonal, nanorod, 26, 100	[100]
Ocimum basilicum	Leaf extract	–	Hexagonal, 50, 14.28	[101]
Phyllanthus niruri	Leaf extract	O-H, C-H, C-O stretching, aromatic aldehyde	Hexagonal wurtzite, quasi-spherical, 25.61	[102]
Agathosma betulina	Dry leaves	O-H of hydroxyl group, Zn-O stretching band	Quasi-spherical, agglomerates, 12-26	[103]
Trifolium pratense	Flower	Hydroxyl, -C-O, -C-O-C, C=C stretching mode	Spherical, 60-70	[104]
Anisochilus carnosus	Leaf extract	O-H of water, alcohol, phenol C-H of alkane, O-H of carboxylic acid, C=O of the nitro group	Hexagonal wurtzite, quasi-spherical, 30-40	[105]
E. crassipes	Leaf extract	–	Spherical, 32-36	[106]
Rosa canina	Fruit extract	C-O and C=O of esters, hydroxyl, C-H stretching	Spherical, 11.3-243	[107]
Solanum nigrum	Leaf extract	O-H, aldehydic C-H, amide III bands of protein, carboxyl side group, C-N of amine, the carbonyl group	Wurtzite hexagonal, quasi-spherical, 20-30	[108]
Aloe vera	Freeze-dried leaf peel	–	Spherical, hexagonal, 25-65	[109]
Azadirachta indica	Leaf	Amide II was a stretching band, C-N stretching band of aliphatic, aromatic amide, an aliphatic amine, alcohol, phenol, secondary amine, C-H of alkane and aromatics, C=C-H of alkynes, C=O, C-C of an alkane	Spherical, 9.6-25.5	[110]
Moringa oleifera	Leaf	O-H, C-H of alkane, C=O of alcohol, carboxylic acid	Spherical and granular, 16-24	[111]
Cocus nucifera	Coconut water	O-H of alcohol and a carboxylic acid, C=O of ketones, C-N of aromatic and aliphatic amines	Spherical and hexagonal, 20-80	[112]
Gossypium	Cellulosic fiber	O-H, [C=O, C-O, C-O-C] (due to Zn precursor)	Wurtzite, spherical, nanorod, 13	[113]
Parthenium hysterophorus	Leaf extract	N-H bending & N-H stretching mode, a phosphorus compound, secondary sulfonamide, monosubstituted alkyne, amine salt, vinyl *cis*-tri substituted	Spherical, hexagonal, 22-35	[114]
Azadirachta indica	Fresh leaves	O-H between H_2O And CO_2, carbonate moieties	Hexagonal disk, nanobuds, 9-40	[115]
Plectranthus amboinicus	Leaf extract	Zn-O, C-O of C-O, $-SO_3$, phosphorus compound	Rod-shaped, 50-180	[116]
Calatropis gigantea	Fresh leaves	–	Spherical, 30-50	[117]
Vitex negundo	Flowers	–	Hexagonal, 10-130	[118]
S. album	Leaves	N-H stretching of amide II, carboxylate group, carbonyl stretching, O-H of alcohol	Nanorods, 70-140	[119]
Vitex negundo	Leaf	OH, C-H, C=C stretching band	Spherical, 38-80	[120]
Nephelium lappaceum	Fruit peels	O-H stretching, H-O-H	Needle-shaped, 50.95	[121]
Aloe barbadensis Miller	Leaf extract	O-H of phenol, amines, O-H of alcohol and C-H of alkanes, the amide of protein and enzymes	Spherical, oval, hexagonal, 8-20	[122]
Sphathodea campanulata	Leaf extract	O-H stretching of polyphenols, nitrile group, C-H, C=O group	Spherical, 30-50	[123]
Citrullus lanatus	Rind	C-N stretch, C-O and alkyl halides groups, COO group, hydroxyl groups	Wurtzite structure, nanorods,	[93]
Punica granatum	Fruit peel extract	O-H stretch, C-C, methylene, C-N, C-O, alcohols, ketones, polyphenols, phenols, amines, carboxylic acids and alkenes	Hexagonal crystalline, 20-30	[94]
Coffea arabica	Coffee ground extract	O-H stretch, -COOH, -OH in phenols, C-O stretch, carboxylic acids, phenols, polyphenols, amines, alcohols, ketones and alkenes	Hexagonal crystalline, 25.4-31.3	[94]

TABLE-3
MICROORGANISMS BASED SYNTHESIS OF ZINC OXIDE NANOPARTICLES

Microorganism name	Reducing group	Size (nm)	Shape	Ref.
Aeromonas hydrophila	Phosphorus compound, vinyl, *cis*-trisubstituted, alkyne	42-64	Spherical, oval	[83]
Lactobacillus sporogens	–	5-15	Hexagonal	[82]
Bacillus licheniformis	O-H, N-H, -C-O	200	Nanaoflowers	[128]
Rhodococcus pyridinivorans	Phosphorus compound, sulphornamide, alkyne, β-lactone, amine salt, alkane, benezene	100-130	Hexagonal phase, roughly spherical	[126]
Pseudomonas aeruginosa	O-H, -CH, ester carbonyl group	27-81	Spherical	[80]
Serratia ureilytica	–	170-600	Spherical to flower-like	[127]
Candida albicans	–	25	Quasi-spherical	[130]
Aspergillus strain	–	15-120	Spherical	[135]
Aspergillus fumigates	–	3.8	Nearly spherical	[136]
Aspergillus terreus	C-N, C-O, aromatic nitro compound, alkyl, amide	54.8-82.6	Spherical	[137]
Alternaria tenuissima	Zinc sulphate hepta hydrate	15.45	Spherical	[138]

TABLE-4
ALGAE-BASED SYNTHESIS OF ZINC OXIDE NANOPARTICLES

Algae name	Reducing group	Size (nm)	Shape	Ref.
Sargassum muticum	Sulfate group, C-O, C-O-SO_3 &-OH group, sulfated polysaccharides	30-57	Spheres	[139]
S. myriocystum	O-H and C O stretching band, carboxylic acid	19-37	Varied	[140]
Chlamydomonas reinhardtii	C=O, N-H, C=O stretch of zinc acetate, C-O-C of polysaccharide	55-80	Nanorod, nanoflower	[79]

by the reaction of ZnO with the cell surface, which can alter permeability of the cell membrane. The nanoparticles then enter the bacterial cell and cause oxidative stress in bacterial cells, inhibiting cell growth and even causing cell death [154]. This activity of nanoparticles suggests the reason of using ZnO NPs in the food industry to preserve food from microbes and to maintain various machineries [155].

Cancer treatment: Recent studies showed that ZnO NPs had higher selectivity for cancer cells than the therapeutic directories of some commonly utilized chemotherapy drugs [156]. The random activity, which usually causes toxic effects and serious health impacts in the normal tissues of humans, limits the maximum permissible dose of chemotherapeutic drugs [129]. The improved permeability and retention effect occurs when the size of nanoparticles improves its entry inside tumour cells. The utilization of the enhanced permeability and retention (EPR) effect in therapeutic strategies is presently considered to be ideal for the exploration of novel anticancer drugs [130]. It is possible for nanoparticles of a certain size to easily enter the tumour interstitial space while being passively held by this localized imbalance, increasing the therapeutic potential. Recent studies have demonstrated the value of ZnO NPs encapsulated in polymethyl methacrylate for identifying the low-abundance biomarkers [131].

Agriculture sector: Agriculture is the heart of nations having developing economies. It is dealing with several concerns including runoff, pesticide accumulation, fertilizers, climate variability, urban development, sustainable natural resource management and the population, which is constantly increasing and also anticipated to increase significantly in future. As a result, we need to implement the effective practices to make agriculture more sustainable [13]. Nanotechnological approaches are changing agriculture and food production in a variety of ways and found very efficient in reducing the fertilizers and pesticides effects. So, it improves overall cropgrowth and enhances grain production [157]. Nano fertilizers supply plants with nutrients and can help the soil recover. These are more efficient than the typical plant nutrients. They can replenish the organic conditions of the soil without having any adverse effects from chemical fertilizers. Nanopowders have also been used successfully as fertilizers and pesticides and also in the wheat seedlings the yield increased by 20-25% on average [158].

Plant growth: Various researchers have demonstrated that metal based nanoparticles can accumulate in edible parts of plants [9], may either decrease or increase crop yield and productivity [159] and may occasionally harm the microbial communities and activity of the soil [157]. ZnO NPs exhibit the potential to germinate seeds and promote plant growth at different phases of development and their antibacterial effect also reduces disease infection. At different developmental stages, ZnO NPs have beneficial and harmful impacts on the plant development and numerous metabolic function. ZnO NPs characteristics influence their absorption, diffusion and accumulation by plants [12,160]. Currently scientific research is focused on studying the impact of ZnO nanoparticles on different plant types [161]. When ZnO NPs were applied to ryegrass, the biomass reduced dramatically, the root tips shortened and the root epidermal cortical cells became widely vacuolated. Individual ZnO NPs were identified in the root endodermis and stele of wheat subjected to ZnO NPs [162, 163].

Heavy metal stress: Pollution is the primary source of heavy metals and their occurrence has a severe impact on nutrition, evolution and the environment [164-167]. Risks associated with heavy metal contamination include food safety, soil pollution, quality and other problems [168-171]. Heavy metals negatively affect living organisms, including plants [172,173]. Heavy metals restrict plant growth and development also at low levels when compared to other metals [174,175]. Zinc oxide nanoparticles has unique electrical and optical properties that make them suitable for use as coatings to remove harmful pollutants like heavy metals [157]. However, Ma *et al*. [176] observed that the metabolic processes of some higher plants are affected by metallic nanoparticles which results in negative impacts on vegetative growth, physiological functions, root development, plant maturity and chlorophyll levels.

Rubber industry: The majority of ZnO is utilized in the rubber industry to produce various crosslinked rubber products [177]. Pure silicone rubber has poor thermal conductivity, although, it is possible to enhance it by using thermal conductivity fillers such as inorganic particles, metal oxides and metal powders. Several thermally conductive powders like Al_2O_3, MgO, Al_2N_3, SiO_2, ZnO and others, may better the thermal conductive nature of silicone rubber despite conserving its resistance to electricity, making them interesting choices for improved engineering materials.

Textile industry: The textile sector has immense commercialization capability for nanotechnological goods. Zinc oxide is not only biocompatible for use in textiles, but ZnO coatings also exhibit superior air permeability and are more efficient in blocking UV radiation compared to bulk forms of ZnO [178]. Huang *et al.* [179] investigated the antibacterial properties and UV resistance of ZnO NPs materials to provide a framework for using ZnO NPs in the textile industry.

Miscellaneous applications: ZnO is applied as compound for gas sensing applications because of its great sensitivity, low price, long operating period and simple structure [180]. It has been employed to identify organic volatiles such as methanol, ethanol, aniline, benzene, triethanolamine (TEA) [59,181], formaldehyde [182] and acetone [183]. In addition, also employed as an optical detector for metal ions like Ag^+ and Li^+ [184]. ZnO is available in various morphologies, biocompatible, cost effective and can be used for various biological operations like drug delivery and bioimaging [185,186]. ZnO quantum dots (size ranging 2-10 nm) were also employed towards cell labelling and tumour therapy because of their particular electronic characteristics. Eventually, ZnO nanowires are naturally fluorescent and can be used for targeted imaging of cancer cells [187]. In order to convert different organic molecules, ZnO has been utilized as a heterogeneous catalyst that is affordable, functional, widely accessible, safe and reusable [188,189]. ZnO is also capable of being applied in solid oxide fuel cells as an electrolyte. ZnO NPs are also utilized in sunscreens and cosmetics because of their capacity to absorb UV radiation and photostability [190]. ZnO has been declared safe for use in industries that deal with food by the Food and Drug Administration [63].

Conclusion and future prospective

This review provides the valuable insights and developments into the formation of ZnO nanoparticles, which will help to enhance its properties to make it fit for its specific applications like cancer therapy, biosensors, rubber, textile industries and agriculture. In past years, research has mainly focused on finding environmental friendly methods to synthesize nanoparticles. Green sources operate as stabilizers and reducers to obtain nanoparticles of desired morphology. Long-term prospects for plant-mediated nanoparticles synthesis include developing the experimental investigations for the commercial production, employing bioinformatics tools to explain phytochemicals participating in nanoparticles production and understanding the specific mechanism responsible for different applications. There is an anticipation that the increasing prevalence of ZnO nanoparticles will give rise to innovative concepts regarding their potential applications.

CONFLICT OF INTEREST

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

REFERENCES

1. H. Siddiqui, K.B.M. Ahmed, F. Sami and S. Hayat, In eds.: S. Hayat, J. Pichtel, M. Faizan and Q. Fariduddin, Sustainable Agriculture Reviews, Springer, Cham., vol. 41, 129 (2020); https://doi.org/10.1007/978-3-030-33996-8_7
2. C.M. Welch and R.G. Compton, *Anal. Bioanal. Chem.*, **384**, 601 (2006); https://doi.org/10.1007/s00216-005-0230-3
3. V.D. Rajput, T.M. Minkina, A. Behal, S.N. Sushkova, S. Mandzhieva, R. Singh, A. Gorovtsov, V.S. Tsitsuashvili, W.O. Purvis, K.A. Ghazaryan and H.S. Movsesyan, *Environ. Nanotechnol. Monit. Manag.*, **9**, 76 (2018); https://doi.org/10.1016/j.enmm.2017.12.006
4. S. Manjunatha, D. Biradar and Y.R. Aladakatti, *J. Farm. Sci.*, **29**, 1 (2016).
5. P. Ahmad, M.N. Alyemeni, A.A. Al-Huqail, M.A. Alqahtani, L. Wijaya, M. Ashraf, C. Kaya and A. Bajguz, *Plants*, **9**, 825 (2020); https://doi.org/10.3390/plants9070825
6. W.M. Semida, A. Abdelkhalik, G.F. Mohamed, T.A. Abd El-Mageed, S.A. Abd El-Mageed, M.M. Rady and E.F. Ali, *Plants*, **10**, 421 (2021); https://doi.org/10.3390/plants10020421
7. K. Zarschler, L. Rocks, N. Licciardello, L. Boselli, E. Polo, K.P. Garcia, L. De Cola, H. Stephan and K.A. Dawson, *Nanomedicine*, **12**, 1663 (2016); https://doi.org/10.1016/j.nano.2016.02.019
8. M. Faizan, J.A. Bhat, K. Hessini, F. Yu and P. Ahmad, *Ecotoxicol. Environ. Saf.*, **220**, 112401 (2021); https://doi.org/10.1016/j.ecoenv.2021.112401
9. A.M. Abdelaziz, S. Dacrory, A.H. Hashem, M.S. Attia, M. Hasanin, H.M. Fouda, S. Kamel and H. ElSaied, *Biocatal. Agric. Biotechnol.*, **35**, 102083 (2021); https://doi.org/10.1016/j.bcab.2021.102083
10. M. Hessien, E. Da'na and A. Taha, *Ceram. Int.*, **47**, 811 (2021); https://doi.org/10.1016/j.ceramint.2020.08.192
11. Zinc Oxide Market - Growth, Trends, COVID-19 Impact and Forecasts (2022 – 2027).
12. M. Ali, X. Wang, U. Haroon, H.J. Chaudhary, A. Kamal, Q. Ali, M.H. Saleem, K. Usman, A. Alatawi, S. Ali and M.F. Hussain Munis, *Ecotoxicol. Environ. Saf.*, **233**, 113311 (2022); https://doi.org/10.1016/j.ecoenv.2022.113311
13. A. Kolodziejczak-Radzimska and T. Jesionowski, *Materials*, **7**, 2833 (2014); https://doi.org/10.3390/ma7042833
14. B. Davarcioglu, in eds.: R. Prasad, V. Kumar and M. Kumar, Nanotechnology Applications in Food Packaging Industry, Nanotechnology, Springer, Singapore (2017); https://doi.org/10.1007/978-981-10-4678-0_6
15. J.I. García-López, G. Niño-Medina, E. Olivares-Sáenz, R.H. Lira-Saldivar, E.D. Barriga-Castro, R. Vázquez-Alvarado, P.A. Rodríguez-Salinas and F. Zavala-García, *Plants*, **8**, 254 (2019); https://doi.org/10.3390/plants8080254

16. L. Rossi, L.N. Fedenia, H. Sharifan, X. Ma and L. Lombardini, *Plant Physiol. Biochem.*, **135**, 160 (2019); https://doi.org/10.1016/j.plaphy.2018.12.005
17. O.J. Nava, C.A. Soto-Robles, C.M. Gómez-Gutiérrez, A.R. Vilchis-Nestor, A. Castro-Beltrán, A. Olivas and P.A. Luque, *J. Mol. Struct.*, **1147**, 1 (2017); https://doi.org/10.1016/j.molstruc.2017.06.078
18. C. Karthikeyan, P. Arunachalam, K. Ramachandran, A.M. Al-Mayouf and S. Karuppuchamy, *J. Alloys Compd.*, **828**, 154281 (2020); https://doi.org/10.1016/j.jallcom.2020.154281
19. O.K. Nayna and S.M. Tareq, *Nanotechnol. Water Wastewater Treat.*, 267 (2019); https://doi.org/10.1016/B978-0-12-813902-8.00013-7
20. E.Y. Shaba, J.O. Jacob, J.O. Tijani and M.A.T. Suleiman, *Appl. Water Sci.*, **11**, 48 (2021); https://doi.org/10.1007/s13201-021-01370-z
21. A.W.M. Mahmoud, E.A. Abdeldaym, S.M. Abdelaziz, M.B. El-Sawy and S.A. Mottaleb, *Agronomy*, **10**, 19 (2019); https://doi.org/10.3390/agronomy10010019
22. N. Rani, P. Singh, S. Kumar, P. Kumar, V. Bhankar and K. Kumar, *Mater. Res. Bull.*, **163**, 112233 (2023); https://doi.org/10.1016/j.materresbull.2023.112233
23. S. Jadoun, R. Arif, N.K. Jangid and R.K. Meena, *Environ. Chem. Lett.*, **19**, 355 (2021); https://doi.org/10.1007/s10311-020-01074-x
24. J.N. Hasnidawani, H.N. Azlina, H. Norita, N.N. Bonnia, S. Ratim and E.S. Ali, *Procedia Chem.*, **19**, 211 (2016); https://doi.org/10.1016/j.proche.2016.03.095
25. T. Arasu, *J. Biosci. Res*, **1**, 259 (2010).
26. R. Suntako, *Bull. Mater. Sci.*, **38**, 1033 (2015); https://doi.org/10.1007/s12034-015-0921-0
27. S. Vijayakumar, S. Mahadevan, P. Arulmozhi, S. Sriram and P.K. Praseetha, *Mater. Sci. Semicond. Process.*, **82**, 39 (2018); https://doi.org/10.1016/j.mssp.2018.03.017
28. K. Lingaraju, H. Raja Naika, K. Manjunath, R.B. Basavaraj, H. Nagabhushana, G. Nagaraju and D. Suresh, *Appl. Nanosci.*, **6**, 703 (2016); https://doi.org/10.1007/s13204-015-0487-6
29. F. Islam, S. Shohag, M.J. Uddin, M.R. Islam, M.H. Nafady, A. Akter, S. Mitra, A. Roy, T.B. Emran and S. Cavalu, *Materials (Basel)*, **15**, 2160 (2022); https://doi.org/10.3390/ma15062160
30. A.A. Barzinjy, *J. Phys.*, **13**, 123 (2020); https://doi.org/10.47011/13.2.4
31. S. Somiya, Handbook of Advanced Ceramics: Materials, Applications, Processing, and Properties, Academic Press: Cambridge, MA, USA; Elsevier: Amsterdam, The Netherlands, 2nd ed., pp. 1–1229 (2013).
32. K. Al Abdullah, S. Awad, J. Zaraket and C. Salame, *Energy Procedia*, **119**, 565 (2017); https://doi.org/10.1016/j.egypro.2017.07.080
33. M. Parashar, V.K. Shukla and R. Singh, *J. Mater. Sci. Mater. Electron.*, **31**, 3729 (2020); https://doi.org/10.1007/s10854-020-02994-8
34. B. Abarna, T. Preethi, A. Karunanithi and G.R. Rajarajeswari, *Mater. Sci. Semicond. Process.*, **56**, 243 (2016); https://doi.org/10.1016/j.mssp.2016.09.004
35. K. Davis, R. Yarbrough, M. Froeschle, J. White and H. Rathnayake, *RSC Advances*, **9**, 14638 (2019); https://doi.org/10.1039/C9RA02091H
36. M. Shandilya, R. Rai and J. Singh, *Adv. Appl. Ceramics*, **115**, 354 (2016); https://doi.org/10.1080/17436753.2016.1157131
37. M. Shandilya and G.A. Kaur, *J. Solid State Chem.*, **280**, 120988 (2019); https://doi.org/10.1016/j.jssc.2019.120988
38. A. Rayerfrancis, P. Balaji Bhargav, N. Ahmed, B. Chandra and S. Dhara, *Physica B*, **457**, 96 (2015); https://doi.org/10.1016/j.physb.2014.09.044
39. Y. Dong, X. Du, P. Liang and X. Man, *Inorg. Chem. Commun.*, **115**, 107883 (2020); https://doi.org/10.1016/j.inoche.2020.107883
40. N.A. Alshehri, A.R. Lewis, C. Pleydell-Pearce and T.G.G. Maffeis, *J. Saudi Chem. Soc.*, **22**, 538 (2018); https://doi.org/10.1016/j.jscs.2017.09.004
41. N. Senthilkumar, E. Vivek, M. Shankar, M. Meena, M. Vimalan and I.V. Potheher, *J. Mater. Sci. Mater. Electron.*, **29**, 2927 (2018); https://doi.org/10.1007/s10854-017-8223-5
42. Y. Sun, H. Guo, W. Zhang, T. Zhou, Y. Qiu, K. Xu, B. Zhang and H. Yang, *Ceram. Int.*, **42**, 9648 (2016); https://doi.org/10.1016/j.ceramint.2016.03.051
43. S. Duo, Y. Li, Z. Liu, R. Zhong and T. Liu, *Mater. Sci. Semicond. Process.*, **56**, 196 (2016); https://doi.org/10.1016/j.mssp.2016.08.018
44. Y. Bao, C. Wang and J. Ma, *Ceram. Int.*, **42**, 10289 (2016); https://doi.org/10.1016/j.ceramint.2016.03.164
45. D.D.S. Biron, V.D. Santos and C.P. Bergmann, *Materials Research*, **23**, (2020); https://doi.org/10.1590/1980-5373-MR-2020-0080
46. H.R. Ghorbani, F.P. Mehr, H. Pazoki and B.M. Rahmani, *Orient. J. Chem.*, **31**, 1219 (2015); https://doi.org/10.13005/ojc/310281
47. M. Anandan, S. Dinesh, N. Krishnakumar and K. Balamurugan, *J. Mater. Sci. Mater. Electron.*, **28**, 2574 (2017); https://doi.org/10.1007/s10854-016-5833-2
48. X.Q. Zhou, Z. Hayat, D.D. Zhang, M.Y. Li, S. Hu, Q. Wu, Y.-F. Cao and Y. Yuan, *Processes*, **11**, 1193 (2023); https://doi.org/10.3390/pr11041193
49. M.S. Pudovkin, P.V. Zelenikhin, V. Shtyreva, O.A. Morozov, D.A. Koryakovtseva, V.V. Pavlov, Y.N. Osin, V.G. Evtugyn, A.A. Akhmadeev, A.S. Nizamutdinov and V.V. Semashko, *J. Nanotechnol.*, **2018**, Article id 8516498 (2018); https://doi.org/10.1155/2018/8516498
50. J.M. Domingues, C.S. Miranda, N.C. Homem, H.P. Felgueiras and J.C. Antunes, *Biomedicines*, **11**, 1862 (2023); https://doi.org/10.3390/biomedicines11071862
51. M.R. Bodke, Y. Purushotham and B.N. Dole, *Ceramica*, **64**, 91 (2018); https://doi.org/10.1590/0366-69132018643692207
52. L. Gnanasekaran, R. Hemamalini, R. Saravanan, K. Ravichandran, F. Gracia, S. Agarwal and V.K. Gupta, *J. Photochem. Photobiol. B*, **173**, 43 (2017); https://doi.org/10.1016/j.jphotobiol.2017.05.027
53. S. Bhaviripudi, E. Mile, V. Steiner, A.T. Zare, M.S. Dresselhaus, A.M. Belcher and J. Kong, *J. Am. Chem. Soc.*, **129**, 1516 (2007); https://doi.org/10.1021/ja0673332
54. M. Adachi, S. Tsukui and K. Okuyama, *Jpn. J. Appl. Phys.*, **42(1A)**, L77 (2003); https://doi.org/10.1143/JJAP.42.L77
55. V. Saravade, Z. Manzoor, A. Corda, C. Zhou, I. Ferguson and N. Lu, *Adv. Opt. Mater.*, **9**, 2100096 (2021); https://doi.org/10.1002/adom.202100096
56. A.V. Rane, K. Kanny, V.K. Abitha, and S. Thomas, *Woodhead publishing*, **121**, (2018); https://doi.org/10.1016/B978-0-08-101975-7.00005-1
57. Y. Wang, X. Zhang, A. Wang, X. Li, G. Wang and L. Zhao, *Chem. Eng. J.*, **235**, 191 (2014); https://doi.org/10.1016/j.cej.2013.09.020
58. X. Li, G. He, G. Xiao, H. Liu and M. Wang, *J. Colloid Interface Sci.*, **333**, 465 (2009); https://doi.org/10.1016/j.jcis.2009.02.029
59. R.A. Ismail, M.H. Mohsin, A.K. Ali, K.I. Hassoon and S. Erten-Ela, *Physica E*, **119**, 113997 (2020); https://doi.org/10.1016/j.physe.2020.113997
60. J.S. Duque, B.M. Madrigal, H. Riascos and Y.P. Avila, *Colloids and Interfaces*, **3**, 25 (2019); https://doi.org/10.3390/colloids3010025
61. N. Mintcheva, A.A. Aljulaih, W. Wunderlich, S.A. Kulinich and S. Iwamori, *Materials (Basel)*, **11**, 1127 (2018); https://doi.org/10.3390/ma11071127
62. V. Amendola and M. Meneghetti, *Phys. Chem. Chem. Phys.*, **11**, 3805 (2009); https://doi.org/10.1039/b900654k
63. W. Al-Dahash, M. Khilkala and S.N. Abd Alwahid, *Iran. J. Chem. Chemical Eng.*, **37**, 11 (2018); https://doi.org/10.30492/IJCCE.2018.31948

64. S.V. Farahani, A. Mahmoodi and M. Goranneviss, *Int. Nano Lett.*, **6**, 45 (2016); https://doi.org/10.1007/s40089-015-0162-7
65. A. Hodaei, A. Ataie and E. Mostafavi, *J. Alloys Compd.*, **640**, 162 (2015); https://doi.org/10.1016/j.jallcom.2015.03.230
66. C.C. Piras, S. Fernández-Prieto and W.M. De Borggraeve, *Nanoscale Adv.*, **1**, 937 (2019); https://doi.org/10.1039/C8NA00238J
67. L. Yang, Nanotechnology-Enhanced Metals and Alloys for Orthopedic Implants, In: Nanotechnology-Enhanced Orthopedic Materials Fabrications, Applications and Future Trends, Woodhead Publishing Series in Biomaterials Chap. 2, pp. 27-47 (2015); https://doi.org/10.1016/B978-0-85709-844-3.00002-1
68. C. Prommalikit, W. Mekprasart, and W. Pecharapa, *J. Phys.: Conf. Series*, **1259**, 012023 (2019); https://doi.org/10.1088/1742-6596/1259/1/012023
69. P. Shah and A. Gavrin, *J. Magn. Magn. Mater.*, **301**, 118 (2006); https://doi.org/10.1016/j.jmmm.2005.06.023
70. E. Lugscheider, S. Bärwulf, C. Barimani, M. Riester and H. Hilgers, *Surf. Coat. Technol.*, **108-109**, 398 (1998); https://doi.org/10.1016/S0257-8972(98)00627-6
71. M.S. Abdel-wahab, *J. Electron. Mater.*, **50**, 4364 (2021); https://doi.org/10.1007/s11664-021-08963-z
72. M. Salavati-niasari, F. Davar and N. Mir, *Polyhedron*, **27**, 3514 (2008); https://doi.org/10.1016/j.poly.2008.08.020
73. E. Darezereshki, A.B. Vakylabad and M. Yousefi, *Int. J. Eng.*, **34**, 1888 (2021); https://doi.org/10.5829/ije.2021.34.08b.10
74. D. Sumanth Kumar, B. Jai Kumar and H.M. Mahesh, Quantum Nanostructures (QDs): An Overview, In: Synthesis of Inorganic Nanomaterials, Elsevier Ltd., Chap. 3, pp. 59-88 (2018).
75. N.F. Raduwan, N. Shaari, S.K. Kamarudin, M.S. Masdar and R.M. Yunus, *Int. J. Hydrogen Energy*, **47**, 18468 (2022); https://doi.org/10.1016/j.ijhydene.2022.03.035
76. K. Xu and J. Chen, *Appl. Nanosci.*, **10**, 1013 (2020); https://doi.org/10.1007/s13204-019-01229-5
77. V. Garg, R.G. Mote and J. Fu, *Appl. Surf. Sci.*, **526**, 146644 (2020); https://doi.org/10.1016/j.apsusc.2020.146644
78. E. Chalangar, O. Nur, M. Willander, A. Gustafsson and H. Pettersson, *Nanoscale Res. Lett.*, **16**, 46 (2021); https://doi.org/10.1186/s11671-021-03500-7
79. M.D. Rao and P. Gautam, *Environ. Prog. Sustain. Energy*, **35**, 1020 (2016); https://doi.org/10.1002/ep.12315
80. B.N. Singh, A.K.S. Rawat, W. Khan, A.H. Naqvi and B.R. Singh, *PLoS One*, **9**, e106937 (2014); https://doi.org/10.1371/journal.pone.0106937
81. K.P. Ghoderao, S.N. Jamble and R.B. Kale, *Optik*, **156**, 758 (2018); https://doi.org/10.1016/j.ijleo.2017.10.046
82. K. Prasad and A.K. Jha, *Nat. Sci.*, **1**, 129 (2009); https://doi.org/10.4236/ns.2009.12016
83. C. Jayaseelan, A.A. Rahuman, A.V. Kirthi, K. Gaurav, S. Marimuthu, T. Santhoshkumar, A. Bagavan, L. Karthik and K.V.B. Rao, *Spectrochim. Acta A Mol. Biomol. Spectrosc.*, **90**, 78 (2012); https://doi.org/10.1016/j.saa.2012.01.006
84. A. Saravanan, P.S. Kumar, S. Karishma, D.-V.N. Vo, S. Jeevanantham, P.R. Yaashikaa and C.S. George, *Chemosphere*, **264**, 128580 (2021); https://doi.org/10.1016/j.chemosphere.2020.128580
85. A.M. Eid, A. Fouda, G. Niedba³a, S.E.-D. Hassan, S.S. Salem, A.M. Abdo, H. F. Hetta and T.I. Shaheen, *Antibiotics*, **9**, 1 (2020); https://doi.org/10.3390/antibiotics9100641
86. S.M. Alsharif, S.S. Salem, M.A. Abdel-Rahman, A. Fouda, A.M. Eid, S. El-Din Hassan, M.A. Awad and A.A. Mohamed, *Heliyon*, **6**, e03943 (2020); https://doi.org/10.1016/j.heliyon.2020.e03943
87. J. Iqbal, B.A. Abbasi, R. Ahmad, A. Shahbaz, S.A. Zahra, S. Kanwal, A. Munir, A. Rabbani and T. Mahmood, *J. Mol. Struct.*, **1199**, 126979 (2020); https://doi.org/10.1016/j.molstruc.2019.126979
88. J. Afzal, X. Wang, M.H. Saleem, X. Sun, S. Hussain, I. Khan, M.S. Rana, S. Ahmed, S.A. Awan, S. Fiaz, O. Aziz, K.A. Kubar, S. Ali and C. Hu, *Biocell*, **45**, 1631 (2021); https://doi.org/10.32604/biocell.2021.014934
89. J. Qu, X. Yuan, X. Wang and P. Shao, *Environ. Pollut.*, **159**, 1783 (2011); https://doi.org/10.1016/j.envpol.2011.04.016
90. X. Fu, J. Cai, X. Zhang, W. Li, H. Ge and Y. Hu, *Adv. Drug Deliv. Rev.*, **132**, 169 (2018); https://doi.org/10.1016/j.addr.2018.07.006
91. P.E. Ochieng, E. Iwuoha, I. Michira, M. Masikini, J. Ondiek, P. Githira, and G.N. Kamau, *Int. J. BiochemiPhys.*, **23**, 53 (2015).
92. S. Rajeshkumar, C. Malarkodi, M. Vanaja and G. Annadurai, *J. Mol. Struct.*, **1116**, 165 (2016); https://doi.org/10.1016/j.molstruc.2016.03.044
93. S. Singh, M. Joshi, P. Panthari, B. Malhotra, A.C. Kharkwal and H. Kharkwal, *Nano-Struct.*, **11**, 1 (2017); https://doi.org/10.1016/j.nanoso.2017.05.006
94. H.M. Abdelmigid, N.A. Hussien, A.A. Alyamani, M.M. Morsi, N.M. Al Sufyani and H.A. Kadi, *Molecules*, **27**, 1236 (2022); https://doi.org/10.3390/molecules27041236
95. J. Ali, R. Irshad, B. Li, K. Tahir, A. Ahmad, M. Shakeel, N.U. Khan and Z.U.H. Khan, *J. Photochem. Photobiol. B*, **183**, 349 (2018); https://doi.org/10.1016/j.jphotobiol.2018.05.006
96. F. Buazar, M. Bavi, F. Kroushawi, M. Halvani, A. Khaledi-Nasab and S.A. Hossieni, *J. Exp. Nanosci.*, **11**, 175 (2016); https://doi.org/10.1080/17458080.2015.1039610
97. A. Muthuvel, M. Jothibas and C. Manoharan, *J. Environ. Chem. Eng.*, **8**, 103705 (2020); https://doi.org/10.1016/j.jece.2020.103705
98. P.C. Nagajyothi, T.V.M. Sreekanth, C.O. Tettey, Y.I. Jun and S.H. Mook, *Bioorg. Med. Chem. Lett.*, **24**, 4298 (2014); https://doi.org/10.1016/j.bmcl.2014.07.023
99. A. Singh, M. Neelam and M. Kaushik, *Results Phys.*, **13**, 102168 (2019); https://doi.org/10.1016/j.rinp.2019.102168
100. B. Malaikozhundan and J. Vinodhini, *Mater. Today Commun.*, **14**, 106 (2018); https://doi.org/10.1016/j.mtcomm.2017.12.015
101. N. Abbes, I. Bekri, M. Cheng, N. Sejri, M. Cheikhrouhou and J. Xu, *Medziagotyra*, **28**, 144 (2022); https://doi.org/10.5755/j02.ms.28314
102. R.R. Wary, S. Baglari, D. Brahma, U.K. Gautam, P. Kalita and M.B. Baruah, *Environ. Sci. Pollut. Res. Int.*, **29**, 42837 (2022); https://doi.org/10.1007/s11356-022-18832-9
103. F.T. Thema, E. Manikandan, M.S. Dhlamini and M. Maaza, *Mater. Lett.*, **161**, 124 (2015); https://doi.org/10.1016/j.matlet.2015.08.052
104. R. Dobrucka and J. Dlugaszewska, *Saudi J. Biol. Sci.*, **23**, 517 (2016); https://doi.org/10.1016/j.sjbs.2015.05.016
105. M. Anbuvannan, M. Ramesh, G. Viruthagiri, N. Shanmugam and N. Kannadasan, *Mater. Sci. Semicond. Process.*, **39**, 621 (2015); https://doi.org/10.1016/j.mssp.2015.06.005
106. S.A. Akintelu and A.S. Folorunso, *Bionanoscience*, **10**, 848 (2020); https://doi.org/10.1007/s12668-020-00774-6
107. S. Jafarirad, M. Mehrabi, B. Divband and M. Kosari-Nasab, *Mater. Sci. Eng. C*, **59**, 296 (2016); https://doi.org/10.1016/j.msec.2015.09.089
108. M. Ramesh, M. Anbuvannan and G. Viruthagiri, *Spectrochim. Acta A Mol. Biomol. Spectrosc.*, **136**, 864 (2015); https://doi.org/10.1016/j.saa.2014.09.105
109. Y. Qian, J. Yao, M. Russel, K. Chen and X. Wang, *Environ. Toxicol. Pharmacol.*, **39**, 736 (2015); https://doi.org/10.1016/j.etap.2015.01.015
110. T. Bhuyan, K. Mishra, M. Khanuja, R. Prasad and A. Varma, *Mater. Sci. Semicond. Process.*, **32**, 55 (2015); https://doi.org/10.1016/j.mssp.2014.12.053
111. S. Abel, J.L. Tesfaye, N. Nagaprasad, R. Shanmugam, L.P. Dwarampudi and R. Krishnaraj, *J. Nanomater.*, **2021**, 4525770 (2021); https://doi.org/10.1155/2021/4525770
112. S. Albukhaty, H. Al-Karagoly and M.A. Dragh, *J. Biotech Res.*, **11**, 47 (2020).

113. S.A. Noorian, N. Hemmatinejad and J.A. Navarro, *Int. J. Biol. Macromol.*, **154**, 1215 (2020); https://doi.org/10.1016/j.ijbiomac.2019.10.276
114. P. Rajiv, S. Rajeshwari and R. Venckatesh, *Spectrochim. Acta A Mol. Biomol. Spectrosc.*, **112**, 384 (2013); https://doi.org/10.1016/j.saa.2013.04.072
115. H.R. Madan, S.C. Sharma, Udayabhanu, D. Suresh, Y.S. Vidya, H. Nagabhushana, H. Rajanaik, K.S. Anantharaju, S.C. Prashantha and P. Sadananda Maiya, *Spectrochim. Acta A Mol. Biomol. Spectrosc.*, **152**, 404 (2016); https://doi.org/10.1016/j.saa.2015.07.067
116. Y. Zheng, Y. Huang, H. Shi and L. Fu, *Inorg. Nano-Metal Chem.*, **49**, 277 (2019); https://doi.org/10.1080/24701556.2019.1661441
117. S. Rajashekara, A. Shrivastava, S. Sumhitha and S. Kumari, *Bionanoscience*, **10**, 654 (2020); https://doi.org/10.1007/s12668-020-00746-w
118. M. Sundrarajan, S. Ambika and K. Bharathi, *Adv. Powder Technol.*, **26**, 1294 (2015); https://doi.org/10.1016/j.apt.2015.07.001
119. K. Kavithaa, M. Paulpandi, T. Ponraj, K. Murugan and S. Sumathi, *Karbala Int. J. Mod. Sci.*, **2**, 46 (2016); https://doi.org/10.1016/j.kijoms.2016.01.002
120. B. Vaishnavi Devi, A. Rajasekar, S. Rajeshkumar, *Plant Cell Biotechnol. Mol. Biol*., **21**, 21 (2020).
121. N. Normah, N. Juleanti, N.R. Palapa, T. Taher, P.M.S.B.N. Siregar, A. Wijaya and A. Lesbani, *Chem. Ecol.*, **38**, 284 (2022); https://doi.org/10.1080/02757540.2022.2040996
122. K. Ali, S. Dwivedi, A. Azam, Q. Saquib, M.S. Al-Said, A.A. Alkhedhairy and J. Musarrat, *J. Colloid Interface Sci.*, **472**, 145 (2016); https://doi.org/10.1016/j.jcis.2016.03.021
123. A.-I. Antonescu (Mintas), F. Miere (Groza), L. Fritea, M. Ganea, M. Zdrinca, L. Dobjanschi, A. Antonescu, S.I. Vicas, F. Bodog, R.K. Sindhu and S. Cavalu, *Plants*, **10**, 1390 (2021); https://doi.org/10.3390/plants10071390
124. H. Chandra, P. Kumari, C. Bontempi and S. Yadav, *Biocatal. Agric. Biotechnol.*, **24**, 101518 (2020); https://doi.org/10.1016/j.bcab.2020.101518
125. H. Al Jabri, M.H. Saleem, M. Rizwan, I. Hussain, K. Usman and M. Alsafran, *Life*, **12**, 594 (2022); https://doi.org/10.3390/life12040594
126. D. Kundu, C. Hazra, A. Chatterjee, A. Chaudhari and S. Mishra, *J. Photochem. Photobiol. B*, **140**, 194 (2014); https://doi.org/10.1016/j.jphotobiol.2014.08.001
127. P. Dhandapani, A.S. Siddarth, S. Kamalasekaran, S. Maruthamuthu and G. Rajagopal, *Carbohydr. Polym.*, **103**, 448 (2014); https://doi.org/10.1016/j.carbpol.2013.12.074
128. R.M. Tripathi, A.S. Bhadwal, R.K. Gupta, P. Singh, A. Shrivastav and B.R. Shrivastav, *J. Photochem. Photobiol. B*, **141**, 288 (2014); https://doi.org/10.1016/j.jphotobiol.2014.10.001
129. H. Agarwal, S. Venkat Kumar and S. Rajeshkumar, *Technol.*, **3**, 406 (2017); https://doi.org/10.1016/j.reffit.2017.03.002
130. Shamsuzzaman, A. Mashrai, H. Khanam and R.N. Aljawfi, *Arab. J. Chem.*, **10**, S1530 (2017); https://doi.org/10.1016/j.arabjc.2013.05.004
131. A. Gupta, D. Singh, S.K. Singh, V.K. Singh, A.V. Singh and A. Kumar, Role of Actinomycetes in Bioactive and Nanoparticle Synthesis, Woodhead Publishing, Chap. 10, pp. 163-182 (2019); https://doi.org/10.1016/B978-0-12-817004-5.00010-5
132. S.P. Venkateswaran V.K. Palaniswamy, R. Vishvanand and R. Periakaruppan, in Eds.: K.A. Abd-Elsalam, R. Periakaruppan and S. Rajeshkumar, In Agri-Waste and Microbes for Production of Sustainable Nanomaterials, Elsevier, Chap. 16 (2022).
133. M. Mabrouk, T.A. Elkhooly and S.K. Amer, *J. Genet. Eng. Biotechnol.*, **19**, 57 (2021); https://doi.org/10.1186/s43141-021-00153-y
134. S.S. Salem and A. Fouda, *Biol. Trace Elem. Res.*, **199**, 344 (2021); https://doi.org/10.1007/s12011-020-02138-3
135. K.V. Pavani, N.S. Kumar and B.B. Sangameswaran, *Pol. J. Microbiol.*, **61**, 61 (2012); https://doi.org/10.33073/pjm-2012-008
136. R. Raliya and J.C. Tarafdar, *Agric. Res.*, **2**, 48 (2013); https://doi.org/10.1007/s40003-012-0049-z
137. R. Chandrasekaran, S. Gnanasekar, P. Seetharaman, R. Keppanan, W. Arockiaswamy and S. Sivaperumal, *J. Mol. Liq.*, **219**, 232 (2016); https://doi.org/10.1016/j.molliq.2016.03.038
138. H.K. Abdelhakim, E.R. ElSayed and F.B. Rashidi, *J. Appl. Microbiol.*, **128**, 1634 (2020); https://doi.org/10.1111/jam.14581
139. S. Azizi, M.B. Ahmad, F. Namvar and R. Mohamad, *Mater. Lett.*, **116**, 275 (2014); https://doi.org/10.1016/j.matlet.2013.11.038
140. S. Nagarajan and K. Arumugam Kuppusamy, *J. Nanobiotechnol.*, **11**, 39 (2013); https://doi.org/10.1186/1477-3155-11-39
141. N. Jain, A. Bhargava and J. Panwar, *Chem. Eng. J.*, **243**, 549 (2014); https://doi.org/10.1016/j.cej.2013.11.085
142. M.A. Alvi and M.S. Akhtar, *Mater. Lett.*, **281**, 128609 (2020); https://doi.org/10.1016/j.matlet.2020.128609
143. S. Suwanboon, P. Amornpitoksuk and C. Randorn, *Ceram. Int.*, **45**, 2111 (2019); https://doi.org/10.1016/j.ceramint.2018.10.116
144. M.M. Khalaf, E. Da'na, K. Al-Amer and M. Hessien, *Molecules*, **24**, 3884 (2019); https://doi.org/10.3390/molecules24213884
145. D. Arun, D. Adikari Mudiyanselage, R. Gulam Mohamed, M. Liddell, N.M. Monsur Hassan and D. Sharma, *Materials*, **14**, 40 (2020); https://doi.org/10.3390/ma14010040
146. S. Gharpure and B. Ankamwar, *J. Nanosci. Nanotechnol.*, **20**, 5977 (2020); https://doi.org/10.1166/jnn.2020.18707
147. S. Thakur and S.K. Mandal, *New J. Chem.*, **44**, 11796 (2020); https://doi.org/10.1039/D0NJ01661F
148. Y. Li, C. Liao and S.C. Tjong, *Int. J. Mol. Sci.*, **21**, 8836 (2020); https://doi.org/10.3390/ijms21228836
149. Z. Zaidi, K. Vaghasiya, A. Vijay, M. Sharma, R.K. Verma and S. Vaidya, *J. Mater. Sci.*, **53**, 14964 (2018); https://doi.org/10.1007/s10853-018-2715-4
150. A. Raja, S. Ashokkumar, R. Pavithra Marthandam, J. Jayachandiran, C.P. Khatiwada, K. Kaviyarasu, R.G. Raman and M. Swaminathan, *J. Photochem. Photobiol. B*, **181**, 53 (2018); https://doi.org/10.1016/j.jphotobiol.2018.02.011
151. M. Maruthupandy, G. Rajivgandhi, T. Muneeswaran, J.M. Song and N. Manoharan, *Microb. Pathog.*, **121**, 224 (2018); https://doi.org/10.1016/j.micpath.2018.05.041
152. S. Gunalan, R. Sivaraj and V. Rajendran, *Prog. Nat. Sci.*, **22**, 693 (2012); https://doi.org/10.1016/j.pnsc.2012.11.015
153. M. Chennimalai, J.Y. Do, M. Kang and T.S. Senthil, *Mater. Sci. Eng. C*, **103**, 109844 (2019); https://doi.org/10.1016/j.msec.2019.109844
154. M. Cassandri, A. Smirnov, F. Novelli, C. Pitolli, M. Agostini, M. Malewicz, G. Melino and G. Raschellà, *Cell Death Discov.*, **3**, 17071 (2017); https://doi.org/10.1038/cddiscovery.2017.71
155. J.C. Stangoulis and M. Knez, *Plant Soil*, **474**, 57 (2022); https://doi.org/10.1007/s11104-022-05330-7
156. S.M. Salah, G. Yajing, C. Dongdong, L. Jie, N. Aamir, H. Qijuan, H. Weimin, N. Mingyu and H. Jin, *Sci. Rep.*, **5**, 14278 (2015); https://doi.org/10.1038/srep14278
157. M. Faizan, S. Sehar, V.D. Rajput, A. Faraz, S. Afzal, T. Minkina, M.F. Adil, S. Sushkova, F. Yu, A.A. Alatar, F. Akhter and M. Faisal, *Plants*, **10**, 2254 (2021); https://doi.org/10.3390/plants10112254
158. S.D. Polishchuk, A.A. Nazarova, M.V. Kutskir, D.G. Churilov, Y.N. Ivanycheva, V.A. Kiryshin and G.I. Churilov, *Modern Appl. Sci.*, **9**, 354 (2015); https://doi.org/10.5539/mas.v9n6p354
159. F. Al-Qurainy, M. Nadeem, S. Khan, M.R. Siddiqui, F.M. Husain, A.R.Z. Gaafar, S. Alansi, A. Alshameri, M. Tarroum, N.A. Alenezi, A.M. Salih and H.O. Shaikhaldein, *Biotechnol. Biotechnol. Equip.*, **35**, 1238 (2021); https://doi.org/10.1080/13102818.2021.1961609

160. Z. Cao, L. Rossi, C. Stowers, W. Zhang, L. Lombardini and X. Ma, *Environ. Sci. Pollut. Res. Int.*, **25**, 930 (2018); https://doi.org/10.1007/s11356-017-0501-5
161. A. Hussain, S. Ali, M. Rizwan, M.Z. Rehman, M.F. Qayyum, H. Wang and J. Rinklebe, *Ecotoxicol. Environ. Saf.*, **173**, 156 (2019); https://doi.org/10.1016/j.ecoenv.2019.01.118
162. S. Mohan, M. Vellakkat, A.U.R. Aravind and R. U, *Nano Express*, **1**, 030028 (2020); https://doi.org/10.1088/2632-959X/abc813
163. M. Rizwan, S. Ali, B. Ali, M. Adrees, M. Arshad, A. Hussain, M. Zia ur Rehman and A.A. Waris, *Chemosphere*, **214**, 269 (2019); https://doi.org/10.1016/j.chemosphere.2018.09.120
164. M.H. Saleem, S. Ali, S. Irshad, M. Hussaan, M. Rizwan, M.S. Rana, A. Hashem, E.F. Abd-Allah and P. Ahmad, *Plants*, **9**, 404 (2020); https://doi.org/10.3390/plants9030404
165. M.H. Saleem, S. Ali, M. Kamran, N. Iqbal, M. Azeem, M. Tariq Javed, Q. Ali, M. Zulqurnain Haider, S. Irshad, M. Rizwan, S. Alkahtani and M. M. Abdel-Daim, *Plants*, **9**, 756 (2020); https://doi.org/10.3390/plants9060756
166. P. Bhatt, S.C. Pandey, S. Joshi, P. Chaudhary, V.M. Pathak, Y. Huang, X. Wu, Z. Zhou and S. Chen, *J. Hazard. Mater.*, **427**, 128033 (2022); https://doi.org/10.1016/j.jhazmat.2021.128033
167. S. Khaleghi, J. Khayatzadeh and A. Neamati, *Mater. Technol.*, **37**, 2522 (2022); https://doi.org/10.1080/10667857.2022.2044218
168. M.H. Saleem, S. Ali, M. Rehman, M. Rizwan, M. Kamran, I.A.A. Mohamed, Z. khan, A.A. Bamagoos, H.F. Alharby, K.R. Hakeem and L. Liu, *Environ. Technol. Innov.*, **19**, 100895 (2020); https://doi.org/10.1016/j.eti.2020.100895
169. M.H. Saleem, M. Rehman, M. Kamran, J. Afzal, H.A. Noushahi and L. Liu, *Environ. Sci. Pollut. Res. Int.*, **27**, 30367 (2020); https://doi.org/10.1007/s11356-020-09232-y
170. H.A. Kareem, M.U. Hassan, M. Zain, A. Irshad, N. Shakoor, S. Saleem, J. Niu, M. Skalicky, Z. Chen, Z. Guo and Q. Wang, *Environ. Pollut.*, **303**, 119069 (2022); https://doi.org/10.1016/j.envpol.2022.119069
171. M.H. Sayadi, S. Ghollasimood, N. Ahmadpour and S.J. Homaeigohar, *J. Photochem. Photobiol. Chem.*, **425**, 113662 (2022); https://doi.org/10.1016/j.jphotochem.2021.113662
172. M.H. Saleem, S. Ali, M.F. Seleiman, M. Rizwan, M. Rehman, N. Aisha Akram, L. Liu, M. Alotaibi, I. Al-Ashkar and M. Mubushar, *Plants*, **8**, 545 (2019); https://doi.org/10.3390/plants8120545
173. R. Suhag, R. Kumar, A. Dhiman, A. Sharma, K. Gopalakrishnan, P.K. Prabhakar, R. Kumar and A. Singh, *Crit. Rev. Food Sci. Nutr.*, **63**, 6757 (2022); https://doi.org/10.1080/10408398.2022.2043237
174. M.T. Javed, K. Tanwir, S. Abbas, M.H. Saleem, R. Iqbal and H.J. Chaudhary, *Environ. Sci. Pollut. Res. Int.*, **28**, 27542 (2021); https://doi.org/10.1007/s11356-020-12269-8
175. S. Singh, P. Parihar, R. Singh, V.P. Singh and S.M. Prasad, *Front. Plant Sci.*, **6**, 1143 (2016); https://doi.org/10.3389/fpls.2015.01143
176. C. Ma, J.C. White, O.P. Dhankher and B. Xing, *Environ. Sci. Technol.*, **49**, 7109 (2015); https://doi.org/10.1021/acs.est.5b00685
177. A. Das, D.Y. Wang, A. Leuteritz, K. Subramaniam, H.C. Greenwell, U. Wagenknecht and G. Heinrich, *J. Mater. Chem.*, **21**, 7194 (2011); https://doi.org/10.1039/c0jm03784b
178. D. Tanasa, N. Vrinceanu, A. Nistor, C.M. Hristodor, E. Popovici, I.L. Bistricianu, F. Brinza, D.-L. Chicet, D. Coman, A. Pui, A.M. Grigoriu and G. Broasca, *Text. Res. J.*, **82**, 832 (2012); https://doi.org/10.1177/0040517511435068
179. R. Huang, S. Zhang, W. Zhang and X. Yang, *IET Collab. Intell. Manuf.*, **3**, 281 (2021); https://doi.org/10.1049/cim2.12029
180. Z. Yuan, E. Han, F. Meng and K. Zuo, *IEEE Trans. Instrum. Meas.*, **69**, 4533 (2020); https://doi.org/10.1109/TIM.2019.2948413
181. C. Wang, *Chem. Phys. Lett.*, **749**, 137471 (2020); https://doi.org/10.1016/j.cplett.2020.137471
182. L. Zhang and W. Jiao, *Mol. Cryst. Liq. Cryst.*, **691**, 15 (2019); https://doi.org/10.1080/15421406.2019.1693111
183. Y.Z. Mao, S.Y. Ma, W.Q. Li, X.L. Xu, D.J. Gengzang, J. Luo and L. Cheng, *Mater. Lett.*, **134**, 80 (2014); https://doi.org/10.1016/j.matlet.2014.07.036
184. M. Maruthupandy, Y. Zuo, J.-S. Chen, J.-M. Song, H.-L. Niu, C.-J. Mao, S.-Y. Zhang and Y.-H. Shen, *Appl. Surf. Sci.*, **397**, 167 (2017); https://doi.org/10.1016/j.apsusc.2016.11.118
185. P. Vishnukumar, S. Vivekanandhan, M. Misra and A.K. Mohanty, *Mater. Sci. Semicond. Process.*, **80**, 143 (2018); https://doi.org/10.1016/j.mssp.2018.01.026
186. V.N. Kalpana and V. Devi Rajeswari, *Bioinorg. Chem. Appl.*, **2018**, 3569758 (2018); https://doi.org/10.1155/2018/3569758
187. Burns, and W. T. Self, *Smart nanoparticles for biomedicine*, **159** (2018); https://doi.org/10.1016/B978-0-12-814156-4.00011-2
188. B. Banerjee, *J. Nanostruct. Chem.*, **7**, 389 (2017); https://doi.org/10.1007/s40097-017-0247-0
189. T.T. Xu, J. Zhang, J.M. Song, H.L. Niu, C.J. Mao, S.Y. Zhang and Y.H. Shen, *Appl. Catal. A Gen.*, **515**, 83 (2016); https://doi.org/10.1016/j.apcata.2016.01.042
190. T.G. Smijs and S. Pavel, *Nanotechnol. Sci. Appl.*, **4**, 95 (2011); https://doi.org/10.2147/NSA.S19419