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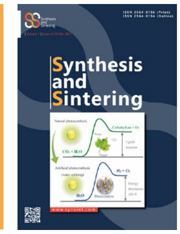

Review article

Sol-gel zinc oxide nanoparticles: advances in synthesis and applications

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ABSTRACT

Zinc oxide nanoparticles (ZnO) exhibit numerous characteristics such as biocompatibility, UV protection, antibacterial activity, high thermal conductivity, binding energy, and high refractive index that make them ideal candidates to be applied in a variety of products like solar cells, rubber, cosmetics, as well as medical and pharmaceutical products. Different strategies for ZnO nanoparticles' preparation have been applied: sol-gel method, co-precipitation method, etc. The sol-gel method is an economic and efficient chemical technique for the formation of nanoparticles (NPs) that has the ability to adjust the structural and optical features of the NPs. Nanostructures are generated from an aqueous solution including metallic and chemical precursors for modifying pH using either a gel or a sol as a yield. Among the various approaches, the sol-gel technique was revealed to be one of the desirable techniques for the synthesis of ZnO NPs. In this review, we explain some novel investigations about the synthesis of ZnO NPs via the sol-gel technique and applications of sol-gel ZnO NPs. Furthermore, we study recent sol-gel ZnO NPs, their significant characteristics, and their applications in biomedicals, antimicrobial packaging, drug delivery, semiconductors, biosensors, catalysts, photoelectron devices, and textiles.

KEYWORDS

Zinc oxide nanoparticles
Sol-gel synthesis
Applications of sol-gel zinc oxide

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1. Introduction

In recent years, nanoparticle applications have received considerable attention in the size range of 1 to 100 nm because of their new properties and have been the research subject of immense [1–4]. Nanoparticles are different from bulky materials in terms of properties [5–8]. ZnO nanoparticles' optical properties depend on the annealing morphology and temperature [9–12]. ZnO properties are usually related to its morphology and structure. Thus, controlling these properties is one of the most important research in making ZnO. To control the ZnO nanoparticle synthesis, monoethanolamine has been used as a structure-directing factor of ZnO crystal formation. The ZnO crystalline structure owns a quartzite structure that has a single hexagonal cell with two lattice parameters a. In this hexagonal structure, four cations surround each anion at the corners that show the quadrilateral coordination and hence the covalent bond of sp3 [13–15].

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Nanoparticles have a special place in almost every part of life such as the delivery of the controlled drug, electronic devices of sensors and photons [16, 17], electrocatalytic water decomposition, nanocomposites for storage of energy, and so on. Its potential applications are because of its electrical, optical, photochemical, and catalytic properties, and environmentally friendly nature of ZnO nanoparticles that have been widely investigated. ZnO nanoparticles have a wide application ranges such as biosensors, gas sensors, solar cells, ceramics, optical detectors, nanogenerators, active fillers for rubber, catalysts, and plastics, UV absorbers, cosmetics, and antiviral coatings, pigments of optical materials, optical and patriotic materials, optical probes, additives in high products of industrial and water and wastewater treatment [18–26]. In various articles, many scientists have reported the characterization and synthesis of nanostructures of ZnO in different ways including co-precipitation [27, 28], sol-gel technique, laser erosion, hydrothermal procedure, and coating deposition, electrochemical sediments, vapor chemical deposition, fabrication of green natural products, and so on. For the development of ZnO compositions, the sol-gel procedure has been interesting between these procedures. For example, the sol-gel procedure has been applied to formation of $Zn_{1-x}Zr_xO$ (x = 0.00, 0.01, 0.03 and 0.05) nanoparticles [29–31]. It is found that the dopant has significantly influenced the electrochemical implementation individually and simultaneously toward uric acid and superb yields have been achieved via the Zr-doped ZnO modified carbon paste electrode (MCPE) [32]. Additionally, Mourad et al. reported the formation of un-doped ZnO and In-doped ZnO nanoparticles via sol-gel technique from 0 to 5 wt% of in values. Their morphological results indicated that the crystallite shapes were hexagonal and turned into cylindrical prismatic after doping [33]. In the case of the nanoparticles, it is known that the range and morphology of nanoparticles can be changed by changing the synthesis method and stoichiometric parameters. Like other nanostructures, ZnO has morphological properties, so the choice of synthesis technique has paramount importance in determining the features of the nanoparticle [34–37]. This study highlights the latest advancements specifically in numerous applications of sol-gel ZnO nanoparticles. Further, in the last 5 years ago, a lot of research about sol-gel ZnO nanoparticles have focused on their either properties and synthesis methods or applications but none of them has, to the best of the author's knowledge, reviewed both characteristics and applications in advance.

In this review paper, the steps of the sol-gel process are extensively investigated. Moreover, we briefly present a discussion summarizing studies on the synthesis of ZnO nanoparticles, their applications, and comparing the results. The various applications of ZnO sol-gel nanoparticles such as hydrogen production, biomedical, sensors, photovoltaics, and photocatalysis fields are extensively evaluated.

2. The structure and properties of sol-gel ZnO nanoparticles

2.1. Formation of ZnO nanoparticles via sol-gel method

The sol-gel method has been considered vitally beneficial for the fabrication of materials due to its economical nature, stability, reproducibility, and inexpensiveness. The sol-gel condition can be applied to fabricate various formations of materials including ceramics, thin-film coatings, and nanoparticles; making a large diversity of applications [38]. Among them, the synthesis of ZnO nanoparticles has attracted much attention from researchers using this procedure. For example, nanocrystalline ZnO was synthesized by Mahato et al. [39]. They hydrolyzed sarin to fabricate the surface-bound non-toxic phosphonate on the nano-zinc oxide surface. They also indicated the values of half-life and rate constant to be 0.16 h and 4.12 h^{-1} in the primary steps of the reaction and 1.9 h and 0.361 h^{-1} at the last steps of the reaction for the reaction of decontamination on nanocrystalline ZnO. Nanocrystalline powder of ZnO using zinc 2-ethyl hexane ethylene glycol monomethyl 1% containing ether was prepared by Ristic et al. [40], with an aqueous solution of isopropanol and tetramethylammonium ($(CH_3)_4NOH$) as precursors. TEM Results of nanoparticles demonstrated that the synthesized particles ranged in the size of 20–50 nm in this survey. Furthermore, the molding method of sol-gel was used to synthesize ZnO nanofibers [41, 42]. A simple method for the synthesis of ZnO nanotubes was reported by Yue et al. [43] with anodic aluminum oxide (AAO) of porous membranes under the condition of two-step anodizing in a solution of oxalic acid. The resulting nanotubes of ZnO were about 70 nm thick and 12 nm thick. Moreover, the sodium hydroxide and temperature role in the ZnO preparation nanoparticles were studied by Mayekar et al. [44]. Their study showed that the size of the particle was increased by raising the temperature and also with a rising concentration of sodium hydroxide [45, 46]. Chemical synthesis is the most principle procedure and contains vast amounts of precursors and variable factors such as time, the concentration of reactants, temperature, etc. Changing these parameters causes diverse morphological varieties in the geometry size of nanoparticles. The results of the various chemical methods that have been used to synthesize zinc oxide nanoparticles are listed below [47, 48].

1. The chemical reaction of zinc metal by alcohol: most alcohol types, including ethanol, propanol, or methanol are applied for synthesizing the chemical zinc oxide nanoparticles. The mixture of reaction is then socketed for 20 minutes and transferred to an autoclave. The suspension obtained to recover the product is centrifuged, washed, and totally dried in a vacuum. In an alcoholic environment, the growth of oxide particles is controllable and slow.

2. Vapor synthesis of transfer: the steam transfer process is the most common procedure for synthesizing zinc oxide nanostructures. In this condition, oxygen and zinc or vapors of the oxygen mixture are transferred and react by others, resulting in the zinc oxide nanostructures formation. There are many methods to produce zinc and vapor of oxygen. Another direct method includes heating powder of zinc under oxygen flow, but the ratio among zinc vapor oxygen pressure and pressure must be controlled to give the desired ZnO nanostructures. This has been shown that changes in this ratio lead to large variations in the morphology of the nanostructures (geometry and size) [49–51].

3. Hydrothermal procedure: this is an attractive procedure due to the low temperature of the process. Particle size control is very easy. This process has some benefits like using simple equipment, growth without catalysts, cost-effective, homogeneous yields, eco-friendly, and low risk compared to other fabrication methods. This procedure is attractive for plastic electronics and microelectronics because of its low reaction temperature. The size and morphology of particles can be justified under the hydrothermal condition via tuning the concentration of precursors, the temperature of the reaction, and time [52–55].

4. Sedimentation method: in this procedure, ZnO is generated via urea as a precursor and using zinc nitrate. In a common production, 0.5 M (4.735 g) of zinc nitrate ($Zn(NO_3)_2{\cdot}6H_2O$) is dissolved in 50 ml of distilled water and the following is remained constant for 30 minutes for complete dissolution. The whole chemical reactions that happened in this condition are indicated in Fig. 1 [56–58].

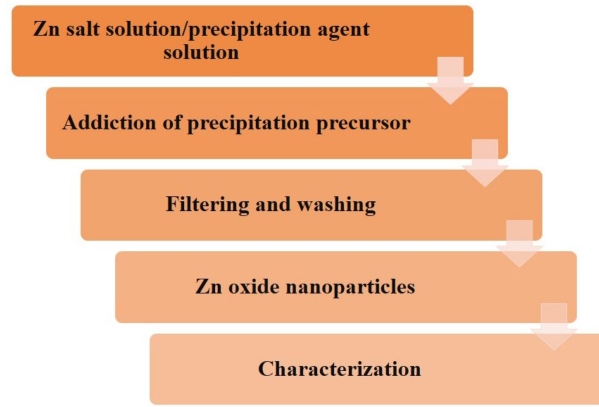

Fig. 1. Precipitation approach.

2.2. Characteristics of sol-gel ZnO nanoparticles

ZnO is a harmless composite that has been used in different areas like solar cells, piezoelectric transducers, micro-sensors, catalysis, environmental sciences, and chemical photoelectrons. The fabrication of metal nanoparticles with specific properties is a new field of research that has attracted a lot of attention. Various methods have been proposed to synthesize these materials, including chemical vapor deposition, arc discharge, hydrogen plasma-metal reaction (HPMR), and laser chemical vapor pyrolysis (LaCVP), hydrothermal, microemulsion, and sol-gel. The characteristics of metal nanoparticles wieldy depend on their synthesis techniques. In general, formation methods of metal nanoparticles can be classified into two approaches: (1) physical routes like sputtering, ball mill, electron spray, beam electron evaporation, laser erosion, etc. (2) chemical-based routes like sol-gel technique, hydrothermal technique, microemulsion technique, polyol method, chemical vapor deposition, simultaneous deposition method, etc. (see Fig. 2) [59, 60].

An economic and efficient chemical method for the production of nanoparticles is the sol-gel method with the ability to adjust the optical and structural features. This involves the process of the nanostructure production from an aqueous media including metal precursors, and chemicals for modification of pH using gel or sol as the intermediate outcome shown in Fig. 3 [61–63].

The method of sol-gel is the well-established synthesis method for the preparation of high-quality ZnO-NPs and also composites of mixed oxides. This procedure can easily control the surface of the material and properties of texture [64-66]. The sol-gel approach consists of five steps: thermal decomposition, polycondensation, hydrolysis, aging, and drying as shown in Fig. 4 [67, 68].

A summary of synthesized ZnO nanocomposites by sol-gel technique, synthesis conditions, and their properties are described in Table 1.

The properties of sol-gel ZnO-NPs, due to the controlled stabilization of nanostructures, modulation of shape, and low temperature for processing, have been studied by many researchers. Recently, biomaterials have been used for synthesizing nanoparticles, especially metal oxidants and metal particles [83, 84].

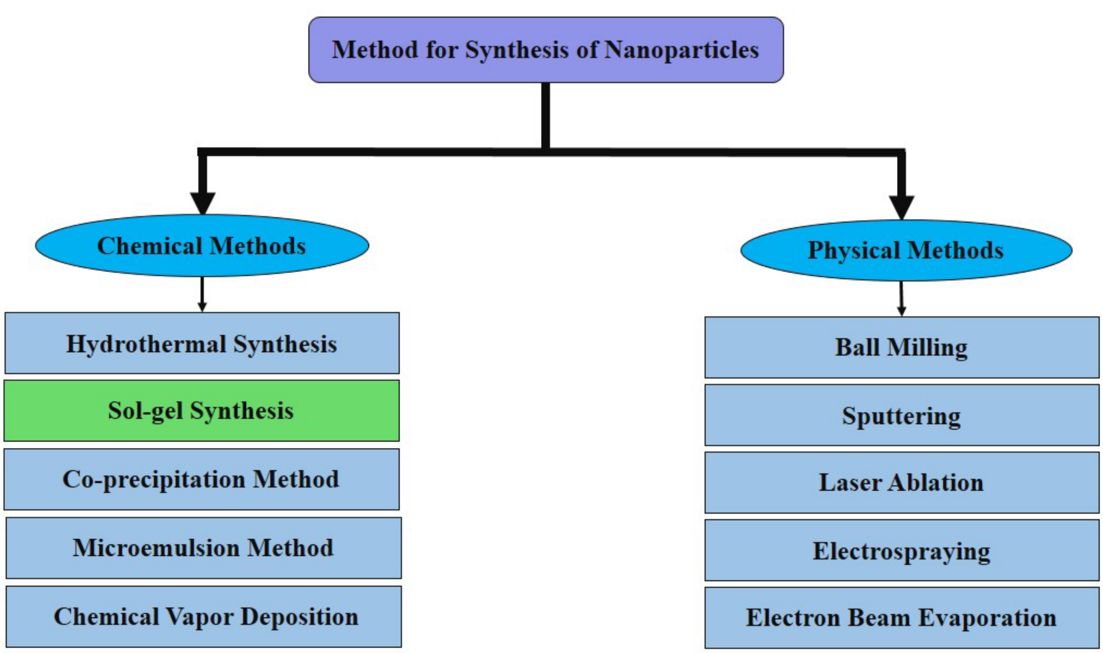

Fig. 2. Different methods of chemical and physical synthesis of ZnO-NPs.

Table 1. A list of ZnO nanoparticles synthesized by sol-gel technique, their synthesis conditions, and properties.

Precursors	Synthesis conditions	Characteristics	Ref.
Zinc 2-ethylhexanoate, $(CH_3)_4NOH$, and isopropanol	Stirring: at room temperature Aging: 30 min–24 h, drying: 60 °C	Particles with a size range of 20–50 nm	[40, 69]
Manganese acetate, ethanol, sodium hydroxide, and zinc acetate (applied as dopant)	Heating in a water bath at 60–65 °C, for 2 h Centrifuge: at 4000 rpm, 20 min	Polycrystalline structures ranged from 21 nm to 73 nm were synthesized, ZnO:Mn^{2+} with higher photocatalytic activity than virgin ZnO under visible light irradiation.	[70–72]
Ethanol, oxalic acid, and zinc acetate dehydrate	Stirring: 60 °C Drying: 24 h, 80 °C Calcination: 500 °C	Randomly oriented aggregates of NPs and nanorods with variable sizes. With an average crystallite size of ~55 nm for decontamination of sarin were fabricated.	[39, 69, 73]
Ethanol, diethanolamine, and zinc acetate	Stirring: at room temperature The ultrathin anodic aluminum oxide (AAO) membrane was then immersed into the sol for 30 min. Annealing: 2 h, 500 °C	ZnO nanotubes with a diameter of 70 nm with the thickness of 12 nm were fabricated in AAO membrane.	[43, 74]
Methanol and zinc acetate dihydrate	Spin coating: 20 s, 3000 rpm Drying: 10 min, 80 °C Annealing: 20 min, 500–575 °C	Nanofilm with a thickness of 160–230 nm on the substrate of Pyrex glass	[75, 76]
Sodium hydroxide and zinc chloride	Stirring: 80 °C Drying: 2 h, 80–100 °C NaOH concentration: 2–10 M	Particles with 20–350 nm size were synthesized and formed from spherical to rod-like structures.	[44, 77]
2-methoxy ethanol, monoethanolamine, and zinc acetate	Spin coating: 2000 rpm Drying: 10 min, 473 or 573 K Irradiation of dried film by KrF excimer LASER (λ = 248 nm, 22 ns Full-Width Half Maximum)	ZnO nanofilms with a thickness of 35–60 nm were achieved.	[78–82]

3. Sol-gel ZnO nanoparticle applications

In the last decade, there has been considerable interest in NPs research, particularly in biomedical applications. The nanotechnology integration into the science of medicine has opened up new opportunities and created a better aspect of molecular biology. As a result, this is a potential for new approaches to treating diseases that were previously difficult to target because of size constraints [85–87]. Currently, this is a wide range of chemical synthesis techniques and materials which are being investigated for biomedical applications, as we reviewed some sorts of medical ZnO nanoparticles in this study. ZnO is also known as

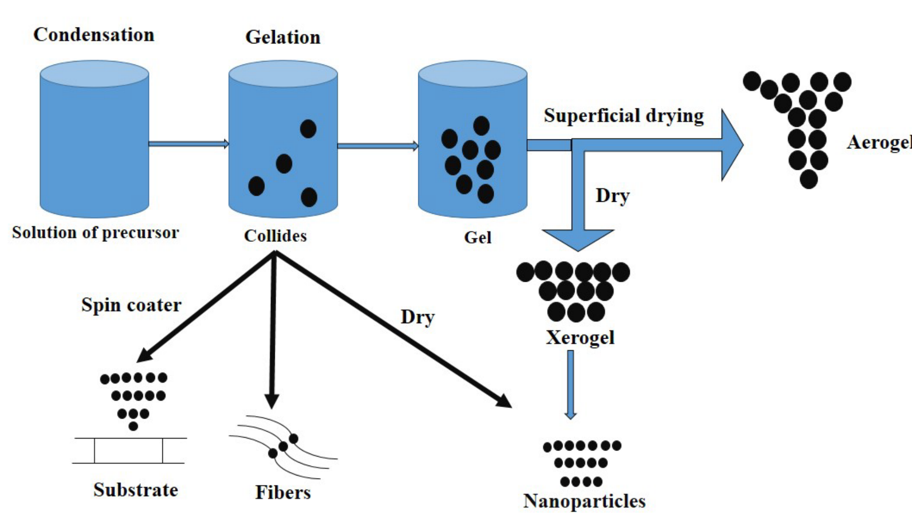

Fig. 3. Synthesis procedure of sol-gel for nanocomposite as an intermediate product.

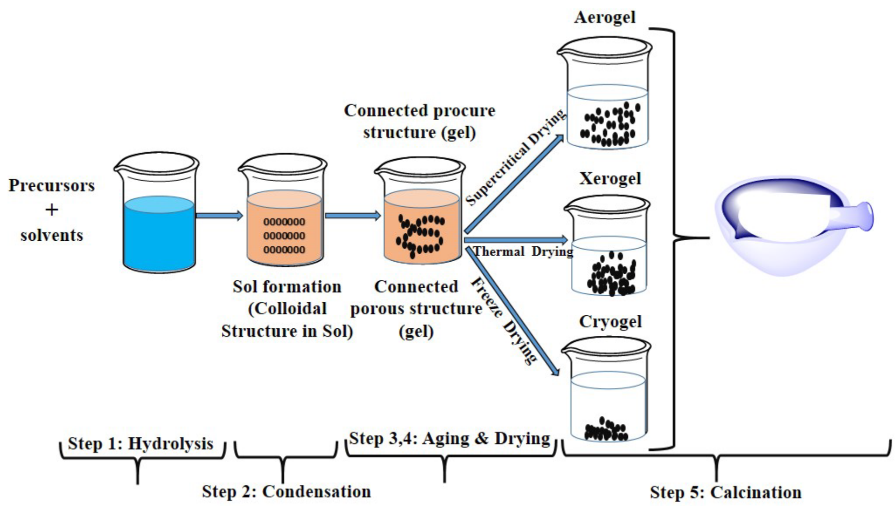

Fig. 4. Steps of synthesis action in the sol-gel process of ZnO-NPs.

a valuable food additive and is widely used in pharmaceutical, cosmetic, and medical applications (Fig. 5). However, the inhalation of dust and fumes of ZnO should generally be avoided [88–92].

3.1. Biomedical applications

As there are several articles available on the various ZnO-NPs applications in medicine and biology, the current developments of ZnO-NPs for applications of biomedical: (a) drug and gene delivery, (b) anticancer, (c) anti-antigenic properties, (d) immunotherapy, (e) antimicrobial activity, (f) wound healing, (g) tissue engineering, (h) diabetes treatments, (i) bioimaging, and (j) biosensing are discussed in this session [93]. Fig. 6 demonstrates the diverse biomedical ZnO-NPs applications as described below [94–97]

Among the various metal nanoparticles, ZnO-NPs have aroused lots of interest from biomedical researchers because of some factors, particularly tunable physicochemical features like surface, size, charge, morphology, etc. that can be useful for their pharmaceutical applications [98]. It should be noted that the effect of enhanced permeability and retention (EPR) can be used on target cancer cells by ZnO-NP through modification of their physicochemical properties. Besides, the appropriate cationic charge balance on the surfaces of ZnO-NPs improves their contact with the cell membrane, preventing quicker serum evacuation. Furthermore, ZnO-NPs with the right shape may be more easily recognized for biological applications. Then, modifying the physicochemical properties of ZnO-NPs may be an appropriate strategy to improve their biological impacts as a requirement for the dependence of the circumstances [95, 99–105].

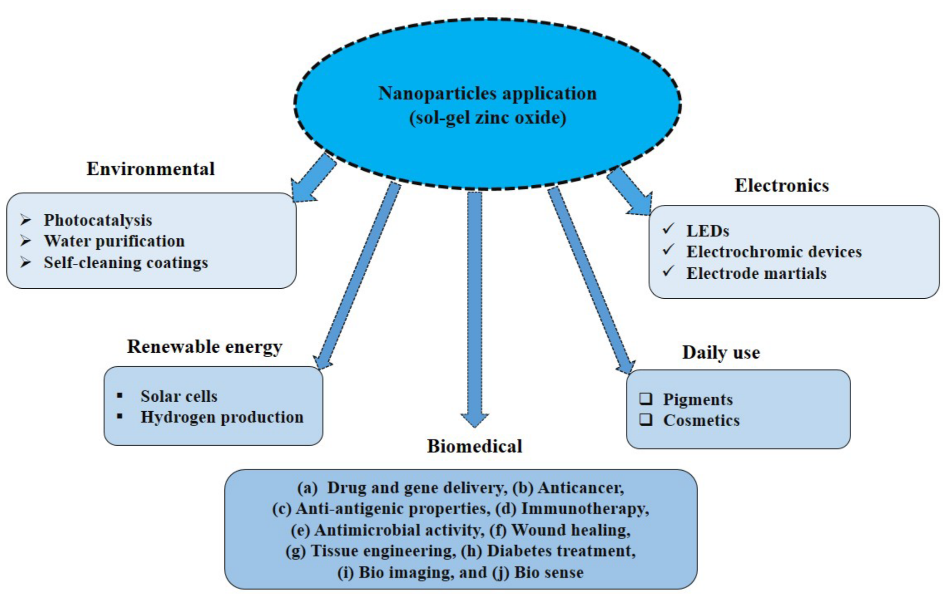

Fig. 5. Different applications of ZnO-NPs.

Fig. 6. Various ZnO-NP applications in medicine and biology.

3.2. Antimicrobial packaging

ZnO is tested as a candidate for drug agent in any micro-scale and formulations of nanoscale. The results have indicated that ZnO-NPs have rendered drug activity that can be bigger than small particles. If the exact action mechanisms of the drug are not clearly understood, it is quickly realized that most of the cell swelling causes are reactive oxygen species (ROS) production. This is produced on the nanoparticle adsorption, particle surfaces, diffusion of zinc ion, and dysfunction of the unit membrane region. The antibacterial ZnO-NPs mechanism has not yet been understood completely, and also the bacteria damage could happen in three ways indicated in Fig. 7 [106, 107].

High heat treatment of ZnO-NP has a significant effect on their medicinal activity, while subsequent temperature treatment results in less activity. The action mechanism of nanoparticles of ZnO is not good understood. Although it is predicted that oxide production may be the main subject of their activity, it has been shown that the particle binding on the surface of microorganisms due to electrical forces can be an evaluated mechanistic behavior. It is a drug of ZnO nanoparticles that can be done using chemical light analysis and oxygen analysis of electrodes. The surface unit of metal nanoparticles is ionic or high and must be prepared with extremely high surface areas, with various crystals and morphologies, having different edges/corners and different reactive locations of the surface. The ZnO-NPs regional unit has been investigated in conjunction with the erosive regimes of the medical method. In addition, to the higher thermal effect on neoplasm erosion, nanoparticles provide anti-neoplastic medical expertise that exhibits a synergistic antineoplastic effect on the heat presence and must be imaged to achieve accurate medical assistance. Some articles have shown that the mechanism of molecular involvement in tumor-mediated erosion of nanoparticles further contributes to the engineering of nanoparticles with suitable properties and composition for synergistic erosion properties [91, 108–111]. For example, in a recent investigation, the biological performance of ZnO nanoparticles was examined toward the Escherichia Coli bacteria, Candida Albicans, and Pseudomonas aeruginosa. A superior antibacterial activity has vitally occurred about Pseudomonasaeruginosa, which demonstrated that the ZnO nanoparticles had superb antimicrobial activity against Pseudomonasaeruginosa [112].

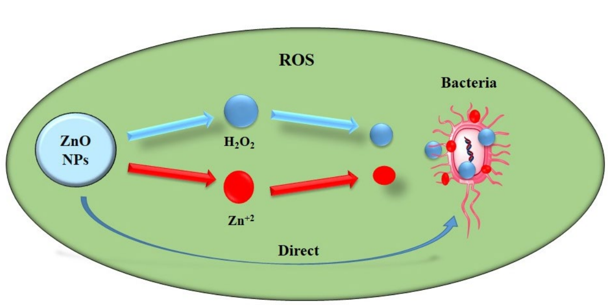

Fig. 7. The ZnO-NP mechanisms for antibacterial.

3.3. Drug delivery

Among the different nanotechnology applications, the delivery of drugs has been proposed as a powerful instrument in the treatment of different diseases, including cancer. The NPs are one of the principal systems in drug delivery. Several investigates have performed ZnO-NPs for drug delivery applications in the treatment of different diseases. In one study, the loaded ZnO quantum dots with doxorubicin have been as an influential drug delivery system analyzed by a primary quick drug release followed by a controlled release in vitro. In this survey, ZnO nanoparticles were encapsulated with chitosan to improve the stability of the nanomaterial led to its cationic charge and hydrophilicity properties [113]. Another major aspect of the application of nanoparticles is their use as a means of gene transfer to various cells, especially tumor cells [82, 114]. There are several benefits to the application of this system for gene transfer. For instance, the plasmid-containing expression genes on the surface of NPs can efficiently be targeted and ensure the safety of the gene to recipient tissues [115, 116]. Therefore, nanoparticles can be a good tool for targeting genes to different cells, such as tumor cells. In another survey, Obayemi et al. synthesized quadrupole nanostructures such as ZnO that could be used as new means of gene carriers [117]. They showed that ZnO nanostructures, such as silicon-coated amino-modified animals, can bind efficiently to DNA through electrostatic interactions and can improve the transmission yield of melanoma cells [117]. Moreover, Li et al. showed that ZnO quantum dots with polycationic coatings could transfer DNA to COS-7 cells [118]. Additionally, the use of this system allowed real-time imaging of gene delivery [19, 118, 119]. Different articles have used different oxides of metal nanoparticles as a suitable carrier for gene silencing and gene delivery [120–123]. However, further studies are required in this area.

3.4. Semiconductors

ZnO is remarkably popular as a good semiconductor that has well potential to substitute traditional Cd-related species used in optical and biology fields [124, 125]. Today, various types of ZnO nanostructures like nanorings, nanoparticles, nanotubes, and nanorods are well known. Bioimaging use of ZnO-NPs is interesting for scientists [125–128]. For example, bright ZnO-NPs can have well photophysical features [125]. It has been indicated that these nanoparticles surfaces can be easily modified. This has been shown that ZnO-NPs can be very stable in aqueous solutions and their quantum yield (QY) can increase up to about 30% after modification of precision [129, 130]. ZnO is generally recognized as a safe substance. ZnO is used in sunscreen yields and is used in the packaging of food as a food additive. Hence, the luminosity ZnO-NP properties can be used in various applications of biological and medical [130].

3.5. Biosensor

Biosensors can diagnose various significant biological molecules with high accuracy and sensitivity [114, 131, 132]. Biosensors are mainly used for the detection of various diseases, cell imaging, measurement of nucleotide sequences, etc. Scientists have discovered in recent decades that ZnO-NPs can be used in a variety of biological applications. For example, a biosensor based on ZnO-NPs was designed for xanthine detection [133]. The first fabricated ZnO-NPs were electro-polymerized in the pyrrole presence on an electrode of platinum to produce a nanocomposite of ZnO/polypyrrole film which was subsequently stabilized by oxidase of xanthine (XOD) to form the working electrode for the biosensor of xanthine. The Ag/AgCl was performed as the reference electrode and Pt as an auxiliary electrode to make the sensor. The ZnO-NPs-based biosensors showed a detection restriction of 0.8 μM. The glucose biosensor was developed by Ren et al. [134] with stabilizing on ZnO-NPs of glucose oxidase. The researchers showed that ZnO-NPs containing enzymatic electrodes generated a response current compared to electrodes without nanoparticles, which may be related to the increased catalytic performance of glucose oxidase with the photovoltaic ZnO-NP effect [132, 134]. In another investigation, Zhang et al. [135] designed a semiconductor pyrolytic graphite electrode based on micro peroxidase-immobilized ZnO-NPs that could be used to construct a biosensor to detect hydrogen peroxide by micro peroxidase electrocatalysis. It is suggested that the effect of ZnO-NP photovoltaic may increase the activity of catalytic micro peroxidase that can be useful in creating a sensitive sensor to the hydrogen peroxide. The ZnO-NP-based biosensor of cholesterol was developed by Khan et al. [136] as stabilizing cholesterol oxidase on a glass plate of indium-tin-oxide (ITO) containing dispersed CS ZnO-NPs [137]. The scientists showed that a biosensor can be used to detect serum cholesterol. They discovered that ZnO-NPs could significantly be used in the systems of cancer diagnosis. Additionally, Pal and Bhand [138] developed the ZnO-NP-based test of ELISA for detecting serum levels of cancer antigens of embryonic. The detection system consisted of a monoclonal carcinoma embryonic antigen-antibody conjugated to ZnO-NP, which formed self-assembled monolayers, and even at 1 pg/ml, smaller quantities of antigen were found [139].

3.6. Catalysts

Fuel cells use precious metals like platinum (Pt) and their alloys as electrocatalysts. However, catalysts show vulnerability and stability loss to methanol that acts as a barrier to the large-scale use of these environmentally efficient cells. Sandstead et al. [102] produced a composite containing nanostructured doped ZnO annealed by graphene oxide as a base. They studied its electrocatalytic activity for the reduction of O_2 and concluded reactions in which doping nanostructures were stable and conductive. The performance of electrocatalytic was assessed by measuring their CV profile [140–142]. Doped nanostructures showed maximum efficiency for skin bacteria (S. aureus) and decreasing of the inhibitory area from 37% to 4%. Therefore, the incorporation of nanostructures of ZnO into skin creams, UV protection, and nosocomial implants is possible. Sandstead et al. [102] analyzed dyes like alizarine Red.S, thymol blue, methylene red, and methylene blue in a solution of hydrogen peroxide with pure and doped copper ZnO nanoparticles. Nanostructures with the spherical morphology were given by polyol decrease process by polyvinylpyrrolidone (PVP) as the coating agent. The catalysis was performed under ambient conditions, i.g. in the absence of any light source. Scientists observed that the doping nanostructures increased as the catalyst increased with increasing copper concentration and were very sensitive to Methylene Blue (MB). Hence, ZnO nanostructures have been feasible and efficient for colorless photo-degradation [143–145].

3.7. Photoelectron devices

The characterization of one-dimensional (1D) nanowires - like strong light-emitting, light absorption, and optical conductivity - can improve the light-emitting diodes (LEDs) performance, optical detectors, sensors, solar cells, field-effect transistors, and nanogenerators. For instance, nanowires of ZnO act as carrier conduction channels in photoelectric devices and reduce the carrier loss of light produced [145–147]. The LEDs' performance and nanowire-based detectors of photoelectric could be improved compared to tools based on thin films of polycrystalline [148, 149]. This paper investigates the sol-gel method for the synthesis of 1D ZnO nanostructures and the growth effect parameters on morphology and growth rate. The main uses of 1D ZnO nanostructures in optoelectronic devices are discussed. Many methods for improving the performance of 1D ZnO-based devices are discussed including inactivation of surface, the effect of photonic and localized surface plasmons. A schematic design of the LED homojunction is provided in Fig. 8a. In the forward bias, UV emission was predominant from the free recombination of exciton with a concentration of about 380 nm, and a weak broad peak of about 630 nm was viewed in the EL collected of the spectrum at ambient temperature [150]. A plan image of the LED is shown in Fig. 8b. The EL spectrum in Fig. 8b shows that the LED presents the excited EL emission at about 380 nm in the forward bias [151–154].

3.8. Textile

Different antimicrobial agents have been utilized in the textile industry and most of them are biocides. Using inorganic nanoparticles has developed immediately owing to many investigations done in the modification and formation of particles for biomedical applications. Various heavy metals and metal oxides either pure or in composites at very low concentrations are toxic to microbes. They can remove bacteria by different processes, including direct damage to cell walls, generation of reactive oxygen species, and via binding to intracellular proteins and inactivating them. Silver (Ag), ZnO, copper oxide (CuO), magnesium oxide (MgO), and titanium dioxide (TiO_2) are several common inorganic materials used in the synthesis of antimicrobial coatings [155]. For example, loaded ZnO nanoparticles on textiles based on cotton fabrics were dried and washed before use. The modification methods were done on samples with a maximum size of 15 to 30 cm. Cotton clothes were coated with a solution of ZnO-NPs at certain concentrations indicated by MIC (minimum inhibitory concentration) and in vitro cytotoxicity. For sequential fabrics

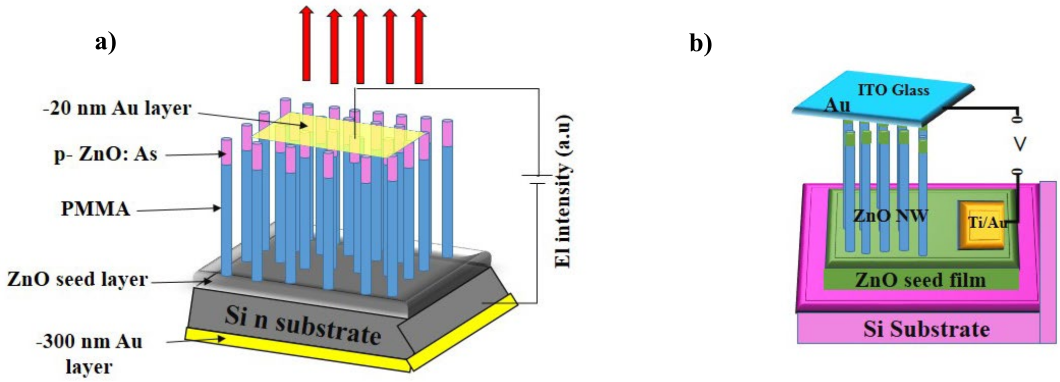

Fig. 8. Schematic design of a) a doped nanorod of p-ZnO/n-ZnO LED of homojunction and b) the nanowire of Au/ZnO LED of Schottky.

treatment with colloidal ZnO, the solution was stirred continuously. All samples were immersed in a colloidal bath for 5 minutes and then pressed with a laboratory pad at constant pressure up to 100% wet. The samples were dried at 80 °C for 5 minutes and then dried at 150 °C for 2 minutes. The following treatments were performed: (1) control that without soybean trypticase (TSB) broth inoculation with bacterial culture (negative control), untreated fabrics in TSB inoculated with bacterial culture (positive control), untreated fabrics in TSB appeared without inoculation (blank) (2) fabrics treated with ZnO-NPs solution [156–158]. Fabric dyes treated with silver or zinc oxide nanoparticles are used to functionalize textile materials. The final product with antibacterial capabilities is determined by embedding these nanoparticles in the structure of other materials. Indigo and commercial dyes have participated in the investigation. It is worth noting that nanoparticles of silver were given in response to the process preparation and indigo dye used for preparing dye commercial baths on site. This approach makes it possible to reduce technological steps. The modified dyes were used to dye cotton fibers. The antimicrobial properties of the textile of the final material were investigated [159, 160].

4. Conclusions

ZnO nanoparticles because of their short size compared to the same materials with bulk shape, have obtained different properties and therefore new advances in biomedicine, biosensors, and biotechnology. They are synthesized by various methods to make affordable metal nanoparticles that are easily scalable and environmentally safe. This is especially true for the production of nanoparticles which should be free of toxic contaminants in applications of therapeutic. The synthesis techniques can provide nanoparticles that have morphology and controlled size. Among these methods, the method of sol-gel is the well-established synthesis method for the preparation of high-quality ZnO-NPs and also composites of mixed oxides. The properties of sol-gel ZnO-NPs, due to the controlled stabilization patterning nanostructures, modulation of shape, and low temperature for processing have been suitable for numerous applications in many fields. In medicine, nanoparticles are performed as agents of antimicrobial-like bandages. Applications are being developed for targeted drug delivery and clinical diagnosis. Sol-gel ZnO-NPs are one of the nanomaterials that have many biomedical applications and could be safely generated at a low cost. However, synthesis methods of these promising particles are expected to be advanced with more desirable features in the future.

CRediT authorship contribution statement

Parisa Shafiee: Data curation, Supervision, Writing – review & editing.
Mehdi Reisi Nafchi: Software, Resources, Methodology.
Sara Eskandarinezhad: Data curation, Resources, Writing – original draft, Investigation, Writing – review & editing.
Shirin Mahmoudi: Investigation, Software.
Elahe Ahmadi: Data curation, Resources, Writing – original draft, Investigation, Writing – review & editing.

Data availability

The data underlying this article will be shared on reasonable request to the corresponding author.

Declaration of competing interest

The authors declare no competing interests.

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