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REVIEW

Recent Advancements of Metal Oxide Nanoparticles and their Potential Applications: A Review

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ABSTRACT

Metal Oxide Nanoparticles (MONPs) have become an important section of nanoparticles, and these nanomaterials have been utilized in different application fields. Thus, it's very important to understand the major and feasible synthesis methods that are involved during the production of MONPs. In our review, we are highlighting some major processes for their synthesis and morphology. This review highlights the status, potential, challenges, and feasibility of different processes like sol-gel, CVD, thermal, flame spray, biological synthesis, and other major techniques to synthesize and their applications. Synthesis of nanomaterial through environmentally friendly and greener routes, which greatly impacts different applications, has also been studied as it has received massive attention as a sustainable, feasible, reliable, and cost-effective route in different fields. These artificially created MONPs exhibit distinct physical and chemical characteristics owing to their substantial surface area and nanoscale dimensions. Their exceptional size, shape, and structure further influence their reactivity, resilience, and diverse properties. Thanks to these attributes, they find wide-ranging uses in commercial and domestic applications, such as catalysis, antimicrobial treatments, bio-sensors, electro-sensors, as well as agriculture and various other significant fields. This review paper states major applications of these MONPs have great aspects and potential in the future and will help researchers gain further insights into these fields.

KEYWORDS

Metal oxide nanoparticles, Theranostics, catalysts, sensors, agricultural and antimicrobial.

INTRODUCTION

The particles ranging from 1 to 100nm are termed nanomaterials. These particles demonstrate unique mechanical, optical, electrical, and magnetic characteristics that differ from those observed in their bulk material. Their significance extends across various fields in physical, chemical, and material science. These Metal Oxide Nanoparticles (MONPs) are used to fabricate micro-electric circuits, sensors, fuel cells, catalysts, etc. A series of MONPs have been synthesized, such as Titanium Dioxide (TiO_2), Silicon Dioxide (SiO_2), Nickel Oxide (NiO), Copper Oxide (CuO), Iron Oxide (Fe_3O_4 Fe_2O_3), Zinc Oxide (ZnO), etc. using different methods, and all these different nanomaterials exhibit different morphology such as spherical, triangular, star, nanowire, etc. [**1**]. Apart from morphology, they have different general characteristics, such as their optical activity, magnetic property, crystallinity, and specific surface area. Due to their high density and constrained size, MONPs exhibit notable enhancements in their physical and chemical properties. Consequently, comprehending the diverse methods of synthesizing these nanoparticles becomes crucial and to study their properties and applications.

In the realm of synthesis, various recent and advanced methods have emerged. Two fundamental approaches can be used to categorize these methods: the top-down approach and the bottom-up approach. The bottom-up approach involves using atoms and molecules as building blocks to synthesize intricate nanostructures. Conversely, the top-down approach achieves the desired nanostructure with distinct properties by miniaturizing bulk particles [**2**]. Further categorization of these methods reveals that the top-down approach involves milling, lithography, and machining, while the bottom-up approach comprises techniques such as CVD, vapor deposition, plasma-assisted deposition, liquid phase method, sol-gel method, electrodeposition, and others [**3**]. Additionally, these approaches can be classified as physical, chemical, or biological synthesis, depending on the nature, process, and materials employed. Among them, biosynthesis methods using plant extract synthesis are particularly noteworthy as they aid in reducing toxic by-products [**4**]. This will help in the greener and environmental synthesis of MONPs. Due to these vast numbers of processes and techniques, many publications have been made on different synthesis methods and the applications of MONPs, which makes it difficult to cover all the methods and applications. Therefore, this review article aims to offer a concise and comprehensive overview of various fundamental strategies involved in the synthesis of MONPs, focusing mainly on sol-gel, co-precipitation, flame spray, solvothermal, and biosynthesis methods, and their applicational advancements have also been discussed concerning some major MONPs. This paper presents a review of the widely used sol-gel method for synthesizing various MONPs, including TiO_2, ZnO, SnO_2, and WO_3. These nanoparticles have various applications like energy, environment, food industry, and medicine, attracting scientific and commercial interest. Notably, the nanomaterials' properties are size-dependent, leading to significant chemical and physical variations. Innovations in recent times have significantly enhanced the modelling and design of medical and biological tools and applications, contributing to the commercial success of nanotechnology in the modern world [**5**]**.** Nanomaterials possess exceptional electrical, mechanical, and thermal stability, surface area, as well as optical and magnetic properties. These enhanced attributes enable their utilization in various domains, including electrical, magnetic, optical, and electronic devices. Moreover, some nanomaterials can be engineered, as seen in TiO_2, AgO, etc. They find extensive applications in science and technology, particularly in the biological and biomedical fields. The unique morphological, structural, and chemical properties of nanomaterials make them an appealing and novel choice for biomedical applications. Nanomaterials, nanorods, nanofibers, and other nanostructures offer researchers the opportunity to explore their applicability in various biomedical processes due to their size compatibility with biological molecules [**6–8**].

This review provides a comprehensive insight into different NP-based applications like agricultural, anti-microbial, sensors, therapy and diagnosis, and catalyst. A study of different MONPs has been done in this review, along with major properties affecting the applications. As many studies have been made in this field, it's difficult for the readers to get a good insight, and this paper resolves this problem and will help the researchers to study for further advancement in the department of MONPs.

TYPES OF METAL OXIDE NANOPARTICLES

Titanium Oxide (TiO_2), a white pigment renowned for its remarkable brightness and high refractive index, presents itself as a non-combustible and odourless powder. With a molecular weight of 79.9 g/mol, TiO_2 possesses boiling and melting points of 3245 K and 2116 K, respectively. These nanoparticles are found in two crystal structures: anatase and rutile. NPs with a composition of 80% anatase and 20% rutile, measuring 3–5 nm and at a concentration of 100 μg/ml, produced six times more reactive oxygen species (ROS) than rutile alone under UV irradiation [**9**]. The rutile form of TiO_2 is considered chemically inert, exhibiting high stability, anticorrosive properties, and strong photocatalytic capabilities. [**10**]. It provides a huge surface area for adsorption, making it a better element to use as a catalyst in catalytic reactions. These NPs can be used in semiconductor photocatalysis as they provide a large surface area for adsorption. They can also be used for photo-sensing. From research, titanium dioxide was found to have excellent properties of self-cleaning and anti-fogging, anti-fouling, and anti-graffiti [**11**] and also shows anti-bacterial properties under UV light irradiation [**12,13**].

Iron oxide (Fe_3O_4, Fe_2O_3) is a chemical element found in the first transition series and group 8 of the periodic table. Various forms of iron oxides exist in nature, including magnetite (Fe_3O_4), maghemite (γ-Fe_2O_3), and hematite (α-Fe_3O_4), which are among the most common. Hematite, known by various names such as ferric oxide, red ochre, kidney ore, and marlite, is one of them. Magnetite, on the other hand, is referred to as black iron oxide, magnetic iron ore, loadstone, ferrous ferrite, or Hercules stone [**14**]. These iron oxides can be characterized by oxygen anions forming close-packed planes, while iron cations occupy octahedral or tetrahedral interstitial sites. Hematite, represented by α-Fe_3O_4, displays paramagnetic properties above its Curie temperature of 956 K. It exhibits weak ferromagnetism and undergoes a phase transition to an antiferromagnetic state at 260 K [**15**]. The magnetic characteristics of hematite are influenced by factors such as crystallinity, particle size, and the degree of cation substitution, with these magnetic iron oxide nanoparticles (MONPs) exhibiting relatively low crystallinity. Maghemite experiences an irreversible crystallographic transformation into hematite around 400°C, and its Curie temperature falls within the range of 820 K to 986 K. On the other hand, γ-Fe_2O_3 particles are smaller than 10 nm and display superparamagnetic behavior at room temperature [**16**].

Zinc oxide (ZnO) is an inorganic compound, presenting itself as a white powder that does not dissolve in water. It naturally occurs in the Earth's crust as zincite. ZnO has the ability to crystallize in two forms: hexagonal wurtzite and cubic zincblende. The wurtzite structure is the most prevalent and stable under regular conditions. ZnO exhibits various colored emissions, including orange, blue, green, and red [**17**]. ZnO nanoparticles have a wide range of applications in agriculture and medicine. They can serve as neurotransmitters and find use in diagnosing the Central Nervous System. Galvanostatic cycling and cyclic voltammetry have been utilized to study the electrochemical characteristics of these nanostructured materials.

Copper oxide nanoparticles (CuO) exhibit a brownish-black appearance as a powder. When exposed to high temperatures and hydrogen or carbon monoxide, they can be reduced to metallic copper. CuO NPs possess several unique characteristics, such as small size, high surface area, biocompatibility, and significant biological and chemical reactivity, effectively killing bacterial cells. Moreover, these nanoparticles can greatly enhance the burning rate of homogeneous propellants, lower the pressure index, and serve as excellent catalysts for AP composite propellants. Temperature, size, and morphology significantly influence the optical properties of CuO NPs [**18**]. In transmission spectra analysis at 400°C, the average nanoparticle size was determined to be 350 nm, and at 1000°C, it increased to 367 nm, corresponding to energy values of 3.38 eV and 3.54 eV, respectively [**19**]. CuO NPs exhibit magnetic properties that are strongly influenced by their morphology [**20**]. In the case of CuO NPs with dimensions ranging from 9 to 16 nm, the peak observed in zero-field cooled magnetization is absent. Moreover, a noticeable divergence between the zero-field cooled and field-cooled systems was detected, indicating hysteresis at room temperature [**21**].

SYNTHESIS OF METAL OXIDE NANOPARTICLES

The development of nanotechnology has been propelled forward by significant advancements in various synthetic methods for tailoring nanomaterials with specific physical and chemical properties. Two primary synthetic approaches are recognized: the Top-Down approach and the Bottom-Up approach, each with its own merits and drawbacks. In the Top-Down approach (destructive approach), The process commences by using an appropriate bulk material as the initial substance. This bulk material is then progressively trimmed down to smaller molecules, which are then transformed into the desired nanoparticles. Conversely, the Bottom-Up approach (also referred to as the constructive approach) works in the opposite manner. Initially, nanoparticles are acquired through the miniaturization of materials at the atomic level. Then, these atomic-level nanoparticles come together through integration or self-assembly processes to form nanostructures. Further classification of the Top-Down approach includes methods such as Milling, Lithography, and machining. On the other hand, the Bottom-Up approach encompasses techniques like CVD (Chemical Vapor Deposition), Vapor Deposition, Plasma-assisted Deposition, Liquid phase method, Sol-Gel method, and Electrodeposition, among others [**3**,**22**].

The sol-gel method exemplifies a bottom-up approach to synthesizing these particles. It stands out for its simplicity, speed, and cost-effectiveness, making it one of the most efficient techniques for producing compared to other physical and chemical methods. The production of high-quality MONPs stands out. Notably, this method offers advantages such as low processing temperature, material homogeneity, and the ability to form complex structures [**23**]. The performance of nanoparticles is significantly influenced by their shape. For instance, gold nanoparticles with a hemispherical shape exhibit superior performance compared to spherical-shaped nanoparticles [**24**]. The sol-gel method offers a versatile approach to preparing various MONPs such as TiO_2, ZnO, SnO_2, WO_3, etc. This technique excels in controlling the shape and size of nanoparticles and involves five essential steps: (i) Hydrolysis, (ii) Polycondensation, (iii) Aging, (iv) Drying, and (v) Thermal decomposition. Among these MONPs, ZnO nanoparticles can be easily and efficiently prepared using the sol-gel technique. In a reported synthesis of ZnO nanostructures [**25**], two grams of zinc acetate dihydrate and eight grams of Sodium Hydroxide are utilized to prepare a sol. Distilled water is added, measured between 10 ml to 15 ml, using a measuring cylinder. The process begins by dissolving two grams of zinc acetate dihydrate in 15 ml of distilled water and separately dissolving 8 grams of sodium hydroxide in 10 ml of distilled water, with each solution stirred for 5 minutes. Next, the sodium hydroxide solution is slowly poured into the zinc acetate solution while continuously stirring using a magnetic stirrer for approximately 5 minutes. Afterward, a burette containing 100 ml of ethanol is employed to titrate the solution drop by drop, gradually forming a white precipitate as the reaction progresses [**25**]. This experimental process involves a series of chemical reactions. When sodium hydroxide is added to the ethanolic solution of zinc acetate, it initiates a full hydrolysis process, forming a ZnO colloid. The ultimate product is achieved through the equilibrium established between hydrolysis and condensation reactions. Upon heating, zinc acetate undergoes hydrolysis, leading to the generation of acetate ions and zinc ions. The excess oxygen electrons present in the alcohol group then bond with the zinc ions, leading to the formation of ZnO nanopowder. As a result, the Sol-gel technique proves successful in obtaining high-purity ZnO nanopowder [**26**].

Lithography, a top-down approach, involves the process of replicating patterns from one medium to another. For a long time, lithography has relied on various types of particle beams. Among these, the electron source stands out due to its remarkable diffraction-limited resolution, allowing for the transfer of nanometer-scale patterns. Electron beams have recently gained popularity for creating nanoscale structures through direct writing and projection printing methods. In the semiconductor industry, Electron Beam Lithography (EBL) has evolved into a widely adopted method for creating master masks and reticules based on computer-aided design (CAD) files [**7**]. These masks are extensively used in optical projection printing to reproduce patterns on silicon wafers. Moreover, EBL has extended its applications to direct writing, where a focused electron beam directly interacts with the resist to perform various tasks. The principle behind Electron Beam Lithography is straightforward. This process entails aiming a focused beam of electrons onto a substrate that is coated with an electron-sensitive material. The solubility properties of this material alter according to the energy imparted by the electron beam. A typical Electron Beam Lithography system bears a close resemblance to a scanning electron microscope (SEM). It consists of a chamber, electron gun, and column, all maintained under high vacuum conditions. The column houses electron-optical elements responsible for generating, accelerating, turning on/off, and focusing/ deflecting the electron beam. [**30**].

Electron-beam lithography (EBL) offers several key advantages over conventional photolithography techniques, notably its exceptional resolution and flexibility in pattern formation. EBL employs two distinct approaches: projection printing and direct writing. EBL has achieved an impressive resolution capability, with reported values as low as sub 10 nm [**1**]. This level of precision is sufficient to meet the demands of most feature sizes. In the context of pattern transfer, EBL utilizes dry etching instead of wet etching, as wet etching becomes challenging when dealing with nanostructures. Dry etching is a subtractive approach that follows the replicated patterns from nanolithography. Additionally, the lift-off process, which occurs after metal deposition, adopts an additive approach. These pattern-transferring techniques form the foundation of major nanofabrication methods.

All the reviewed methods of manufacturing MONPs have shown various environmental implications and economic challenges associated with their fabrication and synthesis. As a result, researchers have sought alternative approaches that offer environmental and economic advantages for NP synthesis. One particularly interesting alternative is the process of synthesis using plant sources as a biological method. This approach has proven suitable for producing MONPs due to its numerous health, environmental, economic, and medicinal benefits. This concept is referred to as "green nanotechnology," which involves using nanotechnology to improve the ecological sustainability of procedures, diminish or eradicate harmful substances, foster environmental restoration, and mitigate expenses and adverse environmental effects. In contemporary times, researchers are actively exploring the utilization of natural materials and substances from the environment as alternatives to conventional synthesis methods. The goal is to create biodegradable and eco-friendly products using green synthesis techniques. Although conventional methods can yield large quantities of nanoparticles with desired properties, they are often intricate and expensive. In contrast, green synthesis offers several advantages, such as rapid production, simplicity, cost-effectiveness, and minimal waste generation. These methods utilize biological agents like enzymes, fungi, microorganisms, plants, or plant extracts as eco-friendly substitutes for chemical and physical methods in the synthesis of nanoparticles. As a result, biological methods have been recommended as more sustainable and environmentally conscious alternatives to traditional approaches. Zinc oxide nanoparticles (ZnO NPs) synthesized using plant extracts demonstrate remarkable antimicrobial properties against human pathogens, effectively combating bacterial and fungal infections [**27**]. Several plant species, including *Trifolium, Justicia adhatoda, Physalis alkekengi L, Cassia auriculata, pretense* flowers, *Aloe barbadensis, Pongamia pinnata, Limonia acidissima, Plectranthus amboinicus, Cochlospermum religiosum, Sedum alfredii* Hence, *Aspidoterys cordata,* and *Bauhinia racemosa*, have been identified as excellent sources for producing these nanoparticles [**28**]. **Table 1** presents a comprehensive summary of the essential characteristics of these MONPs, encompassing their appearance, structure, size, major applications, as well as their advantages and disadvantages.

Table 1. Method of MONP synthesis, their morphology, size, shape and their advantages and disadvantages.

MONP	Method of Synthesis/Reaction Conditions (Temperature, pH, Time)	Morphology/Shape/Size	Advantages	Disadvantages	Ref.
		Physical Approach			
PtO_2	Electron Beam Lithography/ Temp.- 300 °C/ pH- 7-11/ Time- 70-80 min.	Sphere and Rods/45-50nm	Well controlled interparticle spacing	Requires expensive and high-quality machines	[29]
Fe_3O_4	Deposition of gas phase/Temp.- 400 °C/ pH- 5-6/ /Time- 120 min.	Irregular Sphere / 20-50nm	Easy to Execute	Size Control is Difficult	[30]
TiO_2	Laser Ablation/Temp.- 550-600 °C/ pH- 7-11/ Time- 15-20 min.	Amorphous sphere/ 10-50nm	High Purity of NPs produced	High Pressure and conditions needed	[31]
ZnO	Ball Milling/Temp.- 60-70 °C/ pH- 6/ Time- 60-120 min.	Irregular shape/2-20nm	Inexpensive and easy process	NPs have crystal defects and have contaminations	[32]
		Chemical Approach			
ZnO	Sol-Gel Method/Temp.- 400 °C/ pH- 7-11/ Time- 180min.	Spheres, irregular, porous, Spindles/ 81.28-84.98nm	Precisely controlled in size	Weak Bonding, High permeability	[33] [34]
Fe_2O_3	Oxidation/Temp.- 150-200 °C/ pH- 9/ Time- 15-30 min.	Irregular elongated, small spheres/ 50-100nm	Uniform size	Ferrite colloids of small size	[35], [36]
Fe_3O_4	Co-precipitation/Temp.- 140 °C/ pH- 8-9/ Time- 120 min.	Spheres/ 90-95nm	Simple and effective	Inappropriate for synthesis of high untainted particles	[37] [6]
ZnO	Electrochemical/Temp.- 400 °C/ pH- 7-9/ Time- 80-120 min.	Spherical NPs, nanorods/ 5-40nm	Controllable particle size	Inability to reproduce	[33]
TiO_2	Solvothermal/Temp.- 500 °C/ pH- 10/ Time- 160 min.	Elongated, Compact/ ~100nm	Particle size and shapes easily controllable	High pressure and temperature needed	[29]
		Biological Approach			
AgO	Microbial Incubation/Temp.- 150-100 °C/ Time- Many day	Small platelets, spherical or rod like spheres/41-62nm	Good reproducibility and scalability, high yield & low cost	Slow and laborious	[38, 39,40]
ZnO	Via Plants/Temp.- 120 °C/ pH- 5-7 / Time- 10-15 days	Spherical, small/15 – 40nm	Better antimicrobial potential	Slow process	[41] [42]
CuO	Via algae/Temp.- NA / pH- 7-11/ Time- 2-3 days.	Spherical and elongated/ 5-45 nm	High Yield and Low Cost	Slow Process	[43]

Various methods are employed to prepare MONPs with suitable surface chemistry, as depicted in the graphical abstract, including both chemical and physical approaches. **Table 1** provides a detailed comparison of these synthesis methods, aiming to assist researchers in selecting the most appropriate technique for their needs. In summary, there are three main methods for synthesizing MONPs:

1. Top-down (physical) methods: These procedures are intricate and have limitations in controlling particle size within the nanometer range.
2. Bottom-up (chemical) methods: These approaches are simple, manageable, and efficient, allowing control over the size, composition, and shape of the nanoparticles. The factors that influence the size, shape, and composition of nanoparticles (NPs) generated by chemical methods include the type of salt utilized, pH level, and ionic strength.
3. Biological methods: These methods involve green and environmentally friendly fabrication approaches.

Among these techniques, chemical synthesis methods are predominantly preferred because of their cost-effectiveness and high production yield.

APPLICATIONS OF METAL OXIDE NANOPARTICLES

MONPs find diverse applications in various fields, including the fabrication of micro-electric circuits, sensors, fuel cells, catalysts, and more. Their unique properties, distinct from their bulk counterparts, open up new opportunities in agriculture, medicine, pharmaceuticals, environmental management, and food security through nanobiotechnology (NBT) approaches [**44**,**45**]. These applications are of significant importance in the current scenario. Recognizing the significance of MONPs as essential technological materials, the authors of this review present a comprehensive examination of research on these nanoparticles. They cover various aspects, including synthetic strategies and techniques, nanoscale physicochemical properties, and specific industrial applications across different fields of applied nanotechnology. This review article emphasizes the importance of MNOPs as a highly promising material for various applications. The specific role of Fe_3O_4, Fe_2O_3, TiO_2, MnO, ZrO, CoO, and NiO nanoparticles is thoroughly discussed. Nanomaterials have also found widespread use in diverse scientific fields, particularly in biological and biomedical applications. The alterations in their morphological, structural, and chemical properties make them a distinctive and innovative option for biomedical purposes. Overall, this paper comprehensively reviews the different applications of MNOPs across various fields.

Sensors

Sensors play a vital role in preventing and alerting against various incidents, such as fire explosions, atmospheric environmental testing, and detecting poisonous and harmful gases during industrial production. The incorporation of Nanomaterials has led to significant advancements in sensor design, enabling miniaturization, portability, and rapid signal response times. MONPs have been particularly influential in sensor applications due to their versatility in shape production, high extinction coefficients, surface functionalization capabilities, and the inclusion of noble metal nanoparticles. These unique characteristics have made MONPs widely utilized in a range of sensor applications.

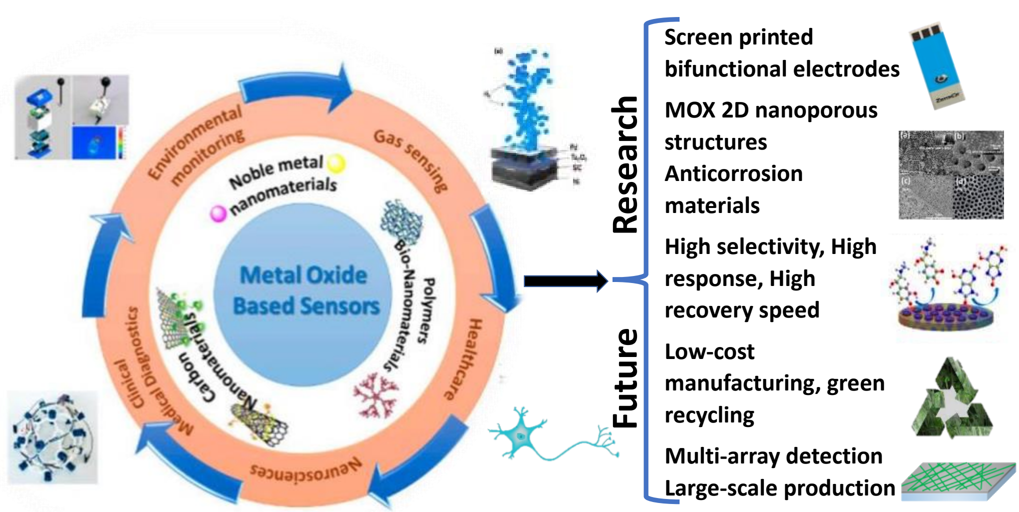

Fig. 1 Different sensing applications of MONPs and their future aspects.

Fig. 1 depicts the recent main applications and future research directions concerning sensors, with a particular focus on the role of MONPs as sensing elements. Metal oxides find widespread use in gas sensing applications, with their technology extending to various industrial sectors and domestic environments. Key examples include their application in the automotive industry, indoor air quality control, and greenhouse gas monitoring [46]. Gas sensors based on carbon dioxide are indispensable in numerous fields, such as air quality monitoring in hospitals and the food industry. They serve as essential instruments for detecting toxic gases. Oxygen-based gas sensors, on the other hand, are primarily utilized in motorized industries and medical facilities. Ozone-based gas sensors play a vital role in medical applications, biotechnological processes, pharmaceuticals, and chemical industries. For detecting combustible, reducing, and oxidizing gases, sensors employing ZnO, TiO_2, SnO/SnO_2, WO_3, CuO/Cu_2O, and V_2O_5 are commonly used [46,47]. These sensors operate primarily by detecting changes in resistance as a response to the presence of target gases [46]. Among commercially used gas sensors, SnO_2 and WO_3 are the most common semiconducting metal oxides [48]. Notably, gas sensors based on ZnO Nanobelts exhibit higher sensitivity to NO gas, while ZnO tetrapods show increased sensitivity in detecting H_2S gas. CuO-SnO_2 gas sensors display exceptional sensitivity to H_2S owing to the sulfurization process resulting in metallic CuS formation. In the case of Cu_2O NCs, their electrical resistance in air (containing 5 ppm H_2S) varies at different temperatures, such as 50, 100, and 150°C. Upon introducing H_2S, an immediate increase in resistance is observed. At 200°C, the Cu_2O-CuO NCs demonstrate good response and recovery behavior, likely due to the thermal activation of oxygen reaction and re-absorption at higher temperatures.

UV sensors/photodetectors hold great significance in everyday life, especially concerning sun/UV radiation exposure. Additionally, they find essential applications in diverse fields like environmental safety, medicine, military defense, flame detection, environmental sensors, and even space exploration [49,50]. TiO_2 has emerged as a promising option instead of the generally used silicon-based UV sensors due to its high photoactivity and stability under UV irradiation, attributed to its bandgap. Furthermore, nanostructures play a crucial role in biosensors. A biosensor is a sensing device consisting of a signal detection transducer and a biologically sensitive and selective component, commonly known as a bio receptor. ZnO is extensively utilized as a biosensor, finding its applications in DNA immobilization, glucose level detection, etc. Extensive research has been conducted on ZnO for its potential application in glucose detection, biomarker detection, and even cancer diagnosis [51]. ZnO has been extensively researched for its application in glucose detection, making it one of the most studied biosensors. TiO_2-based sensors, on the other hand, are employed for H_2O_2 detection in microspheres [52] or macro-mesoporous films [53]. These materials exhibit numerous advantageous properties, including high surface area, biocompatibility, non-toxicity, excellent chemical stability, and catalytic activity. Due to its versatility, SnO2 is employed in various applications, such as light energy conversion, biosensors, smart windows, and electrochemistry. Cholesterol biosensors are specifically utilized to estimate cholesterol concentration in serum/blood samples. The data presented in **Table 2** shows that MONPs have wide-ranging sensing capabilities for various classes of analytes. These encompass a wide range of biomolecules, including dopamine, uric acid, serotonin, glucose, and L-cysteine; pharmaceutical drugs such as olanzapine, salbutamol, and chlorhexidine digluconate; heavy metal ions like lead, zinc, and cadmium; organophosphate insecticides like methyl parathion; antioxidants like glutathione; as well as various other molecules like hydrogen peroxide, hydrazine, catechol, hydroquinone, nonylphenol, hydroxylamine, and nitrates, among others (**Fig. 2**).

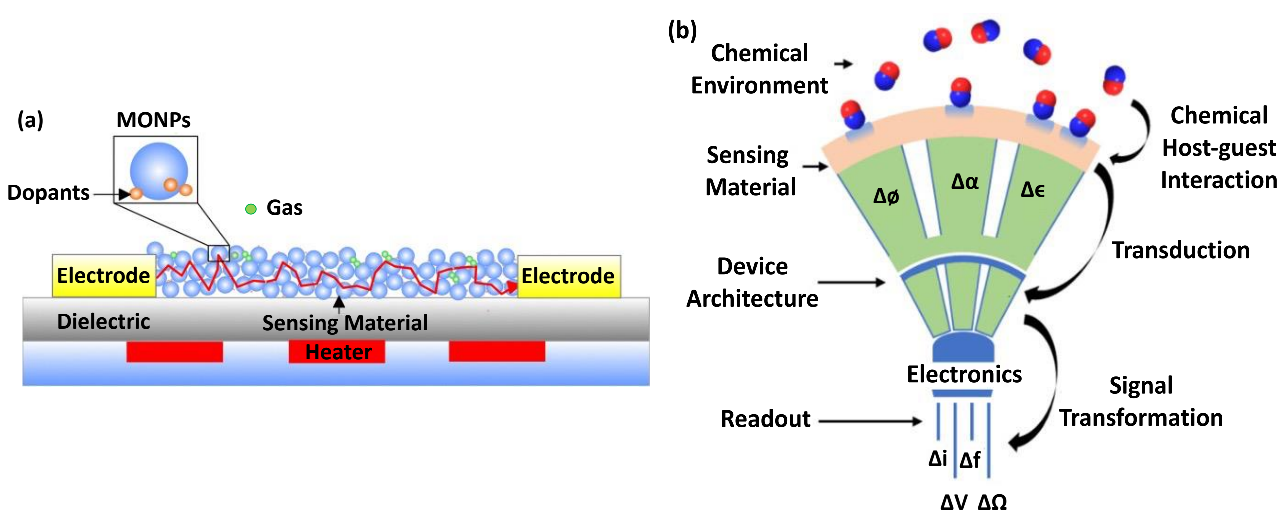

Fig. 2. MONPs as sensing element: (a) Figure illustrating a chemical sensor analyte interacting with the sensing material, changing some of its physical properties, (b) Mechanism of MONPs as a Sensing element in electrochemical sensors.

Table 2. Nanoparticles as efficient electrode modifiers in various electrochemical and bio sensing systems.

MONPs	Size/Morphology and Shape	Modified Electrode	Real Samples/ analytes	Sensitivity and Detection limit	Ref.
Fe_3O_4	16.7 nm/spherical	GOx/NH_2-, Fe@Au/Au	Blood Serum/ Glucose	0.057 μA/mM and 510 μM	[54]
	10-20 nm/cubic	Fe_3O_4/PPy/GO/GCE	Tap Water/ Hydrazine	449.7 μA/mMcm^2 and 1.4 μM	[55]
	60 nm/spherical	Fe_3O_4/rGO/GCE	Human Urine/ Dopamine	19.75 μAmM^{-1}cm^{-2} and 5 nM	[56]
	30 nm/sheets	Bi/Fe_2O_3/G/GCE	Tap Water/ Lead, Zinc, Cadmium	5.31 μAmM^{-1} cm^{-2} and Pb:0.07 μgL^{-1}, Zn:0.11 μgL^{-1}, Cd:0.8 μgL^{-1}	[57]
TiO_2	50 nm/dandelion	TiO_2-GSE	Blood sample/ Arsenic	82.6 μA μM^{-1} and 10 μg L^{-1}	[58]
	267.8 nm/microsphere	Ag-TiO_2 electrode	Apple juice, green tea, industrial effluent/Catechol	0.0249 μM^{-1}	[59]
	110 nm/nanotube array	TiO_2/AuNTAS	Tap water and sea Water/ Bisphenol (Without UV radiation)	2.8 μAμM^{-1}cm^{-2} and 1.0 × 10^7 – 2.89 × 10^{-5} M	[60]
	43nm/Spherical	GO/TiO_2AS/ONPr/GC	Cyanide	165.5 nAnM^{-1}cm^{-2} and 0.1 μM	[61]
MgO	30-50 nm/hexagonal	Cu/MnO_2/MWCNTs/GCE	Human blood/ Glucose	1302 μA mM^{-1}cm^{-2} and 1.7 μM	[62]
	85-90 nm/ Spherical	MnO_2-rGO/GCE	Spiked water Samples/4-nitrophenol	569.2 μA mM^{-1}cm^{-2} and 10 nM	[63]
	NA/ Elongated tubes	Mn_2O_3/Nf/GCE	Disinfectants/ H_2O_2	NA and 0.07 μM	[63]
	300 nm/ thin sheets	MNPs/ MWFNTs–GS/GCE	Disinfector Samples/ H_2O_2	206.3 μA mM^{-1}cm^{-2} and 0.8μM	[64]
CoO	10-20 nm/octahedral	$CuCo_2O_4$/GCE	River water, photographic Solution/ Hydrazine	1.27 μA/μMcm^2 and 8 nM	[65]
	11 nm/ pellets	$NiCo_2O_4$/NF	Tap water, lake water/Hg(II)	29.8 μA/μM and 0.0099 μM	[66]
	5-500 nm/Hollow nanospheres	$NiCo_2O_4$/rGO/GCE	Human Blood/ Glucose	2082.57 μA/mMcm^2 and 0.7μM	[67]
NiO	81.28-84.98nm/Irregular spindle	NiO@PPy/Au/GCE	Human Blood/ Glucose	802.9 μA mM^{-1}cm^{-2} and 0.15μM	[68]
	35-40nm/Spherical	NiONP–DNA/GCE	Serum samples/Glucose	7292.69 μA/mMcm^2 and 0.017 μM	[69]
	81.28-84.98nm /Irregular spindle	NiONPs-CBDHP/GCE	Pharmaceuticals, synthetic biological fluids/ Paracetamol	NA and 0.12 μM	[70]
	25-42 nm/ irregular sphere	NiOxNPs/GCE	Fruit juice, non-alcoholic Beverage/ NADH	0.052 μAμM^{-1} and 106 nM	

Catalyst

MONPs play a crucial role in catalytic applications. Among various catalysts, nanocatalysts derived from MONPs are present. Due to their remarkable surface area, robustness, and stability, these materials serve as excellent alternatives to conventional nanocatalysts [**71**]. The intrinsic properties of MONPs are highlighted in **Fig. 3**. Nanocatalysts, being nano-sized, provide a greater number of active surfaces compared to bulk catalysts, leading to more efficient contact between the reactants and catalysts. This increased surface area and higher number of active sites facilitate faster reactions and improve product yield [**72**]. Furthermore, the insolubility of these catalysts in the reaction mixture offers the benefit of easy separation and reusability of the nanocatalysts [**73**].

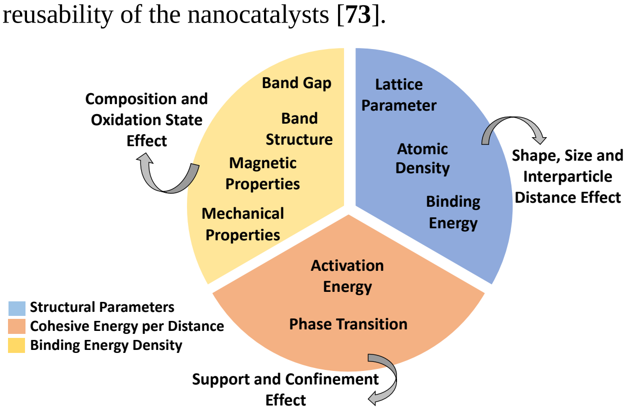

Fig. 3. Intrinsic properties of MONPs depending upon various shapes, sizes, and morphology of MONPs.

Nano-sized Fe and Co powders, with a particle size range of about 10 to 50 nm, find application as catalysts in slurry reactors for the production of green diesel through Fischer-Tropsch Synthesis (FTS). This application improves the FTS technology by enhancing its capability to produce high molecular weight waxes, which can be further hydrocracked to produce liquid fuels. Additionally, it boosts the efficiency of both slurry and fixed-bed reactors employed in FTS from bio syngas, resulting in the generation of long, linear-chain paraffin waxes in fixed-bed and slurry FTS reactors. In another context, nanoparticles of NiO are utilized as catalysts, supported by Al_2O_3, to produce high-quality syngas through the gasification of biomass. The presence of Al_2O_3 as a support for the NiO catalyst aids in reducing tar yield and increasing overall efficiency to an impressive 99%. As a consequence of this improvement, gas yield is substantially increased, with elevated proportions of H_2 and CO in the syngas composition. Simultaneously, the percentages of heavier fractions such as CH_4 and CO are reduced, resulting in an enhanced quality of the syngas produced. Silver nanoparticles hold significant importance due to their diverse applications in catalysis, organic transformations, fine chemical synthesis, and organic intermediate production. The utilization of Ag NPs offers several advantages, such as avoiding the need for ligands and enabling easy separation of catalysts, making the product heterogeneous and cost-effective. These nanoparticles possess a large surface area, leading to excellent catalytic activity for certain reactions. Consequently, researchers have directed their attention towards exploring the catalytic potential of Ag nanoparticles [**74**]. Recent progress in materials science and nanotechnology has led to remarkable advancements in the precise fabrication of MONPs, allowing for the creation of nanoparticles with different shapes, sizes, and compositions. Additionally, the capacity to alter their design and morphology through colloidal science facilitates the creation of catalysts with increased active sites. These advancements act as a crucial link connecting materials with their applications as heterogeneous catalysts, opening up new avenues for innovative catalytic approaches. The scientific debate was initiated when Haruta and Hutchings conducted a study on The catalytic performance of carbon monoxide (CO) when exposed to gold nanoparticles supported on a metal oxide. Their research shed light on the significance of approximately 1–3 nm sub-nanometer clusters and nanoparticles in catalyzing CO oxidation reactions, which greatly influenced the overall catalytic performance. Haruta and his team investigated different approaches to optimize particle size, and they discovered that 3 nm gold nanoparticles were especially effective for catalyzing CO oxidation. This intriguing perception has sparked increased interest in synthesizing various Au-supported nanoparticles, which have been widely adopted as catalysts for numerous catalytic applications. Recently, a diverse array of MONPs has been produced to explore their potential in catalysis extensively. The production of eco-friendly catalysts seems feasible and holds great promise, offering potential solutions to address environmental concerns associated with current chemical processes. Additionally, it could enable high-yield production of goods. Nevertheless, the issue of sustainable preparation of metal nanoparticles raises concerns about the use of environmentally friendly precursors and solvents. Intriguingly, certain studies suggest employing bio-derived materials like starch and various plant-based substances for the synthesis of eco-friendly metal nanoparticles, including Au, Cu, and Ag. These metal nanoparticles are then integrated into various substrates such as CNTs (carbon nanotubes) and proteins like soybeans and poly-L-lysine, developing bio-inspired hybrid materials. The catalytic properties of different MONPs employed in various fields are presented in **Table 3**.

Table 3. Various MONPs synthesized and their catalytic properties.

MONPs	Size/Shape	Starting Material	Solvent/ Oxidant	Products	Selectivity	Catalytic Property	Ref.
CoO	2-4nm/ Spherical	Oefins	H_2O_2	Epoxides	86.1%	Nanocrystals coupled with CNTs as catalysts for chlor–alkali electrolysis systems	[75] [76]
Fe_3O_4	10-20nm/ Cubic	Olefins	CCl_4/tBuOOH	Epoxides	88%	Catalytic oxidation of phenolic and aniline chemical compounds (Fe_3O)	[77]
SnO_2	180nm/ Cylindrical	Dimethyl sulfide (DMS)	NA	Sulfoxide product	90%	Reduction and photodegradation of organic compounds	[78]
Ag_2O	30-40nm/ Flakes	Benzyl alcohol	Acetonitrile/ H_2O_2	Benzaldehayde	73.6%	catalytic oxidation of tryptophan	[79] [80]
Cu_2O	1-10nm/ Spherical	Olefins	TBHP	Epoxides	100%	Reduced RGO for usage as an efficient electrocatalyst in ORR	[81] [82]
TiO_2	2-5nm/Rods	Secondary alcohols	PEG400/ H_2O_2	Ketones	90%	Carbon modified NPs can be used in daylight photocatalysis.	[83-85]
ZnO	25nm/Sheets	Styrene	NA/ H_2O_2	Epoxide product	75%	For photoluminescence properties through catalytic growth	[86] [87]
MgO	70-80nm/	Formaldehyde	Methanol/NA	Formic Acid	35%	Catalysed C_2H_4 hydrogenation	[88,89]
CaO	Nanotubes	Benzyl alcohol	NA/Air	Benzaldehyde	96%	Nanoparticles can be catalysed with pyridines in an aqueous C_2H_5OH medium	[90]
CeO_2	30-40nm/ Flakes	para-xylene	NA/Air	Terephthalic acid	83%	These nanoparticles with their catalytic properties can be used for a variety of biomedical applications	[91] [92]

Therapy and diagnosis

In recent years, there has been immense interest in the use of nanomaterials for targeted therapeutics and diagnostics. These nanoparticles typically fall within the size range of 10-500 nm, and their connections with cells of mammals can be modified in light of the molecule size and useful necessity. Notwithstanding, more regular polymeric nanoparticles, metal, and MONPs can likewise assume a significant part in the identification and outside command over drug conveyance. In recent times, diverse types of nanoparticles (NPs) and drug delivery systems have been designed and implemented for the treatment of cancers, management of diabetes, combating bacterial infections with antimicrobial coatings, crossing the blood-brain barrier, and developing vaccines (**Fig. 4**) [**93**].

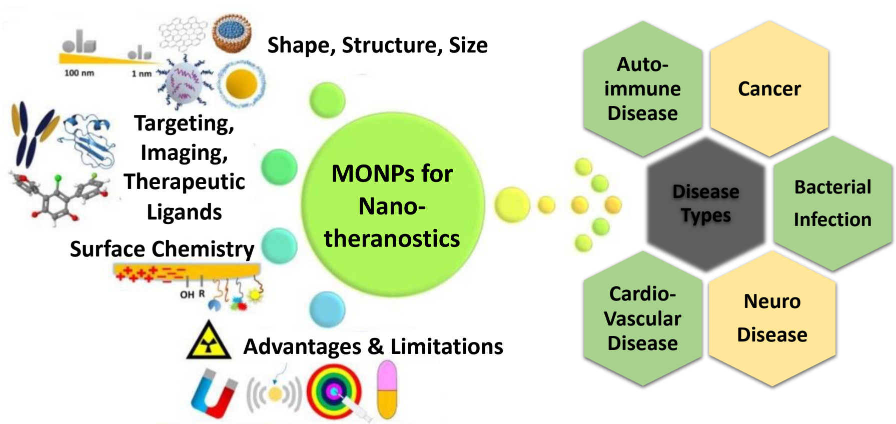

Fig. 4. Nano-theragnostic application of MONPs in different fields like imaging, drug targeting, and cancer therapy.

MONPs have been customized for various applications, including acting as agents to enhance contrast in imaging and serving as vehicles for drug delivery. More recently, they have been explored as therapeutic agents to MONPs (magnetic and optically active nanoparticles) that can induce tumor cell death through magnetic and photonic ablation therapies. These nanoparticles offer a wide range of core materials options, including gold, silver, carbon nanotubes, fullerenes, MnO, lipids, micelles, and more. Significant attention has been given to Fe_3O_4 (magnetite) based NPs. This is primarily due to their exceptional properties, such as being superparamagnetic, biocompatible, and biodegradable. Fe_3O_4 NPs have undergone extensive research for their potential to enhance contrast in MRI (Magnetic Resonance Imaging) [**94**]. Recently, hybrid NP formulations have been modified with exterior coatings. Furthermore, useful tests have been contrived for their capacity to upgrade contrast in elective imaging procedures, notwithstanding MRI [**95**,**96**]. Recent research consistently highlights the various benefits of nanogold compared to other nanomaterials, mainly owing to its distinctive properties. The likelihood of changing the outer layer of nanogold particles with various focuses and the utilization of versatile mixtures significantly broadens the range of potential biomedical applications of these nanoparticles, with a particular emphasis on disease therapy [**97**,**98**]. Functionalized gold nanoparticles have been demonstrated due to their outstanding biocompatibility and the ability to control biodistribution patterns. These nanoparticles emerge as highly promising candidates for cutting-edge therapies [**99**]. Additionally, recent studies have indicated that AgO NPs show potential as nano-silver and have proven to be an effective antitumor agent by inhibiting proliferation and inducing apoptosis in cancer cells. In both in vivo and in vitro experiments conducted on diverse cancer cell lines, the physical properties of nano-silver and the administered doses have exhibited a satisfactory impact on tumors while preserving the health of surrounding tissues [**100**]. Moreover, the application of ZnO has seen significant advancements, particularly in synthesizing novel wound dressings, creating bi-metal "core-shell nanocomposites," puncturing bacterial cellular membranes, producing hydrogen peroxide, demonstrating high absorbency for wound exudates, and promoting blood clotting, among other benefits. Fe_3O_4 nanoparticles (NPs) possess magnetic properties that make them highly suitable for a wide range of applications, including magnetic separation of biological products and cells, diagnostics, and targeted drug delivery systems. These NPs also show promising potential as carriers for vaccine delivery, leading to improved therapeutic effects. In one study, Fe_3O_4 NPs acted as covert carriers, effectively delivering anti-retroviral drugs to latent HIV forms, while their contrasting properties enabled tracking the drug's localization. Additionally, Fe_3O_4 NPs have demonstrated the ability to selectively kill cancer cells while leaving normal cells unharmed. These NPs have been utilized in creating virus-like particles (VLPs) with exceptional applications as vaccines, gene carriers, MRI contrast agents, and drug delivery vectors. On the other hand, ZnO NPs display selective cytotoxicity towards cancer cells both in vitro and in vivo compared to normal cells. The high selectivity of ZnO nanoparticles makes them ideal candidates for cancer drug delivery, and their biodegradable characteristics further enhance their suitability. The Doxorubicin-ZnO nanocomplex has demonstrated efficiency as a drug delivery system against hepatocarcinoma cells, enhancing the effectiveness of chemotherapy by increasing the intercellular concentration of doxorubicin. Additionally, the role of zinc in insulin synthesis, storage, and secretion suggests that ZnO NPs could potentially be utilized as anti-diabetic agents or in alleviating diabetic complications when stabilized or conjugated with specific substances. TiO_2 nanoparticles are extensively used in bone and tissue engineering because they promote cell adhesion, osseointegration, cell migration, and wound healing. These nanoparticles are widely employed in dental and orthopedic applications because of their favorable biocompatibility and mechanical properties. A comprehensive understanding of all the mechanisms related to their anticancer activity is essential to ensure the significant impact of silver nanoparticles in nanomedicine and guarantee patient safety. **Table 4** provides a summary of the major applications of these MONPs, encompassing their synthesis using various precursors and their applications in therapy and diagnosis.

Table 4. Use of MONPs in therapy and diagnosis application.

MONPs	Size (nm)/Coating	Concentration	Application	Ref.
Fe_3O_4	45-48/Manganese (Mn)	5, 10, 20, 50 and 100 mg/L (in vitro)	Molecular labels imaging Drug delivery/MRI bio-magnetic separation	[101] [95] [102] [103] [94] [104]
	43.59/Poly- (ethylene glycol) (PEG)	100 and 500 ppm Fe	MRI bio-magnetic separation	
	30-100/NA	1, 3 and 5 mg/mL	Used in augmenting contrast for MRI	
TiO_2	15 – 40/TiO_2-coated silicon catheters	0.10 to 4.99 mg/m^3	Biomedical implants, Photocatalytic damage	[105,107]
ZnO	81.28-84.98/ Ag and TiO_2 nanoparticles coated over ZnO	0.4 g/L	Used for Targeted drug delivery and controlled drug release	[108] [96] [109] [96] [94]
	79.68 - 87.35/NA	NA	dermato-cosmetics	
	30-50/Chemically pure	20µL of exact	Used in induction of leukemic cells.	
CeO_2	34 – 45/NA	NA	Neuroprotective agents	[110]
SiO_2	10-15/NA	NA	dermato-cosmetics	[111]
CuO	20-22/ Polyhydroxy butyrate (PHB)	29–500 µM	Used in augmenting contrast for MRI	[112] [113] [114] [98] [115] [97] [111]
	8-40/ Cobalt	75, 150, 250, 500, 750 and 1,000 mg/L	Used in reducing cytotoxic effect of brain tumour cell	
	60-90/NA	10.8, 21.6 and 108 mg/L	Effective against gram-positive bacteria	
	42.3/NA	NA	E. coli strain was more	

Anti-microbial

Antimicrobial refers to the application of certain substances with the ability to kill or hinder the growth of a wide range of microorganisms, encompassing bacteria, viruses, protozoans, and fungi such as mold and mildew. Bacterial infections are particularly concerning as they can lead to chronic health issues and high mortality rates. Antibiotics are widely recognized for their effectiveness in treating bacterial infections [**116**]. The fundamental issue emerges from unseemly use, overuse, and misuse of the anti-infection agents for prophylactic and remedial reasons without satisfactory clinical signs, subsequently prompting bacterial protection from anti-microbials. NPs are increasingly involved more for antibacterial reasons as an option for anti-infection agents [**117**]. This infers the utilization of NPs in insert plates and clinical materials. Nanomaterials as antibacterial supplements to anti-toxins are profoundly encouraging and are acquiring enormous interest as they fill the holes where anti-toxins often fall flat [**118**].

In an age where bacterial resistance to traditional antibiotics is on the rise, nanotechnology offers a promising solution with nano antibiotics to combat pathogenic bacteria and infections. MONPs like Fe_2O_3 NPs, CuO NPs, ZnO NPs, and CeO NPs, as well as their various metal oxide hybrids, have shown exceptional potential in the fight against pathogenic strains. Their small particle size enables prolonged attachment to bacterial cell walls. Through the generation of reactive oxygenated species (ROS), these nanoparticles puncture the bacterial cell wall, resulting in the leakage of cytoplasmic components and targeting bacterial DNA, ultimately leading to bacterial death (**Fig. 5**) [**119**]. MONPs represent a promising class of antimicrobial agents, and evaluating their effectiveness against typical bacteria is crucial. However, current testing systems are limited to in vitro formulation testing, often focusing on a single microbial species and rarely addressing multi-species biofilms.

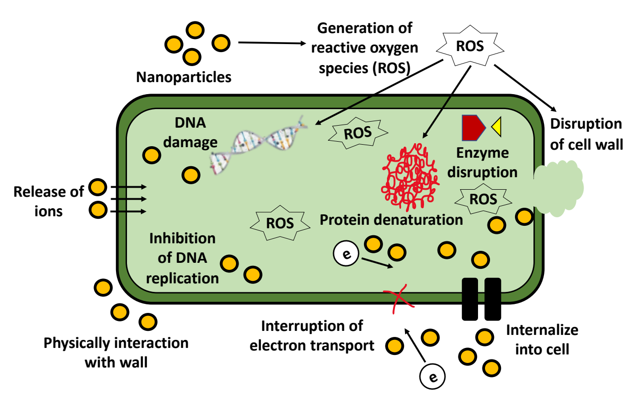

Fig. 5. Antimicrobial activity of MO-based nanoparticles on different microbe cells.

Fig. 6 illustrates the various proposed antimicrobial activities of MONPs, and **Table 5** provides a summary of the common NPs used as antimicrobial agents. Among the MONPs used in this study, Among the tested nanoparticles, ZnO displayed the most potent antimicrobial activity against both positive and negative bacteria. ZnO NPs exhibited remarkable bactericidal potential, whereas Fe_2O_3 NPs demonstrated the least bactericidal activity. The effective antibacterial properties of ZnO nanoparticles have garnered significant global attention. Moreover, zinc oxide is considered a bio-safe material and finds applications in photocatalysis and photo-oxidation reactions involving biological and chemical species [**120**]. These nanoparticles find application in food packaging, leading to improved packaging performance and extended food shelf-life. (Antimicrobial packaging is a system designed to deactivate or eliminate pathogens and spoilage microorganisms found in foods, thereby guaranteeing the quality and safety of food products.) Additionally, TiO_2 has been employed to combat the transmission of various infectious diseases [**121**]. A separate investigation identified doped Cu/TiO2 nanoparticles incorporating a carbon-based allotrope-like graphene oxide as a novel antimicrobial agent. CuO has been utilized as an effective antimicrobial agent, capable of degrading various types of microbial species. Additionally, due to its exceptional chemical properties, the CuO nanoparticle complex has been investigated for its potential as an anticancer agent in biomedicine [**122**,**123**]. Silver nanoparticles (Ag nanoparticles) find versatile applications in biomedicine, such as clinical wound dressing, bio-adhesives, biofilms, and coating materials [**124**]. As a promising alternative, they offer effective cleaning and disinfection of equipment and surfaces in food-related environments [**125**]. From **Table 5**, we can summarize the different antimicrobial activities of various bacteria and microbes.

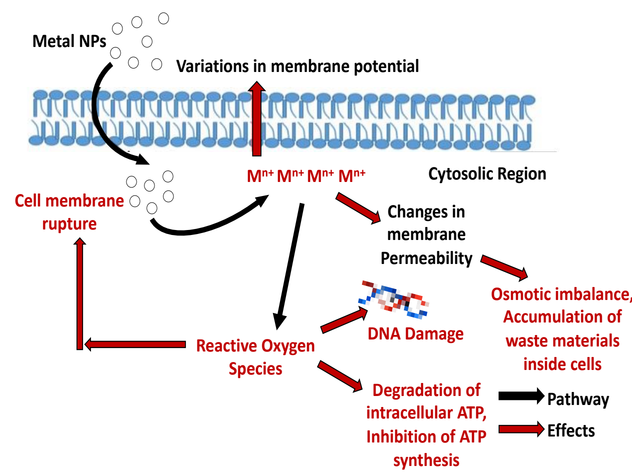

Fig. 6. Antimicrobial mechanism and activity of MONPs in different bacterial cells through cell membrane causing cell damage generating ROS.

Table 5. Antimicrobial activity of different MONPs on different microbe.

MONPs	Size/Shape/Conc.	Microbe or Bacteria	Antimicrobial activity	Ref.
ZnO	100-800 nm/Hexagonal/ 10 mg	E. coli and S. aureus	• Increased production of ROS	[126] [127] [128]
	12, 25, 88, 142, and 212 nm/Spherical/15 mg	S. aureus, Proteus vulgaris	• Increased crystallinity leads to decreased ROS formation and ion release	
	18-20 nm/Spherical and sheet/ 10-15 mg	E. coli and S. aureus	• Difference in bacteria membrane thickness and membrane ROS • Sensitivity affects NP interactions	
MgO	~20 nm/Irregular/	E. coli	• Formation of ROS (UV-illuminated group) • Attachment to bacterial membranes by interacting with phosphate groups. • Causing an increase in membrane permeability	[129] [130] [131]
	30–50 or 70–130 nm/Spherical/ 50-60 mg	E. coli and S. aureus	• Electrochemical interactions between NP and cell walls • Causing leakage of metabolites, prevents cellular function	
	11-55 nm/Plate, grain, and needle/ 40-50 mg	E. coli and S. aureus	• Production of ROS directly oxidizes proteins and DNA • Increased surface area of smaller NP permits for increased ROS production	
CuO	50-80 nm/Spherical/20 mg	E. coli, Proteus mirabilis, and Klebsiella pneumoniae	• Forms pores on bacteria surface, releasing ions, amino acids, and ATP • Nisin causes pores releases ROS	[126]
TiO_2	20 nm/Irregular sheets/ 50 mg	S. aureus, Enterococcus hirae, P. aeruginosa, E. coli	• Surface coatings prevent bacterial adhesion • Light exposure causes ROS formation	[132]
AgO	21.22 ± 5.17 nm/Spherical/ 20-25 mg	E. coli, P. domonas, S. aureus, Salmonella typhi	• Attach to membrane and inhibits cell wall synthesis. • Cannot maintain metabolic activity and cellular upkeep	[133]
	4–24 nm/Spherical and Irregular/ 30-35 mg	E. coli	• Attach to building elements on bacterial membrane • Causes pits in membrane, leading to cell lysis	

Agricultural

Nanoparticles (NPs) are receiving increasing attention in agricultural applications as they offer the potential to improve crop yield and performance while reducing waste and runoff. Extensive research has demonstrated their numerous benefits to plants, such as delivering micronutrients, triggering plant defense mechanisms, and inhibiting plant pathogens. Their sub-100 nm size enables greater reactivity, mobility, and uptake in the root zone of various crops. However, these very properties can also result in NP agglomeration and strong adsorption to soil particles [**134**]. For instance, nanoscale SiO_2, CuO, and ZnO have demonstrated their capability to aid crops during drought conditions and mitigate heavy metal contamination [**135**,**136**]. ZnO nanoparticles (NPs) have demonstrated excellent pesticide efficiency against Artemia salina larvae [**137**]. Regarding the Arachis hypogaea plant, the utilization of ZnO NPs led to enhanced seed germination, rapid shoot growth, improved seedling vigor, and enhanced root development. Moreover, the plants exhibited faster flowering, and there was a noticeable increase in pod size and overall yield [**138**]. Similarly, in a study involving *Solanum lycopersicum*, ZnO NPs were observed to improve the germination rate and increase protein content [**139**]. Numerous studies have reported the potential of ZnO NPs to enhance the yield of various food crops [**140**]. These particles are also used as nano-fertilizers for plant growth [**141**].

Nano-fertilizers are typically applied to plants either through the soil, where they are taken up by the plant roots, or by foliar spraying. A considerable portion of the fertilizers used to supply additional nutrients to plants comprises inorganic fertilizers. These fertilizers are chemically synthesized and formulated with suitable concentrations and combinations to provide the three essential nutrients (nitrogen, phosphorus, and potassium - N, P, and K) required for various crops and growing conditions. Compared to conventional fertilizers, nano-fertilizers offer several advantages. They enhance soil fertility, increase crop yield, and improve crop quality. Additionally, nano-fertilizers are non-toxic, less harmful to the environment and human health, and can reduce costs and increase profitability. **Table 6** displays various MONPs used as nano-fertilizers to promote the growth and impact of different plants. It also provides information on the concentration of nano-fertilizers used for each plant. On the other hand, MONPs as Nano-pesticides are commonly employed in agriculture to protect plants from pest attacks and enhance harvest yields. Although pesticides are highly effective and reliable for pest and disease prevention, their application can lead to adverse effects, such as environmental pollution [**142**]. Numerous studies have indicated that applying pesticides at lower doses is safer; however, at such reduced levels, the effectiveness of pesticides is significantly compromised. With our current knowledge, nanotechnology, and innovative approaches have the potential to address the limitations associated with the reduced effectiveness of lower pesticide doses and environmental pollution. Nano pesticides might offer a method for controlling the conveyance of pesticides and accomplishing more noteworthy adequacy of a lot more modest portion of a substance.

Table 6. Impact of MONPs as nano-fertilizers on different plants.

MONPs as Nano fertilizer	Size/Shape	Plant Name	Conc. (ppm)	Impact on Plants	Ref.
ZnO	53.7 nm/ Hexagonal and pseudo-spherical	Cucumis sativus	400-800	Increased root dry weight and fruit gluten	[143] [144] [145] [146]
	40 nm/ Nanoflakes	Brassica napus	1-2000	Root elongation	
	8 nm/ Spherical	A. hypogaea	1000	Pod yield per plant increased up to 34%	
	30-57 nm/ Hexagonal crystal	C. arietinum	1.5	Shoot dry weight and antioxidant activity improved	
	20-60 nm/ Spherical	Z. mays	10	Plant height and dry weight increased	
TiO_2	12-15 nm/ Spherical	Spinacia oleracea	0.25-4	Plant dry weight improved by 73%	[147]
	8-35 nm/ Spherical	V. radiata	10	Increased the plant growth and nutrient content	
	20-30 nm/ Spherical	V. unguiculata	125	Yield of cowpea increased up to 26-51%	
Fe/SiO_2	2-10 nm/ Crystalline	Hordeum vulgare	0-25	Mean germination time improved	[149]
CeO_2	18 nm/ Cubic	Cucumis sativus	400	Boosting content of starch and globulin	[150]
MgO	20-50 nm/ Quasi-Spherical	Vigna unguiculata	2.5	Shoot and root length as well as chlorophyll content increased	[151]
Fe_3O_4	14.7 nm/ Spherical	Glycine max	30-60	Content of Chlorophyll increased	[152]
	40-50 nm/ Octahedral Prism	Pisum sativum	250-500	Weight of seed and chlorophyll increased	[153]
CuO	4.8 nm/ Spherical	Zea mays	10	51% plant growth	[148] [154] [155] [156]
	5-20 nm/ Spherical	Lactuca sativa	130-600	Increased length of shoot and root	
	32 nm/ Spherical	Cajanus cajan L	20	Increased the length of shoot and root	
	4.8 nm/ Spherical	Vigna radiata L	125	Shoot and root length increased	

Agrochemical organizations are currently focusing on the process that involves reducing the particle size of conventional chemical emulsions to the nanoscale. Furthermore, research has shown that nanoparticles of certain metals can act as suppressants against pests and pathogens [**157**]. For instance, at a concentration of 100 mg/kg, researchers discovered that silver nanoparticles effectively hindered the mycelial growth and conidial germination of powdery mildew fungus on cucurbits and pumpkins. As a result of these findings, silver nanoparticles have garnered significant attention as a promising pesticide for agricultural applications [**158**]. **Table 7** shows different MONPs utilized as Nano pesticides and Nano formulation and their effect on the pests to enhance plant growth. Nanotechnology has made significant advancements in various agricultural applications, including nano-fertilizers, nano-pesticides, nano-biosensors, and environmental remediation agents. However, gaining a comprehensive understanding of the fate and environmental impacts of nanomaterials remains a major challenge in agricultural and environmental sciences. To address this, collaborative research among institutes exploring different uses of nanomaterials becomes crucial in developing efficient, multifunctional, stable, cost-effective, and environmentally friendly nanomaterials. Such collaborations would also aid in comprehending the role, fate, behavior, and ecotoxicity assessment of nanomaterials. While the application of nanomaterials may enhance the growth and yield of crop plants, it is essential to acknowledge that the response may vary depending on the plant species [**167**]. Consequently, for the commercial application of nanomaterials, it is imperative to conduct comprehensive investigations, screening, and optimization of the nanomaterials for different plant species to ensure both their effectiveness and safety.

Table 7. Impact of MONPs as nano-pesticides to prevent plants from different pests and diseases.

MONPs as Nano-Pesticides	Size/Shape	Pest/Causative Agent	Plant Disease	Impact on Plants	Ref.
TiO_2	50 nm/ Hexagonal	Tebuconazole/Rust and moulds	Leaf senescence and decay	Photocatalytic activity higher and reduction in bacterial growth.	[159]
SiO_2	25 nm/ Spherical	Validamycin/NA	Leaf senescence and decay	Release rate improved by 50%	[160]
CuO	5-45 nm/ Spherical	Issatchenkia orientalis (yeast)/ Xanthomonas	Bacterial blight in Punica granatum	Bacterial growth inhibition	[161] [162]
ZnO	8 nm/ Spherical	Salmonella typhimurium/ Aspergillus niger	Disease in Capsicum annuum	Growth of mycelia delayed	[163] [164]
Fe_3O_4	18 nm/ Cubic	Bacteria/ B. cinerea, R. solani and F.oxysporum	Fungal disease	Fungal growth inhibition up to 60-80%	[165] [42]
AgO	30-35 nm/ Cylindrical	Spaherotheca fusca/ Xanthomonas campestris	Bacterial blight	Reduced bacterial infection significantly	[166]
	23 nm/ Spherical	Aphis nerii / Xanthomonas	Bacterial spot disease	Significantly inhibit the bacterial growth	[166]

CONCLUSION & FUTURE PROSPECTIVE

In conclusion, we have provided a comprehensive summary of the reported synthesis routes for various MONPs fabrication. The synthesis procedures have been systematically elaborated, highlighting the advantages and disadvantages of physical and chemical methods, such as ambient temperature processing, precise control over texture, faster production, and cost-effectiveness. Notably, The discussion has covered various MONPs such as TiO_2, ZnO, SnO_2, Fe_2O_3, among others, along with a summary of materials characterization, including crystal structure, morphology, optical properties, bandgap, elemental composition, shape, size, and other relevant characteristics. Furthermore, we have explored the diverse roles of MONPs in numerous applications, including photocatalysis, catalysis, biosensors, gas sensors, electrochemical sensors, biomedical applications, therapy, diagnosis, antimicrobial, and agriculture. The scientific discussions and summarized data presented in this review are anticipated to be of great value to researchers worldwide who study MONPs and their diverse applications.

Currently, nanoparticles (NPs) have gained widespread usage and have become integral to our society and scientific endeavors. Nanoscience continues to captivate significant research attention. This review article effectively showcases how MNOPs significantly influence diverse applications that hold crucial importance for future developments. MONPs have emerged as vital elements in applied nanotechnology and are found to have applications in trace gas sensors, batteries, solar cells, catalysis, energy conversion, architecture, medicine, food, agriculture, cosmetics, textiles, therapy, diagnosis, and biomedicine, among others. However, challenges persist in the use of MONPs in nanotechnology. There is a need for designing and synthesizing novel, robust, and flexible nano-oxides with properties such as high sensitivity, excellent selectivity, reduced size, extended lifetimes, and rapid response. Addressing these challenges will be essential to further harnessing the potential of MONPs in various fields. Here, our focus is on some of the important methods for the fabrication of MONPs, and we have tried to figure out the most feasible, cost-effective, and environmentally friendly method of synthesis of MONPs.

Subsequently, applying eco-friendly practices has become increasingly indispensable for accomplishment in today's time, and it's important to focus on these methods as they provide a wide range of applications and important trends in different fields. Additional attention should be given to the meticulous selection of nano-oxide types, morphologies, hierarchical structures, and the optimal choice of additives' composition. This approach is crucial for attaining superior performance in detecting specific environmental reductants or oxidants. This review includes all the important applications of MONPs that will help further research in different fields of agriculture, medicine, sensors, etc.

Abbreviation

MONP- Metal Oxide Nanoparticles, Go- Graphene Oxide, PPy-Polypyrrole, GCE-Glassy carbon electrode, rGo-reduced graphene oxide, G-Graphene, GSE- Gold strip Electrode, NTAS-, Nanotube Arrays, MNPS- Manganese Nanoparticles, MWFNTs- Multi-walled fullerenes nanotubes.

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CONFLICTS OF INTEREST

The authors declare that "There are no conflicts to declare".

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GRAPHICAL ABSTRACT