Novel synthesis approaches and applications of NiO nanoparticles

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Abstract: Nanoparticles have gained significant attention in various fields due to their unique properties and potential applications. NiO nanoparticles (NiO NPs) exhibit size-dependent properties, such as enhanced surface area, altered electronic structure, and different optical and magnetic behaviors compared to bulk NiO. NiO NPs have attracted significant attention due to their unique properties and potential applications in various fields. The novel synthesis approaches and applications of NiO NPs present an exciting area of research that holds promise for addressing critical challenges in various fields, from energy storage to environmental sustainability. The present review provides the brief information of novel synthesis approaches and applications of NiO NPs. This review article also demonstrate the versatility and potential of NiO NPs in various fields, highlighting their importance in current research and future perspectives of NiO NPs.

Keywords*: Nanoparticles, novel synthesis, environmental sustainability, optical properties.*

I. Introduction

Nanostructured materials have attracted significant attention due to their unique properties and potential applications in various fields. Nanostructured materials refer to materials that have been intentionally structured at the nanometer scale, typically ranging from 1 to 100 nanometers in size [1, 2]. These materials can be engineered to exhibit unique physical, chemical, mechanical, and optical properties compared to their bulk counterparts. Nanostructured materials have gained popularity in recent years due to the development of new techniques and processes [3, 4]. Various synthesis techniques have been used to develop nanostructured metal oxides with different geometric shapes [5]. Due to their unique structure and diverse properties, nanomaterials have become an advanced class of materials science. Metal oxide nanoparticles and nanocomposites based on them are rapidly being used in a variety of applications [6, 7]. The use of heterojunctions to enhance the electrical, photovoltaic, optical and gas sensing capabilities of nanostructured metal oxide composites is widespread. Nanostructured materials find applications in a wide range of fields, including electronics, catalysis, energy storage, biomedical devices, and environmental remediation, due to their unique properties and potential for innovation [7-9].

Compared to the other MOSs, a p-type NiO metal oxide semiconductors (MOS) is the most conspicuous material due to its thermodynamic stability and unique physiochemical properties. It has a widespread band gap of 3.6 – 4.2 eV [10]. Nickel oxide nanoparticles (NiO NPs), in particular, have shown great promise in diverse areas such as catalysis, energy storage, and sensing. One novel synthesis approach for NiO NPs is the use of green chemistry principles, which involve minimizing the use of hazardous substances and reducing waste [11]. This can be achieved through methods such as the use of plant extracts or other natural products as reducing and stabilizing agents. These green synthesis methods not only offer environmental benefits but also produce nanoparticles with high purity and controlled size and shape [12, 13]. The novel synthesis approaches for NiO NPs, including sol-gel methods, hydrothermal techniques, and thermal decomposition, have enabled the production of well-defined nanostructures with tailored properties. The applications of NiO NPs are diverse and continually expanding. Due to their unique optical, electrical, and magnetic properties, NiO NPs have found applications in gas sensors, catalysts, energy storage devices, and biomedical imaging. Their potential in these fields has spurred extensive research and development efforts to further explore and harness their capabilities for practical use [14]. One of the key applications of NiO NPs is in the field of gas sensing, where their high surface-to-volume ratio and excellent redox properties make them suitable for detecting gases such as CO, NO_2, and NH_3. Additionally, NiO nanoparticles have also been utilized as electrode materials in lithium-ion batteries, where their high theoretical capacity and good cyclability have shown great potential for improving battery performance [15, 16]. Furthermore, the catalytic properties of NiO NPs have been explored in CO oxidation and organic synthesis, demonstrating their potential in environmental and industrial applications [17, 18]. The unique properties of NiO NPs continue to drive research efforts towards developing new synthesis approaches and exploring their wide-ranging applications in nanotechnology [18, 19].

II. Synthesis approaches of NiO nanoparticles

Novel synthesis approaches offer opportunities to tailor the properties of NiO NPs for various applications, including catalysis, gas sensing, energy storage, and biomedical applications [20, 21]. Several novel synthesis approaches for NiO NPs have been explored to enhance control over particle size, morphology, and properties [21]. Figure 1 shows the different types of approaches of NiO nanoparticles.

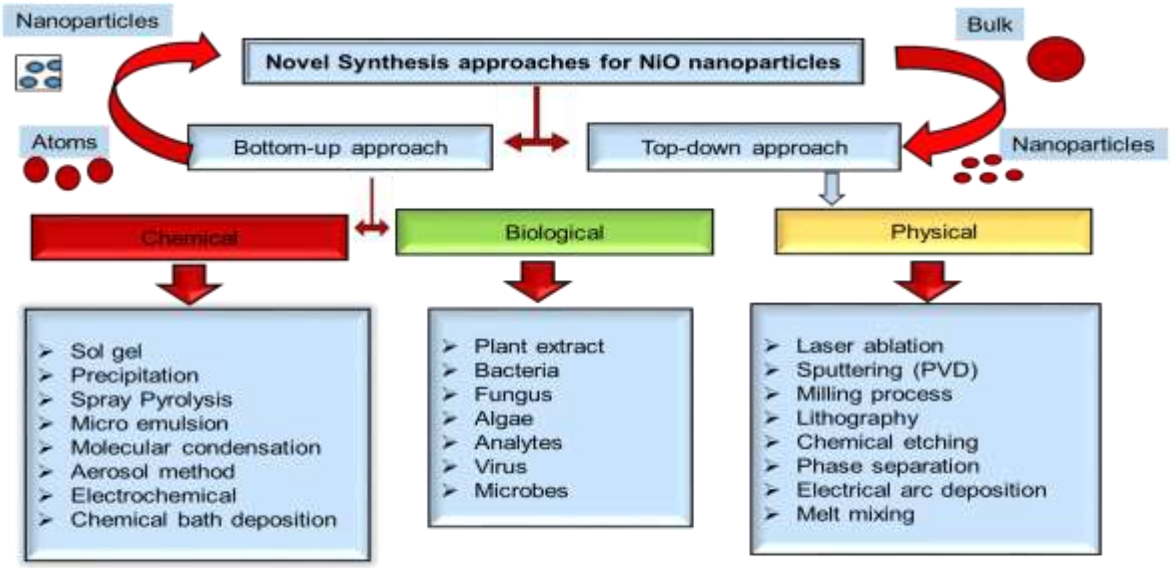

Figure 1: Different types of approaches of NiO nanoparticles

1. **Microwave-Assisted Synthesis:** This method involves using microwave irradiation to heat the reaction mixture, leading to rapid and uniform heating. This can result in the formation of NiO nanoparticles with controlled size and morphology in a shorter reaction time compared to conventional methods. Using a sol-gel technique, nickel oxide (NiO) nanoparticles were created at various pH values, and microwave assistance was used to calcine them. The shape, structure, and electrical characteristics of NiO nanoparticles were investigated in relation to pH. The synthesized sample's cubic structure and pure NiO composition were disclosed by the XRD data. Other than that, NiO showed a spherical morphology with considerable aggregation in SEM and TEM pictures. Additionally, all of the produced NiO is visible to be highly homogeneous at the nanoscale work carried out by Salleh NA [22]. Another author Agrawal S [23] synthesized NiO NPs by microwave assisted method. Using citric acid as a chelating agent, the microwave gel combustion process has been effectively used to create nanoparticles of Co doped NiO of the compositions. Using XRD, TEM, FESEM, and EDAX, microstructural and compositional studies were performed. According to the authors, structural characterisation demonstrates the impurity-free single-phase production of Co-doped Nickel oxide nanoparticles. Particle size was observed to rise with an increase in Co concentration, based on estimates from XRD and the Hall-Williamson relation. FTIR spectra reveal the bonding relationships between Co ions and the Ni lattice structure. UV-visible absorption and fluorescence emission spectroscopy were used for optical studies. The absorbance spectra show that when the dopant concentration increases, there is a commensurate decrease in the band gap [23].
   Jena A, et al [24] synthesized NiO nanoparticles by using microwave assisted method.
   NiO has been produced by a microwave-induced chemical synthesis method utilizing nickel's metalorganic complex in a microwave oven similar to a home microwave. Precursor material used in this work was a unique metalorganic complex of nickel, namely a β-ketoester of nickel, which was synthesized and described. The authors reported that XRD, SEM, and TEM were used to characterize the NiO nanoparticles. It was discovered that the NiO's particle size ranged from 7 to 40 nm. Using a vibrating sample magnetometer to study the magnetic behavior of the NiO nanoparticles, it was found that the magnetic ordering in NiO changes with decreasing particle size, producing a tiny, detectable coercivity.
2. **Green Synthesis:** Green synthesis methods involve using natural sources such as plant extracts, microorganisms, or environmentally friendly chemicals as reducing or capping agents. These methods are often more sustainable and can lead to the synthesis of NiO nanoparticles with unique properties. One promising approach is the use of green synthesis methods, which involve the use of natural extracts or biomolecules to

reduce and stabilize nickel oxide nanoparticles. This not only offers an eco-friendly and sustainable production route but also leads to the development of nanoparticles with improved stability and biocompatibility.

Sabouri Z et al [25] employ green synthesis method for synthesis of NiO nanoparticles. Using nickel nitrate hexahydrate as the Ni precursor and starch as the stabilizing/capping agent, respectively, a "green" co-precipitation method was used to create dispersed nickel oxide nanoparticles (NiO-NPs). Ammonia was added as a complex agent during the process. The NiO-NPs' optical, magnetic, photocatalytic, structural, and FTIR/UV-Vis, XRD, FESEM, EDX, VSM, and TGA/DTG properties have all been investigated. Following calcination processes, magnetic measurement verified the superparamagnetic behavior of NiO-NPs at room temperature. Based on computed band gap values of around 3.55 eV, NiO-NPs can be used as photocatalysts since they are semiconductors.

Ahmad B, et al [26] produced NiO NPs by using Aloe vera gel extract and evaluation of antimicrobial activity. For the production of nickel oxide (NiO) nanoparticles (NPs), an eco-friendly and economical green synthesis utilizing aloe vera gel was chosen, and the impact of annealing temperatures (300, 400, and 500 °C) on NPs characteristics was examined. Pure NiO NPs (face-centered-cubic) were formed, and XRD revealed that the grain size increased with temperature. NiO NPs had a band gap of 3.2 eV and a refractive index of 2.65. The specific surface areas that are annealed at 300, 400, and 500 degrees Celsius are 58.41, 42.19, and 40.89 m2/g, in that order. The antibacterial activity was assessed against strains of bacteria, including Gram-positive (Bacillus subtilis, Staphylococcus aureus), Gram-negative (Escherichia coli, Pasturella multocida), and fungal (Aspergillus niger, Aspergillus flavus, Penicillium notatum) bacteria. The antibacterial activity of the NPs that were annealed at 500 °C was excellent.

3. **Template-Assisted Synthesis:** Templates such as porous materials, polymers, or biological structures can be used to control the size and shape of NiO nanoparticles. By using templates, it is possible to create NiO nanoparticles with tailored properties for specific applications. Nimisha et al [27] demonstrates the environmentally friendly synthesis of nickel oxide nanoparticles utilizing black tea as a reducing agent and vermicelli as a template. Measurements using XRD, UV, and SEM were used to analyze the final product. When the sample was evaluated in the breakdown of Methylene Blue dye under solar cell illumination, it demonstrated good photocatalytic behavior. Additionally, the material's nanosheets shape holds promise for use in energy production and storage applications.
4. **Electrochemical Synthesis:** Electrochemical methods can be used to synthesize NiO nanoparticles by applying a potential to a nickel electrode in a suitable electrolyte solution. This method allows for precise control over particle size and morphology and can be easily scaled up for industrial production. Channu VR et al [28] For use in lithium ion batteries and supercapacitor applications, nanosized NiO anode material was created by pyrolyzing an oxalate precursor that was made from nickel carbonate hydrate and oxalic acid through a rheological phase reaction. X-ray diffraction (XRD), scanning electron microscopy (SEM), transition electron microscopy (TEM), and differential scanning calorimetry–thermogravimetric analysis (DSC–TGA) were used to characterize the produced material. The capacitive behavior of working electrodes fabricated from these novel NiO nanoparticles was investigated using cyclic voltammetry. The results of X-ray diffraction indicate that when the calcination temperature rises, the nanomaterials' particle sizes get bigger. The material's increased porosity is thought to be the cause of its superior electrochemical performance when produced at 400 °C.
5. **Combustion Synthesis:** Combustion synthesis involves the rapid exothermic reaction between metal nitrates and a fuel, leading to the formation of NiO nanoparticles. This method offers advantages such as simplicity, high purity, and the ability to produce nanoparticles with narrow size distributions.
6. **Chemical Precipitation:** Nickel salts are dissolved in a solvent, and a base is added to precipitate nickel hydroxide. The hydroxide is then calcined to form NiO nanoparticles.
7. **Hydrothermal Method:** Nickel salts are dissolved in water, and the solution is heated under high pressure in a sealed vessel. This leads to the formation of NiO nanoparticles.
8. **Sol-Gel Method:** Nickel salts are dissolved in a solvent, and a gel is formed by adding a hydrolyzing agent. The gel is then dried and calcined to obtain NiO nanoparticles.
   Zorkipli NN et al [29] synthesized NiO NPs by sol gel method. In this method, the calcination temperature was set at 450 °C, while the solution's pH was maintained at NiO's morphology, structure, and particle size were all examined. The absence of impurities in the formation of NiO's cubic structure was verified by structural investigation. Analysis of morphology and elements showed the NiO:Ni:O ratio. A morphological study revealed that the average diameter of the NiO nanoparticles was about 32.9 nm.
9. **Thermal Decomposition:** Nickel complexes are heated to high temperatures, leading to the decomposition and formation of NiO nanoparticles. Li X, Zhang X et al [30] NiO nanoparticle arrays have been produced by thermally breaking down the precursor nickel dimethylglyoximate. XRD, TEM, SAED, and UV–vis spectrophotometry were used to describe the products' structure, morphology, and characteristics. TEM demonstrates that NiO nanoparticles make up one-dimensional arrays. These NiO nanoparticles crystallize with

a polycrystalline structure, according to XRD and SAED data. NiO nanoparticles have an optical absorption band gap of 3.51 eV. Wang Y. et al [31] Nickel acetate, sodium hydroxide, and Tween 80 were the raw ingredients used in a solid-state reaction which produced NiO NPs with an average size of 10 nm. DTA, TG, XRD, and FTIR were used to study the reaction. TEM was used to examine the size and shape of NiO nanoparticles. DTA and TG looked into the NiO nanoparticles' catalytic potential for the thermal breakdown of ammonium perchlorate. When compared to bulk NiO particles, NiO nanoparticles have better catalytic performance. The decomposition temperature drops by 93 °C and the heat of decomposition rises from 590 to 1490 J g−1 when 2% NiO NPs are added to ammonium perchlorate.

10. **Microemulsion Method:** Nickel salts are dissolved in a water-in-oil microemulsion, where the reaction occurs in the confined space of the microemulsion droplets, leading to the formation of NiO nanoparticles. Du Y et al [32] a water-in-oil microemulsion has been used to create nanoscale nickel oxides. Nitrogen adsorption/desorption, transmission electron microscopy (TEM), and powder X-ray diffraction (XRD) were used to evaluate the as-synthesised materials. By adjusting the mixing technique, calcining temperature, and ratios of water, surfactant, and oil in the microemulsion, the particle size of nickel oxide can be regulated between 11.5 and 31.5 nm. As-synthesised nickel oxide is used to create and study gas sensors. Their sensitivity to ethanol, nitrogen dioxide, and hydrogen sulfide is significantly higher than that of devices based on the traditional bulk NiO. According to the authors, a NiO sensor with a particle size of 11.5 nm has a high degree of selectivity and a high response value, which makes it especially intriguing for applications involving the monitoring of H_2S gas. Palanisamy P Aerosol-OT was used as a surfactant in a water-in-oil microemulsion process to create NiO nanoparticles. The purpose of the study is to comprehend the distribution and size of nanoparticles that are co-precipitated without surfactant and those that are generated with it. The molar ratio of water to surfactant, or R-ratio, was varied throughout the synthesis of the nanoparticles. It was discovered that although the particles were polydispersed when produced outside of the microemulsion formation regime at high R-ratio, their size distribution was limited within the microemulsion forming regime. Furthermore, a broad size distribution of co-precipitated nanoparticles was observed, which was similar to that of nanoparticles generated at high R-ratio. Using a transmission electron microscope (TEM) and X-ray diffraction (XRD), phase identification and particle size analysis were performed.

III. Applications of of NiO nanoparticles

NiO nanoparticles have a wide range of applications due to their unique properties. NiO NPs have a wide range of applications in various fields [34, 35]. Figure 2 shows applications of NiO nanoparticles. NiO nanoparticles is play a vital role in many applications including biomedical, solar cell, gas sensor, optical sensor and optoelectronic devices [35-40].

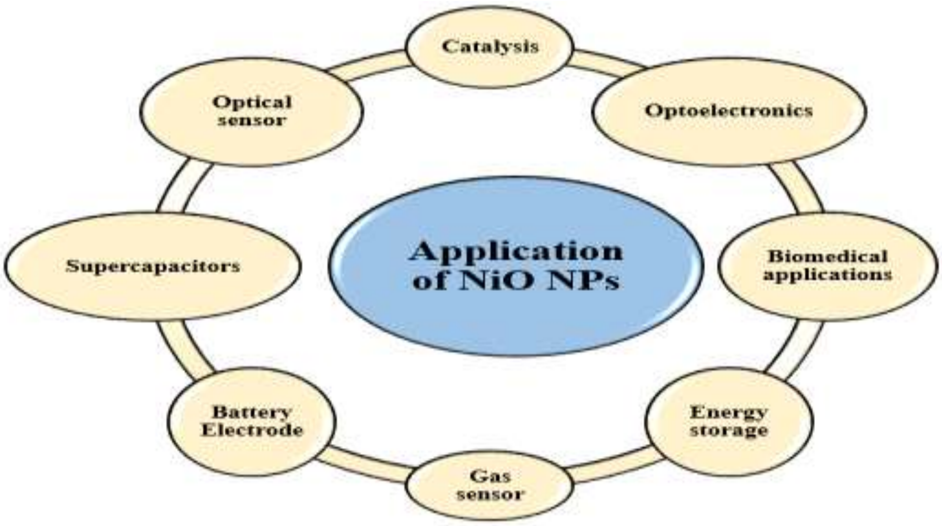

Figure 2: Different types of applications of NiO nanoparticles

1. **Catalysis:** NiO NPs have shown great potential as catalysts in various chemical reactions. They have high catalytic activity and can be used in reactions such as hydrogenation, oxidation, and carbon dioxide conversion.
2. **Energy storage:** NiO NPs have been studied for their potential use in energy storage devices such as batteries and supercapacitors. They have shown promising performance in terms of high capacity, long cycle life, and fast charge-discharge rates.

3. **Optoelectronics:** NiO NPs have also been utilized in optoelectronic devices such as solar cells and sensors. They exhibit excellent light absorption and can be used to enhance the efficiency of solar cells.
4. **Biomedical applications:** NiO NPs have shown potential in various biomedical applications. They have been studied for their use in drug delivery systems, where they can be loaded with therapeutic agents and targeted to specific sites in the body. Additionally, NiO nanoparticles have antimicrobial properties and can be used in wound dressings to prevent infection. Furthermore, NiO NPs have been investigated for their potential in cancer therapy. They have shown promise in photothermal therapy, where the nanoparticles are heated by light to destroy cancer cells.
5. **Gas sensing applications:** NiO is known to exhibit p-type semiconductor behavior. When exposed to reducing gases such as CO, H_2, or hydrocarbons, NiO undergoes a reduction reaction, resulting in a change in its resistance. This change in resistance is utilized for gas sensing. The high surface area-to-volume ratio of NiO NPs, along with their enhanced surface reactivity, contributes to their excellent gas sensing properties. This enables them to detect low concentrations of gases with high sensitivity and selectivity. NiO NPs are often incorporated into composite materials to improve their sensing performance. For example, combining NiO NPs with other metal oxides or polymers can enhance the overall gas sensing properties, such as response time, recovery time, and selectivity.
6. **Supercapacitors:** NiO NPs are used in the development of high-performance supercapacitors for various applications, including energy storage in portable electronics, electric vehicles, and renewable energy systems. Their low cost and abundance make them attractive for large-scale energy storage applications. NiO NPs offer a high specific capacitance, which is crucial for supercapacitors to store and release energy efficiently. The high specific capacitance is attributed to the Faradaic redox reactions that occur at the surface of NiO NPs. NiO NPs have emerged as promising materials for supercapacitors applications due to their high specific capacitance, good cycling stability, and less expensive.

IV. Future perspectives of NiO nanoparticles

The future perspectives of nickel oxide nanoparticles are promising, as researchers continue to explore their unique properties and potential applications. Some key future directions and advancements in the field of NiO nanoparticles are listed in this section as below.

1. **Enhanced Gas Sensing Properties**: Researchers are working on improving the gas sensing properties of NiO nanoparticles by tuning their size, shape, and surface properties. This could lead to more sensitive and selective gas sensors for various applications, including environmental monitoring and industrial safety.
2. **Energy Storage and Conversion**: NiO nanoparticles show potential for use in energy storage devices, such as lithium-ion batteries and supercapacitors, due to their high theoretical capacity and good cycling stability. Future research may focus on improving their performance and integrating them into practical devices.
3. **Catalysis**: NiO nanoparticles are effective catalysts for various chemical reactions, and future research may focus on optimizing their catalytic activity and selectivity for specific reactions. This could lead to more efficient and environmentally friendly catalytic processes. NiO NPs find applications in catalytic converters for automotive exhaust systems, hydrogen production through steam reforming of hydrocarbons, and various other industrial processes.
4. **Optoelectronic Applications**: NiO nanoparticles have shown promise in optoelectronic devices, such as solar cells, photodetectors, and light-emitting diodes (LEDs). Future research may explore ways to improve their efficiency, stability, and compatibility with other materials for these applications.
5. **Biomedical Applications**: NiO nanoparticles have potential applications in biomedicine, such as drug delivery, bioimaging, and cancer therapy, due to their biocompatibility and controlled release properties. Future research may focus on developing targeted delivery systems and optimizing their performance in biological environments.
6. **Environmental Remediation**: NiO nanoparticles have been studied for environmental remediation applications, such as wastewater treatment and air purification. Future research may explore their use in removing specific pollutants and improving the efficiency of these processes.

V. Conclusions and Future Scope:

NiO nanoparticles show great potential in the field of energy storage and conversion. They can be used as electrode materials in lithium-ion batteries, supercapacitors, and fuel cells due to their high specific capacity and excellent electrochemical performance. Additionally, NiO nanoparticles have also been explored for their catalytic properties in various chemical reactions, opening up opportunities in fields such as environmental remediation and industrial processes. The novel synthesis approaches of nickel oxide nanoparticles offer exciting opportunities to engineer their properties for diverse applications, ranging from environmental remediation to biomedical uses. As research in this field continues to evolve, the development of scalable and cost-effective synthesis strategies will be pivotal in unlocking the full potential of nickel oxide nanoparticles.

Further research and development in novel synthesis approaches and understanding the applications of NiO nanoparticles will continue to drive innovation in the field of nanotechnology and material science. Another innovative approach for synthesizing NiO nanoparticles is the utilization of microwave-assisted methods. This technique offers several advantages such as rapid and uniform heating, energy efficiency, and the ability to control the size and morphology of the nanoparticles. Additionally, the use of microwave irradiation can lead to the synthesis of highly crystalline and pure NiO nanoparticles in a shorter reaction time compared to conventional methods.

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