Synthesis Approaches and Applications of Nickel Oxide Nanoparticles

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***Abstract*: Nickel oxide nanoparticles are nanoscale particles of nickel oxide, a chemical compound with the formula NiO. These nanoparticles have a wide range of applications in various fields due to their unique properties resulting from their small size and high surface area-to-volume ratio. The synthesis of metal oxide materials at the nanoscale combines materials science and technology, resulting in a growing number of applications in research and technology. The synthesis of metal oxides, particularly Nickel oxide on the nanoscale, is receiving a lot of attention these days because of its potential uses in a variety of fields. The synthesis of Nickel oxide nanoparticles has been reported using both bottom-up and top-down approaches. This review article emphasizes the different synthesis approaches of nickel oxide (NiO) and its applications in the various fields like optical, gas sensor, batteries, etc. The current research review also provide future perspectives of NiO nanoparticles.**

***Keywords* - Nickel oxide, bottom-up, sensors, nanomaterials, surface area-to-volume ratio.**

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1. Introduction:

Material science is an interdisciplinary field that explores the structure, properties, processing, and applications of materials. It encompasses a broad range of materials, including metals, ceramics, polymers, composites, semiconductors, and nanomaterials. The primary goal of material science is to understand the relationships between the internal structure of materials and their macroscopic properties, which, in turn, enables the development of new and improved materials with specific functionalities. It has evolved into a main focus for all scientific endeavors. Material science is widely used in a wide range of industrial, technology, and medical sectors. In numerous fields of research, such as photo catalytic, electronics, electrode of super capacitor, sensors, transducers, optoelectronics, solar cells, and biosensors, the usage of diverse nanomaterials is very desirable. Extraordinary material results in numerous domains are making a significant contribution to study. The research community is working to strengthen all aspects of material science in order to better serve humanity as a whole [1, 2]. A prominent application of material science is the production of conventional and advanced nanoparticles for their intended use in a variety of industries. These tiny nanoparticles have a number of desirable and inherent qualities, including a large surface area, excellent thermal stability, great catalytic activities, and exceptional mechanical, electrical, and magnetic characteristics [3]. These astounding properties of nanomaterials inspire scientists to use the ease of nanotechnology to

produce even more creative work. The development of materials specifically suited for industries including aircraft, electronics, medicinal devices, energy storage, construction, and more depends heavily on material science [3, 4].

Nickel oxide (NiO) nanoparticles exhibit different properties compared to their bulk counterparts due to quantum confinement effects. These properties may include altered optical, electronic, magnetic, and catalytic properties. Due to its good repeatability, large specific surface areas, high sensitivity, cheap cost, and environmental friendliness, gas sensors based on p-type NiO are currently attracting greater attention [5- 7]. Nickel oxide (NiO) is a p-type metal oxide semiconductor with a widespread band gap of 3.6-4.2eV. NiO is the most stunning substance because of its thermodynamic stability and unusual optical, magnetic, and chemical features [8, 9]. Nickel oxide is used in a variety of applications today, including electronics, capacitor–inductor devices, tank circuits, transparent heat mirrors, temperature sensors and varistors, batteries, micro-super capacitors, electro chromic and chemical or temperature sensing devices [10, 11]. It's utilized to make nickel cermet, polymers, and textiles, as well as nanowires, nanofibers, and specialised alloys and catalysts. Antiferromagnetic layers, accelerators, and radar absorption materials, as well as aeronautical and active optical filters, are all examples of its applications [12, 13]. Due to their numerous uses, nano metal oxides are receiving a lot of interest from scientists. Because of the reduction in size, they have a larger surface area, which makes the surface shape vitally important to their optical and electrical properties. Among the several nano metal oxides, nickel oxide (NiO) nanoparticles have received the most attention because to their exceptional chemical stability and advantageous opto-electrical properties. NiO is a substance that is antiferromagnetic due to its cubic structure. This NiO is therefore utilized in materials with antiferromagnetic properties [13].

This work discusses the various p-type NiO nanomaterial synthesis approaches and their applications.

2. Synthesis approaches of NiO nanoparticles:

NiO nanoparticles have previously been created utilizing a number of techniques, as illustrated in Figure 1.

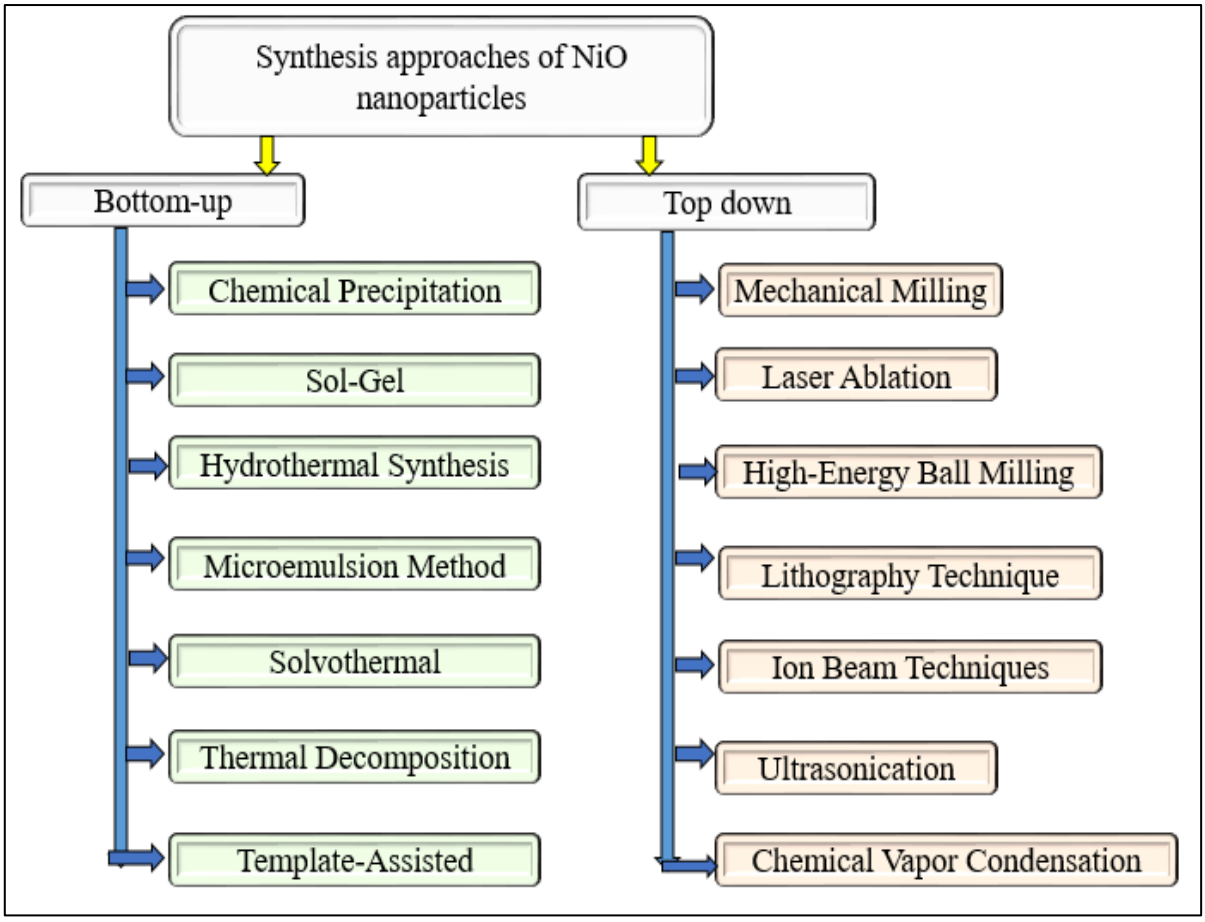

Figure 1: Synthesis approaches of NiO nanoparticles

The co-precipitation, sol-gel, spray pyrolysis, solvothermal, precipitation, and hydrothermal are a few of the approaches. The use of microemulsions, physical vapour deposition, sputtering, thermal oxidation, and combustion are more examples. These approaches can be used to produce nanoparticles that have a wide surface area, a high degree of crystallization, variable particle size, and small crystallite size.

2.1 Bottom-up approaches

Bottom-up approaches in the synthesis of NiO nanoparticles involve building up the material from smaller components, such as atoms or molecules, to form the final nanoparticles. These methods are typically based on chemical or physical processes that allow precise control over the size, shape, and composition of the nanoparticles. Some common bottom-up approaches for synthesizing NiO nanoparticles include:

2.1.1 Chemical Precipitation: In this method, a soluble nickel salt, such as nickel nitrate or nickel chloride, is mixed with a base (e.g., sodium hydroxide) in an aqueous solution. The addition of the base results in the formation of nickel hydroxide, which subsequently undergoes thermal treatment (calcination) to convert it into NiO nanoparticles.

2.1.2 Sol-Gel Method: The sol-gel process involves hydrolyzing a metal alkoxide precursor, such as nickel ethoxide or nickel acetate, in a solvent to form a sol (colloidal suspension). The sol is then allowed to undergo a gelation process, leading to the formation of a solid gel. Subsequent heat treatment (calcination) of the gel results in the formation of NiO nanoparticles.

2.1.3 Hydrothermal Synthesis: In the hydrothermal method, a reaction is carried out in a closed vessel under high-temperature and high-pressure conditions. A solution containing the nickel precursor and a suitable hydroxide source is heated, and the NiO nanoparticles nucleate and grow under these controlled conditions.

2.1.4 Microemulsion Method: This technique involves the use of surfactants and co-surfactants to form a microemulsion system, where the reactants are confined within nanometer-sized droplets. By controlling the composition and conditions of the microemulsion, NiO nanoparticles can be synthesized with precise control over size and morphology.

2.1.5 Solvothermal Synthesis: Similar to the hydrothermal method, the solvothermal approach involves the reaction of metal precursors in a solvent at elevated temperatures and pressures. This method allows the synthesis of NiO nanoparticles with controlled crystallinity and size.

2.1.6 Thermal Decomposition: In this method, organometallic precursors are decomposed thermally in a controlled atmosphere to produce NiO nanoparticles. For example, nickel acetylacetonate can be thermally decomposed to form NiO nanoparticles.

2.1.7 Template-Assisted Synthesis: Templates, such as porous materials or micelles, can be used to guide the formation of NiO nanoparticles. The precursors are introduced into the templates, and the reaction leads to the formation of nanoparticles with the template's shape and size.

These bottom-up approaches offer advantages like precise control over the size, shape, and properties of NiO nanoparticles. Researchers can tailor the synthesis conditions to obtain nanoparticles suitable for specific applications, ranging from catalysis and sensing to energy storage and biomedical uses [14, 15].

2.2 Top-down approaches:

Top-down approaches in the synthesis of NiO nanoparticles involve the reduction of larger bulk materials, such as NiO bulk powders or bulk nickel compounds, to obtain nanoparticles. These methods typically involve physical processes that break down the larger materials into smaller particles. Some common top-down approaches for synthesizing NiO nanoparticles include:

2.2.1 Mechanical Milling: Mechanical milling is a solid-state method where bulk NiO powders are subjected to mechanical forces, such as ball milling or attrition milling. The mechanical energy leads to the fracturing and size reduction of the bulk particles into nanoparticles.

2.2.2 Laser Ablation: In laser ablation, a high-power laser is focused on a target material (e.g., nickel metal or NiO bulk) in a liquid medium. The laser ablation process generates a plasma that results in the production of NiO nanoparticles in the liquid.

2.2.3 High-Energy Ball Milling: This method utilizes high-energy impacts between balls and the bulk NiO powders to produce nanoparticles. The repeated collisions and deformation break down the bulk material into smaller particles.

2.2.4 Lithography Techniques: Lithography techniques, such as electron beam lithography or photolithography, can be used to pattern bulk nickel-containing films. Subsequent etching processes can then create NiO nanoparticles with controlled shapes and sizes.

2.2.5 Ion Beam Techniques: Ion beam techniques, such as ion implantation or focused ion beam (FIB) milling, can be employed to modify and reduce bulk NiO materials into nanoparticles with precise control over their location and size.

2.2.6 Ultrasonication: Ultrasonication involves subjecting bulk NiO materials to high-frequency ultrasonic waves in a liquid medium. The cavitation and shear forces created by ultrasonication break down the larger particles into nanoparticles.

2.2.7 Plasma Techniques: Plasma-based methods, such as plasma sputtering or plasma-induced reduction, can be utilized to generate NiO nanoparticles from bulk nickel-containing materials.

2.2.8 Chemical Vapor Condensation: In this method, a vapor of nickel-containing precursors is generated and then rapidly cooled to condense into nanoparticles. The process can be controlled to achieve the desired size distribution.

Top-down approaches often offer advantages such as scalability and simplicity in some cases. However, they may not provide the same level of control over particle size and shape as bottom-up approaches. Top-down methods are particularly useful when working with bulk materials that are already available or when large quantities of nanoparticles are needed for specific applications [11, 15].

3. Literature Survey:

Khandagale, P. et al. [16] synthesized NiO nanoparticles by using co-precipitation method. In this work Nickel chloride hexahydrated was used as source material of nickel oxide and ammonia solution used as a precursor. The synthesized nanoparticles of NiO were characterized by using TEM, XRD, SEM, FTIR & EDAX. Author also reported important applications of NiO nanoparticles. Results of XRD showed that synthesis nano powder was amorphous in nature. SEM result indicate that occurrence of particle is rod shape & highly agglomerated. From TEM, particle sizes of nanoparticles were found to be range is 31.87 nm. From FTIR spectrum of NiO nanoparticle showed that significant absorption peak occur at 447.49 cm^{-1} is due to Co-O stretching vibration mode. TEM results also confirmed the synthesis of NiO nanoparticles by using co-precipitation method.

Hui Lim et al. [17] synthesis of single crystalline NiO NP's by using co-precipitation method. From the SEM, morphology of NiO NP's are found to be uniform rodlike crystals with mean z-diameter between 1600 nm to 2600 nm using Zetasizer. NiC_2O_4 and NiO FT-IR spectra after a 10-minute synthesis at 100°C. The FT-IR spectra of NiC_2O_4 revealed a faint, broad band at 3390 cm^{-1}, which corresponded to the O-H stretching vibration, and a strong broad band at 1600 cm^{-1}, which belonged to the water H-O-H bending vibration. The co-precipitation approach was used to successfully synthesise high purity NiO sub-micro rods.

Abdallah, A.M et al. [18] synthesized NiO nanoparticles using the co-precipitation method. X-ray Powder Diffraction (XRD), Transmission Electron Microscopy (TEM), Fourier Transform Infrared Spectroscopy

(FTIR), UV-VIS Spectroscopy, and Vibrating Sample Magnetometer were used to examine the structural, morphological, optical, and magnetic properties of NiO nanoparticles (VSM). NiO nanoparticles have a face-centered-cubic lattice structure with a crystallite size of 22.77 nm, as revealed by their XRD pattern.

Kaur, N et al. [19] prepared NiO nanoparticles using the cost-effective co-precipitation technique. Nickel chloride hexahydrate ($NiCl_2.6H_2O$) used as source of nickel oxide, cetyl trimethyl ammonium bromide, and sodium hydroxide are used as precursors to prepapre NiO NPs. NiO NPs FTIR spectra in the 4000–500 cm^{-1} range. The O–H stretching of absorbed water molecules on the surface of NPs caused the band at 3286 cm^{-1}. The strong peak of C–N bonds resulted in an absorption band at 1027 cm^{-1}. The absorption at 704 cm^{-1} was attributed to the Ni–O–H bond's vibration. The surface chemistry of synthesised NPs is revealed by FTIR analysis, as well as the stretching vibrations of NiO NPs. The synthesised NiO NPs have an average crystallite size of about 25.6 nm, which validates the FCC crystal structure. The synthesis of spherical NiO NPs with an average particle size of 35 nm can be seen in TEM micrographs. As a result, this research demonstrates a straightforward method for synthesising NiO NPs and their implications in a photo catalyst regime for the elimination of hazardous pigments from water.

Zorkipli, N.N.M, et al. [20] synthesized nickel oxide nanoparticles by using sol-gel process. The pH of the solution was kept at 11, and the calcination temperature was kept at 450°C. NiO was studied for its structure, morphology, and particle size. The cubic structure of NiO was created without impurities, according to structural studies. The ratio of NiO, Ni, and O was discovered using morphological and elemental investigations. NiO nanoparticles with an average diameter of 32.9 nm were discovered by morphological investigation.

Shamim, A., et al. [21] synthesized nickel oxide nanoparticles by using simple and low cast sol-gel method. To obtain nickel oxide nanoparticles, the sol-gel technique was followed by the formation of precipitates, which were then dried and calcined at 550°C. X-ray diffraction (XRD), scanning electron microscopy (SEM), and energy dispersive spectroscopy (EDS) were used to evaluate the nanopowder that had been prepared. By dissolving 3-4g of salt in 100ml deionized water, nickel nitrate hexahydrate was formed. To completely dissolve the salt, we swirled the solution. The salt solution was titrated by dropping 0.5M NaOH into the burette and stirred constantly. We checked the PH on a very regular basis. When the pH was 11, the precipitates formed. Nickel precipitates had a greenish hue to them. The precipitates were cleaned 4-5 times with de-ionized water before being dried at 95 ° C to eliminate moisture. A muffle furnace was used to calcined dried precipitates at 550°C for 3 hours. The calcined material was ground with a mortar and pestle before samples were taken. According to the XRD data, the average particle size of NiO NPs is 45nm. Crystallization of NiO NPs is indicated by the appearance of crystallographic planes like 111, 200, and 220. JCPDF # 47-1049 was used to match diffraction peaks for NiO nanoparticles.

Alagiri, M., et al. [22] synthesized nickel oxide nanoparticles by using sol-gel technique. In the presence of agarose polysaccharide, nickel oxide nanoparticles were synthesised using the sol–gel technique. X-ray diffraction, transmission electron microscopy, UV–visible spectrophotometer, and superconducting quantum interference device magnetometer were used to investigate the structure, morphology, optical, and magnetic properties of the product. The synthesized nickel oxide nanoparticle has a face-centered cubic structure, according to the X-ray diffraction data. The nickel oxide nanoparticles have a spherical form and a diameter of roughly 3 nm, as seen by TEM images. The product's composition was confirmed via FTIR analysis. NiO nanoparticles have a 3.51 eV optical absorption band gap. At 300 K, magnetic measurements revealed superparamagnetic behaviour in nickel oxide nanoparticles. Furthermore, due to the presence of uncompensated moments on the nanoparticles' surface, the nanoparticles exhibit ferromagnetic interactions at 4.2 K.

Kayani, Z.N., et al. [23] low-cost sol-gel method was used to synthesize nanocrystalline nickel oxide nanoparticles. Ammonium hydroxide and nickel nitrate were used as precursors to make NiO nanoparticles

via a sol-gel method. The NiO nanoparticles were annealed at temperatures ranging from 400 to 1000 ° C. X-ray diffraction (XRD), Fourier transform infrared spectroscopy (FT-IR), vibrating sample magnetometer (VSM), and thermogravimetry/differential thermal analysis (TGA/DTA) were used to characterized the nanoparticles. Authors reported the synthesized NiO nanoparticles have a good nanocrystalline hexagonal structure, according to the XRD data. With raising the annealing temperature from 400 °C to 1000 °C, their grain size grew from 12.4 nm to 20.7 nm. As the calcination temperature increased, the peaks sharpened and the crystallite size grew. Optical transmission experiments revealed minimal absorbance in the infrared and visible ranges, with a band gap of 3.02 eV at 400 °C and 3.14 eV at 1000 °C. The increase in the band gap is attributable to a rise in the number of defects. The chemical composition and synthesis of NiO nanoparticles were determined using Fourier transform infrared spectroscopy (FT-IR).

Ningsih, S.K.W., et al. [24] by using nickel nitrate hexahydrate as a precursor, sodium hydroxide as an agent precipitator, and aquadest as a solvent, NiO nanopowder were synthesized using the sol-gel method. Authors reported after drying at 110°C, the powders were heated in the furnace for 1.5 hours at 400°C. It was black powder that was used to make the product. SEM, ED-XRF, and X-ray diffraction (XRD) were used to characterize the product (SEM). The NiO produced was 97.1 % NiO, according to the ED-XRF pattern. NiO forms were frequently formed in monoclinic structure, according to the XRD pattern. NiO was found to have a crystalline size of 40-85 nm. The powder had a spherical shape and a uniform distribution size of 0.1-1.0 µm, as shown by SEM micrographs.

Desai, J.D., et al. [25] deposited thin films of NiO on ITO substrates by using Spray Pyrolysis System. The structural studies using an X-ray diffractometer (XRD) were carried out to study crystallographic characteristics. According to the author, NiO crystallizes in a cubic bunsenite structure was found from XRD. Direct transitions have an optical band gap of 3.67 eV. The morphological characteristics of the produced films were studied using field emission scanning electron micrographs (FESEM). Auger Electron Spectroscopic (AES) examinations were used to acquire elemental depth profiles of film contents.

Wang, W.N., et al. [26] synthesized nickel nanoparticles from nickel nitrate hexahydrate with hydrogen, formic acid, and ethanol. Author reported the pressure and carrier gas flow rate are both important in the conversion of NiO to nickel in LPSP. Larger nanoparticles, occasionally submicron particles, are formed when the pressure and carrier gas flow rate are both lower. Weak NiO peaks coexisted with strong nickel peaks in several cases in this study, owing to the fact that nanoparticles have a larger surface potential than submicron particles, making them simpler to oxidise. Another reason could be that in certain situations, the reduction is partial due to H2 depletion. For the synthesis of nanoparticles, a considerably greater precursor concentration is advantageous. Submicron particles were discovered at extremely low concentrations (0.15 M), which can be explained using the proposed mechanism. In the manufacture of nickel nanoparticles from nickel metallic salts, co-solvents such as formic acid and ethanol can also be used as reducing agents. In addition, when compared to employing H2 as the reductant directly, they can generate a safer environment. This LPSP approach is thought to be a viable technology for large-scale dry nanoparticle production with controllable size and morphology.

Patil, P.S. et al. [27] deposited nickel oxide thin films on to glass substrates at temperature 350 °C using simple and inexpensive spray pyrolysis technique. NiO was synthesis from of hydrated nickel chloride salt precursor solution. The deposition temperature was determined using the pyrolytic breakdown properties of a precursor $NiCl_2 6H_2O$, according to the authors. Author mentions that, the film thickness increases from 0.028 to 0.23 m as the spraying solution volume increases from 30 to 75 ml. According to XRD analyses, all of the films deposited were NiO (cubic phase) with orientation in the (1 1 1) direction. As the film thickness grows, the crystallinity improves marginally. IR studies of a typical film revealed the presence of NiO phase with some hydration and chloride ions. Author also reported that, with increasing film thickness, the optical band-gap energy of NiO declines from 3.58 to 3.4 eV. All of the samples had a room temperature electrical

resistivity of 10^4 Ω cm, with thicker films being more resistive. NiO films were found to be p-type according to thermo-emf measurements.

Raj, K.P., et al. [28] reported using a Sonochemical method, nickel oxide (NiO) nano powder was synthesized. Sodium hydroxide (NaOH) is added to nickel nitrate $Ni(NO_3)_2$ solution and aggressively stirred until the pH reaches 7.2. During the precipitation stage, ultrasonic waves were used, and after drying in the oven, nano powder NiO was obtained.

Meybodi, S.M., et al. [29] synthesized nanocrystalline nickel oxide particles of crystallite size of ~20 nm by a novel Sonochemical method. Meybodi have reported as per TEM micrographs, the synthesized powder had a cubic morphology, which was due to NiO's NaCl-like structure. Ultrasonic irradiation caused cavitation, which resulted in a reduction in the crystallite size of NiO particles. The NiO powder synthesis in this study was a non-stoichiometric nanocrystalline substance that ranged from green to black in appearance. Furthermore, the presence of nickel vacancy in photoluminescence spectra indicated the p-type nature of nickel (II) oxide semiconductor.

Kristl, M., et al. [30] have made an attempt to synthesize nanoparticles of nickel and cobalt sulfides with different stoichiometries (NiS, Ni_3S_4, $CoS_{1.097}$ and Co_9S_8) by using sonochemical method. Authors reported Increase the power of ultrasonic irradiation to change the shape of the product and the optical band gap energy. When compared to alternative methods for preparing sulphide nanoparticles, the ultrasonic method has showed advantages.

Wang, H., et al. [31] reported a novel method for the preparation of copper monosulfide (CuS) and nickel monosulfide (NiS) nanoparticles. Sonochemical technique was used for the preparation of copper monosulfide (CuS) and nickel monosulfide (NiS) nanoparticles from an aqueous solution containing metal acetate [$Cu(CH_3COO)_2$ or $Ni(CH_3COO)_2$] and thioacetamide (TAA) in the presence of triethanolamine (TEA) as a complexing agent in surrounding atmosphere. After characterization the nanoparticles that have been prepared. Authors reported nanoparticles has a consistent shape, a narrow size distribution, and is quite pure. For the synthesis of CuS and NiS nanoparticles, it was discovered to be a mild, convenient, and effective technique.

Koltypin, Y., et al. [32] prepared amorphous Ni powder from $Ni(CO)_4$ using sonochemical method. Authors reported using this method, particle size was found to be 10 nm. SEM, TEM, DSC, thermogravimetric analysis, X-ray diffraction, and SQUID magnetization studies were carried on the nickel nanoparticles. The amorphous nature of the particles is confirmed by these tests.

Reddy, A.M., et al. [34] developed thin films of NiO on glass substrate using PVD method. Nickel oxide thin films of different thickness were developed on glass substrates using the dc reactive magnetron sputtering method in a pure oxygen atmosphere at 150 W sputtering power at 523 K substrate temperature. X-ray diffraction was used to study the crystalline characteristics of NiO films as a function of film thickness. At a film thickness of 350 nm, XRD investigations showed that the preferred orientation is (200), and the orientation of the films shifted from (200) to (220). At a film thickness of 350 nm, the highest optical transmittance was %, with a band gap of 3.82 eV. At a film thickness of 350 nm, the lowest electrical resistivity of 5.1 Ω cm was found, and thereafter, resistivity increased with film thickness [33].

Hammadi, O.A., et al. [35] fabricated UV photodetector by depositing 25 nm NiO nanoparticles on an n-type silicon substrate by a closed-field unbalanced dual magnetron sputtering method. Author reported the fabricated photodetector had a maximum spectrum responsivity of 4.8 mA/W at 318 nm and 1.87 % quantum efficiency. This is a nice attempt at producing high-quality, low-cost nanostructures for UV detection. Peaks at 37.125° and 43.156° can easily be indexed as NiO crystal planes (111) and (012). Both diffraction peaks are indexed to NiO's face-centered cubic crystalline structure, which corresponds to JCPDS 22-1189.

Asrami, P.N., et al. [36] have been take efforts by using a reactive radio frequency (RF) magnetron sputtering method, a nanostructured nickel oxide thin films was developed on the F-doped SnO_2 conducting glass. The

immobilisation of glucose oxidase enzyme (GOx) for impedimetric glucose quantification was successfully accomplished using the Nano-NiO thin film. The potentiometric results for the newly developed FTO/Nano-NiO/GOx biosensor revealed a high sensitivity of 4.45 k/mM for glucose detection in the 0.20–4.0 mM range, good electrocatalytic activity, and a low detection limit of 24 mM thanks to suitable enzyme activity and stability. The suggested disposable biosensor showed promise for real-time sample analysis with unknown interfering factors.

Teixeira, et al. [37] deposited thin film of nickel-zinc oxide by the PVD E-beam deposition technique. The optical properties of the absorber samples were improved by the PVD, according to the results of solar absorptance and selectivity. The deposited thin film of nickel-zinc oxide had a selectivity of 11.55 (0.9703/0.084), which was close to the ideal optical selective film, and an absorptance of Planck black body. The success of the copper bulk RMS roughness and thin film surface nanostructuration was validated by AFM pictures. The optical properties of the absorber samples are improved by nanostructuration of the copper substrate, according to the results of solar absorptance. According to the FTIR and XRD data, a ZnO semiconductor thin film PVD E-beam was produced on a copper substrate, making this thin film suitable for future photovoltaic designs in solar power plants.

Zhou, Q., et al. [38] synthesized hierarchical ultrathin NiO nanoflakes by using hydrothermal. Author reported the synthesized NiO nanoflakes material has a diameter found to be 300–400 nm and a thickness of 10–15 nm. The methane sensing performances of a side-heated gas sensor were comprehensively examined using the manufactured ultrathin NiO nanoflakes. High sensitivity, low optimal working temperature, rapid reaction and recovery time, outstanding selectivity and stability to CH_4 gas were all demonstrated by the hierarchical ultrathin NiO nanoflakes sensor that was produced. Furthermore, from 0.2 to 50 ppm, a solid linear relationship between the sensor response and gas concentration was found.

Ahire, D.V., et al. [39] successfully synthesis nanostructured NiO by hydrothermal process. Author and his team synthesis NiO nanostructured by using Nickel Chloride ($NiCl_2$), a Nickel precursor, and Thioglycerol, a capping reagent. Scanning electron microscopy (SEM), transmission electron microscopy (TEM), and X-ray diffraction were used to study the structure, morphology, and crystallite size of nickel oxide nanocrystals. The nickel oxide nanoparticles exhibit a hexagonal structure with a consistent size distribution of 20-38 nm for NiO with stabilizing agent and 23-100 nm for NiO without stabilizing agents, according to TEM images. The XRD measurements revealed phase pure, cubic nickel oxide synthesis. By using a screen-printing method, thick films of NiO were developed for the study of gas sensing study. Author reported maximum gas response found to H_2S of 10 ppm gas concentration at 150 °C.

The numerous synthesis approaches, as illustrated in figure 1, are here explored based on the literature survey. These approaches are highly beneficial for the production of NiO nanoparticles and for the development of thin and thick film NiO sensors.

4. Applications of NiO nanoparticles:

NiO nanoparticles have remarkable physical, chemical, electrical, and catalytic capabilities, among others. Thus, NiO nanoparticles is employed in a variety of fields, as illustrated in Figure 2.

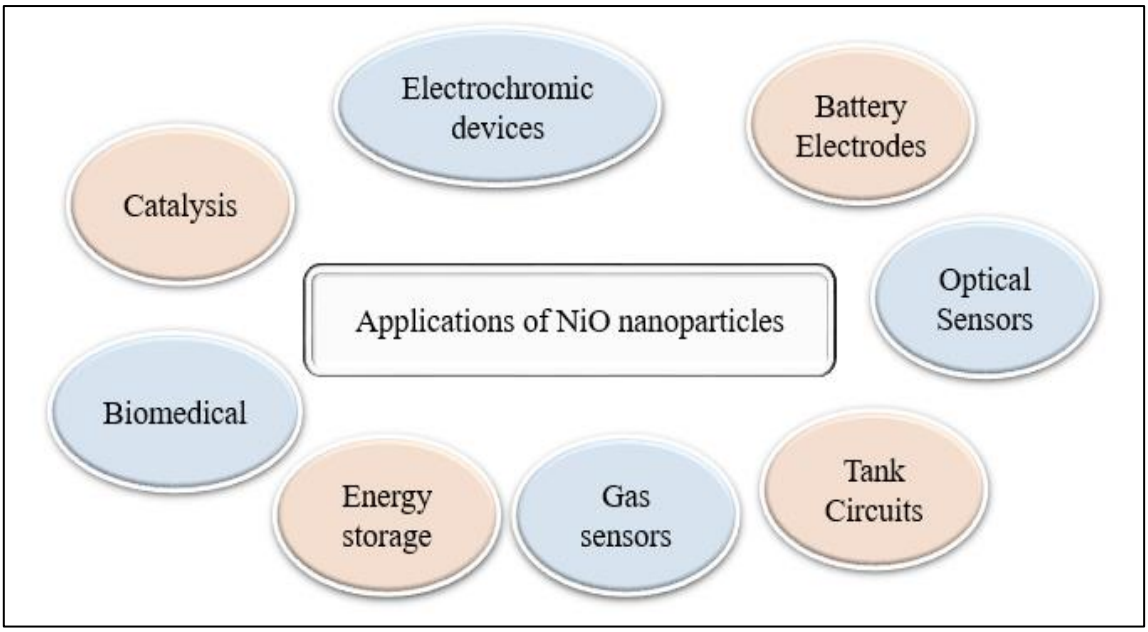

Figure 2: Applications of NiO nanomaterials

4.1 Catalysis: Nickel oxide nanoparticles are used as catalysts in various chemical reactions, including oxidation reactions and water splitting processes. Their high surface area enhances catalytic activity and efficiency.

4.2 Gas sensors: Nickel oxide nanoparticles are utilized in gas sensors to detect various gases, such as carbon monoxide (CO) and nitrogen dioxide (NO_2). Their sensitivity to gas molecules is attributed to changes in electrical resistance upon gas adsorption.

4.3 Energy storage: Nickel oxide nanoparticles are studied for potential use in energy storage devices, such as lithium-ion batteries and supercapacitors, due to their ability to store and release charge efficiently.

4.4 Electrochromic devices: These nanoparticles can be used in electrochromic devices, which are capable of changing their optical properties in response to an external electrical stimulus. They find application in smart windows and displays.

4.5 Photocatalysis: Nickel oxide nanoparticles can act as photocatalysts, promoting chemical reactions under light irradiation. This property is useful in environmental remediation and solar energy conversion.

4.6 Biomedical applications: Researchers are exploring the potential of nickel oxide nanoparticles in biomedical applications, such as drug delivery, bioimaging, and cancer therapy. However, their biocompatibility and toxicity need careful consideration for medical use.

Conclusion:

Current Nickel Oxide Nanomaterials Synthesis Approaches and Applications are covered in this review study. Research into the fabrication of nickel oxide nanoparticles has lately grown due to its new qualities and features. Nanoscale nickel oxide also finds use in a wide range of industries, including electronics, super capacitor electrodes, sensors, transducers, optoelectronics, solar cells, biosensors, batteries, micro-super capacitors, and electric vehicles. This review will be helpful for numerous scholars in the future who are working to synthesize nickel oxide nanoparticles.

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