Synthesis and Charecterization of Nanoparticle for Sensor or Battery Applications: A Review

Ramanna P. Kavali

Guest Faculty, Department of Physics, Raichur University, Raichur, Karnataka, India

ABSTRACT

Nanoparticles are particles of sizes ranging from 1 to 100nm with one or more dimensions. The nanoparticles are generally classified into the organic, inorganic and carbon based particles in nanometric scale that has improved properties compared to larger sizes of respective materials. The nanoparticles show enhanced properties such as high reactivity, strength, surface area, sensitivity, stability, etc. because of their small size. The nanoparticles are synthesised by various methods for research and commercial uses that are classified into three main types namely physical, chemical and mechanical processes that has seen a vast improvement over time. Nanoparticles have revolutionized the landscape of energy storage and conservation technologies, exhibiting remarkable potential in enhancing the performance and efficiency of various energy systems. This article explores the versatile applications of nanoparticles in three key points, battery technologies, super capacitors, and solar energy conversion. Nanoparticle based electrodes have exhibited exceptional surface area, porosity, and conductivity, contributing to enhanced energy and power densities. The synergy of nanomaterials with novel electrolytes has also extended the operational lifespan of super capacitors, addressing concerns regarding energy loss over cycles. Furthermore, nanoparticles have played a pivotal role in the field of solar energy conversion. In photovoltaics, nanoparticles with tailored optoelectronic properties have enabled improved light absorption, charge separation, and electron transport, ultimately boosting the efficiency of solar cells. Moreover, nanoparticles have been employed as catalysts in photocatalytic systems for solar fuel generation, driving the sustainable production of clean energy carriers. In this concise review, we highlight the recent advancements, challenges, and future prospects of nanoparticles in these critical energy domains. While the transformative impact of nanoparticles is evident, several challenges such as large scale synthesis, cost-effectiveness, and long term stability must be systematically addressed to ensure their seamless integration into practical energy applications

Keywords: Nanoparticles, Battery, Sensor, rechargeable power

INTRODUCTION

Nanotechnology has gained huge attention over time. The fundamental component of nanotechnology is the nanoparticles. Nanoparticles are particles between 1 and 100 nanometres in size and are made up of carbon, metal, metal oxides or organic matter. The nanoparticles differ from various dimensions, to shapes and sizes apart from their material.

Development of rechargeable power sources is essential for the progress of electronic devices and biomedical instruments like pacemakers. Portable power technology is crucial in their usage. Used widely in lithium-ion batteries, the cathode material known as layered $LiCoO_2$ offers both great cycle durability and convenience in production, thanks to its reliable discharge capacity. A similarly popular cathode material, layered $LiNiO_2$, has been noted for its more exacting production criteria, therefore, a hybrid of the two known as $LiNi1\text{-}xCoxO_2$ has gained attention for its ability to blend the best features of both LiNiO2 and $LiCoO_2$.

Nanomaterials continue to revolutionize various scientific domains due to their unique properties and versatile applications. This study explores the forefront of nanomaterial research, presenting a comprehensive investigation into fabrication techniques, advanced characterization methodologies, and diverse application possibilities. Embarking on the escalating significance of advanced nanomaterials, this study confronts present challenges and endeavours to bridge gaps in our comprehension, establishing itself at the forefront of this rapidly evolving field.

Researchers are increasingly focusing on renewable and clean energy sources in response to the global energy problem and growing environmental worries brought on by the usage of fossil fuels. Innovative energy storage devices, such as fuel cells, batteries, and super capacitors (SCs), have received a lot of attention during the past few decades. These technologies provide the ability to store and use energy in cleaner and more ecologically friendly ways, therefore reducing the negative effects of fossil fuels on our world. They represent a viable route toward a more sustainable and efficient energy future. In the pursuit of sustainable and efficient energy solutions, the remarkable world of nanoparticles has emerged as a beacon of innovation and promise. The utilization of these minuscule entities, with their unique properties and versatile applications, has opened new avenues across the spectrum of energy storage and conversion.

Recently, the hematite (_-Fe2O3), one of the important metal oxide materials, has received a considerable attention due to it variety of properties such as narrow band gap (2.0–2.2 eV), bio-compatibility, thermodynamically stable, environmental friendly, low-synthesis cost, and so on.23 It is widely used for various applications such as biological and medical fields, gas, chemical and biosensors, magnetic recording media, catalysts, magnetic devices, optical, photo electrochemical and photo catalytic, and so on.

The simple and facile hydrothermal synthesis of iron oxide nanoparticles and their detailed characterizations in terms of their morphological, structural and compositional properties. Finally, the as-synthesized iron oxide nanoparticles were used as efficient electron mediators for the fabrication of efficient and robust chemical sensor for the effective and highly sensitive detection of phenyl hydrazine using simple and reliable *I–V* technique. The fabricated phenyl hydrazine sensor based on iron oxide nanoparticles exhibited high sensitivity and lower experimental detection.

Electrochemical techniques have recently showed many advantages in medical and biological analysis such as high sensitivity, low cost, rapid response, and simplicity. In the era of nanomaterials, several electrochemical systems have been developed using various nanomaterials such as nanostructured metal oxides. Amongst the nanostructured metal oxides, zinc oxide semiconductor nanocrystals (ZnO NCs) have been widely used in photocatalytic [3],
photonic spintronic , and many other optoelectronic applications. This could be attributed to their wide band gap (3.37 eV) and large excitonic binding energy (60 meV). However, the use of ZnO NCs as a single electrode modifier in electrochemical biosensors is limited since it behaves as n-type semiconductor. This causes fast recombination of the generated electron-hall pairs and low operating speed, and thus, the capability of direct electron transfer is rather difficult. Instead, implementation of artificial electron shuttles or using hydride substances to liberate the captured-(stored)-electrons is highly recommended.

LiCo1-xNixO2 nanoparticles by urea route as cathode for lithium-ion battery

LiCo1-xNixO2 (x = 0, 0.25, 0.5, 0.75, 1) powders are synthesized using the urea; the crystalline structure and surface morphology of the prepared powders are investigated through XRD, FTIR, FE-SEM, and EDX analyses. X-ray diffraction indicates a hexagonal crystal structure for the LiCoO2 phase, Additionally, the XRD pattern of prepared LiCoO2 doped with Ni metal (x = 0.25) shows the formation of a cubic LiCoO2 nanostructure, FTIR spectra analysis of LiCoO2 and LiCo1-xNixO2 revealed several vibrational modes, such as (C=O and O–H). FESEM results indicate that all samples have nanostructure dimensions, An EDX spectrum reveals the presence of transition metals (Co) in LiCoO2, transition metals (Co and Ni) in LiCo1-xNixO2, and transition metals (Ni) in LiNiO2.

Advanced nanomaterials: fabrication, characterization and applications

Nanomaterials continue to revolutionize various scientific domains due to their unique properties and versatile applications. This study explores the forefront of nanomaterial research, presenting a comprehensive investigation into fabrication techniques, advanced characterization methodologies, and diverse application possibilities. Embarking on the escalating significance of advanced nanomaterials, this study confronts present challenges and endeavours to bridge gaps in our comprehension, establishing itself at the forefront of this rapidly evolving field. Our study seeks to achieve a twofold objective - advancing the synthesis of nanomaterials with tailored properties and pushing the boundaries of characterization techniques to reveal intricate details at the nanoscale. The Fabrication section introduces innovative methods such as Top-Down Lithography, highlighting their role in achieving precise control over nanomaterial structures. Characterization, a pivotal phase, unfolds with meticulous scrutiny, using advanced technologies and instruments such as Transmission Electron Microscopy (TEM), provide precise insights into the properties and structures of nanomaterials. In the Applications section, exploring how advanced nanomaterials make a big impact in areas like electronics and medicine, showcasing their versatility and potential for groundbreaking advancements.

Metal-based nanoparticles, sensors, and their multifaceted application in food packaging

Due to the global rise of the human population, one of the top-most challenges for poor and developing nations is to use the food produces safely and sustainably. In this regard, the storage of surplus food (and derived products) without loss of freshness, nutrient stability, shelf life, and their parallel efficient utilization will surely boost the food production sector. One of the best technologies that have emerged within the last twenty years with applications in the packaging of food and industrial materials is the use of green mode-based synthesized nanoparticles (NPs). These NPs are stable, advantageous as well as eco-friendly. Over the several years, numerous publications have confirmed that these NPs exert antibacterial, antioxidant, and antifungal activity against a plethora of pathogens. The storage in metal-based NPs (M-NPs) does not hamper the food properties and packaging efficiency. Additionally, these M-NPs help in the improvement of properties including freshness indicators, mechanical properties, antibacterial and water vapor permeability during food packaging. As a result, the nano-technological application facilitates a simple, alternate, interactive as well as reliable technology. It even provides positive feedback to food industries and packaging markets.

Electrochemical-sensor applications of zinc oxide/graphene oxide nanocomposite

Nanostructured metal oxides received considerable research attention due to their unique properties that can be used for designing advanced nanodevices. Thus, in the present study, zinc oxide/graphene oxide (ZnO/GO) nanocomposite was synthesized, characterized and implemented in an electrochemical system. The formation of a compacted ZnO/GO nanocomposite was confirmed by field emission scanning electron microscopy, high-resolution transmission electron microscopy (HRTEM), X-ray diffraction (XRD), and attenuated total reflectance spectroscopy. HRTEM showed that ZnO nanocrystals (NCs) are well formed on the GO surface and are interconnected via GO functional groups. From the XRD patterns, the average size of ZnO NCs was found to be about 21.7 ± 2.3 nm which is in agreement with the HRTEM results. The newly developed nanocomposite-based electrochemical system showed a significant improvement in both electrical conductivity and the electrocatalytic activity as noted from the cyclic voltammetry measurements. Consequently, direct electron transfer efficiency was confirmed and used for the amperometric detection of hydrogen peroxide ($H2O_2$). Fast and sensitive electrochemical responses for the detection of $H2O^2$ at 1.1 V in the linear response range from 1 to 15 mM with the detection limit (S/N = 3) of 0.8 mM were obtained. These results demonstrated that the prepared ZnO/GO/CPE displayed a good performance along with high sensitivity and longterm stability.

Iron Oxide Nanoparticles for Phenyl Hydrazine Sensor Applications

Iron oxide nanoparticles were synthesized by a simple hydrothermal process and characterized in details of their morphological, structural and compositional properties. The iron oxide nanoparticles were found to be well-crystalline and grown in very high density which were used as efficient electron mediators for the fabrication of highsensitive phenyl hydrazine sensor. The fabricated hydrazine sensor demonstrated a high sensitivity of 57.88 A mM−1 cm−2 with an experimental detection limit of 97 M. The observed linear dynamic range (LDR) for the fabricated sensor was 97 m−1.56 mM.

Spinel $ZnCo_2O_4$ Nanoparticles

Spinel $ZnCo_2O_4$ nanoparticles were synthesized by means of the microwave-assisted colloidal method. A solution containing ethanol, Co-nitrate, Zn-nitrate, and dodecylamine was stirred for 24 h and evaporated by a microwave oven. The resulting solid material was dried at 200 ^oC and subsequently calcined at 500 ^oC for 5 h. The samples were characterized by scanning electron microscopy (SEM), transmission electron microscopy (TEM), X-ray diffraction (XRD), and Raman spectroscopy, confirming the formation of spinel ZnCo2O4 nanoparticles with average sizes between 49 and 75 nm. It was found that the average particle size decreased when the dodecylamine concentration increased. Pellets containing ZnCo2O4 nanoparticles were fabricated and tested as sensors in carbon monoxide (CO) and propane (C3H8) gases at different concentrations and temperatures. Sensor performance tests revealed an extremely high response to 300 ppm of CO at an operating temperature of 200^oC.

Cost-Effective Electrochemical Devices

Nanomaterials have gained significant attention as a remarkable class of materials due to their unique properties and the fact that they encompass a wide range of samples with at least one dimension ranging from 1 to 100 nm. The deliberate design of nanoparticles enables the achievement of extremely large surface areas. In the field of cost effective electrochemical devices for energy storage and conversion applications, nanomaterials have emerged as a key area of research. Their exceptional physical and chemical properties have led to extensive investigations aimed at improving the performance and cost-effectiveness of electrochemical devices, including batteries, super capacitors, and fuel cells. The continuous development and enhancement of these high-performance materials are driven by the demand for enhanced productivity, connectivity, and sustainability at a reduced cost. This review focuses on the electrochemical performance of electrodes, energy storage, and electrochemical sensors (ES) based on nanotechnology. It discusses the application of nanotechnology in electrochemistry for water purification and the fate of substances in water, while also introducing green nanotechnology and cost-effective, high-fidelity product creation through electrochemical methods.

The study emphasizes the synthesis of novel nanomaterials, such as metal–organic frameworks (MOFs), covalent organic frameworks (COFs), and MXenes, with applications in electrochemical devices. Furthermore, it explores the integration of nanostructures with electrochemical systems in economically significant and future applications, along with the challenges faced by nanotechnology based industries. The paper also explores the interplay between nano materials and biosensors, which play a vital role in electrochemical devices.

$Fe_xCo_{3-x}O_4$ nanoparticles for sensor applications

Fe substituted Co_3O_4 nanoparticles which produced by microwave refluxing method. The detailed investigation of magnetic properties with different concentration of Fe substitutions revealed the ferromagnetic behavior due to the anti-ferromagnetic interaction of magnetic sublattices. High resolution transmission electron microscopy (HR-TEM) studies confirmed the spherical morphology of nanoparticles with a size between 8 and 20 nm. The absence of other phases than Co_3O_4 was ruled out by XRD, TEM and Raman spectroscopy analyses. X-ray photoelectron spectroscopy analysis evidenced the presence of Fe^{3+}, Co^{2+} and Co^{3+} ions in the samples. Photoemission spectra confirmed the absence of defect states in the samples. Magnetic measurement analysis revealed that the strong influence of Fe concentration on the saturation magnetization values of Co_3O_4 nanoparticles. These structural and optical properties of the Fe substituted Co_3O_4 are suitable for various gas sensor applications.

ZnO nanoparticles for effiZient gas sensors

Zinc oxide nanoparticles were synthesized using simple chemical method. The prepared nano zinc oxide was characterized using XRD and UV-Visible spectroscopy, S.E.M..T.E.M., The optical band gap was calculated from UV-Visible absorption measurement. The particles size was estimated using XRD pattern. Gas response of Zinc oxide films are checked for different concentration of reducing and oxidizing gases.

CONCLUSION

Nanotechnology is improving our everyday lives by enhancing the performance and efficiency of everyday objects. It provides a clean environment by providing safer air and water, and clean renewable energy for a sustainable future. Nanotechnology has gained a wide attention where more investment is made for the research and development by top institutions, industries and organisations.

Nanotechnology has established to be an advanced field of science where extensive research is carried out to implement the technology. It is being tested for various new applications to increase the efficiency and performance of the object or process and subsequently reduce the cost so that it is accessible for everyone. The nanotechnology has a great future due to its efficiency and environmental friendly property.

This review concludes that fabrication and characterization are pivotal for optimizing properties at nanomaterials. Although simple synthesis methods can yield nanoparticles with the appropriate size, shape, and property that can withstand environmental conditions, they still require enhancement. Additionally, nanomaterials with mixed compositions are being synthesized for use in various fields. Numerous uses of nanomaterials have been investigated in a variety of fields, including as biomedical, energy, environment, photovoltaic, sensing, and catalysis. Since nanotechnology plays an active role in the decontamination of water and the recycling of wastewater. Thus future challenges faced by modern society can be fixed with a better understanding and the rapid development of nanotechnology.

REFERENCES

[1]. Hasan S. 2015/ A Review on Nanoparticles : Their Synthesis and Types Biosynthesis : Mechanism 4 9–11.
[2]. Assessment R. 2007. Nanoparticles in the Environment.
[3]. Kumar, U. P., Nesaraj, A. S. 2013, J. Nano. Adv. Mat., 1(2), 75-86; https://doi.org/10.9734/AJOPACS/2017/34683
[4]. Chu, B. 2007. Energy, 210(320), 160-230.
[5]. Kolahalam, L. A., Viswanath, I. K., Diwakar, B. S., Govindh, B., Reddy, V., & Murthy, Y. L. N. 2019. Review on nanomaterials: Synthesis and applications. Materials Today: Proceedings, 18, 2182-2190.
[6]. Baig, N., Kammakakam, I., & Falath, W. 2021. Nanomaterials: A review of synthesis methods, properties, recent progress, and challenges. Materials Advances, 2, 1821-1871.
[7]. Elong, K., Roshidah, R., Mohd Mokhtar, N. A., Azahidi, A., Kamarulzaman, N. 2012. Advanced Materials Research, 545, 182-184; https://doi.org/10.4028/www.scientific.net/AMR.545.182
[8]. Chokshi, N. P., & Ruparelia, J. P. 2020. Journal of The Institution of Engineers (India): Series A, 101, 433-443; https://doi.org/10.1007/s40030-020-00454-4

[9]. Wang, Y., Cheng, T., Yu, Z. E., Lyu, Y., Guo, B. 2020. Journal of Alloys and Compounds, 842, 155827; https://doi.org/10.1016/j.jallcom.2020.155827

[10]. Nguyen, T. P., Giang, T. T., Kim, I. T. 2022. Chemical Engineering Journal, 437, 135292;https://doi.org/10.1016/j.cej.2022.135292

[11]. I. Hussain, I. Shaheen, R. Ahmad *et al.*,2023. "Binder-free cupricion containing zinc sulfide nanoplates-like structure for flexible energy storage devices," Chemosphere, vol. 314, Article ID 137660.

[12]. R. W. Foley and A. Wiek, 2013. "Patterns of nanotechnology innovation and governance within a metropolitan area," Technology in Society, vol. 35, no. 4, pp. 233–247.

[13]. Thenmozhi, K., Narayanan, S.S. 2007. Electrochemical sensor for H_2O_2 based on thionin immobilized 3-aminopropyltrimethoxy silane derived sol–gel thin film electrode. Sens. Actuators B Chem. 125, 195–201.

[14]. Shen, G., Chen, P.C., Ryu, K., Zhou, C.2009. Devices and chemical sensing applications of metal oxide nanowires. J. Mater. Chem. 19, 828–839.

[15]. Chu, D., Masuda, Y., Ohji, T., Kato, K.2009. Formation and photocatalytic application of ZnO nanotubes using aqueous solution. Langmuir 26, 2811–2815.

[16]. Willander, M., Nur, O., Zhao, Q., Yang, L., Lorenz, M., Cao, B., *et al*. 2009. Zinc oxide nanorod based photonic devices: recent progress in growth, light emitting diodes and lasers. Nanotechnology 20, 332001.

[17]. Pearton, S., Norton, D., Heo, Y., Tien, L., Ivill, M., Li, Y., *et al*. 2006. ZnO spintronics and nanowire devices. J. Electron. Mater. 35, 862–868.

[18]. Godlewski, M., Guziewicz, E., Kopalko, K., Łuka, G., Łukasiewicz, M., Krajewski, T., *et al*.2011. Zinc oxide for electronic, photovoltaic and optoelectronic applications. Low Temp. Phys. 37, 235–240.

[19]. O¨ zgu¨r, U¨ ., Alivov, Y.I., Liu, C., Teke, A., Reshchikov, M., Dogˇan, S., *et al*. 2005. A comprehensive review of ZnO materials and devices. J. Appl. Phys. 98, 041301.

[20]. Janotti, A., Van de Walle, C.G. 2007. Native point defects in ZnO. Phys. Rev. B 76, 165202.

[21]. Schulz, P., Kelly, L.L., Winget, P., Li, H., Kim, H., Ndione, P.F., *et al*. 2014. Tailoring electron-transfer barriers for zinc oxide/C60 fullerene interfaces. Adv. Funct. Mater. 24, 7381–7389.

[22]. Xie, L., Xu, Y., Cao, X. 2013. Hydrogen peroxide biosensor based on hemoglobin immobilized at graphene, flower-like zinc oxide, and gold nanoparticles nanocomposite modified glassy carbon electrode. Colloids Surf. B Biointerfaces 107, 245–250.

[23]. Chawla, S., Pundir, C.S.2012. s An amperometric hemoglobin A1c biosensor based on immobilization of fructosyl amino acid oxidase onto zinc oxide nanoparticles-polypyrrole film. Anal. Biochem. 430, 156–162.

[24]. A. A. Ibrahim, G. N. Dar, S. A. Zaidi, A. Umar, M. Abaker, H. Bouzid, and S. Baskoutas. 2012. *Talanta* 93, 257.

[25]. S. Shukla, S. Chaudhary, A. Umar, G. R. Chaudhary, and S. K. Mehta. 2014. *Sens. Actuat. B: Chem.* 196, 231.

[26]. I. Tiwari, M. Gupta, P. Sinha, and S. K. Aggarwal. 2012. *Electrochim. Acta* 76, 106.

[27]. H. T. Homad *et al.*, 2023. Synthesis and characterization of LiCo1-xNixO2 nanoparticles by urea route as cathode for lithium-ion battery. Journal of Ovonic Research. Vol. 19, No. 6, p. 783 – 791.

[28]. *Vicky* Kapoor *et al*., 2024. E3S Web of Conferences 511, 01003.

[29]. Antul Kumar, *et al*. , 2021. Metal-based nanoparticles, sensors, and their multifaceted application in food packaging. *J Nanobiotechnol , 19:256.*

[30]. Ehab Salih *et al*., 2016. Synthesis, characterization and electrochemical-sensor applications of zinc oxide/graphene oxide nanocomposite. J Nanostruct Chem , 6:137–144.

[31]. S. W. Hwang *et al*., 2014. Synthesis and Characterization of Iron Oxide

[32]. Nanoparticles for Phenyl Hydrazine Sensor Applications. American Scientific Publishers. Vol. 12, 1–5.

[33]. Juan Pablo Morán-Lázaro *et al*., 2016. Synthesis, Characterization, and Sensor Applications of Spinel ZnCo2O4 Nanoparticles. Sensors, 16, 2162; doi:10.3390/s16122162

[34]. Hosam M. Saleh, *et al*., 2023. Synthesis and Characterization of Nanomaterials for Application in Cost-Effective Electrochemical Devices. Sustainability, 15, 10891. https://doi.org/10.3390/su151410891

[35]. T. V. Kolekar. *et al*., 2013. Synthesis and characterization of ZnO nanoparticles for efficient gas sensors. Archives of Applied Science Research, 5 (6):20-28