IJCRT.ORG ISSN : 2320-2882

INTERNATIONAL JOURNAL OF CREATIVE RESEARCH THOUGHTS (IJCRT)

An International Open Access, Peer-reviewed, Refereed Journal

Investigation of Humidity Sensing Properties of Spinel Cobalt Ferrite Nanomaterials

Shakuntala A. Shinde

Department of Physics,

Sharadchandra Arts, Commerce and Science College, Naigaon, Dist. Nanded- 431709.

Abstract

The present work reports the synthesis and humidity sensing properties of spinel cobalt ferrite ($CoFe_2O_4$) nanoparticles prepared *via* a simple and cost-effective sol–gel auto-combustion technique. The synthesized material was characterized for its structural, morphological, and humidity sensing properties. The humidity sensing measurements were carried out at room temperature. The fabricated sensor exhibited a maximum humidity response of 30.29%, indicating effective interaction between water molecules and the active surface of the sensing material. The enhanced sensing performance is attributed to the porous morphology and high surface activity of $CoFe_2O_4$ nanoparticles, which facilitate efficient adsorption and desorption of moisture molecules. Furthermore, the sensor demonstrated good repeatability and appreciable long-term stability, retaining nearly 95% of its initial response after 15 days of testing. The response variation during the stability period was minimal, confirming the reliability of the prepared sensing material for practical humidity monitoring applications. The obtained results suggest that sol–gel-derived $CoFe_2O_4$ is a promising candidate for low-cost and efficient humidity sensor devices.

Keywords: $CoFe_2O_4$ nanoparticles, Sol–gel synthesis, Humidity sensor, Room temperature sensing.

Introduction

Humidity sensing has attracted considerable attention due to its vital role in environmental monitoring, industrial processing, agricultural management, healthcare systems, food storage, and electronic devices [1, 2]. Accurate monitoring and control of humidity are essential for maintaining product quality, human comfort, and operational stability in various applications [3, 4]. In recent years, the development of efficient, low-cost, and highly sensitive humidity sensors has become an important research area in materials science and sensor technology [5].

Among different sensing materials, metal oxide semiconductors have emerged as promising candidates for humidity sensing applications because of their excellent chemical stability, low fabrication cost, simple preparation techniques, and good sensing performance [6, 7]. Particularly, spinel ferrites have gained significant interest owing to their unique structural, electrical, magnetic, and surface properties [8]. Spinel ferrite materials possess high surface activity and porous morphology, which facilitate effective adsorption and desorption of water molecules during humidity sensing processes [9, 10].

The $CoFe_2O_4$ is an important spinel ferrite material that exhibits remarkable electrical conductivity, thermal stability, corrosion resistance, and magnetic behavior [11]. Due to these advantageous properties, $CoFe_2O_4$ has been extensively explored for applications in catalysis, energy storage, magnetic devices, gas sensing, and environmental monitoring [12]. The humidity sensing performance of $CoFe_2O_4$ is mainly influenced by its nanostructure, grain size, porosity, and surface-active sites, which contribute to efficient interaction with atmospheric moisture [13, 14].

Various synthesis techniques such as hydrothermal, co-precipitation, combustion, and sol–gel methods have been employed for the preparation of $CoFe_2O_4$ nanomaterials [15]. Among these methods, the sol–gel technique offers several advantages including simplicity, low processing temperature, excellent compositional homogeneity, controlled particle size, and cost-effective large-scale production [16]. The method also enables the formation of porous nanostructures favorable for humidity sensing applications.

In the present work, $CoFe_2O_4$ nanoparticles were synthesized using a simple sol–gel auto-combustion method and investigated for humidity sensing applications. The structural and sensing characteristics of the prepared $CoFe_2O_4$ nanomaterial were systematically studied. The fabricated humidity sensor exhibited a maximum response of 30.29% along with good repeatability and nearly 95% retention of the initial sensing response after 15 days, indicating appreciable long-term stability. The obtained results demonstrate that $CoFe_2O_4$ can serve as a promising material for the development of efficient and low-cost humidity sensing devices operating at room temperature.

Experimental

Synthesis of $CoFe_2O_4$ Nanoparticles

$CoFe_2O_4$ nanoparticles were synthesized using a simple sol–gel auto-combustion technique. Analytical grade cobalt nitrate hexahydrate [$Co(NO_3)_2 \cdot 6H_2O$] and ferric nitrate nonahydrate [$Fe(NO_3)_3 \cdot 9H_2O$] were used as precursor materials, while citric acid monohydrate [$C_6H_8O_7 \cdot H_2O$] served as a chelating and fuel agent. Stoichiometric quantities of the precursor salts were dissolved in deionized water under continuous magnetic stirring to obtain a clear homogeneous solution. Subsequently, citric acid was added to the solution to facilitate complex formation and to suppress undesirable precipitation of metal hydroxides during the synthesis process.

The pH of the reaction mixture was adjusted to approximately 7.0 using liquor ammonia solution. The prepared solution was continuously stirred at 80–90 °C for nearly 2 h until a viscous gel was formed. Upon further heating, the obtained gel underwent self-combustion, producing a fluffy ash-like precursor material. The resulting powder was calcined at 500 °C for several hours to improve crystallinity and phase formation. Finally, the calcined product was finely ground using an agate mortar to obtain $CoFe_2O_4$ nanopowder for humidity sensing applications.

Characterization and Humidity Sensing Measurements

The structural properties of the synthesized $CoFe_2O_4$ nanoparticles were investigated using X-ray diffraction (XRD) analysis, while the surface morphology was examined using scanning electron microscopy (SEM). The surface area and porosity characteristics were evaluated using Brunauer–Emmett–Teller (BET) analysis. Humidity sensing measurements were carried out at room temperature under different relative humidity conditions using a Keithley source meter. The sensing response, repeatability, and stability of the fabricated humidity sensor were systematically analyzed.

Results and discussion

Structural and morphological study

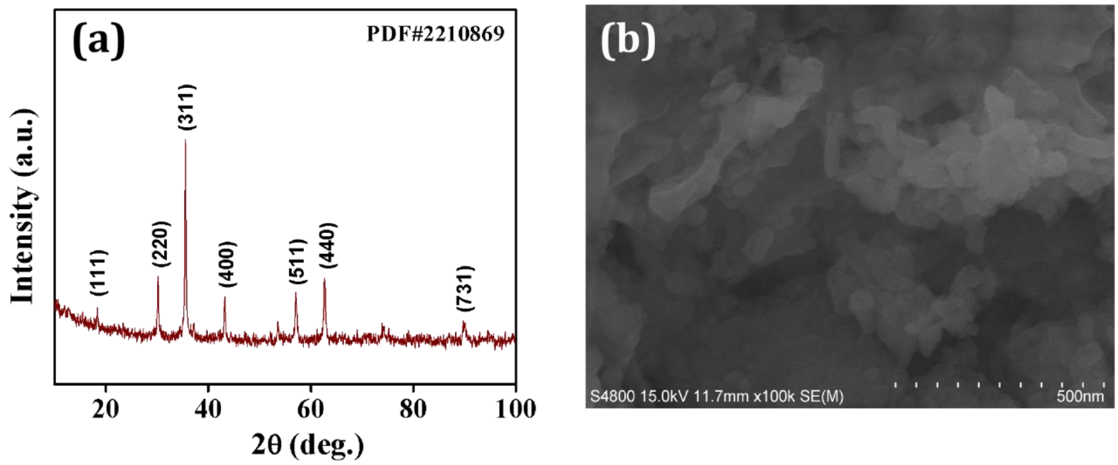

Figure 1: The XRD pattern, and (b) SEM image of the CoFe2O4 nanoparticles humidity sensor.

The X-ray diffraction (XRD) pattern of the synthesized Cobalt Ferrite nanoparticles is presented in Fig. 1a. The diffraction peaks observed at different 2θ values correspond to the crystallographic planes of (111), (220), (311), (400), (422), (511), (440), (533), and (731), which are well matched with the standard JCPDS card No. 22-1086. The obtained diffraction pattern confirms the successful formation of single-phase spinel $CoFe_2O_4$ without the presence of any noticeable impurity peaks. The sharp and intense diffraction peaks indicate the good crystallinity of the synthesized nanoparticles.

The surface morphology of the prepared $CoFe_2O_4$ nanoparticles was investigated using scanning electron microscopy (SEM), as shown in Fig. 1b. The SEM images reveal irregularly shaped nanoparticles with agglomerated and randomly distributed grain structures. The agglomeration of nanoparticles may be attributed to magnetic interactions and atmospheric moisture adsorption during sample handling and storage. Such porous and interconnected morphology can provide a larger active surface area, which is beneficial for enhanced humidity sensing performance by facilitating effective adsorption and desorption of water molecules.

The Brunauer–Emmett–Teller (BET) surface area analysis of the synthesized $CoFe_2O_4$ nanoparticles is shown in Fig. 2a. The specific surface area of the prepared material was found to be 22.15 $m^2\ g^{-1}$, indicating the presence of sufficient active sites for humidity adsorption. A relatively higher surface area generally contributes to improved sensing characteristics due to increased interaction between the sensing material and water vapor molecules.

Furthermore, the Barrett–Joyner–Halenda (BJH) pore size distribution curve presented in Fig. 2b demonstrates the porous nature of the synthesized nanoparticles. The average pore diameter was calculated to be approximately 110.55 nm, suggesting the existence of mesoporous to macroporous characteristics in the prepared $CoFe_2O_4$ material. The porous structure plays a crucial role in humidity sensing by promoting rapid diffusion and transport of moisture molecules through the sensing layer, thereby enhancing the sensor response and stability.

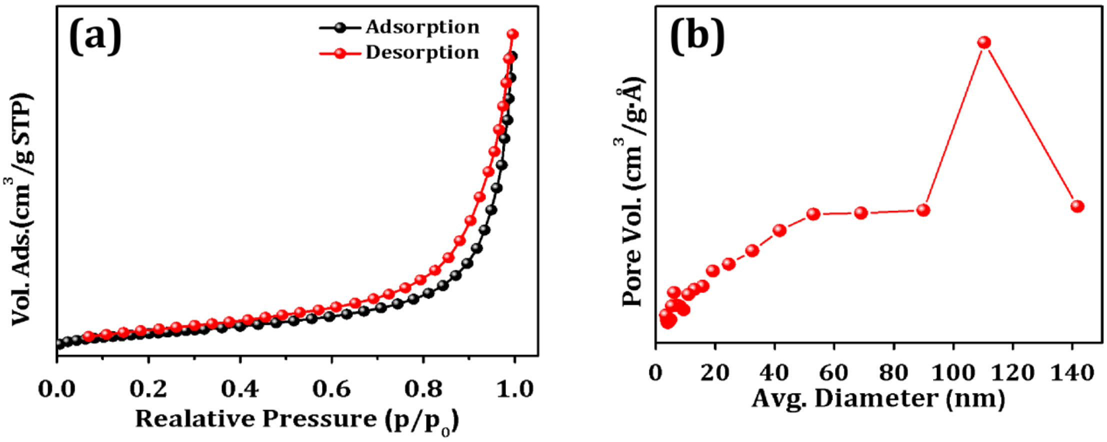

Figure 2: (a) The BET , and (d) pore-size distribution of the $CoFe_2O_4$ nanoparticles humidity sensor.

Humidity Sensing Performance

The dynamic humidity sensing properties of the prepared $CoFe_2O_4$ nanoparticle sensor are shown in Fig. 3. The sensor shows promising response toward humidity exposure at room temperature, demonstrating the efficient sensing capability of the synthesized $CoFe_2O_4$ nanoparticles.

As observed in the response–recovery curve, the sensor initially maintained a stable baseline resistance under dry atmospheric conditions. Upon exposure to humid atmosphere, a rapid decrease in resistance was observed due to adsorption of water molecules onto the active surface of the sensing material. The adsorbed water molecules dissociate into hydroxyl ions and protons, enhancing protonic conduction through the sensing layer and thereby reducing the electrical resistance of the sensor. The fabricated humidity sensor exhibited a maximum sensing response of 30.29% with quick response (11 sec) and recovery (23 sec) time.

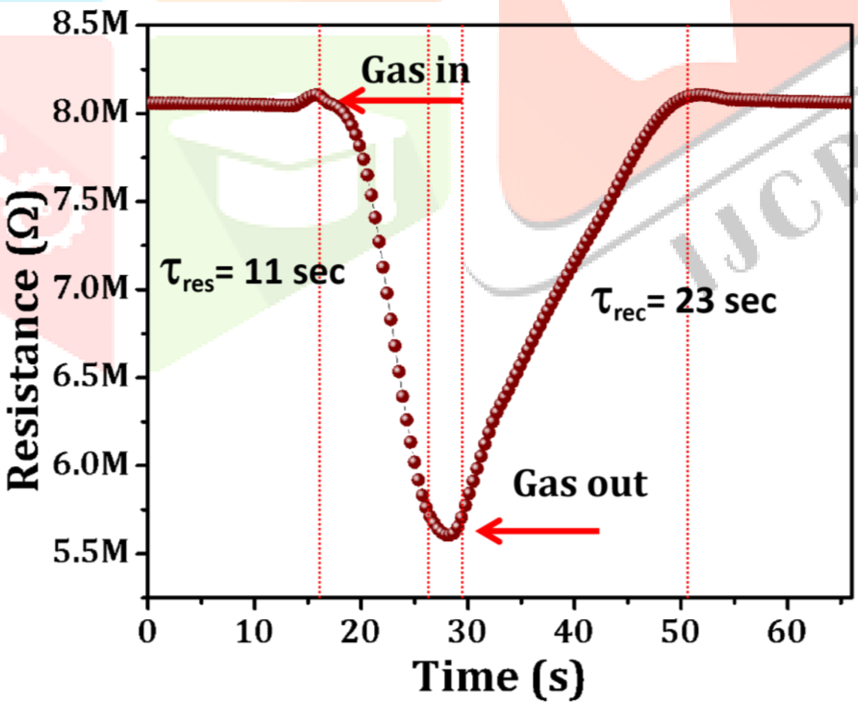

Figure 3: Response and recovery curve of the $CoFe_2O_4$ nanoparticles humidity sensor.

From the transient response curve, the response time and recovery time were determined using the 90% signal variation criterion. The response time corresponds to the duration required for the sensor to achieve 90% of the total resistance change after exposure to humidity, whereas the recovery time represents the time required to regain 90% of the initial baseline resistance after removal of humidity. As indicated by the marked regions in Fig. X, the sensor demonstrated relatively fast response and recovery behavior, confirming the efficient adsorption and desorption kinetics of water molecules on the porous $CoFe_2O_4$ surface.

The enhanced humidity sensing behavior of the synthesized $CoFe_2O_4$ nanoparticles can be attributed to their porous morphology, interconnected grain structure, and appreciable surface area. The porous network facilitates rapid diffusion of moisture molecules into the sensing layer, while the larger number of active adsorption sites promotes effective interaction between water vapor molecules and the sensor surface. These factors collectively contribute to improved sensitivity and fast sensing characteristics. Fig. 4 shows the response *vs.* Time cure of the $CoFe_2O_4$ nanoparticles.

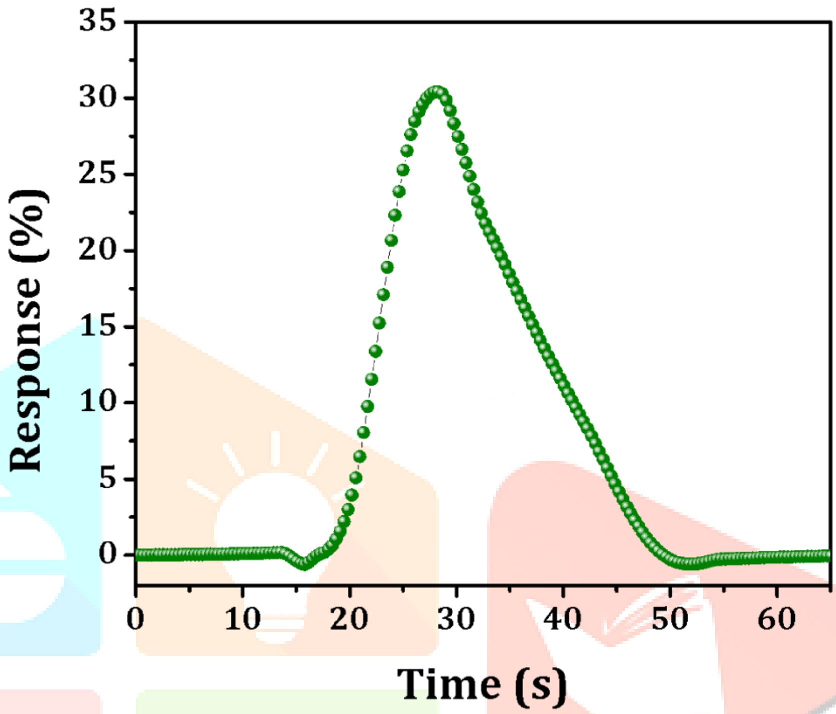

Figure 4: Response *vs* time curve of the $CoFe_2O_4$ nanoparticles humidity sensor.

Furthermore, the $CoFe_2O_4$ nanoparticles sensor exhibited good stability. The sensing response retained nearly 95% of its initial value after 15 days (shown in Fig. 5), indicating appreciable long-term durability and reliability of the prepared sensing material. The obtained results suggest that sol–gel-derived $CoFe_2O_4$ nanoparticles are promising candidates for low-cost and efficient room-temperature humidity sensing applications.

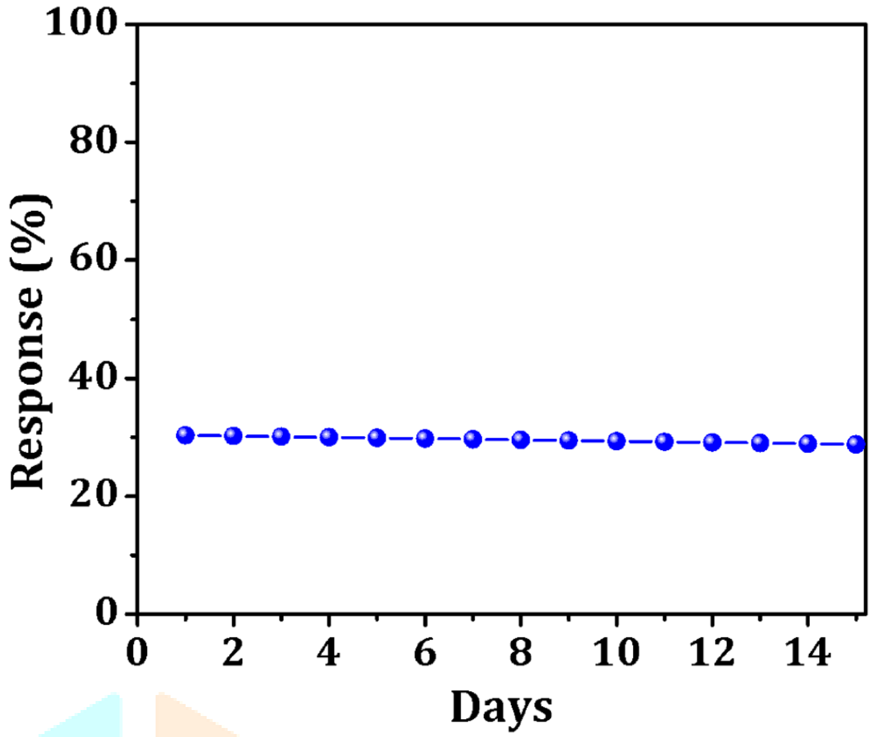

Figure 5: The long-term stability of the $CoFe_2O_4$ nanoparticles humidity sensor.

Conclusions

In the present study, $CoFe_2O_4$ nanoparticles humidity sensor was successfully perpared using a simple and cost-effective sol–gel auto-combustion method for humidity sensing applications. X-ray diffraction analysis confirmed the formation of single-phase spinel $CoFe_2O_4$ with good crystallinity, while SEM observations revealed agglomerated and porous nanoparticle morphology favorable for moisture adsorption. BET analysis demonstrated a surface area of 22.15 $m^2 g^{-1}$ with an average pore diameter of 110.55 nm, indicating the porous nature of the synthesized material. The fabricated humidity sensor exhibited appreciable sensing performance at room temperature with a maximum humidity response of 30.29%. The sensor showed rapid and reversible response–recovery characteristics with quick response (11 sec) and recovery (23 sec) time which may attributed to efficient adsorption/desorption of H_2O on the porous $CoFe_2O_4$ surface. The enhanced sensing behavior was mainly attributed to the high surface activity, porous structure, and interconnected grain morphology of the synthesized nanoparticles.

Furthermore, the sensor demonstrated good repeatability and long-term stability, retaining nearly 95% of its initial response after 15 days of operation. The obtained results indicate that sol–gel-derived $CoFe_2O_4$ nanoparticles are promising materials for the development of low-cost, stable, and efficient room-temperature humidity sensing devices suitable for environmental monitoring and related applications.

References

1. Farahani, H., Wagiran, R. and Hamidon, M.N., 2014. Humidity sensors principle, mechanism, and fabrication technologies: a comprehensive review. *Sensors*, *14*(5), 7881-7939.
2. Li, J., Fang, Z., Wei, D. and Liu, Y., 2024. Flexible pressure, humidity, and temperature sensors for human health monitoring. *Advanced healthcare materials*, *13*(31), 2401532.
3. Mahmood, M.H., Sultan, M. and Miyazaki, T., 2019. Significance of temperature and humidity control for agricultural products storage: overview of conventional and advanced options. International Journal of Food Engineering, 15(10), 20190063.
4. Zaharieva, S., Georgiev, I., Georgiev, S., Borodzhieva, A. and Todorov, V., 2025. A method for forecasting indoor relative humidity for improving comfort conditions and quality of life. Atmosphere, 16(3), 315.
5. Duan, Z., Jiang, Y., Yan, M., Wang, S., Yuan, Z., Zhao, Q., Sun, P., Xie, G., Du, X. and Tai, H., 2019. Facile, flexible, cost-saving, and environment-friendly paper-based humidity sensor for multifunctional applications. ACS applied materials & interfaces, 11(24), 21840-21849.
6. Xie, T., Abdul Rahman, A.F., Abu Bakar, A. and Arsad, A., 2025. Design and optimization of metal oxide-based humidity sensors: A review on mechanisms and material engineering. Journal of Cluster Science, 36(4), 148.
7. Wawrzyniak, J., 2023. Advancements in improving selectivity of metal oxide semiconductor gas sensors opening new perspectives for their application in food industry. Sensors, 23(23), 9548.
8. Salih, S.J. and Mahmood, W.M., 2023. Review on magnetic spinel ferrite ($MFe2O4$) nanoparticles: From synthesis to application. Heliyon, 9(6).
9. Tomina, E.V., Sladkopevtsev, B.V., Tien, N.A. and Mai, V.Q., 2023. Nanocrystalline ferrites with spinel structure for various functional applications. Inorganic Materials, 59(13), 1363-1385.
10. Gaffar, S., Kumar, A. and Riaz, U., 2023. Synthesis techniques and advance applications of spinel ferrites: A short review. Journal of Electroceramics, 51(4), 246-257.
11. Patil, K., Saleem, M., Phadke, S. and Mishra, A., 2022. Structural, electrical and magnetic properties of (Cu/Co) Fe_2O_4 spinel ferrite materials. Applied Physics A, 128(11), 988.
12. Zhang, R., Qin, C., Bala, H., Wang, Y. and Cao, J., 2023. Recent progress in spinel ferrite ($MFe2O4$) chemiresistive based gas sensors. Nanomaterials, 13(15), 2188.
13. Kumar, Y., Sharma, A. and Shirage, P.M., 2017. Shape-controlled $CoFe_2O_4$ nanoparticles as an excellent material for humidity sensing. RSC advances, 7(88), 55778-55785.
14. Priya, R.S., Chaudhary, P., Kumar, E.R., Balamurugan, A., Srinivas, C., Prasad, G., Yadav, B.C. and Sastry, D.L., 2021. Evaluation of structural, dielectric and electrical humidity sensor behaviour of $MgFe_2O_4$ ferrite nanoparticles. Ceramics International, 47(11), 15995-16008.
15. Longchar, C., Xavier, A.R. and Nath, D., 2025. Synthesis of Ferrite Nanomaterials: A comparative Analysis of Sol-Gel Auto-Combustion and Co-Precipitation Methods-A Review. Research Digest on Engineering Management and Social Innovations, 1(2), 29-48.
16. Chang, C., Rad, S., Gan, L., Li, Z., Dai, J. and Shahab, A., 2023. Review of the sol–gel method in preparing nano TiO_2 for advanced oxidation process. Nanotechnology Reviews, 12(1), 20230150.
17. Raut, S.D., Awasarmol, V.V., Ghule, B.G., Shaikh, S.F., Gore, S.K., Sharma, R.P., Pawar, P.P. and Mane, R.S., 2018. γ-irradiation induced zinc ferrites and their enhanced room-temperature ammonia gas sensing properties. Materials Research Express, 5(3), 035702.
18. Raut, S.D., Awasarmol, V.V., Ghule, B.G., Shaikh, S.F., Gore, S.K., Sharma, R.P., Pawar, P.P. and Mane, R.S., 2018. Enhancement in room-temperature ammonia sensor activity of size-reduced cobalt ferrite nanoparticles on γ-irradiation. Materials Research Express, 5(6), 065035.