

GAMMA-IRRADIATION EFFECTS ON DIFFERENT METAL OXIDE NANOPARTICLES

Abstract

Metal Oxide Nanoparticles (MONPs) have attracted significant attention due to their unique optical, magnetic, and electrical properties and wide-ranging applications in optoelectronic devices, supercapacitors, Li-ion batteries, solar cells, catalysts, liquid crystal displays, drug delivery, sensors, etc. The ability to modulate both the physical as well as chemical properties of MONPs plays a vital role in the designing of novel devices, consequently enhancing their significance in various industries and scientific fields. Recently, gamma (γ)-irradiation has emerged as a promising technique for modifying the physicochemical properties of nanomaterials. This chapter presents the γ -irradiation effect on different MONPs such as TiO_2 , ZnO , SnO_2 , MoO_3 , CuO , WO_3 , MgO , etc. highlighting the modification in their structure, morphology, composition and functional properties. These modifications can be ascribed to various underlying mechanisms, including the generation of defects, phase change, surface modification, and grain growth.

Keywords: Nanoparticles; γ -irradiation; Metal oxides; Gas sensors.

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I. INTRODUCTION

Nanotechnology, which uses nanoscience in real-world applications, is a rapidly advancing field in science and engineering and has witnessed remarkable growth due to its multidisciplinary nature. This fascinating area has evolved through the amalgamation of electronics, physics, chemistry, materials science, biology, and medicine, leading to the development of novel functional materials at the nanoscale level. The unique characteristics of MONPs, such as their optical properties, increased ductility at elevated temperatures, cold welding capabilities, paramagnetic behaviour and catalytic and selective activities; make them highly valuable in the realm of nanotechnology, leading to their widespread application in various fields. The interaction with electromagnetic radiation is a highly investigated aspect of metal oxides [1]. It is known that ionizing radiation (alpha, beta, gamma, neutron, and proton) induces changes in the physical characteristics of MONPs encompassing optical, electrical, and structural changes. Gamma rays have dual effects when they interact with materials. Firstly, they cause ionization, leading to secondary reactions with ejected electrons. Secondly, they induce atomic displacement, resulting in the creation of defects within the atomic lattice [2].

Gamma radiation refers to extremely energetic electromagnetic radiation that originates from the nucleus of an atom and is produced by the decay of radioactive isotopes or through nuclear reactions. This high-energy gamma radiation possesses remarkable penetrating abilities, except neutrons, exhibits strong ionizing properties, and can be generated artificially in laboratory settings using artificially produced radionuclides like Co-60 and Cs-137 isotopes [3].

Nowadays, the study of gamma radiation interactions with matter holds significant practical and theoretical importance. This is due to the widespread applications of γ -irradiation in various fields such as in agriculture for crop improvement, seed sterilization, and pest control, in material science for enhancing material properties, polymer cross linking and modifying surfaces, in medical and pharmaceutical for sterilization of medical equipment, medical devices, radiation therapy for cancer treatment, etc. Radiation-induced processes in MONPs have garnered significant attention due to the potential opportunities they offer for enhancing material properties or modifying materials themselves by inducing diverse effects on materials at the atomic and molecular levels [4].

This chapter explores γ -irradiation effects on different MONPs and sheds light on their behaviour under radiation exposure. Additionally, understanding the potential alterations in their structural, optical, mechanical, electronic, and chemical properties will aid in their usage across various domains including catalysis, sensing, optoelectronic devices, drug delivery, and environmental remediation.

II. METAL OXIDE NANOPARTICLES: AN OVERVIEW

The term "nano" originates from the Greek word "nanos," which means dwarf. Nanomaterials are a class of materials that exhibit unique characteristics at the nanoscale level, typically ranging from 1 to 100 nanometers in size. These materials are designed and tailored to have specific features, making them distinct from their bulk counterpart. At the nanoscale, materials often exhibit distinctive properties and behaviours due to their high

surface area-to-volume ratio and quantum confinement effects[5]. These characteristics can differ significantly from those exhibited by the same substance in its bulk state, making nanomaterials highly desirable for a wide range of applications. For instance, specific metal particles demonstrate surface plasmon resonance, semiconductor particles exhibit quantum confinement, and magnetic materials display superparamagnetism. This phenomenon highlights the unique behaviours and properties of nanomaterials. Nanomaterials can be classified into various categories based on their dimensions, composition, and properties. Some common types include nanoparticles, nanotubes, nanowires, nanocomposites and nanostructured materials. These materials can be engineered to possess desired characteristics, such as enhanced mechanical strength, improved electrical conductivity, superior chemical reactivity and even unique optical properties [6].

The characteristics of nanoparticles are largely influenced by the methods utilized for their synthesis. The synthesis of nanomaterials involves numerous methods, including (i) The Top-down method which involves breaking down bulk materials into smaller structures and retaining their original properties without atomic-level control (ii) The Bottom-up method, also referred to as molecular nanotechnology or molecular manufacturing involves building nanomaterials atom by atom or molecule by molecule.

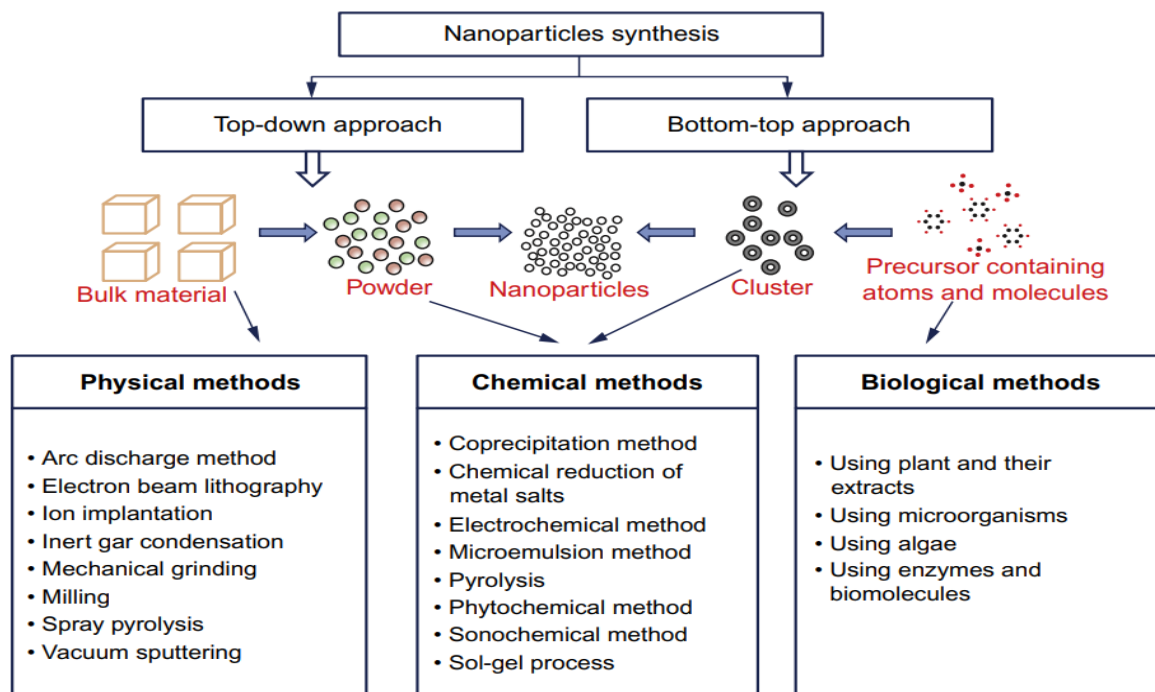


Figure 1: Top-Down and Bottom-Up Approach for Synthesis of Nps[7].

Each method has its advantages and limitations, depending on the desired properties and intended use. In the field of electronics, nanomaterials are utilized for high-performance transistors, displays, and sensors. In the realm of medicine, they hold promise for drug delivery, medical imaging and even targeted cancer therapies. Moreover, nanomaterials play a vital role in developing sustainable energy solutions and mitigating environmental issues [8].

Researchers have documented categories of NPs, such as metal NPs, polymer NPs, and MONPs. Notably, MONPs stand out as highly versatile and adaptable substances because of their remarkable optical, electrical and magnetic characteristics. Metal oxides consist of metal atoms bonded to oxygen atoms, creating a wide range of chemical compositions and structures. Metal oxides play a crucial role in numerous natural processes and are widely used in industries and technological applications because of their diverse properties [9]. Some common examples of metal oxides include iron oxide (rust) (Fe_2O_3), aluminum oxide (Al_2O_3), titanium dioxide (TiO_2), tin oxide (SnO_2), magnesium oxide (MgO), copper oxide (CuO) etc.

Extensive research efforts have been dedicated to nanostructured oxide materials owing to their substantial surface areas, distinctive adsorptive properties, presence of surface defects, and fast diffusivities. Metal oxides exhibit a wide array of remarkable properties, making them superconductors and excellent insulators. Some oxides possess inert characteristics, serving as effective corrosion protection layers, while others act as chemically active catalysts. As a result, oxides play a vital role in various established and emerging technologies, where their surfaces and interfaces with other materials are often crucial for device functionality. Therefore, knowing the surface properties of oxides, encompassing their geometric and electronic structures, interactions with adsorbed entities like molecules or NPs, and interface formations, holds significant importance across numerous technological domains [10].

MONPs find application in two main classes: high surface area materials and materials that utilize size-dependent properties. For example, supercapacitor materials take advantage of the large surface area per weight or film thickness to perform their function. This property is based on geometric considerations rather than on physical properties. Whereas, tunable light-emitting devices rely on the distinct size dependence of luminescence wavelength. In catalysis, both the high surface area, as well as size-dependent properties, is significant factors. The catalytic activity can be enhanced by changing the surface site energy by varying the size of the particle. This effect also applies to high surface area sensors. In order to have application specificity, enhanced performance, stability as well as longevity, controlled reactivity, multifunctionality, and compatibility of MONPs, modification in their properties is essential. Some of the key methods for tailoring include synthesis method, doping, surface functionalization, and composite formation, by controlling the reaction condition and by irradiation (with e.g., ions, neutrons, electrons, and γ -rays).

In addition to the known detrimental effects of irradiation, there are also certain advantageous effects that can enhance the properties of MONPs by the creation of atomic defects and dislocations. Hence, in order to study the effect of gamma radiation in MONPs, several experimental techniques such as X-ray diffraction (XRD), Scanning Tunneling Microscopy (STM), Transmission Electron Microscopy (TEM), Atomic Force Microscopy (AFM), Photoluminescence (PL), Scanning Electron Microscopy (SEM) etc. offer means to directly detect the modification induced in the structural, optical, morphological and electrical properties within MONPs[11].

Table 1: MONPs Characterization Techniques

Techniques	Characterization
X-Ray Diffraction (XRD)	Crystal structure (Crystallite size/Strain analysis) and lattice parameters
Scanning Electron Microscopy (SEM)	Morphology (shape and size), topography, and crystallographic information about how the atoms are arranged in the sample.
Transmission Electron Microscopy (TEM)	Crystallinity, shape and size
Scanning Tunneling Microscopy (STM)	Atomic scale-resolution imaging and spectroscopy, surface topography and electronic structure analysis.
Atomic Force Microscopy (AFM)	Surface topography (map the surfaces of insulating, semiconducting, and metallic samples)
X-Ray Photoelectron Spectroscopy (XPS)	Chemical analysis of samples (chemical bonding, chemical composition and oxidation states)
Photoluminescence (PL) spectroscopy	The concentration of impurities, band gap and recombination mechanism.
Raman Spectroscopy	Vibrational level and rotational modes of samples
UV-Vis Diffuse Reflectance Spectroscopy (UV-DRS)	Optical properties
Fourier Transform Infrared (FTIR) spectroscopy	Functional groups present in the sample
Brunauer-Emmett-Teller (BET) analysis	Measurement of the specific surface area of materials
Vibrating Sample Magnetometer (VSM)	Magnetic properties (magnetic moment, magnetic susceptibility, coercivity)
X-Ray emission spectroscopy (XES)	Electronic states (electron band gap), chemical bonding and local coordination of atoms

III.INTERACTION MECHANISM BETWEEN GAMMA RADIATION AND MATTER

Gamma radiation is a form of ionizing radiation that interacts with matter as it passes through. When high-energy photons, which are generated by γ -irradiators, encounter matter, they undergo three distinct processes of interaction. These processes include the photoelectric effect, Compton and other scattering phenomena, as well as the pair production process. The contribution of each process to the absorption of photons is influenced by two main factors: the energy of the photons and the atomic number of the material they interact with. Different processes contribute to this absorption, and their significance varies based on these factors[3]. If the energy of these gamma rays is below 1.022 MeV, both the Compton and photoelectric effects play significant roles. However, when the energy surpasses this threshold, pair production also becomes a possibility. Generally, gamma rays with energy of

1.33 MeV were employed, consequently revealing the presence of all these processes. This high-energy gamma radiation causes ionization within the material creating electron-hole pairs. The initial knock-out electrons acquire enough energy to displace other atoms in the target material through subsequent secondary and higher-order collision processes. As a result, a chain of collisions and displacement cascades occurs, leading to various structural changes in the material. The defects produced can adversely impact the structural, optical, physical, chemical, and electrical characteristics of the irradiated material, potentially leading to significant effects on its overall performance.

As a high-energy photon beam with an initial intensity of I_0 traverses through a material, the reduction in intensity can be determined using the Beer-Lambert equation [12]:

$$I = I_0 \exp\left(-\frac{\mu}{\rho} x\right)$$

In this equation, the variable x represents the path length in (cm), while μ/ρ denotes the total mass attenuation coefficient in units of ($\text{cm}^2 \text{g}^{-1}$). Additionally, ρ (g cm^{-3}) refers to the density of the material. The total mass attenuation coefficient considers the combined influences of all three-photon absorption processes namely the photoelectric effect, Compton scattering, and pair formation. These processes collectively contribute to the overall attenuation of the high-energy photon beam as it passes through the material. It is worth noting that high-energy photons experience an exponential decrease in intensity as they travel through matter.

1. Gamma-Radiation Sources: Gamma source is a material sample that releases gamma rays and is commonly used for irradiation or imaging purposes. It may also be referred to as a radiation source, radioactive source, or isotope source. Gamma rays originate from various sources, both natural and artificial. Gamma rays naturally generated on Earth include those originating from the gamma decay process of radioisotopes that occurs naturally such as potassium-40. Artificial sources include fission processes in nuclear reactors and high-energy physics experiments like neutral pion decay and nuclear fusion. Cobalt-60 (^{60}Co) and Caesium-137 (^{137}Cs) are extensively utilized artificial gamma radiation sources. ^{60}Co possesses a 5.27-year half-life and emits gamma rays of energy 1.173 MeV and 1.332 MeV while ^{137}Cs possess a 30.1-year half-life and produce gamma rays having 0.662 MeV energy [13]. Additionally, interactions between the atmosphere of Earth and cosmic ray particles can generate gamma rays' secondary radiation. Some exceptional terrestrial gamma-ray sources, not stemming from nuclear processes, include lightning strikes as well as terrestrial gamma-ray flashes and generate elevated energy emissions due to naturally occurring high voltage conditions. Astronomical processes also contribute to the production of gamma rays through the generation of very high-energy electrons. These electrons can produce secondary gamma rays through mechanisms such as bremsstrahlung, inverse Compton scattering, and synchrotron radiation. However, a significant portion of astronomical gamma rays are blocked by Earth's atmosphere. To prevent radioactive contamination, gamma sources are typically sealed and transported with heavy shielding.

IV. TYPES OF DEFECTS INDUCED BY GAMMA-IRRADIATION IN METAL OXIDE NANOPARTICLES.

MONPs have captured significant interest in various fields owing to their distinctive characteristics and potential applications. γ -irradiation, which involves the use of high-energy γ -rays, can cause a variety of defects in MONPs. These defects in the form of vacancies (empty lattice sites), interstitials (extra atoms inserted into the lattice), dislocations (which are line defects), and grain boundaries (which represent interfaces between different crystal orientations) play a significant role in influencing the overall performance and characteristics of the material. The types and densities of defects depend on factors such as the material's composition, crystal structure, radiation dose, radiation energy, and irradiation conditions. One of the primary mechanisms through which γ -irradiation induces defects is by moving atoms from their designated positions within the lattice structure [4]. As a result, vacancies and interstitials in the lattice are created; leading to lattice distortions and structural rearrangements. For example, defects can affect the material's mechanical strength, electrical conductivity, thermal stability, and optical properties. They can act as scattering centres for charge carriers, impeding their mobility and reducing conductivity. Defects can also influence the recombination of charge carriers, affecting the efficiency of devices such as solar cells or LEDs [14]. They can provide active sites for chemical reactions, affecting the material's catalytic activity and selectivity. Defects can also influence the material's interaction with other molecules or NPs, leading to changes in adsorption, desorption, or surface reactions. However, not all defects induced by γ -irradiation are detrimental. In some cases, the controlled introduction of defects can be beneficial for specific applications. For instance, defects can be intentionally introduced to tailor the bandgap of nanomaterials for improved light absorption in solar cells. Understanding the types and consequences of these defects is essential for optimizing the performance of MONPs and ensuring their safe and efficient application across a range of domains including catalysis, sensing, energy storage, and biomedical applications [15]. On the basis of the nature of MONPs and the impact of γ -irradiation on them, the defects are classified into different types which are as follows:

- 1. Point Defects:** Point defects are localized in nature, and occur at specific lattice sites within the crystal of MONPs and significantly influence its electronic, optical, and catalytic properties. They include:
 - **Vacancies:** Vacancies are created when an atom is missing from its regular lattice sites.
 - **Interstitials:** The normally unfilled volume between the regular atomic lattice sites is termed void or interstice. Extra atoms occupying these voids are referred to as interstitial impurities which lead to lattice distortion.
 - **Substitutional Defects:** When foreign atoms take the place of original atoms within the lattice, it leads to alteration in the characteristics of the material.
 - **Frenkel Defect:** When an atom leaves its sites and integrates into the structure at an interstitial, a vacancy is created. This defect, consisting of both vacancy and interstitial atom, is known as the Frenkel defect.

- **Schottky Defect:** Simultaneous presence of one anion vacancy and one cation vacancy within the lattice.
 - **Color Centers:** These defects refer to the point defects or point defect clusters that involve trapped electrons or holes. Oxygen vacancies in materials are referred to as “color centers” or “F centers” (from *Farbe*, the German word for colour). The natural occurrence of oxygen vacancies is a common phenomenon in every oxide, in the form of Frenkel and Schottky defects. Exposing them to gamma rays leads to a change in their concentration. These defects play a crucial role in determining the optical, electronic, and transport characteristics of the material.
2. **Surface Defects:** γ -irradiation can also induce defects at the surface or grain boundaries of MONPs. These defects can include atomic rearrangements, structural reconstructions, and the creation of surface states. Surface defects alter the surface energy, chemical reactivity, and surface-to-volume ratio of MONPs. They can influence the interaction between MONPs and their surroundings, leading to changes in their stability and catalytic activity.
 3. **Dislocations:** γ -irradiation can introduce dislocations in the crystal lattice of MONPs. Dislocations are line defects that occur as a line or one-dimensional imperfection in the crystal lattice when there is a misalignment or disruption in the regular arrangement of atoms within the lattice. They can be classified as edge dislocations, screw dislocations, or mixed dislocations, depending on the orientation of the misalignment. Dislocations can affect mechanical properties, such as the strength and ductility of MONPs.
 4. **Grain Boundaries:** γ -irradiation can also affect the grain boundaries of MONPs, which are the interfaces between neighbouring crystalline grains. It is a defect that occurs at the boundary between two grains and is characterized by a unique structure that accommodates the structure and orientation of both grains but cannot have the structure of either. These defects can change the transport properties, such as electrical conductivity and diffusion rates in MONPs.
 5. **Phase Transformation:** Under γ -irradiation, MONPs may undergo phase transformations, leading to the formation of different crystalline phases or amorphous regions. Phase transformations can introduce defects, such as stacking faults and twinning, which impact the structural and functional properties of MONPs [16].

V. THE EFFECT OF GAMMA RADIATION EXPOSURE ON OXIDES

γ -irradiation is a powerful technique that can modify the properties of metal oxides, leading to enhanced functionality and new applications. Herein, the effects of γ -irradiation on various MONPs, including their structural changes, electronic properties, and potential applications have been discussed. Various MONPs and their combinations in varying ratios were examined in the forms of powdered substances and thin films to determine their vulnerability when exposed to gamma radiation.

1. Gamma-Irradiated SnO₂NPs: SnO₂ serves as a representative example of a semiconductor of n-type that is optically transparent, possessing band gap (E_g) of 3.62 eV at a temperature of 300 K. Due to this wide band gap, SnO₂ exhibits great versatility and is employed in a range of fields including its use in resistors, transparent heating elements, gas sensors, energy-efficient "low-emissivity" window coatings, electrodes for glass melting furnaces, and antistatic coatings[17]. Tin oxide is unique because tin has the ability to exist in two oxidation states, namely 2⁺ and 4⁺. Due to this characteristic, flexible adjustment of oxygen composition on the surface of tin oxide takes place. This particular attribute of oxides holds significant importance in understanding and customizing the distinctive chemical characteristics of these materials. Oxides have a significant impact on Gas sensors operating in a solid-state configuration, with diverse range of oxides exhibiting sensitivity to both oxidizing as well as reducing gases through changes in their electrical characteristics. SnO₂ was one of the earliest and continues to be the most commonly employed substance in such applications due to its remarkable selectivity, durability, and sensitivity for sensing CO₂, CO, and H₂ gases[18]. Efforts to enhance sensing performance in gas sensors have been ongoing, exploring various approaches like chemical doping, creating composites with the nanostructures of carbon or noble metals, and modifying the surface through irradiation techniques (utilizing methods like γ -rays, neutron beam, and electron beam). When metal oxides undergo high-dosage irradiation, lattice defects like vacancies, structural distortions (dislocations), and defect clusters are generated. These lattice defects serve as sites where carriers are captured, leading to carrier recombination. Additionally, being exposed to substantial radiation levels causes notable alterations to the electrical characteristics of irradiated metal oxides. Two essential radiation impacts are to be considered: (1) transient effects arising from the production of electron-hole pairs, and (2) permanent effects brought about by material bombardment with radiation, inducing modification in the lattice of the crystal. Due to these factors, the gas-sensing performance of SnO₂ NPs is expected to be significantly improved through γ -ray irradiation [19].

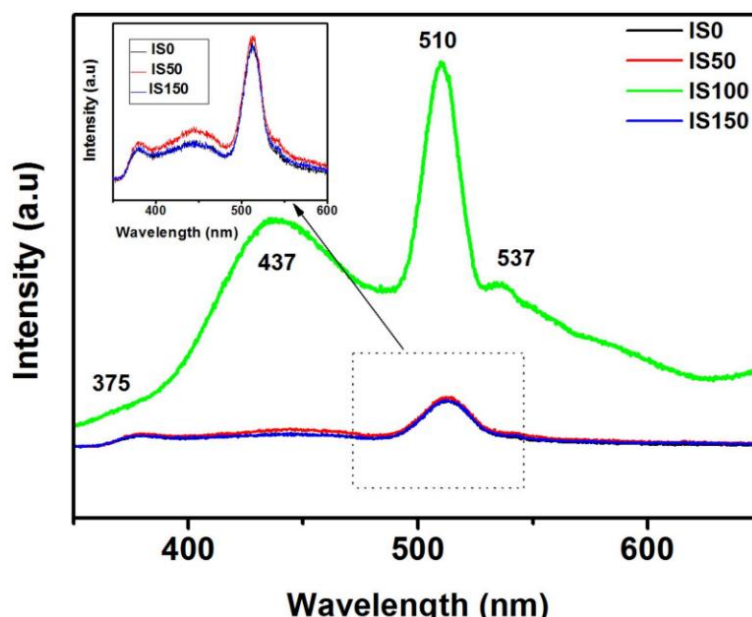


Figure 2: Photoluminescence (PL) Spectra of Irradiated SnO₂ samples [20].

In recent times, substantial endeavours have been directed towards enhancing the efficacy of SnO₂NPs in various applications, particularly in gas sensing. Lavanya et al., 2016[20] in their studies presented a novel method for synthesizing SnO₂NPs by employing microwave irradiation. They further exposed these NPs to varying doses of gamma radiation ranging from 0 to 150 kGy in order to impart desirable physicochemical properties and to investigate their gas-sensing properties. The irradiated samples were subjected to thorough characterization using X-ray powder Diffraction (XRD), Transmission Electron Microscopy (TEM and HR-TEM), and Photoluminescence (PL) in order to assess the impact of gamma irradiation on the structural, morphological, and optical properties of SnO₂NPs. The results reveal that the fundamental crystal structure of the irradiated SnO₂ NPs remained unaltered. Additionally, the electrical characteristics and the ability to CO sensing were examined within 150°C to 400°C temperature range to investigate the γ -irradiation impact. The presence of defects was revealed through PL, and HR-TEM provided evidence of a damaged overlayer. These layers lead to a higher concentration of unpaired bonds and available lattice positions, creating favourable conditions for CO adsorption on the surface of irradiated SnO₂ NPs. Consequently, this facilitated the activation of oxygen species like O⁻ and O²⁻, leading to enhanced reactivity with the reducing gas. Hence, the activated oxygen species displayed improved reactivity towards CO gas.

Resistive sensors utilizing SnO₂NPs exposed to γ -irradiation demonstrated enhanced CO sensing capabilities in comparison to non-irradiated SnO₂ counterparts, with a higher response and operated at a lower temperature. After optimizing the irradiation level of the γ -ray dose and operational temperature, a notable ten-fold improvement in CO response was attained. Specifically, the response towards CO increased ten-fold for SnO₂ NPs that had been exposed to 50 kGy of irradiation and operating at 150 °C. These outcomes propose that irradiating SnO₂ NPs by γ -rays can serve as an effective technique for elevating the sensing capabilities, particularly for carbon monoxide detection. Hence, the improved sensing properties, in contrast to SnO₂ NPs that were not subjected to irradiation, were ascribed to the damage caused on the surface of irradiated samples [21].

γ -irradiation significantly influences the optical characteristics of MONPs as well. In their study, Khodair et al., 2019[22] examined γ -irradiation impact using a Co-60 radioactive source on the optical properties of thin films of Sn_{1-x}Mg_xO fabricated on glass substrates through chemical spray pyrolysis method. In the research, it was discovered from UV spectrophotometry that with variation in Mg doping from 0% to 8%, prior to irradiation the band gap energy values were 3.94 eV and declined to 3.72 eV, and following irradiation this decrement undergoes 3.92 eV to 3.59 eV owing to induced structural defects resulting in the formation of color centers and oxygen vacancies in oxides [23]. Additionally, all-optical constants i.e., absorption coefficient and transmittance coefficient increased with the percentage of doping both before and after irradiation. The study revealed through UV spectrophotometry that as the Mg doping level rose from 0% to 8%, the energy band gap values decreased. Prior to irradiation, the values declined from 3.94 eV to 3.72 eV, and following irradiation, they decreased from 3.92 eV to 3.59 eV.

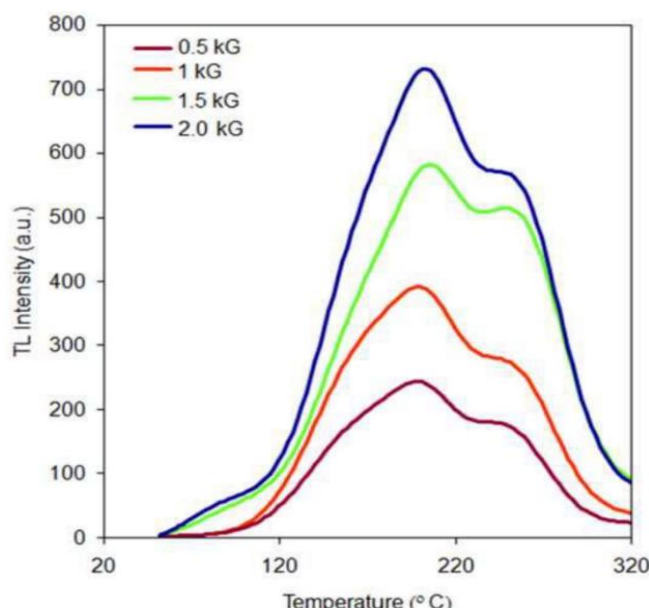


Figure3: A Graphical Representation Illustrating the Correlation between Radiation Dose and TL Intensity [24].

Thermoluminescence (TL) refers to the phenomenon where a solid material, encompassing inorganic substances, semiconductors, or insulators, emits light when subjected to heating after being exposed to radiation. Numerous phosphors show characteristics that make them suitable for application in dosimeters and radiation detectors. Thermoluminescence (TL) is closely linked with the band arrangement within solids, notably impacted by foreign elements (impurities) and structural defects (lattice imperfections) commonly called defect centers. These centers form when ions with a certain charge migrate from their initial positions, creating vacant sites that have the potential to interact with unbound charge carriers. TL has undergone thorough theoretical and experimental investigation, establishing its reliability as a dosimetry technique. It serves as a valuable and practical method for investigating the characteristics of traps as well as trapping levels within solid materials. Substances with thermoluminescent properties emit light, and this emission can be described through glow curve, which might exhibit multiple glow peaks while undergoing heating [25].

A thermoluminescence study was performed on $\text{SnO}_2:\text{Eu}^{3+}$ NPs, which were synthesized using the sol-gel method and subsequently exposed to γ -irradiation in 2014 by Bajpai et al., [24]. The XRD examination unveiled a highly crystalline tetragonal rutile structure, while electron microscopy exhibited spherical shapes with average dimensions ranging from 15-20 nm. To explore the TL characteristics of the $\text{SnO}_2:\text{Eu}^{3+}$ NPs, they were exposed to irradiation using a Co-60 source at normal room temperature. The glow curve of TL exhibited variations in the intensity of TL peaks, corresponding to changes in the dopant concentration. The TL response demonstrated linearity within the range of 0.5 kGy-2.0 kGy. The luminescence observed in these NPs primarily originates from deep traps located in the surface states, with energy levels falling within the band gap of the semiconductor. When surface ions are excited, electrons and holes are readily trapped at these surface states. In NPs, a significant number of surface ions lack full coordination, facilitating the simpler excitation of electrons or holes liberated from the ions.

Consequently, they become trapped within surface states situated within forbidden band gap. Electrons and holes are produced upon exposure to ionizing radiations and are typically captured by pre-existing structural imperfections or those induced by the incident ionizing radiations. When the sample is heated, the trapped charge carriers within that surface state are liberated and recombined, resulting in a luminescence phenomenon referred to as thermoluminescence. Notably, NPs, due to their small size, may not be captured earlier by high-energy radiation, but as the dose increases, they generate trapping and luminescence centers, resulting in an increase in thermoluminescence intensity with dose. Recent research on various luminescent nanomaterials has revealed their promising potential for applications in ionizing radiation dosimetry, especially for measuring high radiation doses utilizing this TL technique. This is particularly significant as conventional microcrystalline phosphors tend to saturate at higher dose levels, whereas the emerging luminescent nanomaterials show enhanced capabilities in this regard.

- 2. Gamma-Irradiated Magnesium Oxide (MgO) NPs:** Magnesium oxide (MgO) is categorized as a semiconductor with remarkable and exclusive chemical, mechanical, optical, and electrical attributes. Notably, it possesses a wide energy band gap, offers stability, is cost-effective, and is environmentally safe. MgO is renowned for its extensive uses in electronics coatings, ceramics, adsorption, and catalysis. This popularity stems from its possession of surface structural defects and simple stoichiometry. Moreover, it stands out as a distinctive solid with a high ionic character. Remarkably, in aqueous environments, MgO exhibits exceptional bactericidal properties as a result of superoxide (O_2^-) formation occurring on its surface [26]. Notably, interactions with various forms of radiant energy, including nuclear radiation, lasers, and UV, play a vital role in numerous research applications. When solid materials come into contact with ionizing radiation, their microstructural properties undergo alterations.

While gamma radiation holds a vital function in both science and technology, prolonged human contact with gamma radiation of high levels can lead to cancer due to the damage it inflicts on the DNA within human cells. To mitigate the detrimental outcomes of radiation exposure, shielding is utilized as an effective method to decrease the strength of gamma-ray emission to a secure level, thereby protecting individuals from its adverse consequences [27]. The Absorption probability of gamma rays while traversing through a substance is directly related to the density, thickness as well as on cross-sectional γ -absorption properties of the substance. The linear attenuation coefficient (μ) is a fundamental parameter used to characterize how much of a monoenergetic beam is absorbed when it passes through a material per unit thickness. It is quantified in cm^{-1} units. The mass attenuation coefficient, on the other hand, remains constant for a specific element or compound since it represents the linear attenuation coefficient normalized per unit density of the material [28]. Researchers have a keen interest in investigating NPs as potential materials for radiation shielding because of their intriguing size-dependent properties, among the various types of materials explored for this purpose.

In research conducted by Amini et al., 2018[29], the structural characteristics and mass attenuation coefficient of MgO NPs were investigated both prior to and following the γ -irradiation of 20kGy dose. The XRD pattern of MgO NPs reveals a growth in the crystal size after exposing them to a 20 kGy dose of irradiation. SEM images

demonstrated that γ -irradiation leads to an enlargement in the MgO NPs grain size (D), causing them to agglomerate. Concerning optical absorption, absorption spectra obtained from UV-visible spectrophotometer, indicate minor alteration in the values of the band gap of irradiated MgO NPs due to the effects of γ -irradiation. The observation reveals a decrease in the mass attenuation coefficient of MgO NPs following irradiation, leading to the conclusion that the mass attenuation coefficient diminishes as the size of NPs increases.

Amini & Majles Ara, 2020[6] investigated the γ -irradiation impact on MgO NPs and studied the alteration caused by irradiation on their optical as well as structural characteristics. By utilizing a Co-60 source MgO NPs were exposed to various doses of irradiation i.e. 100 Gy, 1 kGy, 10 kGy, and 20 kGy. The MgO NPs were first synthesized using the sol-gel method. Subsequent analysis via XRD revealed the existence of both cubic and hexagonal structures within the material and demonstrated an increment in the size of the crystal with higher gamma-ray dose rates. The absorption UV-Vis spectra of the MgO NPs revealed that higher dose rates resulted in a reduction value of band gap. The observed variation in band gap can primarily be ascribed to the quantum size phenomenon, which arises because of the intense interaction between gamma radiation and the surface oxides of magnesium. Additionally, as the level of irradiation dose increases, the mass attenuation coefficient decreases. Consequently, it can be inferred that as the size of NPs increases, the mass attenuation coefficient decreases. This phenomenon is influenced by the cross-section of photon interaction with materials, which is dependent on the surface-to-volume ratio of NPs. As a result, the study demonstrated that gamma irradiation-induced diverse impacts on both the structural as well on the optical properties of the irradiated MgO NPs.

- 3. Gamma-Irradiated Zinc Oxide (ZnO) NPs:** ZnO has garnered significant attention in research among different MONPs because of its remarkable magnetic, electrical, chemical, mechanical, and optical characteristics and these attributes set it apart from what is observed in its bulk counterpart. ZnO is a semiconductor that belongs to the II-VI groups, having a hexagonal Wurtzite crystal structure and has emerged as a prominent material for semiconductor fabrication. It exhibits a substantial band gap measuring 3.37 eV and are non-toxic. Additionally, ZnO exhibits efficient photon emission, has the ability to be easily n-doped, has ease of fabrication at low temperatures, high transparency (with a translucency exceeding 80%) as well as high conductivity, low cost and non-toxicity, and higher electron mobility[30]. A notable alteration in both the structural and light-related characteristics is observed in ZnO nanoparticles following exposure to γ -irradiation.

γ -irradiation of ZnO NPs induces defects, such as oxygen vacancies and interstitials, which alter their optical properties, electronic structure and morphology. Due to these induced defects, ZnO NPs show improved photocatalytic performance, making them highly effective for applications such as water purification, air disinfection and solar cells. Additionally, gamma-irradiated ZnO NPs exhibit improved antibacterial properties, making them suitable for antibacterial coatings and medical applications. Based on the study conducted by Qindeel, 2017 [31], a noticeable increase in grain size, accompanied by the formation of agglomerates in various shapes has been observed as the gamma dose rate rises. Hence, γ -irradiation offers the potential to manipulate both

size and shape effectively. Higher gamma doses facilitate the production of NPs with aligned orientation and increase the crystallinity of the sample. In addition to it, when employing low doses of gamma radiation, the band gap energy decreases. Conversely, higher doses result in a rise in the band gap, which is advantageous for the window layer of solar cells. The variation in the band gap arises mainly from quantum size phenomenon which emerges due to the intense interplay of zinc's surface oxide with gamma radiation. This notable finding strongly indicates that irradiation plays a significant role in altering the particle size, subsequently impacting the band gap [32]. Hence, it is crucial to conduct a comprehensive examination of the impacts of γ -irradiation on different materials. This is necessary to make well-informed choices regarding appropriate materials for shielding purposes.

Exposure to gamma-ray leads to a variety of modifications in the structural characteristics of irradiated materials such as ionization, atomic excitation, structural defects, and hematopoietic damage. Particularly concerning materials like ZnO nanowires, γ -irradiation exerts more detrimental impacts on their morphological and structural characteristics. Therefore, in the process of selecting appropriate shielding materials for radiation facilities, essential considerations include the capacity of a material to withstand radiation-induced damage, economic feasibility, and mechanical traits. Consequently, it becomes imperative to thoroughly investigate the impact γ -irradiation causes on various materials to make informed decisions regarding suitable shielding materials.

It is essential to alter the electrical and optical characteristics of ZnO to expand its usability in various applications, particularly those involving short-wavelength technologies like white LEDs, UV photo-detectors, and UV LEDs. Moreover, its utility extends to functions like barrier and cladding layers in optoelectronic and photonic devices with heterostructures. Pervez et al., 2018 [13] carried out a study focusing on the influence of absorbed doses of gamma rays on the ZnO thin film doped with Magnesium. 200 nm-thick thin film of ZnO doped with Mg was produced on a glass slide using the sol-gel spin-coating method. The film was then exposed to a high flux of 579.96 Giga gamma photons per second per square centimeter from a Co-60 gamma source. The effects of radiation doses ranging from 0 kGy to 100 kGy on the thin film's surface morphology, optical properties, and lattice parameters were analyzed. The results showed a significant alteration in the surface morphology as a direct consequence of the absorbed dose. Additionally, dislocation density and lattice strain exhibited a non-linear and monotonic increase, while the bandgap and the size of the crystallites show decrement as the absorbed dose increases and is attributed to defects induced due to gamma radiation which changes the lattice parameters. The nanostructures underwent a reduction in size and a change in their hexagonal morphology due to the absorbed dose. Furthermore, both the transmittance as well as absorbance spectra of the irradiated thin film were substantially modified due to the radiation exposure. These findings collectively demonstrate the considerable gamma radiation influence on the Mg-doped ZnO thin film, shedding light on its behaviour under varying absorbed doses.

Regulating the electrical conductivity of nanostructures made from metal oxides is essential for facilitating their utilization in the fields of electronics and optoelectronics. In this context, γ -irradiation can be employed to modify the conductivity of ZnO NPs.

The gamma irradiation impact on electrical conductivity (DC) has been demonstrated by Swaroop et al., 2015[33]. The slight changes in room temperature electrical conductivity can be linked to band gap energy which increases due to γ -irradiation. Moreover, a significant reduction in conductivity was observed at elevated temperatures following γ -irradiation [34].

- 4. Gamma-Irradiated Titanium Dioxide (TiO₂) NPs:** Due to its exceptional activity, chemical stability, non-toxic nature, and cost-effectiveness, TiO₂ finds extensive use in various environmental remediation applications. Academic research and industrial applications have extensively explored heterogeneous photocatalysts based on TiO₂. Nonetheless, photo-conversion efficiency is constrained when exposed to solar light owing to the broad intrinsic band gap where rutile possesses 3.06 eV and anatase has a 3.23 eV value of band gap energy. Utilizing sunlight effectively for energy production or initiating chemical reactions continues to be a challenging task. The most commonly utilized approaches involve chemical modification through doping and composite formation. These modifications are aimed at enhancing the ability of the material to absorb visible light. Additionally, cooperative catalysts are introduced to enhance the effective photo generated carrier separation. Nevertheless, due to the high rate of recombination of electron-hole doped TiO₂ NPs photoelectrochemical efficiency remains constrained. Minimizing the recombination rate of electron-hole pairs and extending the lifetime of these pairs, as they diffuse to the surface of the catalyst and trigger redox reactions, holds significant importance [35]. In this context, employing γ -irradiation treatment is a promising method to enhance charge separation. γ -irradiation of TiO₂ NPs generates oxygen vacancies and also causes modifications in the crystal structure. These defects significantly enhance TiO₂ photocatalytic activity, making it an excellent material for solar cells, self-cleaning surfaces, and water treatment technologies. γ -irradiated TiO₂ NPs also exhibit improved performance in hydrogen production and pollutant degradation applications[36].

In a study by Samet et al., 2018 [36], an investigation was carried out on the impact of gamma-rays on various properties of copper-doped TiO₂ NPs where 0 to 6 at. %. Copper doping levels were done. The gamma-ray doses selected for irradiation ranged from 14 to 60 KGy. After exposure to gamma radiation, the samples demonstrate a crystalline core structure surrounded by a disordered shell, resulting from the creation of oxygen vacancies. The presence of these oxygen vacancies on the surface of TiO₂ NPs significantly enhances the photocatalytic activity of Cu-doped TiO₂ catalysts. To evaluate their photocatalytic activity, the researchers assessed methylene blue (MB) degradation. The finding demonstrated the introduction of defect sites onto the surfaces of TiO₂ catalysts, due to γ -irradiation which significantly improved the photocatalytic efficiency. This improvement was attributed to the creation of states where oxygen vacancies trap electrons. The increase in visible light absorption was explained through two mechanisms: the substitution of Ti⁴⁺ with Cu²⁺ ions and the creation of extra oxygen vacancies due to irradiation. These factors resulted in the introduction of isolated states in band gap of the TiO₂ catalyst. The research also demonstrated a direct correlation between the dosage of gamma irradiation and defect site density. These defects played a crucial role in determining the fate of both electrons as well as holes generated through the photoexcitation process. The existence of defective sites hindered electron-hole pairs from recombining which resulted in the enhancement of photo generated carrier

concentration at the surface of crystallite [37]. Consequently, the photocatalytic activity of TiO_2 NPs was greatly enhanced when exposed to sunlight. Overall, this study shows the efficiency of utilizing cooperative effects between Cu^{2+} and oxygen vacancies to promote the photoelectrochemical characteristics of TiO_2 NPs. The gamma treatment preparation technique holds promise for the efficient production of catalysts on a large scale. These materials possess excellent light absorption capability in the visible spectrum and exhibit improved photocatalytic performance, which makes them suitable for wide range of applications in addressing environmental issues.

An investigation was conducted in 2021 by Cadatal-Raduban et al., [38] to analyze how Co-60 gamma radiation affects the characteristics of TiO_2 thin films. The primary aim was to evaluate the suitability of these irradiated TiO_2 thin films for their use in optoelectronic and photonic devices. The research reveals that irradiated thin films of TiO_2 have the potential to serve as photoconductive sensors for vacuum ultraviolet (VUV) rays and their performance can be further enhanced after undergoing recovery from γ -ray irradiation. Initially, the photocurrent experiences a decrease following exposure to 3.4 kGy gamma rays, which leads to the creation of oxygen vacancies as well as trivalent states of titanium ions. These changes are verified through optical spectroscopy techniques including photoluminescence, revealing transmission edge to be red-shifted, reduction in optical band gap, and the emergence of a wide absorption band spanning the wavelength range of 392-528 nm. The detector's photosensitivity significantly improves, showing an increase of about 8 times as compared to its initial sensitivity prior to exposure to radiation and a remarkable 124-fold increase compared to its immediate state after irradiation. As the demand for detectors in the VUV light region grows with the advancement of light sources and applications, these results illustrate the capacity of TiO_2 thin films to function as detectors for VUV radiation, especially when exposed to gamma rays after being fabricated, which enhances their photoconductivity [39].

- 5. Gamma-Irradiated Molybdenum Trioxide (MoO_3) NPs:** Currently, there is significant research interest in transition metal oxides due to their ability to generate distinct phases by modulating the ratio of metal to oxygen. Among various transition metal oxides, MoO_3 has emerged as a particularly appealing candidate due to its capacity for exhibiting distinctive changes in electrical as well as in optical characteristics based on its underlying structure. MoO_3 is categorized as a semiconductor exhibiting a broad bandgap ranging from 2.8 to 3.6 eV and possesses n-type conductivity. Its exceptional stability in ambient conditions with its broad bandgap renders it a promising material for applications such as transparent conducting layers in optical components and high-power transistors.

Additionally, MoO_3 finds use in various applications, including highly reactive photocatalysts, lithium-ion battery anodes, and gas sensors, owing to its remarkable electrochemical and chromogenic properties [40]. Three commonly observed polymorphic structures are exhibited by crystalline MoO_3 namely: a stable orthorhombic phase referred to as the α -phase, along with two less stable phases known as the hexagonal termed as h-phase and the monoclinic phase termed as β -phase. Among these phases, the hexagonal phase is of particular interest due to its unique properties, despite the challenges associated with its synthesis and maintaining its stability. The tunnelling structure of h- MoO_3 displays prominent physical as well as chemical characteristics,

showcasing distinct 1-D behaviour. This characteristic has garnered significant attention from researchers and further underscores its significance in various applications. The metastable hexagonal MoO_3 retains its stability in this phase within a temperature range of approximately $410\text{ }^\circ\text{C}$ to $436\text{ }^\circ\text{C}$. However, upon a further increase in temperature, it undergoes a permanent and irreversible phase transition to the α -phase. Maintaining phase stability is a vital factor in the effective utilization of photonic devices and optoelectronics. External factors such as ionizing and non-ionizing radiation, temperature, physicochemical characteristics, and pressure can all potentially influence phase stability and must be taken into consideration [41].

An investigation was conducted in 2020 by Sen et al., [42], in order to investigate the effects of γ -irradiation on metastable hexagonal MoO_3 NPs at varying absorbed doses ranging from 0 kGy to 120 kGy , and subsequently assessed the changes incurred in its structural as well as in optical properties. The XRD analysis revealed a peak shift towards lower 2θ values accompanied by peak broadening (rising from 0.18° to 0.19°) when the original sample was exposed to a greater absorbed gamma dose of 120 kGy . Moreover, the average strain and the dislocation density increase after irradiating MoO_3 NPs with a 120 kGy gamma dose. The analysis of functional groups indicated changes in the stretching and vibration peak positions of metal oxide bonds ($\text{Mo}=\text{O}$, $\text{Mo}-\text{O}$) with increasing irradiation dose. Irradiated samples undergo a gradual decrease in the band gap value as the irradiation dose was increased, as calculated from the diffuse reflectance data of the UV–vis-NIR spectrophotometer. At a gamma dose of 40 kGy , there was an observed rise in the reflectance spectra, but as the absorption dose was further increased to 80 kGy and 120 kGy , there was a progressive decline in the reflectance. This suggests that initially, at a lower dosage, there was an enhancement in the stoichiometry of h- MoO_3 NPs. However, as the absorbed dose of gamma radiation increased further, it led to imperfections in the crystallinity of h- MoO_3 . The decrease in the band gap value with higher absorbed doses indicates the occurrence of crystal imperfection or defects, such as vacancies in the h- MoO_3 NPs. When gamma radiation interacts with the NPs, certain atoms may be removed, leading to the formation of point defects. These crystal defects create localized states within the band gap, causing the Fermi level to shift towards the conduction band. Subsequently, these states function as recombination centers, affecting the material's optical properties. Hence, by reducing the optical band gap of NPs, the conductivity increases [43].

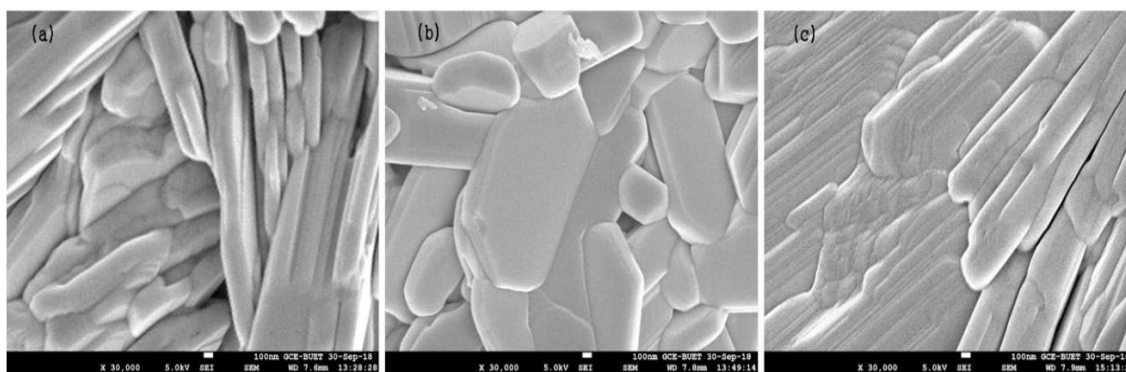


Figure 4: FESEM Analysis of A-Moo3 Nps (A) Un-Irradiated (0 Kgy), Irradiated with Varied Doses (B) 10 Kgy , (C) 120 Kgy [44].

A study exploring the impact of ^{60}Co gamma radiation on the characteristics of nanostructured α - MoO_3 for potential use in optoelectronic and photonic devices has been studied by 2019 by Sen et al., [44]. The simple hydrothermal method has been used for the synthesis of α - MoO_3 NPs and subsequently subjected to low doses i.e., 10 kGy and high doses i.e., 120 kGy of gamma radiation. γ -irradiation causes significant changes in the structural characteristics, bandgap, surface morphology, and functional properties NPs after the irradiation process. XRD patterns revealed a reduction in crystallite size at a lower absorbed dose of 10 kGy followed by an increase at a higher dose of 120 kGy. This suggests that the crystallinity deteriorated for the low dose but improved for the high dose. Conversely, alteration in both the lattice strain as well as in dislocation density exhibited changes opposite to the crystallite size. For, 10 kGy low gamma dose, the (021) preferential orientation demonstrated a shift towards a reduced diffraction angle (2θ) compared to the unirradiated sample. Conversely, the shift in the opposite direction occurred for 120 kGy high gamma dose. The intensity of diffraction peaks decreased for the lower dosage due to the generation of structural irregularities, while it increased for the higher dosage, demonstrating improved crystallinity at higher absorbed doses. The outcomes of the field emission scanning electron microscopy (FESEM) highlighted the noticeable impact of gamma radiation doses on the micrographs, affecting the layered structure and grain size of the α - MoO_3 NPs as shown in Figure 4. The intensity of gamma radiation significantly influenced Mo=O stretching vibration and Mo–O–Mo bending vibrations in the α - MoO_3 NPs. Additionally, the optical band gap exhibited a gradual increase spanning from 2.78 to 2.90 eV with the absorbed doses being increased from 0 to 120 kGy. These findings demonstrated that α - MoO_3 NPs exhibit the capability to endure high gamma radiation doses. Moreover, they undergo alterations that significantly reduce defects, resulting in improved crystallinity. This makes them promising candidates for the design and development of optoelectronic and photonic devices intended for use in applications such as space satellites and situations involving nuclear radiation exposure.

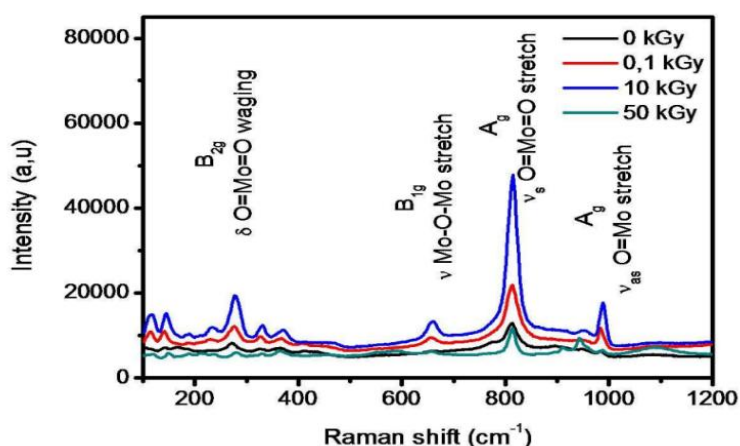


Figure 5: Raman Analysis of Γ -Ray Irradiated sprayed Thin Film MoO_3 [45].

Modification of nanostructured Molybdenum trioxide (MoO_3) thin films through exposure to gamma-ray irradiation was reported in 2018 by Chandoul et al [45]. Thin films of MoO_3 were fabricated on glass substrates using a spray pyrolysis technique at a temperature of 500 °C. Afterward, the samples underwent exposure to gamma rays at different doses (0.1, 10, and 50 kGy) using a Co-60 radioisotope. XRD pattern indicates an orthorhombic structure similar to that of α - MoO_3 , with a preference for (0k0)

orientations as confirmed by Raman spectroscopy. The crystallite size for un-irradiated thin film was found to be 105.62nm. For a radiation dose of 0.1kGy it increases to 109 nm. Upon exposure to a radiation dose of 10 kGy the crystallite size was found to be 105.74nm and with a higher radiation dose of 50 kGy, the size decreased to 109 nm. From Raman spectra measurements as shown in Figure 5, it is evident that there is a noticeable rise in Raman intensity with increasing particle sizes within the span of 0.1-10kGy, but for 50 kGy gamma dose a decrease in the Raman intensity has been observed as the size of particle reduces. For the dose of 10 kGy, the band gap decreases, which can be due to the formation of localized states within the forbidden band gaps. Conversely, for doses of 0.1 kGy and 50 kGy, the energy of the band gap increases. This outcome arises from the interaction between gamma radiation and materials, causing annihilation of defects within the material. Additionally, a decrease in defects along the grain boundaries is observed, accompanied by a reduction in structural irregularities and lattice strain. Room temperature photoluminescence measurements were conducted using 300 nm wavelength excitation and a decrease in intensity of PL confirms the rise in defect densities, which is consistent with the outcomes of the structural investigation. Moreover, this study highlights the potential applications of nanostructured thin films of MoO₃ in γ -dosimetry fields, including uses in photocatalysis, optoelectronic devices, gas sensors, and electrochromic and photochromic devices.

- 6. Gamma-Irradiated Copper Oxide (CuO) NPs:** CuO is a chemical compound derived from two elemental constituents i.e., copper and oxygen. These elements are categorized as elements of d-block and p-block of the periodic table. Within a crystalline structure, a copper ion is surrounded by four oxygen ions. CuO NPs have garnered significant interest because of their applications in modern technologies and their abundant accessibility [46]. CuO is classified as a p-type oxide semiconductor, possessing a band gap of 1.2 eV, and exhibits a monoclinic crystal arrangement. γ -irradiation of CuO NPs introduces defects, such as oxygen vacancies and interstitials, which influence their catalytic properties. γ -Irradiated CuO NPs show enhanced performance in gas sensing applications, pollutant degradation, and energy storage devices. They hold promise for use in environmental monitoring, air quality control, and energy storage technologies [47].

Sarker et al., 2021 [48] studied the impact of γ -irradiation ranging from 20 to 100 kGy on CuO thin films prepared using the thermal spray pyrolysis technique on glass substrates. XRD results show that the crystallinity of films declines as the gamma doses increase, leading to a gradual decrease in the crystallite size from 59.13 to 46 nm. However, the fundamental monoclinic crystal structure remains unchanged. The increase in γ -irradiation absorbed dose results in higher dislocation density and lattice strain due to the formation of defects. The number of crystallites per unit surface area rises with increasing dose, indicating enhanced crystallization of the nano CuO thin films. When γ -photons interact with targeted nanomaterials and penetrate them, the atoms within the nanomaterials undergo displacement and lead to the breakdown of molecules and crystallite size, resulting in a net reduction in crystallite size. This reduction is likely due to the breakdown of certain grain boundaries and the decrease in crystallite sizes, which, in turn, induces strain and imperfections in the crystal structure, including dislocations and oxygen vacancies. The induced strain increases from 15.986×10^{-4} to 17.144×10^{-4} , and the dislocation density rises from 2.1244×10^{15} to 2.4461×10^{15} lines per square

meter with increasing absorbed doses. These changes indicate an increase in crystallographic imperfections and defects in the prepared CuO thin films. Moreover, as the dose increases, the value of N_c i.e., the number of crystallites per unit surface area rises from 29.3748×10^{16} to 36.2946×10^{16} per square meter, which revealed a higher abundance of crystallization in the CuO nanostructured thin films. A UV-Vis spectrophotometer was employed to assess the optical characteristics. The results demonstrated a reduction in the optical energy band gap (OBG) energies from 2 eV to 1.72 eV as the doses increased from 0 to 100 kGy. Even though there is slight deterioration of crystallinity and narrowing of the OBG, there were no apparent changes in the monoclinic phase of the initial CuO thin film under the applied absorbed doses. The gamma irradiation doses led to an increase in both the refractive index and the high-frequency dielectric constant of thin films made from CuO material. The refractive index (n) holds great importance as an optical property of semiconductor materials. Determining the refractive index values of optical semiconductors is of utmost significance; particularly in the context of photovoltaic applications. The dielectric properties of a substance have a substantial impact in various applications involving electronic devices. These characteristics are linked to its ability to restrict the flow of electrons when it becomes polarized in response to an external electric field. Nonetheless, it is essential to have materials possessing high-frequency dielectric constants (ϵ_ω) and static dielectric constants (ϵ_0), in order to effectively develop advanced photovoltaic devices [49,50].

- 7. Gamma-Irradiated Tungsten Oxide (WO₃) NPs:** Tungsten oxide (WO₃), a significant semiconductor possessing n-type characteristics distinguished by 2.7eV band gap. It stands as a highly promising option for diverse applications like electrochromic devices, photocatalysts, biosensors, supercapacitors, and gas sensors, due to its exceptional structural as well as physical properties, non-toxic nature, and chemical stability. Therefore, WO₃ has garnered significant attention as a prominent functional semiconductor metal oxide, impacting diverse research fields spanning from condensed matter physics to solid-state chemistry [51]. Extensive research has been conducted on tungsten oxide (WO₃) film due to its impressive electrochromic (EC) characteristics. These EC materials hold significant potential for a wide range of applications, including smart windows, auto rear-view mirrors with adjustable reflectivity and optical displays. Additionally, an exciting avenue for utilizing EC films lies in their application for controlling various systems and devices on low-orbit satellites and spacecraft [52]. Ionizing radiation, particularly in the form of γ -rays, holds significance in understanding its impact on devices used in satellites and space shuttles. Evaluating these effects is crucial for optimizing the efficient utilization of such equipment in space missions. Consequently, it becomes crucial to assess the structural, and electrochromic (EC) modification in WO₃ films with respect to received radiation dose, particularly for space mission expeditions. Glass materials find extensive use in various applications related to low-orbit satellites and spacecraft, making it essential to examine the effects of radiation on them. The outcomes of radiation-induced damage in glass can be categorized into three divisions: first, the displacement of atoms caused by the transfer of energy and momentum, second the ionization and the capture of charges, and third the photochemical or the radiolytic consequences. The effects of these outcomes are dependent on both the radiation energy and the overall amount of dosage given [53].

The presence of trapped electrons in optical glasses containing transition elements acts as a safeguard against discoloration. These trapped electrons play a role in producing new colors induced by irradiation. Exposure to ionizing radiation leads to the generation of excitons, which are pairs of bound electrons and holes. Consequently, the radiation leads to the displacement of atoms and the fracture of chemical bonds due to either radiolytic processes or knock-on dislocation. As a result of these processes, color centers are generated due to the trapping of electrons and holes at the sites that have been damaged[52]. Glass-coated tungsten oxide samples were exposed to five distinct gamma-ray doses: 0.93 kGy, 1.4 kGy, 2.6 kGy, 4.5 kGy, and 21.1 kGy, and these exposures were carried out under ambient room temperature conditions.

The irradiation with the Co-60 radioisotope caused noticeable changes in the color of WO₃ films on the samples, resulting in dark-brownish tones that varied depending on the applied dose. The Co-60 radioisotope, possessing 9.3 Ci activities, was selected as the most suitable gamma radioisotope source, as it induced maximum ionization effects in the samples. The average transmittance of the films is below 90% for the unirradiated samples. With increasing gamma-ray dosage, there is a reduction in transmittance across all wavelengths. γ -irradiation induces the emergence of three primary optical density bands in the samples, spanning wavelengths around 380-460 nm, 570 nm, and 1400 nm. These modifications are attributed to the existence of defect sites. The presence of defect centers could result in an increase in the quantity of ion-trapping sites, causing a higher accumulation of protons within the irradiated thin films of WO₃ [54].

In the domain of gas sensors, WO₃ is utilized in the detection of a diverse range of gases, including NO₂, CO, H₂, C₂H₅OH, and NO. Efforts have been made to improve the characteristics of MONPs through post-treatment processes. For instance, subjecting them to high-energy ionizing radiations like X-rays, gamma radiation, β , and α particle is widely recognized to induce substantial alterations in their microstructural and morphological properties. This, in turn, leads to the creation of various defects, which can effectively modify the optical, electrical, and sensing properties of the metal oxides. The gas response, denoted by S, is $S = R_0/R$, calculated as the ratio of the baseline resistance (R_0) in synthetic air to the electrical resistance (R) of the sensor under various NH₃, CO₂, and CO concentrations. The response time (τ_{res}) is defined as the duration taken by the sensor to reach 90% of its saturation signal, while the recovery time (τ_{rec}) is the time required to return the signal back to 90% of the baseline signal [55].

In one of the studies conducted by Lavanya et al., 2017[56], they investigated resistive sensors utilizing WO₃NPs irradiated with gamma rays. These sensors were subjected to testing to detect NH₃, CO, and CO₂ in the air. The findings revealed that exposure to gamma irradiation led to a decrement in the response to NH₃, while the response toward CO₂ increased. Moreover, the WO₃-based sensor that underwent γ -irradiation exhibited a notable improvement in its NH₃ recovery time compared to the unirradiated WO₃-based sensor. These observations suggest that modification in the surface microstructure caused by γ -irradiation causes a notable alteration in acid-base properties of the sensing layer composed of WO₃NPs. The results clearly demonstrate that the use of γ -irradiation holds promise to be effectively utilized to tailor the sensing characteristics of WO₃NPs, offering potential enhancements for sensor applications.

Table 2: Characteristics and Applications of Gamma Irradiated MONPs

Material	Characteristics	Gamma dose	Applications	References
SnO ₂	Structural and morphological	0-150 kGy	Gas Sensor	[20]
MgO	Mass attenuation constant and optical	0.1-20 kGy	Dosimeter, Shielding material	[29],[6]
ZnO	DC electrical conductivity	20-80 kGy	Electronics	[33]
CuO	Optical and morphological	20-100 kGy	Photovoltaic	[48]
TiO ₂	Optical	3.4 kGy	Vacuum ultraviolet photoconductive detectors	[38]
MoO ₃	Structural and optical	10 & 120kGy	Optoelectronic and photonic devices	[42], [44]
WO ₃	Structural and electrical	50-100 kGy	Serotonin sensor, Gas sensors	[56]
CeO ₂	Electrical and optical	25-100 kGy	Dosimetry	[57]
Al-doped ZnO	Electrical	0.20 Gy	Sensors and electronics	[58]
Mg-doped ZnO	Optical and structural	20-100 kGy	Optoelectronic and photonic devices	[13]
Cu-doped TiO ₂	Optical, structural, and Photocatalytic	14-60 kGy	Photocatalyst	[59]
Sn _{1-x} Mg _x O	Optical	9 kGy	Energy storage	[22]
VO ₂	Optical and electrical	3-100 kGy	Thermal shielding	[60]
TeO ₂	Electrical and optical	3-14 Gy	Dosimeter	[61]

VI. CONCLUSION

γ -irradiation has emerged to be a valuable technique for customizing the characteristics of MONPs. The examples mentioned above demonstrate the diverse effects of γ -irradiation on metal oxides, leading to enhanced functionalities and the possibility to use them in diverse fields. As the need for nanoelectronics and microelectronic valuable devices continues to rise, radiation-induced materials with tailored properties have become a focal point for potential futuristic applications. While substantial advancements have been achieved in understanding the mechanisms behind radiation-induced effects, additional research is essential to comprehensively grasp the intricacies of these processes. This is essential in order to unlock and harness the full spectrum of possibilities, without posing

risks to human health and the environment. As evidenced by recent studies, γ -irradiation role in shaping the behaviour and attributes of MONPs is poised to play a progressively substantial role in the realm of materials science.

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