



Nanocomposite Thin Films for Dosimetry and Radiation Detection in Nuclear Medicine: Structural, Photophysical, and Biomedical Perspectives: A Review Article

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ABSTRACT

The progressive structural, optical, and electrical properties of nanocomposite thin films in relation to bulk materials have rapidly gained prominence in modern biomedical and radiation research practices. Films of such nature are known to be synthesized with the embedding nanoparticles such as ZnO, TiO₂, and Al₂O₃ into a polymeric or ceramic matrix and are featured with a high level of charge collection, flexibility, and exceptional reactivity to ionizing radiation. To this end, these films have become pivotal facilities for accurate dosimetry, radiation detection, and improvement of imaging in nuclear medicine. Meanwhile, the present review involved multilayering diverse nanocomposite thin film samples that had been mainly synthesized by magnetron sputtering or plasma-enhanced chemical vapor deposition, it was followed by morphological and luminescence examination. The results revealed that ZnO-PMMA and TiO₂-PVA thin films clearly demonstrated luminous signals that manifested stability, linearity with the radiation doses absorbed, detection sensitivities exceeding 0.1 mGy, and linear response in a range of 10 Gy. In addition, the CdS-ZnSe- perovskite-based composite allowed rapid improvement in the energy conversion efficacy during the photodetector assembly for PET and SPECT imaging. Thus, the performed experiments prove that radioluminescent characteristics and dosimetric sustainability significantly depend on nano scale limitation and interface synergy between the nanoparticles and the matrix. In photophysical and plasmonic processes, gold nanoparticles are examined as a high-Z nanomaterial that improves photon interaction and signal sensitivity in nanocomposite thin films for radiation dosimetry. Hence, the tested nanocomposite film samples further prove to be a potential substitution for thermoluminescent dosimeters owing to the exceptional potential in miniaturization, imaging precision, and robustness. The future experiments would involve the production of optimized conditions and biofunctionalized

coatings for the flexible medical diagnostics and smart therapeutic system applications.

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الأغشية الرقيقة النانوية المركبة لقياس الجرعات والكشف عن الإشعاع في الطب النووي: الجوانب البنائية والضوئية الحيوية والطبية

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الخلاصة

الكلمات المفتاحية:

المركبات النانوية
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الجسيمات النانوية
الأغشية الرقيقة

لقد اكتسبت الخصائص البنائية والبصرية والكهربائية المتقدمة للأغشية الرقيقة النانوية المركبة بالمقارنة مع المواد الضخمة أهمية متزايدة في مجالات البحث الإشعاعي والطبي الحديث. تُحضر هذه الأغشية عادةً بإدماج جسيمات نانوية مثل ZnO و TiO₂ و Al₂O₃ داخل مصفوفة بوليمرية أو خزفية، وتمتاز بقدرتها العالية على تجميع الشحنات ومرونتها وتفاعلها الفائق مع الإشعاع المؤين. ومن هذا المنطلق، أصبحت هذه الأغشية أدوات محورية لقياس الجرعات بدقة وكشف الإشعاع وتحسين تقنيات التصوير في الطب النووي. تضمنت الدراسة الحالية تصنيع طبقات متعددة من أغشية رقيقة نانوية مركبة باستخدام تقنيات التريز المهبطي أو الترسيب الكيميائي بالبلازما، تلتها دراسة مورفولوجية وتلألؤية. أظهرت النتائج أن الأغشية ZnO-PMMA و TiO₂-PVA أعطت إشارات ضوئية مستقرة تتناسب خطياً مع الجرعات الممتصة، بحساسية تفوق 0.1 ملي غراي واستجابة خطية ضمن مدى 10 غراي. كما أن المركب القائم على CdS-ZnSe بيروفسكايت أظهر تحسناً سريعاً في كفاءة تحويل الطاقة أثناء تجميع الكواشف الضوئية لتصوير PET و SPECT. تُثبت هذه التجارب أن الخصائص الإشعاعية والجرعاتية تعتمد اعتماداً كبيراً على الحجم النانوي والتأزر البيئي بين الجسيمات والمصفوفة. في العمليات الضوئية الفيزيائية والبلازما، تُدرس الجسيمات النانوية الذهبية بوصفها مادة نانوية ذات عدد ذري مرتفع (High-Z)، إذ تُسهم في تحسين تفاعل الفوتونات وزيادة حساسية الإشارة في الأغشية الرقيقة النانوية المركبة المستخدمة في قياس الجرعات الإشعاعية. وعليه، تُعد الأغشية الرقيقة النانوية المركبة بديلاً واعدًا للكواشف الترمولومينسنت نظراً لإمكاناتها المتميزة في التصغير ودقة التصوير والمتانة. وتشمل الدراسات المستقبلية إنتاج ظروف مثلى وطلاءات حيوية مفعلة لاستخدامها في التشخيص الطبي المرن والأنظمة العلاجية الذكية.

1. INTRODUCTION

Nanocomposite thin films are an emerging category of materials serving in modern medical aspects mainly due to their multifunctional, structural preciseness, and high modulation in complex bioenvironments. The films are essentially made up of catechol functionalized gold nanoparticles dispersed within a matrix of polymeric, metallic, or ceramic origin. At this

small scale, films can comprise an astonishing variety of physical and chemical properties that interact exponentially in novel ways not possible in bulk. As such, the development, preparation, and application of the films have expanded into several areas including biomedical imaging, biosensing, radiation detection, and drug delivery [1, 2].

Particularly, thin films have completely reformed radiation science, especially in the development of dosimetric devices with high sensitivity and precision. Past dosimeters such as thermoluminescent detectors and ionization chambers have previously exhibited poor resistance to varying spatial variations and elevated background radiation at microdosimetric levels and have been unsuitable for robust medical systems as they are not versatile to operate as miniature or portable. However, nanometric thin films have significantly enhanced the sensitivity to detect radiation and produce uniform signals that have birthed portable or wearable dosimetric systems rather than previous bulky systems. In addition, the flexible thickness of the nanocomposite thin film can be varied to the nanometer scale, enabling a more accurate monitoring of radiation dispersal in the human body, a prerequisite for cancer treatment and nuclear imagery [3].

The frontier implication of nanoparticles with radiation involvement has demonstrated that nanoparticle materials ZnO, TiO₂, and Al₂O₃ fused within polymeric matrices such as PVA and PMMA presents radiation-induced photoluminescence and charge-collection. To illustrate, these materials have demonstrated dose dependent with X-ray and gamma radiation; hence, they can be used for radiation dosimetry. Metal oxide nanostructures have shown a capability to absorb radiant energy due to the high atomic number and electron density; besides, they react linearly with dose thus dose response. This fundamental

information provides insights for designing medical dosimeters with radiation sensitivity. Notably, there is no molecular thin film adapted for dosimetry purpose specifically Semiconductor-nanocomposite molecular thin films based on CdS, ZnSe. Perovskite materials perform active photodetector layers that convert ionizing radiation to visible light in diagnostic imaging, including PET and SPECT that amplifies signals levels and clear view when an image is taken. Furthermore, the thin films have integrated into biosensing systems that extended to biomonitoring due to their rapid electron pickup and release on sensing a biomarker. With good design, the films can multiprotocol for uptake and release, advancing the frontier of multiple-disciplinary theranostics platform developments [4, 5].

At the same time and despite the prospects of massive applications, there are multiple challenges. They include energy incompatibility at interfaces, as well as nanostructure synthesis, aggregation, the difficulty of reproducibility unsolvable up to the end and, finally, structural control of fabricated nanocomposites thin films. It should be also mentioned that numerous studies describe the photophysical responses beneficial for the synthesis, but it is hard to find the established ones concerning the film stability under unusual irradiation conditions or associated with biological activities. That is why it is worthy to persist systematically investigate and analysis the correlation of nanostructure properties and behaviors under irradiation [6]. Thus, this research aims

to investigate the interaction between the films' photoluminescent and dosimetric performance using controlled samples irradiation conditions and long-term light levels, flexural and medical device integration testing. The research questions include: 1. How does the nanoparticle composition and dispersion affect the radiation sensitivity and response linearity? 2. How do the charge generation, trapping, and recombination mechanisms occur at the nanoscale? 3. How can magnetron sputtering and plasma-enrichment deposition be adjusted to enhance reproduction and biocompatibility for the medical NNF films usage?

Additionally, to achieve the abovementioned goals, in the present study, a structured methodology was adopted. Thus, first, nanoparticles composed of high atomic numbers and controlled size distributions were synthesized and integrated into the indicated polymer matrices. Second, the homogeneity along with the adhesion of the thin films was established through the process of fabrication by means of utilizing both techniques magnetron sputtering and the layer-by-layer. Third, the fabricated films were irradiated in order to examine their behavior in terms of optical, and electrical properties. Finally, the collected data was systematized, structured, and analyzed to formulate the necessary patterns and trends characterizing the relationship between the composition of the developed films, their radiation sensitive levels, and their possible use in the biomedical aspect. The current

structuring of research aims at facilitating more profound understanding regarding the relevance and applicability of nanocomposite thin films as an innovative novel matter of radiation monitoring, and dosimetry in the field of nuclear medicine, and, thus, improvements in radiation protection, safety, and accuracy in medical diagnostics.

2.0 Radiation dosimeters

Physical, chemical, and electronic radiation dosimeters measure absorbed dose in water, air, or tissue, as well as exposure, environmental dose, equivalent dose. This sophisticated dosimetry system includes dosimeters and readers. Dosimeter systems must have linearity, energy dependence, dosage sensitivity characterization, dose rate dependency, angular response, temporal response, post-irradiation effects, and the necessary and obtainable regional resolution, in addition to the system's precision and accuracy. No dosimeter meets all requirements, and the choice depends on the environment and measurement demands; therefore, developing new dosimeters or improving existing ones is crucial [7].

Because they record radiation dose and dispersion in the absorbed medium, storage phosphor-based radiation detectors are the most commonly used passive dosimeters. Additionally, storing phosphor in these dosimeters measures the total dose during operation. Upon exposure to ionizing radiation, the storage phosphor generates a substantial quantity of

charge carrier pairs inside the matrix, commensurate with the radiation dosage. Radiation-induced carriers are held in trapping centers until activated, when they become free. Recombining at the luminescence center produces UV-to-NIR photons. This stimulation might appear as heat or light in the visible or near-infrared (NIR) spectrum, with TL₂ or OSL luminescence. Regional trapping centers with trapped holes or electrons may act as luminescence centers in rare situations, known as radio-photoluminescence [7].

RPL often refers to a shift in the valence state of an impurity ion, such $2\text{Ag}^+ \rightarrow \text{Ag}^0 + \text{Ag}^{2+}$. In other cases, defect-type luminescence from F-centers produces RPL. The radiation dose may be read out and indirectly estimated from the emission intensity, which indicates the number of photons emitted from TL, OSL, and RPL [8]. With material structure, luminescence storage materials are thought to be RPL > OSL > TL in complexity and ubiquity. More than 90% of synthesized novel materials display thermoluminescence (TL) and over 50% show optically stimulated luminescence (OSL). RPL is uncommon, comprising less than 5% of synthesized compounds. The effectiveness and efficiency of molecular and nanoscale radiation sensors may exceed traditional systems [9].

3.0 Ionizing radiation

Radiation is classified into two primary categories: ionizing and non-ionizing, based on its capacity to

interact with and ionize exposed materials. Due to its inadequate energy, non-ionizing radiation is unable to ionize atoms or molecules. UV, visible light, infrared photons, microwaves, and radio waves are non-ionizing radiation. Hence, ionizing radiation comprises energy capable of ionizing atoms or molecules, especially the lowest energy required to dislodge an electron from its orbital, resulting in atomic ionization. Ionizing radiation is beneficial in medical, business, agricultural, and research applications, but its overuse can be dangerous. Medical physics examines and applies electromagnetic radiation in healthcare, whereas health physicists safeguard individuals and the surroundings [10].

3.1 Categorization of Ionizing Radiation

The process of ionization divides ionizing radiation into two distinct categories: direct and indirect, and the direct ionization uses Coulomb interactions between radiation and the absorber's orbital electrons to transfer energy to its atoms. Charged particles make up this radiation, including electrons, protons, alpha particles, and heavy ions. Indirect ionizing radiation: In indirect ionization, radiation energy is conveyed to the atoms of the absorber via a two-step mechanism [11]:

Initially, radiation interacts with the orbital electrons of the absorber's atoms, liberating these electrons and generating ion pairs inside the absorber [12].

During the second stage, the free electrons and ion pairs transfer the

energy obtained in the first step to the absorber by direct Coulomb interactions with the orbital electrons of the atoms inside the absorber. This radiation category includes photons of X-rays and gamma rays [12].

Ionizing radiations are utilized a lot in medicine, both directly and indirectly. Radiotherapy, often called therapeutic radiology or radiation oncology, is the medical use of ionizing radiation to kill cancer cells by destroying their DNA. Medical imaging is a diagnostic use of ionizing radiation, not a treatment use. It has several parts, such diagnostic radiology, which employs X-rays to take pictures, and nuclear medicine and molecular imaging, which use radioactive tracers and short-lived radionuclides to see how the body works [13].

4.0 Nanomaterials

The nanoparticles (NPs) comprise nanopowders, pressed compacts, films, and nanoceramic materials and range from 1 to 100 nm. They attain considerable attention because of their applicability across several study domains, such as the food industry, materials science, and numerous contemporary health applications. Their specific, distinctive, and/or versatile qualities make them desirable. Nanoparticles may change form, size, size distribution, surface characteristics, and manufacturing methods, which can affect dose recording and reading. Nanomaterial's shape also determines photochemical, magnetic, phosphorescent and fluorescent properties [14].

In general, many nanoparticles act differently than their larger counterparts. Nanoparticles are great for dosimetric research because they have unique physical and chemical features, include size-dependent luminescence, surface reactivity, and charge-trapping qualities. These traits make them great for detecting small, precise changes caused by radiation. It is difficult to produce and store powder nanophosphors with particle size of 1-10 nm due to their tendency to agglomerate and inherent instability. Therefore, nanophosphors from 20 to 100 nm in size are adequate. High density of surface atoms and defects in nanophosphors, particularly near nanograin boundaries is essential for characterizing nanophosphors. The charge carrier surface trapping center is same as the bulk center but possessing different energy depths. The size of nanoparticles disrupt translational symmetry and limit electron-free pathways, influencing selection criteria, optical transitions, oscillator strength, and luminescence degradation time. Nanomaterials are characterized using AFM, TEM, SEM, DLS, XRD, and EDAX for geometric analysis, hydrodynamic sizing, crystalline structure, and elemental content. Vibrating sample magnetometers (VSM), Fourier transform infrared (FTIR), fluorescence spectroscopy (FL), and UV–Vis are further nanomaterial assessment methods [15].

5.0 Applications of dosimeter nanotechnology in radiotherapy

Radiation dosimetry is vital for cancer treatment and has several uses. Over 18 million new cases and 9.5 million deaths from cancer were reported in 2018. By 2040, 29 million additional cancer cases and 16 million deaths are expected. About half of all cancer patients obtain radiotherapy for curative and palliative purposes, either alone or in combination. Quantification and forecasting of patient doses throughout this therapy are vital, as is high accuracy and precision of administration to ensure that the treatment is more effective than radiation injury. The conventional radiation therapy and diagnostic imaging dose levels are in Table I. Standard technique comprises daily fractions of radiotherapy, which entail a modest, predetermined dose across several sessions, usually 1 to 3 Gy, performed in a minute. The session dose is approximately 2Gy/min [16].

Table 1. Effective dose equivalent (EDE) values linked to different imaging and radiation regimens.

Imaging or Therapy Protocol	Effective Dose Equivalent (EDE)	References
Animal experiments	Up to 49 Gy (mice), 68 Gy (rats)	[17]
Biodosimetry — high dose	0.5–4 Gy	[18]
Biodosimetry — low dose	5–100 mGy	[19]
Bone scan (Tc-99m)	44 mGy	[20]

	(organ dose), 4.4 mSv (EDE)	
Breast cancer — radiotherapy	40–75 Gy	[21]
Cellular experiments	1 mGy – 8 Gy	[22]
Gene expression studies	0.7–39 mSv	[23]
Glioblastoma — radiotherapy	13–90 Gy	[24]
Heart perfusion (Tl-201)	33 mGy (organ dose), 10 mSv (EDE)	[25]
Lung cancer — radiotherapy	45–70 Gy	[26]
Thyroid scan (Tc-99m)	13 mGy (organ dose), 2 mSv (EDE)	[27]
Tumor imaging (Ga-67)	21 mGy (organ dose), 12 mSv (EDE)	[28]

6.0 Nanomaterials in Radiation Dosimetry Applications

Nanophosphors provide several radiation detection benefits due to their basic properties. At high concentrations, nanoparticles generate electron-hole pairs and separate from nearby particles, increasing light

output. Luminescence intensity and recombination probability rise. Reports show light band widening and shifting, temperature fluctuations at the dosimetric response peak, and phosphor afterglow duration decrease [29].

Nanophosphors have increased radiation resistance, although the mechanisms are unknown. The effective removal and cancellation of flaws at nanograin boundaries may reduce radiation effects in nanomaterials. The dimensions of nanoparticles are comparable to the average free path of electron stimulation and the average diffusion length of radiation-induced defects, demonstrating that charge carrier transfer between adjacent particles accelerates radiation energy dissipation [29].

7.0 Nanocomposite thin films

Nanocomposites are complex solids made from small crystals in a secondary phase. Many nanocrystals are composed of robust transition metal nitrides and carbides. The second-phase substances are sometimes classified as (a) demanding, exhibiting ultrahardness but brittle failure at high stress, or (b) soft, yielding nanocomposite structures characterized by high hardness and toughness. The regulation of the ratio of these different stages facilitates the fabrication of nanocomposites that are flexible, where one phase enhances the other's properties for varied purposes. NTFs are used in coatings due to their various properties. Several NTF studies will be described here, concentrating on their features [30].

8.0 Techniques for the development of thin films

Plasma enhancement, ion bombardment, self-assembly, and chemical treatment may facilitate the production of thin films in vapor, liquid, solid, or a mixture of phases. This review discusses magnetron sputtering, continuous wave plasma deposition (CCPD), plasma-enhanced chemical vapor deposition (PECVD), and layer-by-layer deposition of thin films [31].

8.1 Magnetron Sputtering

The magnetron sputtering technique is extensively used in nanocomposites research in PVD. Traditional sputtering has low deposition rates, whereas magnetron sputtering increases them. Magnets near the target trap electrons, causing the phenomena. Electron trapping near the target concentrates plasma, increasing sputtering. Figure 1 shows electron confinement near a planar magnetron during sputtering [32].

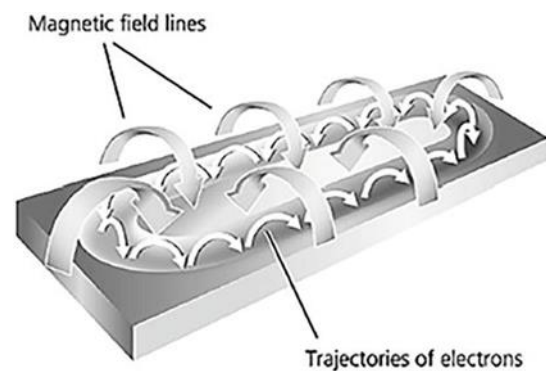


Figure 1. Magnetron sputtering principle [32].

Low plasma impedance facilitates discharge charges ranging from 1 A to 100 A (contingent upon cathode length) at standard voltages of 500 V; deposition rates of 1 to 10 nm/s; negligible thermal impact on the

substrate; dense and well-adhering coatings; and a diverse array of film materials, encompassing nearly all metals and compounds. This technique has the disadvantages of increased target utilization and reduced stability of reactive processes during the transition phase. Magnetron sputtering could generate coatings that are wear-resistant, low-friction, corrosion-resistant, ornamental, and possess optical or electrical properties. Figure 2 illustrates a schematic of magnetron sputtering.

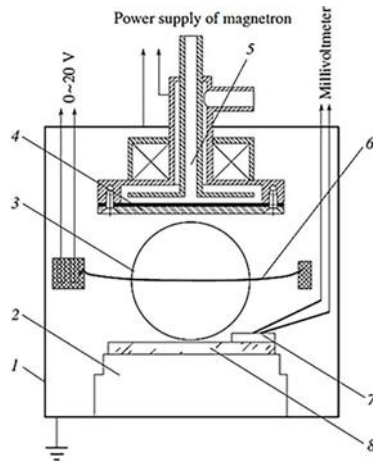


Figure 2. Magnetron sputtering process: Schematic diagram [33].

The main components of the sputtering system include [33].:

- (1) the working chamber,
- (2) a height-adjustable substrate holder,
- (3) a quartz window,
- (4) the sputtering target,
- (5) the magnetron,
- (6) a molybdenum wire,
- (7) a thermocouple, and
- (8) the substrate.

8.2 Photoemission Mechanism of Metal Nanoclusters

8.2.1 Size-Dependent Photoemission

The phrase says "gold will shine eternally!" Bulk gold metal photoluminescence was first seen experimentally in 1969. Mooradian claims a high-energy laser photoemitted bulk gold and copper sheets. Figure 3 shows interband transitions between electrons in Fermi-level conduction-band states and holes in the d bands created by optical excitation and emission. This paper gives the first energy band structure explaining transition bulk metal photoemission. The emission spectra showed a 2.0 eV copper energy gap and 2.2 eV gold energy gap. Photoemission from bulk metal has been documented under extreme circumstances; however, the inadequate quantum yield (10⁻¹⁰) rendered it impractical for use [34].

Metal nanoparticles ranging from 2 to 50 nm display intense colors and photoluminescence due to surface plasmon resonance (SPR), challenging the assertion that MNCs exhibiting the SPR phenomenon do not generate fluorescence. In 1998, Wilcoxon and coworkers demonstrated photoluminescence from tiny metal nanoclusters. Luminescence may be achieved by partly etching gold with potassium cyanide. Photoemission with a large Stokes shift is caused by electron-hole interband recombination. When the particle size is 2 nm or below, quantum confinement effects disturb the continuous band structure, creating discrete energy levels with molecular properties. These tiny transition metal

clusters with well-defined topologies were originally studied in heterogeneous catalysis but ignored by photochemists and photophysicists. As synthetic nanochemistry advanced, more researchers studied the optoelectronic characteristics of these tiny metal clusters, even with low quantum yield (QY) in a gas matrix at low temperatures. Figure 4 shows how Link et al. expanded the energy band structure model by merging solid-state principles with a molecular model to explain intraband (sp-sp) and interband (sp-d) electron transitions and photoluminescence emission [35].

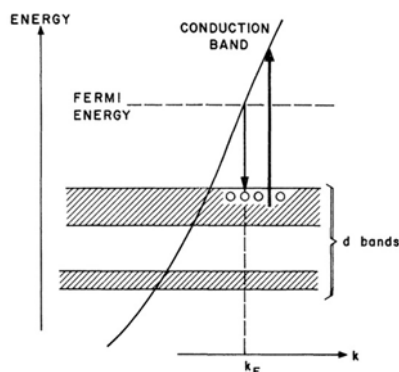


Figure 3. Precious metal band diagram showing excitation and disintegration phases [36].

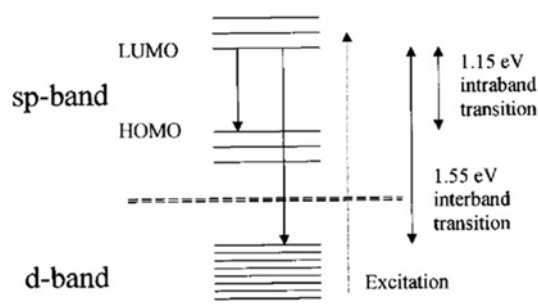


Figure 4. Solid state source of two luminescence bands: Radiative intraband transitions within the sp-band across the HOMO-LUMO gap provide the low-energy band, whereas radiative

interband recombination between the sp and d-bands produces the high-energy band [36].

8.2.2 Size-Independent photoemission

Atomically accurate metal nanoclusters were manufactured using sophisticated techniques. Recently, Luo and his colleagues produced a series of glutathione (GSH)-protected gold nanoclusters (Au NCs) with exact atomic compositions (Au₂₉SG₂₇, Au₃₀SG₂₈, Au₃₆SG₃₂, Au₃₉SG₃₅, Au₄₃SG₃₇) and discovered that they all emitted light at around 610 nm, therefore contradicting the traditional quantum confinement effect (QCE) mechanism. Through adjusting surface ligand coverage, the emission wavelength may be changed from 600 to 810 nm, demonstrating that surface-protective ligands are essential for modulating the photoluminescence of Au nanoclusters. Moreover, Au NCs with identical core atoms, while differing protective ligands exhibit diverse photoluminescent properties. These findings demonstrate that MNC photoemission is influenced by factors outside the metal core. Coordination ligands, surface metal atom valence states, and nanocluster formation morphologies may affect emission properties [37].

Ligand Effect

Stabilizing bare metal nanoclusters with organic/inorganic scaffolds and/or surface protective ligands was necessary because of their strong contacts and persistent aggregation to reduce surface energy. Silver

nanoclusters with few atoms are incubated in noble gas matrices, glasses, and zeolites. Nonetheless, the dimensions of solid matrices restrict their biological applicability. Dickson et al. developed a water-soluble dendrimer (PAMAM) scaffold in 2002 that served as templates for the encapsulation of organic MNCs. Since that time, template-assisted and ligand-induced etching have produced organic ligand-capped luminous MNCs. Figure 5 shows numerous solution-based MNC synthesis methods with different capping ligands. Luminescent MNCs are significantly influenced by synthesis parameters such as metal ion reduction, reactant ratio, and reaction temperature [38].

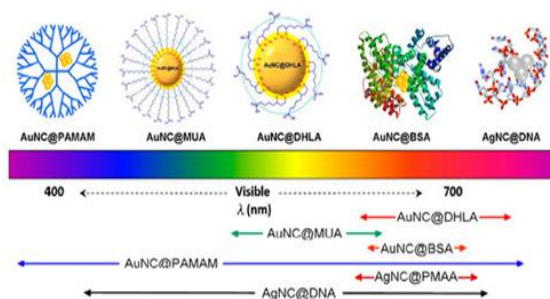


Figure 5. Representative luminous noble-metal nanoclusters scaled by emission wavelength across the spectrum. Current research reveal protected compounds can adjust metallic nanocluster emission wavelengths [39].

State-related metal valence photoemission

MNCs are bright due to their surface metal valence state, cluster size, and surface-capping ligands. Yang et al. found that glutathione-protected gold nanoparticles (GS-Au NPs) of the same size but different metal valence states

had different luminescence characteristics. GS-Au nanoparticles with a 2 nm core size lose luminescence after NaBH₄ treatment but keep their core size. The metal-centered quantum confinement effect (QCE) cannot explain this strange discovery if this is correct (precise dimensions). XPS confirmed that the brilliant gold nanoparticles' 40–50% gold(I) composition caused their distinctive optical properties. When stimulated at 420 nm, it produces orange colour at 565 nm for many microseconds. However, at 530 nm, it emits the same hue for nanoseconds [40].

Gold Nanoparticles: Photoemission and Plasmonic Properties

Nanocomposite thin films for nuclear medicine dosimetry and radiation detection need gold nanoparticles. Their high atomic number increases photon absorption via photoelectric interactions, improving radiation sensitivity. Polymeric or hybrid nanocomposite films with gold nanoparticles increase charge creation, energy transfer, and photoluminescence modulation. These enhance dose-response linearity and signal stability. Biomedical radiation sensors use biocompatible, chemically stable gold nanoparticles. For precise radiation monitoring, their configurable size and surface functions maximize optical and dosimetric performance.

9.0 Applications of Nanocomposite Thin Films in the Medical Field

Nanocomposite thin films have emerged as the most promising class of

functional materials in contemporary medicine in recent years. Nanocomposite thin films have been shown to have unique structural, electrical, optical, and mechanical characteristics and are thus seen as promising for use in various medical settings. In addition, nanoparticles within polymeric, metallic, or ceramic matrices have a combination of physical and chemical characteristics that are only rarely found in their constituent bulk materials or often difficult to detect. The thinness of the nanometer scale, morphology controllability, and the ability to interact selectively with biological systems or the target material make them useful for a variety of medical and biomedical applications, including diagnosis, treatment, biosensing, and radiation dosimetry. nanocomposite thin films are widely used in modern medicine for pace stile medicine based on real-time monitoring, high-precision surveillance, and proper treatment. With regard to radiation dosimetry and nuclear medicine, nanocomposite thin films have gained additional importance because they allow the measurement of ionizing radiation. Traditional dosimeters Thermoluminescence or Ionization Chamber system facing various measurement challenges that include a lack of spatial resolution and weak sensitivity. Some studies have also shown that common dosimeters have a lack of max charge collection, almost equal response, and Uniform [1, 41, 42].

New nanocomposite thin films can solve these problems and not only have

the uniform response but can also achieve the enhanced charge collection and design flexible, compact dosimeters. For example, nanoparticles of ZnO, TiO₂, and Al₂O₃ in polyvinyl alcohol or polymethyl methacrylate are highly sensitive to radiation. These materials have high atomic numbers and electron densities. When irradiated with X and gamma rays, they emit radiation signals that are photoluminescent or electrical and proportional to the ionizing dose. These composites fluoresce or produce electrical signals when they exposed to X-ray or gamma ray, due to the absorbed dose, offering high-dose resolution for diagnostic imaging and therapeutic administration [43].

In nuclear medicine, the applications of nanocomposite thin films have gone from monitoring to dose detection and imaging. Semiconducting nanostructures-based thin films, composed of CdS and ZnSe, or perovskite-based composites, have active photodetector and scintillator layers. Thus, radiation with high energy is converted to visible light. Detection sensitivity and resolution time are crucial for positron emission tomography and single-photon emission tomography imaging systems. Both parameters affect the image quality and diagnostic precision [44]. Furthermore, nanoparticle size and surface chemistry can be tailored to modulate optical absorption and emission properties, thereby enhancing detection efficiency and reducing background noise during clinical imaging. Another major medical application of nanocomposite thin films

is represented by biosensing and diagnostic platforms [45].

High surface-to-volume ratio promotes the immobilization of enzymes, antibodies, and nucleic acids on the surfaces of the nanocomposites to detect biomarkers of cancer, cardiovascular, and infectious diseases. Graphene oxide, carbon nanotube, or metal-oxide nanoparticle composites have been employed to fabricate electrochemical biosensors having ultralow detection limits and rapid response times [46]. Such thin films could transduce the interactions between biological molecules into measurable electrical or optical signals, enabling real-time and noninvasive diagnostics. The sensors have supported patient monitoring and point-of-care testing units in the hospital, for which portability, flexibility, and biocompatibility were required. Another significant application area was drug delivery systems and the production of antibacterial coatings. Thin films comprising silver, copper oxide, or zinc oxide nanoparticles have been deposited in medical devices, implants, and surgery tools to prevent bacterial colonization and biofilm formation. The controlled ion release from the thin films ensured long-term antibacterial effectiveness without affecting the structural properties of the substrate. Furthermore, polymer-based nanocomposite thin films containing biodegradable polymer matrices such as chitosan or polylactic acid could regulate degradation rates of the therapeutic drug at the interface location [47].

Next, nanocomposite films find a prevalence in engineering tissues owing to their mechanical flexibility and biocompatibility that allow the films to be integrated as isolator-scaffold structures or overcoats that enhance advanced cell attachment, spreading, and differentiation. In addition, osteoconductive bioactive nanofillers, such as hydroxyapatite or silica enhance and stimulate bone regeneration and integration, respectively thanks to incorporated drug conductive carbon nanomaterials maintain neural or myocardium healing. Consequently, each of the mentioned applications of medical nanocomposite thin films evidences a complete overlap of nano- and material science and biomedicine. The multi-functionality of nanocomposites permits them to detect, shield, and signal in a single miniaturized device. It is critical that technological improvements in coating films, such as sol-gel physical framework sputtering, and molecular self-assembly are primarily focused on guaranteeing the deenergization properties and commercial readiness. Finally, the increasing development of smart nanocomposite films is expected to be realized in combinative wearable adhesives, implantation dosimeters, and personalized therapeutic systems that will entirely transform the 21st century's nuclear medicine and well-being [48].

10.0 Challenges and Ethical Considerations, Future Perspectives

Despite significant advances in nanocomposite thin-film research,

major difficulties remain until these materials may be used clinically. Film repeatability and standardization are limited by nanoparticle size, surface charge, and matrix dispersion, which greatly impact photoluminescence and dosimetric sensitivity. Nanoscale interface instability and aggregation may cause uneven charge transfer and energy responsiveness under sustained irradiation. Nanocomposite materials' long-term biocompatibility is another issue. Nanoparticles' cytotoxicity, accumulation, and disintegration create ethical questions concerning patient safety, environmental impact, and waste management in medical and wearable systems. Responsible innovation requires transparent regulatory processes and extensive toxicity testing [49].

Since integrated radiation and health-monitoring systems may hold sensitive personal data, nanoscale dosimeters and smart biological sensors must respect privacy and data governance. Researchers and developers must combine technology innovation with biomedical ethics, informed consent, and international biosafety regulations [50].

Future research should concentrate on biofunctionalized and stretchy nanocomposite coatings that integrate with human tissue and flexible electronics. Tuneable optical responses and self-healing films are possible with advances in magnetron sputtering accuracy, plasma deposition control, and machine-learning-guided optimization. Hybrid quantum-dot–perovskite designs may improve radioluminescence efficiency for next-

generation imaging. Material science, medical physics, and computational modelling must be combined to turn nanocomposite thin films from laboratory prototypes into clinically validated, sustainable, and ethically compliant nuclear medicine and personalized healthcare devices.

4. Conclusion

The nanocomposite thin films represent a revolutionary material platform for radiation detection and medical dosimetry, offering outstanding sensitivity, flexibility, and reproducibility that render them alternative and more capable options compared to traditional dosimeters. Careful adjustment of nanoparticles' composition and film quality and deposition parameters can tailor luminescent and electrical characteristics to offer-driven diagnostic or therapeutic benefits. The application of ZnO, TiO₂, and perovskite nanostructures in polymer matrices has increased accuracy and robustness of detection in repeated instances of radiation exposure. We have finalized other additional applications, which include the advancement of these films into all-purpose biosensors and drug-releasing coatings. However, the creation of such coating development applications might need more investigation on the standardization of fabrication procedures, durability that is confirmed experimentally under biological situations, and biocompatibility discusses for implantable devices. In a constructive way, possible directions

for growth further include the development of stretchable or wearable dosimeters that may safely connect to smart monitoring and health systems. Furthermore, researchers must resolve the absence of reproducibility and the interpretation of signal and assess if these nanocomposite thin films, which are presently an investigational laboratory prototype, turn out to be clinically validated and regulatory commercial instrument for nuclear medicine and radiotherapy.

References:

- [1] S. Sakthinathan *et al.*, "A review of thin-film growth, properties, applications, and future prospects," *Processes*, vol. 13, no. 2, p. 587, 2025.
- [2] A. G. Memon, A. S. Giwa, and J. Ahmad, "Nanotechnology and thin films: explores nanoscale thin films, nanocomposites, nanoparticles, and their application," in *Thin Films and Coatings: Engineering Applications*: Springer, 2025, pp. 187-215.
- [3] E. Aboelezz and B. W. Pogue, "Review of nanomaterial advances for ionizing radiation dosimetry," *Applied Physics Reviews*, vol. 10, no. 2, 2023.
- [4] B. A. El-Badry, G. Khouqeer, and M. Zaki, "Gamma rays induced modifications in the structural, optical and photoemission properties of PVA/TiO₂ nanocomposite films," *Physica Scripta*, vol. 98, no. 2, p. 025821, 2023.
- [5] A. Abd El-Lateef, M. Zaki, and S. I. Elkalashy, "Physical insight in thermophysical features of gamma-irradiated PVA/Al₂O₃ films," *Journal of Materials Science: Materials in Electronics*, vol. 36, no. 9, pp. 1-18, 2025.
- [6] R. Saha, M. H. Munshi, M. Akter, A. A. R. Shikder, and T. Islam, "Synthesis techniques, fundamental properties, and emerging applications of nanocomposites: A comprehensive review," *SPE Polymers*, vol. 6, no. 2, p. e70004, 2025.
- [7] D. K. Aswal and A. Chandra, "Ionizing Radiation Measurements," in *Handbook on Radiation Environment, Volume 2: Dose Measurements*: Springer, 2024, pp. 1-17.
- [8] H. Kawamoto, M. Koshimizu, Y. Fujimoto, and K. Asai, "Radiophotoluminescence behavior in Ag-doped phosphate glasses," *Japanese Journal of Applied Physics*, vol. 62, no. 1, p. 010501, 2022.
- [9] G. Okada, "Novel radiophotoluminescence materials and applications," *Journal of the Ceramic Society of Japan*, vol. 129, no. 7, pp. 419-424, 2021.
- [10] B. Intakhab and M. Maqbool, "Types of Non-Ionizing Radiation and its Interaction with Matter," in *An Introduction to Non-Ionizing Radiation*: Bentham Science Publishers, 2023, pp. 21-37.
- [11] M. Alvandi, R. N. Javid, Z. Shaghaghi, S. Farzipour, and S. Nosrati, "An in-depth analysis of the adverse effects of ionizing radiation exposure on cardiac catheterization staffs," *Current Radiopharmaceuticals*, vol. 17, no. 3, pp. 219-228, 2024.

- [12] K. Apte and S. Bhide, "Basics of radiation," in *Advanced radiation shielding materials*: Elsevier, 2024, pp. 1-23.
- [13] S. V. Mathan, M. Rajput, and R. P. Singh, "Chemotherapy and radiation therapy for cancer," in *Understanding cancer*: Elsevier, 2022, pp. 217-236.
- [14] S. Xiong and D. Liang, "High-temperature diffusion behavior, wear-resistance and corrosion-resistance properties of Al₂O₃, MoS₂, and ZnO nanoparticles on copper surfaces," *Surfaces and Interfaces*, vol. 58, p. 105840, 2025.
- [15] R. D. Prasad *et al.*, "A review on modern characterization techniques for analysis of nanomaterials and biomaterials," *ES Energy & Environment*, vol. 23, p. 1087, 2024.
- [16] M. D. Salman, Y. M. Radzi, A. A. Rahman, A. A. Oglat, and M. A. Dheyab, "Advancements and applications of dosimetry techniques in modern medical radiation therapy: a comprehensive review," *Journal of Radioanalytical and Nuclear Chemistry*, vol. 333, no. 8, pp. 3713-3737, 2024.
- [17] F. Gao *et al.*, "Effects of ultra-high dose rate radiotherapy with different fractions and dose rate on acute and chronic lung injury in mice," *Heliyon*, vol. 10, no. 22, 2024.
- [18] M. Boogari, H. Mozdarani, A. Mahmoudzadeh, and A. Ebrahimi, "Identification of radiation-sensitive genes as biomarkers for biodosimetry: an ex vivo analysis of TNFRSF10B, ZMAT3, POLH, and PLK2 in human blood samples," *BMC Medical Genomics*, vol. 18, no. 1, pp. 1-14, 2025.
- [19] K. Brzóska, M. Abend, G. O'Brien, E. Gregoire, M. Port, and C. Badie, "Calibration curve for radiation dose estimation using FDXR gene expression biodosimetry—premises and pitfalls," *International Journal of Radiation Biology*, vol. 100, no. 8, pp. 1202-1212, 2024.
- [20] S. F. Alhujaili *et al.*, "Radiation dose assessment and establishment of diagnostic reference levels for MDP Tc-99m bone scans: A multi-hospital study in Saudi Arabia," *Applied Radiation and Isotopes*, vol. 218, p. 111695, 2025.
- [21] A. M. Brunt *et al.*, "Patient-and clinician-assessed five-year normal tissue effects following one-week versus three-week axillary radiotherapy for breast cancer: Results from the phase III FAST-Forward trial randomised nodal sub-study," *Radiotherapy and Oncology*, p. 110915, 2025.
- [22] Y. F. Ali, I. M. Hassan, H. M. Abdelhafez, and O. S. Desouky, "0.5 Gy confers resistance to a subsequent high dose of γ -rays by modulating HO-1/Nrf2 and apoptosis pathways," *Scientific Reports*, vol. 15, no. 1, p. 9199, 2025.
- [23] C. Sakai *et al.*, "Transcriptomic Profiling in Mycobacterium avium Complex Pulmonary Disease Identifies Clusters Linked to Disease Severity and Neutrophil Activation," *American Journal of Respiratory and Critical Care Medicine*, no. ja, 2025.

- [24] O. Gal, M. P. Mehta, and R. Kotecha, "Radiotherapeutic advances in the management of glioblastoma," *Journal of Neuro-Oncology*, vol. 170, no. 3, pp. 509-520, 2024.
- [25] M. M. Patel, B. E. Adrada, M. S. Guirguis, G. Whitman, T. W. Moseley, and G. M. Rauch, "Current Concepts in Molecular Breast Imaging," *Journal of Breast Imaging*, vol. 7, no. 1, pp. 104-118, 2025.
- [26] X. Liu, K.-W. Li, R. Yang, and L.-S. Geng, "Review of deep learning based automatic segmentation for lung cancer radiotherapy," *Frontiers in oncology*, vol. 11, p. 717039, 2021.
- [27] P. S. Sundaram, P. Subramanyam, and G. Dinesh Kumar, "The Role of Nuclear Medicine in Thyroid and Parathyroid Disorders," in *Surgical Management of Thyroid and Parathyroid Diseases*: Springer, 2024, pp. 209-242.
- [28] Y. M. Aye, "Local diagnostic reference level at Nuclear Medicine Centers in Thailand and Myanmar," 2024.
- [29] D. Bidwai, N. K. Sahu, S. Dhoble, A. Mahajan, D. Haranath, and G. Swati, "Review on long afterglow nanophosphors, their mechanism and its application in round-the-clock working photocatalysis," *Methods and Applications in Fluorescence*, vol. 10, no. 3, p. 032001, 2022.
- [30] S. Ahmad, I. Ashraf, M. A. Mansoor, S. Rizwan, and M. Iqbal, "An overview of recent advances in the synthesis and applications of the transition metal carbide nanomaterials," *Nanomaterials*, vol. 11, no. 3, p. 776, 2021.
- [31] S. Rubin, D. Mizrahi, N. Friedman, H. Edri, and T. Golan, "The world of advanced thin films: design, fabrication, and applications," *Fusion of Multidisciplinary Research, An International Journal*, vol. 4, no. 1, pp. 393-406, 2023.
- [32] P. Borowski and J. Myśliwiec, "Recent advances in magnetron sputtering: From fundamentals to industrial applications," *Coatings*, vol. 15, no. 8, p. 922, 2025.
- [33] L. Y. Beliaev, E. Shkondin, A. V. Lavrinenko, and O. Takayama, "Optical, structural and composition properties of silicon nitride films deposited by reactive radio-frequency sputtering, low pressure and plasma-enhanced chemical vapor deposition," *Thin Solid Films*, vol. 763, p. 139568, 2022.
- [34] M. Pattabi and R. M. Pattabi, "Photoluminescence from gold and silver nanoparticles," *Nano Hybrids*, vol. 6, pp. 1-35, 2014.
- [35] T. M. S. Ashrafi and G. Mohanty, "Surface plasmon resonance sensors: a critical review of recent advances, market analysis, and future directions," *Plasmonics*, pp. 1-21, 2025.
- [36] H. Jin, J. M. Kahk, D. A. Papaconstantopoulos, A. Ferreira, and J. Lischner, "Plasmon-induced hot carriers from interband and intraband transitions in large noble metal nanoparticles," *PRX Energy*, vol. 1, no. 1, p. 013006, 2022.

- [37] M. H. Naveen, R. Khan, and J. H. Bang, "Gold nanoclusters as electrocatalysts: Atomic level understanding from fundamentals to applications," *Chemistry of Materials*, vol. 33, no. 19, pp. 7595-7612, 2021.
- [38] F. H. Haghighi *et al.*, "Surface modification of TiO₂ nanoparticles with organic molecules and their biological applications," *Journal of Materials Chemistry B*, vol. 11, no. 11, pp. 2334-2366, 2023.
- [39] M. F. Matus and H. Häkkinen, "Understanding ligand-protected noble metal nanoclusters at work," *Nature Reviews Materials*, vol. 8, no. 6, pp. 372-389, 2023.
- [40] J. Yang, F. Yang, C. Zhang, X. He, and R. Jin, "Metal nanoclusters as biomaterials for bioapplications: atomic precision as the next goal," *ACS Materials Letters*, vol. 4, no. 7, pp. 1279-1296, 2022.
- [41] T. Hassan *et al.*, "Functional nanocomposites and their potential applications: A review," *Journal of Polymer Research*, vol. 28, no. 2, p. 36, 2021.
- [42] S. Sharma, P. Sudhakara, A. A. B. Omran, J. Singh, and R. Ilyas, "Recent trends and developments in conducting polymer nanocomposites for multifunctional applications," *Polymers*, vol. 13, no. 17, p. 2898, 2021.
- [43] P. Dhatarwal and R. Sengwa, "Poly (vinyl pyrrolidone) matrix and SiO₂, Al₂O₃, SnO₂, ZnO, and TiO₂ nanofillers comprise biodegradable nanocomposites of controllable optical properties for optoelectronic applications," *Optik*, vol. 241, p. 167215, 2021.
- [44] I. Roy, S. Krishnan, A. V. Kabashin, I. N. Zvestovskaya, and P. N. Prasad, "Transforming nuclear medicine with nanoradiopharmaceuticals," *ACS nano*, vol. 16, no. 4, pp. 5036-5061, 2022.
- [45] J. Boo, I. H. Han, and G. Kim, "Nanocomposite Radiation Detectors for Gamma-Ray Spectroscopy," *Journal of Radiation Protection and Research*, vol. 50, no. 2, pp. 63-90, 2025.
- [46] A. Ayoib, "Hybrid Nanomaterials in Biosensors for Advanced Point-of-Care Diagnostics: DNA-, Enzyme-, or Immunosensor-Based, for Healthcare," in *Hybrid-Nanomaterials: Fabrication, Characterization and Applications*: Springer, 2024, pp. 123-153.
- [47] T.-H. Tsung, Y.-C. Tsai, H.-P. Lee, Y.-H. Chen, and D.-W. Lu, "Biodegradable polymer-based drug-delivery systems for ocular diseases," *International journal of molecular sciences*, vol. 24, no. 16, p. 12976, 2023.
- [48] J. Ghosh, N. S. Rupanty, T. Noor, T. R. Asif, T. Islam, and V. Reukov, "Functional coatings for textiles: advancements in flame resistance, antimicrobial defense, and self-cleaning performance," *RSC advances*, vol. 15, no. 14, pp. 10984-11022, 2025.
- [49] J. Nambi Krishnan, K. R. Venkatachalam, O. Ghosh, K. Jhaveri,

A. Palakodeti, and N. Nair, "Review of thin film nanocomposite membranes and their applications in desalination," *Frontiers in Chemistry*, vol. 10, p. 781372, 2022.

[50] A. Rana, D. Gautam, P. Kumar, and A. K. Das, "Architectures, Benefits, Security, and Privacy Issues of Internet of Nano Things: A Comprehensive Survey, Opportunities, and Research Challenges," *IEEE Communications Surveys & Tutorials*, vol. 27, no. 2, pp. 1152-1190, 2024.