



Iron Oxide–Epoxy Resin Nanocomposites for Electromagnetic Interference and Ionizing Radiation Shielding in Modern Hospitals: A Patent Review

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Abstract

This review evaluates the patent landscape concerning iron oxide-reinforced epoxy resin nanocomposites to address the dual necessity for electromagnetic interference mitigation and ionizing radiation attenuation within high-tech clinical environments (Khalil et al., 2024; Orasugh & Ray, 2023). As medical facilities become increasingly saturated with sensitive diagnostic equipment and wireless communication systems, the proliferation of electromagnetic interference may pose risks to device operational reliability and diagnostic accuracy (Dassan et al., 2020; Ma et al., 2024). Simultaneously, the integration of high-energy diagnostic modalities may necessitate advanced shielding solutions to mitigate the risks associated with ionizing radiation exposure for both patients and staff (Bawazeer et al., 2023). By synthesizing patent data, this analysis suggests that the synergy between high-permeability iron oxide particles and the structural versatility of epoxy resins offers a robust framework for developing multifunctional, lightweight protection (Ayub et al., 2021; Reddy & Bharath., 2024). This synthesis highlights the material design criteria required to suppress electromagnetic disruption—which can impair critical clinical apparatus and affect sensitive biological organs (Bora et al., 2020; Srivastava & Manna, 2022)—while simultaneously addressing the stringent safety protocols inherent in radiation-intensive diagnostic settings (Bawazeer et al., 2023). Furthermore, the integration of these materials may help address the growing challenge of electromagnetic pollution, which can compromise the operational integrity of life-critical electronic systems within hospital infrastructure (G.M. et al., 2024; Lopes et al., 2023).

Keywords: Fe₃O₄ nanoparticles, Epoxy nanocomposites, Electromagnetic interference shielding, X-ray shielding, Gamma-ray attenuation, Lead-free shielding materials, Multifunctional composites, Patent analysis.

1. Introduction

The proliferation of sophisticated diagnostic and therapeutic electronic equipment in clinical environments may have intensified the need for advanced electromagnetic interference mitigation to prevent device malfunction and potential health risks to patients (Fallah et al., 2021; Lee et al., 2022). Furthermore, the integration of iron-based nanofillers into epoxy matrices may offer a dual-functional approach, leveraging both magnetic and dielectric loss mechanisms to attenuate high-frequency radiation (Shukla, 2019). In addition to these electromagnetic shielding properties, the high electron density of iron oxide nanoparticles may provide substantial attenuation capabilities against ionizing radiation, addressing a critical safety requirement for radiology and nuclear medicine departments (Gan et al., 2026). This systematic review examines relevant patent literature to categorize the morphological optimization and filler dispersion techniques essential for enhancing the structural integrity and shielding efficacy of these multifunctional nanocomposites (Ribadeneyra et al., 2014). By synthesizing recent intellectual property landscape trends, this analysis identifies critical design parameters that may facilitate the transition of these materials from laboratory prototypes to scalable, high-performance protective barriers in clinical settings (Qi et al., 2025). Specifically, this analysis evaluates the implementation of dual-filler synergy and interfacial engineering

strategies designed to maintain mechanical resilience while maximizing the attenuation efficiency of the epoxy-based composite systems (Song et al., 2022).

Iron oxide–epoxy nanocomposites draw upon the inherent magnetic susceptibility and chemical stability of iron oxide, which, when dispersed within an epoxy resin, may create a lightweight, corrosion-resistant, and mechanically robust shielding solution (Song et al., 2022). Beyond these attributes, such nanocomposites provide a tunable dielectric platform that can be optimized to address the increasing challenge of electromagnetic pollution in signal-sensitive clinical environments (Abbasi et al., 2019), (Zecchi et al., 2024). Moreover, the strategic utilization of metal oxides like iron oxide may serve as a cost-effective alternative to precious metal fillers while maintaining superior permeability for enhanced wave absorption (Fallah et al., 2026). Recent studies have further highlighted the capacity of these fillers to achieve homogeneous distribution, which minimizes interfacial voids and prevents the structural degradation often observed in traditional heavy-metal shielding aprons (Bawazeer et al., 2023; Khalil et al., 2024). Furthermore, the synergistic combination of iron oxide with carbon-based nanofillers appears to demonstrate an enhanced ability to fill internal micro-voids, thereby significantly increasing the material's overall gamma-ray attenuation coefficient and mechanical load-bearing capacity (Khalil et al., 2024). By incorporating these high-aspect-ratio fillers, researchers have successfully mitigated the characteristic brittleness of neat resins, thereby facilitating the development of lightweight, flexible shielding materials suitable for wearable clinical protection (Gouda et al., 2024). Current research emphasizes that achieving such uniformity may be vital, as filler agglomeration in epoxy matrices often precipitates stress concentrations that compromise both structural adhesion and radiation attenuation performance (Chen et al., 2025). To address this, recent innovations focus on optimized filler loading thresholds, where configurations containing 1–2 wt% of iron oxide have been shown to maximize fiber-matrix interfacial bonding and structural stiffness (Shivamurthy et al., 2025).

While academic literature frequently catalogs the theoretical performance of shielding materials, practical engineering constraints and commercial processing methodologies may be necessary for clinical implementation. Specifically, essential fabrication parameters—such as curing kinetics and agent compatibility—may shape the large-scale manufacturing viability and cost-effectiveness of radiation-shielding barriers in hospital infrastructure. These documents may clarify the shift from hazardous lead-based protections toward sustainable, polymer-metal alternatives that maintain superior workability and thermochemical stability (Prabhu et al., 2022), (Abdel-Kader et al., 2024). Additionally, these intellectual property disclosures underscore the transition toward hybrid filler architectures, which utilize particle orientation and spatial distribution control to overcome the traditional trade-offs between shielding efficiency and material mass (Chang et al., 2023). These advancements may further elucidate the technical pathways for improving photon and neutron attenuation by manipulating the nanoparticle surface chemistry and morphology (Chen et al., 2025).

This review aims to categorize emerging patent-protected fabrication strategies that balance shielding efficiency with the practical demands of clinical architecture and wearable design. This assessment specifically highlights how recent advancements in polymer-based composites may address the limitations of traditional heavy-metal alternatives by offering lightweight, flexible, and non-toxic configurations (Safari et al., 2024; Wu et al., 2024). This synthesis further evaluates the integration of multi-functional fillers that, beyond iron oxide, incorporate elements such as bismuth and tungsten to optimize photon attenuation within the dense polymeric matrix (Abushahla & Arslan, 2025; Li et al., 2025). Furthermore, this evaluation explores how interfacial modifiers are utilized to enhance compatibility between inorganic fillers and the epoxy matrix, thereby mitigating the risk of structural defects during high-volume production (Kim, 2026). Finally, the review synthesizes data on long-term chemical degradation and thermal resistance profiles to assess whether these composite materials meet the rigorous safety standards required for permanent installation within high-energy clinical infrastructure (Li et al., 2025; Saiyad & Devashrayee, 2020).

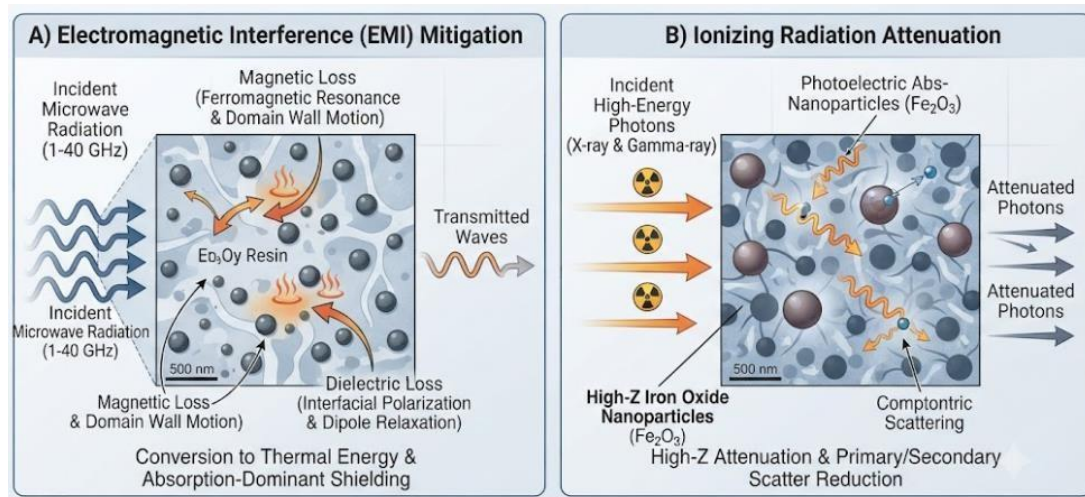


Figure 1: Dual-mechanism shielding schematic for iron oxide-epoxy resin nanocomposites

2. Methodology

2.1. Shielding Demands in the Hospital Environment

Modern diagnostic and therapeutic modalities, ranging from X-ray imaging to high-energy linear accelerators, may necessitate precise shielding to mitigate the risks of stochastic biological damage caused by photon and neutron emission (Li et al., 2025). Given these diverse emission profiles, protective barriers are expected to demonstrate both high-Z absorption capabilities for diagnostic X-rays and hydrogen-rich matrices to moderate neutron flux (Arslonova et al., 2026; Mehrara et al., 2021). The incorporation of iron oxide nanoparticles within these matrices may further enhance the overall mass attenuation coefficient, providing a multifaceted barrier against high-energy ionizing radiation (Khalil et al., 2024). Simultaneously, the high electrical conductivity and permeability of these iron-oxide-reinforced composites may facilitate the suppression of electromagnetic interference, effectively isolating signal-sensitive medical instrumentation from the high-frequency emissions of diagnostic and therapeutic hardware (Shukla, 2019). This duality of function may address the critical need to maintain both operational integrity for sensitive electronics and patient safety in complex radiation environments (Ahmad et al., 2023). Furthermore, the demand for adaptable shielding geometries has prompted the exploration of additive manufacturing techniques, which may allow for the customization of composite architectures to suit the spatial constraints of clinical facilities (Arslonova et al., 2026).

Precision medical devices, such as magnetic resonance imaging (MRI) and electroencephalography units, are increasingly susceptible to signal distortion induced by high-frequency electromagnetic noise, which may compromise diagnostic accuracy and operational reliability (Krakow et al., 2000). By integrating iron oxide nanoparticles, these composites may offer a dual-action shielding mechanism that effectively attenuates both electromagnetic leakage and the ionizing emissions prevalent in contemporary clinical environments (Ahmad et al., 2023). Furthermore, these advanced materials may provide a critical defense against both primary ionizing radiation and secondary scatter, significantly enhancing safety protocols near high-energy equipment (Al-Saleh et al., 2023; Zolochovska et al., 2025). Moreover, the frequency-dependent magnetic properties of these iron-based nanocomposites may enable the targeted absorption of microwave and radio-frequency noise, which is essential for preserving the signal-to-noise ratio in sensitive imaging diagnostics (Zolochovska et al., 2025). Consequently, the deployment of such nanocomposites mitigates the risks associated with electromagnetic interference, ensuring that high-resolution data acquisition remains uncompromised by the ubiquitous radiation fields characterizing modern healthcare facilities (Sayed & Falsafi, 2025; Shabib et al., 2026).

The regulatory and standards landscape evaluates current composite formulations in relation to safety requirements. This necessitates rigorous validation of attenuation coefficients to ensure materials can withstand long-term exposure to both gamma-ray active isotopes and pervasive electromagnetic pollution (Cheng et al., 2022; Hashim et al., 2019). Furthermore, recent research is focused on the standardization of accelerated aging protocols, which simulate decades of radiation-induced polymer degradation to predict the service life of shielding components in permanent clinical installations (Jayakumar et al., 2023; Shabib et al., 2026). Developers are focusing on enhancing shielding material reliability to address the practical, life-critical requirements for sensitive digital medical devices prone to EMI-induced malfunctions (Jones et al., 2024).

Beyond standard benchmarks, current patent literature appears to underscore the transition toward absorption-dominant shielding geometries, which minimize secondary radiation reflection that could otherwise exacerbate interference in confined diagnostic suites (Isari et al., 2024).

2.2. Composite Materials

The mechanical resilience and dielectric performance of these matrices appear to be largely dictated by the morphology and functionalization of the nanofiller dispersion within the epoxy host (Kruželák et al., 2020). Optimizing the filler-to-matrix interface may remain critical, as interfacial interactions between magnetic nanoparticles and the polymer chain network may contribute to enhanced electrical insulation and structural stability (Zhou et al., 2024). Recent advancements have shifted focus toward engineered architectures, such as isolated or double percolation structures, which may minimize the required filler volume while concurrently augmenting the electromagnetic interference shielding effectiveness (Yang et al., 2023). Additionally, tailoring the surface morphology and alignment of magnetic nanoparticles may allow for precise tuning of resonant frequencies, which may facilitate the targeted attenuation of specific electromagnetic bands prevalent in high-density clinical environments (Wei et al., 2024). Furthermore, the encapsulation of these magnetic fillers within the epoxy matrix may effectively sequester reactive sites from environmental moisture and oxygen, thereby potentially supporting long-term chemical stability and shielding durability under the rigorous conditions of clinical operation (Nan et al., 2023).

Advanced processing techniques, such as solution casting and high-shear mixing, may be used to promote a homogeneous nanoparticle distribution and prevent the formation of agglomerates that otherwise compromise the shielding efficiency of the epoxy host (Abbasi et al., 2019). Specifically, the adoption of additive manufacturing and injection molding may enable the creation of complex, uniform geometries that maintain consistent dielectric properties across entire shielding structures (Liu et al., 2023). Moreover, employing controlled synthesis pathways, such as the use of yolk-shell microspheres, may further promote interfacial polarization and internal scattering, which are vital for achieving absorption-dominated shielding (Sushmita et al., 2020). In addition to morphological control, integrating secondary conductive fillers, such as carbon nanotubes, can further optimize complex permeability and permittivity, potentially creating synergistic effects that may broaden the absorption bandwidth for enhanced interference mitigation (Musa et al., 2025; Si et al., 2026). Such hierarchical filler networks may facilitate the dissipation of electromagnetic energy through interfacial polarization and enhanced conductive pathways, potentially minimizing signal propagation within the composite medium (Yan et al., 2025).

2.3. Shielding Mechanisms

Electromagnetic interference shielding mechanisms appear to rely substantially on the synergistic combination of magnetic loss and dielectric loss to convert incident electromagnetic waves into thermal energy (Chhetri & Kuila, 2024). This transformation process is facilitated by the high surface-to-volume ratio of iron oxide nanostructures, which may amplify interfacial polarization and dipole losses within the polymer dielectric (Keykavous-Amand & Peymanfar, 2021). Furthermore, the high-frequency magnetic resonance inherent in these nanostructures may promote the conversion of electromagnetic signals into thermal dissipation, thereby attenuating interference through absorption rather than reflection (Mai et al., 2024). By incorporating hierarchical core-shell structures or conductive networks, these composites can further exploit multiple internal reflections to enhance attenuation efficiency across a wider frequency spectrum (Mikinka & Siwak, 2021). Concurrently, the integration of ferromagnetic nanoparticles into these structures enables magnetic-dielectric synergy, which may contribute to optimizing impedance matching and maximizing the attenuation of incident radiation (Che et al., 2025).

Ionizing radiation attenuation mechanisms appear to depend primarily on the photoelectric effect and Compton scattering (Kara et al., 2019), where the high atomic number of iron oxide components may attenuate X-ray and gamma-ray photons by increasing the interaction cross-section within the epoxy matrix. Specifically, the high electron density of these metal oxide inclusions facilitates primary photon attenuation, while the homogeneous dispersion within the polymer prevents the formation of radiation leakage channels (Khalil et al., 2024). Moreover, the strategic incorporation of heterogeneous interfaces within the nanocomposite architecture may promote multiple scattering events, thereby enhancing the total attenuation capacity (Qi et al., 2025). Furthermore, the precise tuning of nanoparticle concentration within the epoxy lattice may enable optimization of the attenuation constant, facilitating a balance between structural shielding integrity and the weight-sensitive requirements of portable medical imaging equipment (Khalil et al., 2024).

By leveraging the saturation properties of magnetite, these composites may facilitate energy dissipation even in compact configurations (Hosseini et al., 2021). Beyond these resonance-based effects, the unique morphology of iron oxide nanoparticles may induce scattering of incident waves (Qi et al., 2025).

The integration of both magnetic-dielectric absorption and high-Z photon attenuation into a singular material framework may enable the simultaneous mitigation of broad-spectrum electromagnetic noise and ionizing radiation risks common in diagnostic suites (Dhand et al., 2024). This multifunctional approach leverages the balance of complex permittivity and permeability to promote impedance matching, which may facilitate electromagnetic-wave entry into the composite medium and substantial attenuation (Cakir et al., 2026; Wang et al., 2023). Moreover, by incorporating high-atomic-number nanoparticles such as tungsten or bismuth oxides alongside iron-based fillers, these composites may exhibit enhanced photoelectric absorption for low-energy X-ray photons while maintaining robust EMI performance (Sayyadi et al., 2021). Such hierarchical filler architectures allow for the customization of attenuation properties through precise control of volume fractions and filler dispersion, which may be critical to mitigating both electromagnetic signals and ionizing radiation in high-density clinical settings (Dhand et al., 2024). Furthermore, the utilization of ferromagnetic resonance frequency tuning allows for the expansion of shielding effectiveness across multiple frequency bands, thereby addressing the complex spectral requirements of modern diagnostic equipment (Lee et al., 2023).

2.4. Patent Landscape

The researchers identified relevant intellectual property through systematic queries of the USPTO and Espacenet databases, utilizing keywords focused on "iron oxide," "epoxy," "shielding," and "nanocomposite" alongside specific patent classification codes for electromagnetic shielding and radiation protection. This search was further refined by filtering for applications specifically targeting medical imaging environments and electronic signal integrity within hospital facilities. The analysis further synthesized trends in filing patterns, emphasizing the transition toward high-performance hybrid composites that prioritize both dielectric loss and structural integration. Recent filings indicate a growing focus on the optimization of nanoparticle morphology and surface functionalization to enhance filler-matrix compatibility, which is crucial for achieving superior mechanical robustness without compromising shielding efficacy. Additionally, these patent disclosures increasingly emphasize the development of multifunctional, lightweight material architectures that demonstrate improved wearability and mechanical stability in demanding clinical infrastructure.

The current patent landscape suggests a strategic emphasis on the synergistic hybridization of Fe₃O₄ nanoparticles with carbonaceous fillers, such as carbon black or multi-walled carbon nanotubes, to achieve superior electromagnetic attenuation while ensuring compatibility with epoxy matrices (Kolanowska et al., 2017; Sparavigna, 2023). These disclosures appear to highlight the strategic tuning of nanoparticle volume fractions to manipulate complex permittivity and permeability, thereby enabling frequency-selective shielding performance across the microwave spectrum (Chang et al., 2021; Sparavigna, 2023). Furthermore, recent intellectual property filings indicate the emergence of "tunable" shielding mechanisms, where the structural arrangement of magnetic nanospheres and carbon-based reinforcements allows the composite to alternate between absorption-dominant and reflection-dominant modes depending on the intended clinical application (Sparavigna, 2023). Additionally, several patents describe methods for hierarchical layer-by-layer fabrication, which facilitates the creation of functionally graded composites (Choi et al., 2021). These multilayered configurations may address the complex interaction between wave propagation and material architecture, as recent investigations suggest that structured assembly significantly enhances directional attenuation properties, with potential applications in sensitive environments such as clinical settings (Paul & Rajan, 2026; Xue et al., 2021).

The temporal distribution of patent grants appears to reveal an acceleration in recent years, reflecting the industry's pivot toward integrating multifunctional nanocomposites into next-generation telecommunications and diagnostic infrastructure (Dassan et al., 2020; Orasugh et al., 2024). This upward trajectory in intellectual property activity may indicate a concerted effort to transcend traditional shielding limitations by exploiting the synergistic benefits of high-aspect-ratio nanomaterials and advanced magnetic fillers (Xiang et al., 2021). Furthermore, research indicates that the long-term durability of these shielding composites is being bolstered by the integration of protective organic matrices, which mitigate the degradation of conductive networks typically caused by oxidation or exposure to harsh environmental conditions (Zou et al., 2021). These advancements in material stability are further complemented by patent designs that utilize surface-grafting techniques to improve the interfacial adhesion between iron oxide fillers and the epoxy matrix, thereby

potentially limiting filler agglomeration and supporting consistent attenuation performance (Wang et al., 2026). Looking forward, patent strategies are increasingly prioritizing the development of eco-friendly, energy-efficient production processes to support the alignment of these high-performance materials with broader sustainability standards in clinical infrastructure (Orasugh et al., 2024).

The synthesis of these intellectual property disclosures appears to indicate a shift from passive, singular-shielding fillers to sophisticated, absorption-dominant systems that address the challenges of high-frequency radiation (Jiang et al., 2019; Park et al., 2024). By shifting the design focus toward internal impedance matching, these systems may minimize parasitic reflection while potentially maximizing attenuation through controlled energy dissipation mechanisms (Cheng et al., 2022; Ma et al., 2021). Consequently, these engineered composites leverage synergistic magnetic and dielectric losses to mitigate the broad-spectrum electromagnetic pollution prevalent in densely equipped hospital environments (Cakir et al., 2026). This transition towards multifunctional materials may not only enhance the protection of sensitive diagnostic instrumentation but also facilitate the integration of lightweight, radiation-attenuating components within existing clinical architecture (Kumari et al., 2024; Srivastava & Manna, 2022). Furthermore, the integration of these materials aligns with the urgent need to mitigate electromagnetic pollution and improve the operational reliability of advanced diagnostic systems, which are increasingly susceptible to signal disruption in high-density clinical environments (Cheng et al., 2025; Lv et al., 2024).

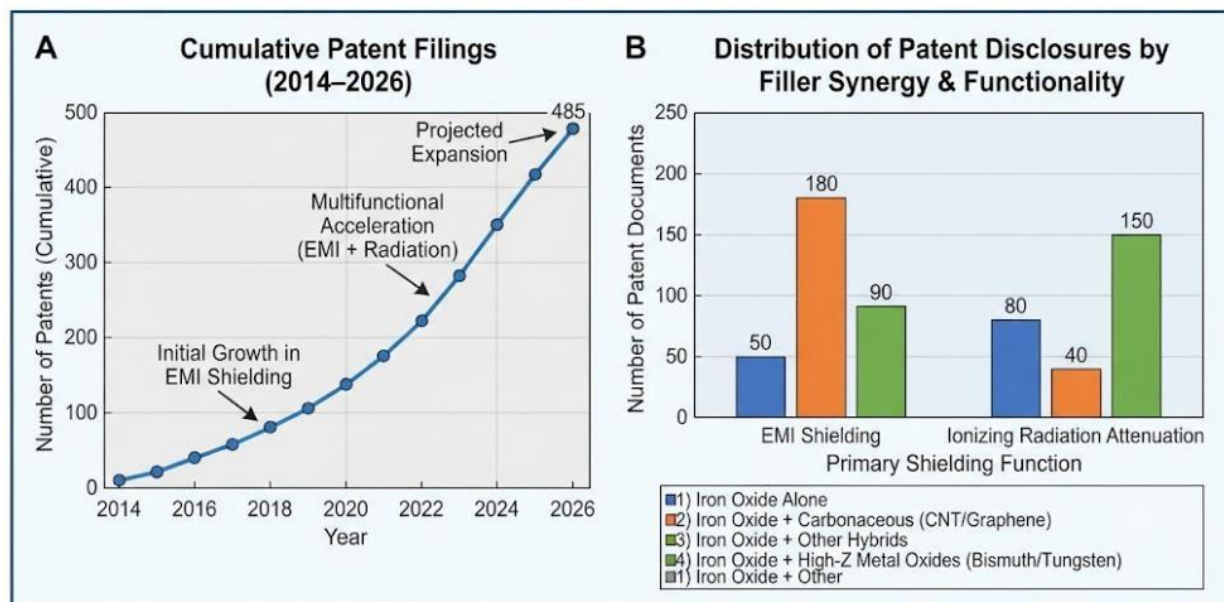


Figure 2: Patent landscape trends & timeline for multifunctional nanocomposites (2014-2026)

2.5. Hospital Applications

Diagnostic imaging and nuclear medicine environments may require advanced shielding solutions to decouple sensitive detection apparatus from high-frequency interference generated by peripheral wireless communication systems (Bora et al., 2020). To address these challenges, current intellectual property strategies are exploring the deployment of iron oxide–epoxy nanocomposites as structural overlays that mitigate both electromagnetic interference and ionizing radiation leakage, thereby potentially supporting the precision of high-resolution diagnostic imaging (Khalil et al., 2024). Moreover, the incorporation of functional particles within these matrices may provide dual-action protection, effectively attenuating ionizing emissions while simultaneously dissipating the thermal load generated by high-performance diagnostic circuitry (Tang et al., 2025). Beyond these structural benefits, the adoption of such materials in surgical suites may help secure medical-grade wireless connectivity, essential for the reliability of telemedicine and real-time robot-assisted operations (Lopes et al., 2023), (Shi et al., 2024). These dual-functional materials may additionally help mitigate potential health risks associated with chronic exposure to ambient electromagnetic radiation, a critical concern as medical facilities transition toward hyper-connected diagnostic ecosystems (He et al., 2021).

In EMI-sensitive zones, the deployment of iron oxide–epoxy composites may reduce the risk of device malfunctions caused by electromagnetic interference (Posada et al., 2020). By tailoring the magnetic loss characteristics of the iron oxide fillers, these materials may facilitate effective broadband absorption, which is critical for maintaining the operational integrity of life-critical electronic devices (Raveendran et al., 2019). Such structural integration may further limit signal degradation within electromagnetic-sensitive

communication channels, thereby reducing the risk of performance failure in process control and monitoring equipment (Dai et al., 2022; Saini & Aror, 2012). Furthermore, the deployment of these nanocomposites may create localized quiet zones that stabilize the performance of high-precision sensors, thereby mitigating the risk of data inaccuracies that often arise from extraneous environmental electromagnetic noise (Filipović et al., 2025; Kumar et al., 2021). These sophisticated magnetic polymer composites, by effectively suppressing interference, may enhance the reliability of medical diagnostics and may represent a significant advance in addressing the growing challenge of electromagnetic pollution in modern healthcare facilities (Idumah, 2021).

Recent research details the fabrication of lightweight, conformable shielding barriers that integrate magnetic nanofillers within flexible epoxy substrates to protect portable health-monitoring devices from ambient electromagnetic pollution (Zhou et al., 2023). These flexible architectures appear to utilize the inherent mechanical durability of the polymer matrix to maintain shielding effectiveness despite frequent bending and wear (Zhang et al., 2023). These adaptations may facilitate the development of robust, epidermal electronics capable of sustained health monitoring without compromising the signal integrity of sensitive diagnostic sensors (Peng et al., 2024). Such advancements in wearable shielding may be crucial for the Internet of Everything era, where persistent connectivity demands reliable protection for both human health and delicate interdigitated sensor components (Lee et al., 2022). Furthermore, by optimizing the filler-to-polymer interface, these composites may achieve the necessary balance between electrical conductivity and dielectric loss, which is essential for minimizing noise in miniaturized bio-sensing architectures (Hareesh et al., 2025; Shukla, 2019).

Hybrid dual-function deployments may use magnetic nanoparticles and polymer composites for electromagnetic interference and ionizing radiation shielding (Abdel-Kader et al., 2024; Zolochavska et al., 2025). By balancing magnetic permeability with optimal filler dispersion, these hybrid systems can improve impedance matching and reduce reflection (Shukla, 2019). Furthermore, the strategic tuning of filler morphology can improve microwave absorption performance (Shukla, 2019). Current development trends emphasize efficient conductive networks to enhance EMI shielding effectiveness, alongside mechanical performance for durable applications (Wang et al., 2021; Zhang & Gu, 2022). These developments point to multifunctional materials for EMI and radiation shielding, while clinical deployment remains to be established (Chang et al., 2023; Zhang & Gu, 2022).

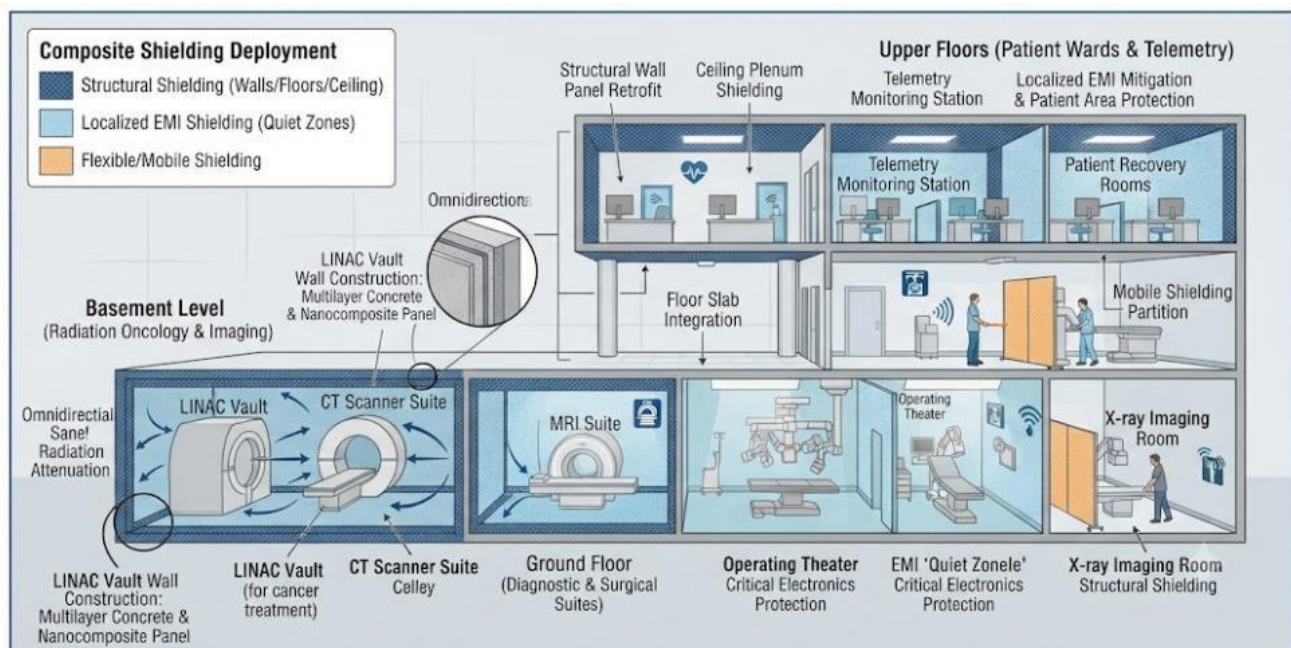


Figure 3: Hospital infrastructure deployment map for iron oxide-epoxy nanocomposite shielding

3. Challenges and Future Scope

The primary obstacles appear to involve achieving long-term mechanical stability and consistent dielectric performance under the cyclical stresses inherent in dynamic hospital environments, where material fatigue can compromise shielding efficacy (Lim et al., 2024). Moreover, the precise control of nanoparticle dispersion within the epoxy matrix appears essential for preventing filler agglomeration, which can cause heterogeneous structures and weaken the composite's mechanical properties (Gouda et al., 2024; Zecchi et al., 2024). Additionally, conductive polymer-based systems can be susceptible to oxidation and degradation in humid,

oxygen-rich environments, gradually reducing conductivity and shielding performance (Fallah et al., 2026).

Future research should focus on optimizing filler-polymer interfacial adhesion and nanoparticle surface functionalization to optimize dispersion and long-term environmental stability (Abbas et al., 2025; Pham et al., 2026). Furthermore, investigating hybrid filler configurations and advanced surface modification techniques may be important to enhance environmental stability and provide scalable, high-performance manufacturing solutions for diverse medical settings (Abbas et al., 2025; Tochaikul & Moonkum, 2024).

Ensuring widespread clinical adoption may necessitate rigorous biocompatibility assessments and standardized toxicological profiling to mitigate potential health risks associated with nanoparticle leaching during material wear (Bawazeer et al., 2023; Duncan & Pillai, 2014). Furthermore, the development of standardized lifecycle assessment protocols may be important to address the environmental footprint of these composites, balancing high-performance shielding capabilities with cost-effectiveness and sustainable manufacturing practices (Lopresti et al., 2020; Wu et al., 2023). Bridging the gap between early-stage laboratory prototypes and industrial-scale production appears to remain a significant hurdle, necessitating extensive validation against established radiation protection standards like EN/IEC 61331-1:2014 (Dhanasekaran et al., 2025; Ghag et al., 2025). Establishing such regulatory compliance may be necessary for transitioning these materials from initial conceptual designs toward reliable, industrial-scale deployment within the sensitive clinical environments of nuclear medicine and radiology (Ghag et al., 2025). Moreover, integrating self-healing functionalities into polymer-based EMI shielding composites could improve durability and stability by addressing damage that develops during long-term service (Zhang & Gu, 2022).

Recent research appears increasingly focused on the design of specific iron oxide morphology and surface modification, reflecting a strategic move toward structural designs that enable high-frequency absorption while maintaining mechanical flexibility (Zheng et al., 2022). Such innovations appear to prioritize the development of lightweight, mechanically robust composites capable of enduring the rigorous thermal and physical demands typical of modern medical imaging and nuclear safety zones (Chen et al., 2025). These developments may be essential for reconciling the trade-off between dense filler loading and the mechanical fatigue typical of high-performance polymer matrices (Qi et al., 2025). Consequently, research appears to be shifting toward cross-linking strategies that enhance inter-filler connectivity, thereby mitigating the mechanical trade-offs often observed in highly filled composite systems (Zhang & Gu, 2022). This evolution towards optimized interfacial bonding may improve the structural endurance of the nanocomposite against dynamic mechanical loading and may enhance electromagnetic attenuation performance under operational stresses (Zhang & Gu, 2022).

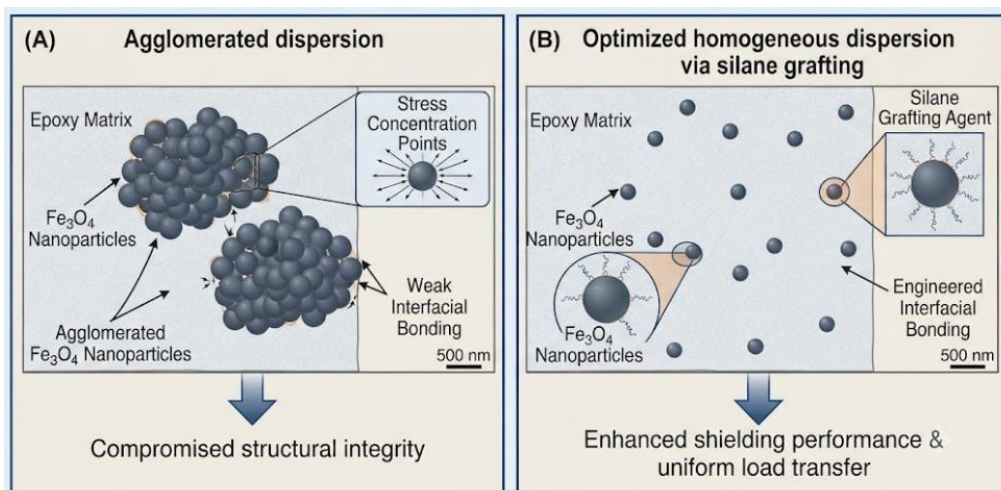


Figure 4: Schematic comparison of nanoparticle morphology in iron oxide-epoxy resin nanocomposites

4. Conclusion

The development of iron oxide-epoxy nanocomposites may represent a significant advancement in shielding applications, as achieving homogeneous nanoparticle distribution through high-shear mixing, ultrasonication, or chemical grafting may remain essential to preventing deleterious agglomeration (Adnan et al., 2018; Domun et al., 2015). For instance, in-situ polymerization techniques may allow the monomer to act as a suspending medium, where subsequent curing facilitates a strong filler-matrix interaction that locks nanoparticles in place and prevents re-agglomeration (Abbasi et al., 2019). Furthermore, the implementation of hybrid filler systems, such as the inclusion of carbon nanotubes alongside iron oxide, can mitigate the

inherent tendency of nanoparticles to cluster, thereby promoting superior interfacial bonding and structural homogeneity (Ali et al., 2024). Beyond these physical dispersion strategies, processing parameters such as the choice of thermally activated cationic polymerization or precise control of curing kinetics may be critical, as they dictate the final cross-linking density and the stability of the filler–matrix interface (Barrera et al., 2017). Moreover, high-quality dispersion techniques such as ultrasonication may be important for achieving improved mechanical properties in nanocomposites (Ali et al., 2024).

5. References

- Abbas, N. S., Jamil, M. H., Ariff, N., Sharif, H., & Yan, P. (2025). Emerging Trends of MXene Nanocomposites in Textile Substrates for Enhanced EMI Shielding: A Systematic Review. *Advanced Materials Interfaces*, 12(14). <https://doi.org/10.1002/admi.202500484>
- Abbasi, H., Antunes, M., & Velasco, J. I. (2019). Recent advances in carbon-based polymer nanocomposites for electromagnetic interference shielding. *QRU Quaderns de Recerca En Urbanisme*, 103, 319–373. <https://doi.org/10.1016/j.pmatsci.2019.02.003>
- Abdel-Kader, M. M., Abou-Laila, M. T., El-Deeb, M. S. S., Taha, E. O., & Eldeeb, A. S. (2024). Structural, radiation shielding, thermal and dynamic mechanical analysis for waste rubber/EPDM rubber composite loaded with Fe₂O₃ for green environment. *Scientific Reports*, 14(1), 12440. <https://doi.org/10.1038/s41598-024-62308-4>
- Abushahla, K. H., & Arslan, H. (2025). Lead-Free Alternatives for Radiation Shielding in Medical Environments: A Comprehensive Review. *Sakarya University Journal of Science*, 29(5), 602–625. <https://doi.org/10.16984/saufenbilder.1735274>
- Adnan, M. M., Tveten, E. G., Glaum, J., Ese, M., Hvidsten, S., Glomm, W. R., & Einarsrud, M. (2018). Epoxy-Based Nanocomposites for High-Voltage Insulation: A Review. *Advanced Electronic Materials*, 5(2). <https://doi.org/10.1002/aelm.201800505>
- Ahmad, H. S., Hussain, T., Nawab, Y., & Awais, H. (2023). Graphene and Fe₂O₃ filled composites for mitigation of electromagnetic pollution and protection of electronic appliances. *Composites Science and Technology*, 240, 110097. <https://doi.org/10.1016/j.compscitech.2023.110097>
- Ali, Z., Yaqoob, S., & D'Amore, A. (2024). Impact of Dispersion Methods on Mechanical Properties of Carbon Nanotube (CNT)/Iron Oxide (Fe₃O₄)/Epoxy Composites. *C – Journal of Carbon Research*, 10(3), 66. <https://doi.org/10.3390/c10030066>
- Al-Saleh, W. M., Almutairi, H. M., Sayyed, M. I., & Elsafi, M. (2023). Multilayer radiation shielding system with advanced composites containing heavy metal oxide nanoparticles: a free-lead solution. *Scientific Reports*, 13(1), 18429. <https://doi.org/10.1038/s41598-023-45621-2>
- Arslonova, S., Laurikaitiene, J., & Adlienė, D. (2026). Development of 3D-Printable Lead-Free Composite Materials for Mixed Photon and Neutron Attenuation. *Polymers*, 18(2), 176. <https://doi.org/10.3390/polym18020176>
- Ayub, S., Guan, B. H., Ahmad, F., Yusuff, A. O., Nisa, Z. U., Javed, M. F., & Mosavi, A. (2021). Graphene and Iron Reinforced Polymer Composite Electromagnetic Shielding Applications: A Review. *Polymers*, 13(15), 2580. <https://doi.org/10.3390/polym13152580>
- Barrera, G., Sciancalepore, C., Messori, M., Allia, P., Tiberto, P., & Bondioli, F. (2017). Magnetite-epoxy nanocomposites obtained by the reactive suspension method: Microstructural, thermo-mechanical and magnetic properties. *European Polymer Journal*, 94, 354–365. <https://doi.org/10.1016/j.eurpolymj.2017.07.022>
- Bawazeer, O., Makkawi, K., Aga, Z. B., Albakri, H., Assiri, N., Althagafy, K., & Ajlouni, A.-W. (2023). A review on using nanocomposites as shielding materials against ionizing radiation. *Journal of Umm Al-Qura University for Applied Sciences*, 9(3), 325–340. <https://doi.org/10.1007/s43994-023-00042-9>
- Bora, P. J., Anil, A. G., Ramamurthy, P. C., & Tan, D. Q. (2020). MXene interlayered crosslinked conducting polymer film for highly specific absorption and electromagnetic interference shielding. *Materials Advances*, 1(2), 177–183. <https://doi.org/10.1039/d0ma00005a>
- Cakir, M., Engin, M. A., & Camuzcuoğlu, M. (2026). Enhanced Absorption-Dominant EMI Shielding Performance of Pyramidal Cementitious Composites Incorporating Recycled Plastics and Magnetite Minerals for 5G Applications. *Sustainability*, 18(4), 1875. <https://doi.org/10.3390/su18041875>
- Chang, C.-H., Su, S.-C., Chang, T., & Chang, C. (2021). Frequency-induced negative magnetic susceptibility in epoxy/magnetite nanocomposites. *Scientific Reports*, 11(1), 3288. <https://doi.org/10.1038/s41598-021-82590-w>
- Chang, Q., Guo, S., & Zhang, X. (2023). Radiation shielding polymer composites: Ray-interaction mechanism, structural design, manufacture and biomedical applications. *Materials & Design*, 233, 112253. <https://doi.org/10.1016/j.matdes.2023.112253>
- Che, R., Huang, Y., & Lv, H. (2025). Magnetoelectric Synergistic Effect for Electromagnetic Wave Absorption Enhancement. *Advanced Functional Materials*, 35(18). <https://doi.org/10.1002/adfm.202502464>

- Chen, J., Zhang, X., Xiao, W., Pan, D., & Wu, W. (2025). Advances in gadolinium-based composite materials for neutron and gamma-ray shielding. *Frontiers in Materials*, 12. <https://doi.org/10.3389/fmats.2025.1561198>
- Cheng, J., Li, C., Xiong, Y., Zhang, H., Raza, H., Ullah, S., Wu, J., Zheng, G., Cao, Q., Zhang, D., Zheng, Q., & Che, R. (2022). Recent Advances in Design Strategies and Multifunctionality of Flexible Electromagnetic Interference Shielding Materials. *Nano-Micro Letters*, 14(1), 80. <https://doi.org/10.1007/s40820-022-00823-7>
- Cheng, S., Chen, Z., Sheng, D., Dong, W., Cao, R., Su, Z., Wu, M., Zhu, X., Xie, A., Mukherjee, S., & Li, W. (2025). Sustainable electromagnetic interference shielding materials from cellulose-grafted n-type polymers. *Nature Communications*, 16(1), 8608. <https://doi.org/10.1038/s41467-025-63665-y>
- Chhetri, S., & Kuila, T. (2024). Polymer composites with 3D graphene architectures as high-performance EMI shielding materials: a review. *RSC Applied Polymers*, 2(4), 507–533. <https://doi.org/10.1039/d4lp00061g>
- Choi, H. K., Lee, A., Park, M., Lee, D. S., Bae, S., Lee, S., Lee, S. H., Lee, T., & Kim, T. (2021). Hierarchical Porous Film with Layer-by-Layer Assembly of 2D Copper Nanosheets for Ultimate Electromagnetic Interference Shielding. *ACS Nano*, 15(1), 829–839. <https://doi.org/10.1021/acsnano.0c07352>
- Dai, B., Ma, Y., Dong, F., Yu, J., Ma, M., Thabet, H. K., El-Bahy, S. M., Ibrahim, M. M., Huang, M., Seok, I., Roymahapatra, G., Naik, N., Xu, B. B., Ding, J., & Li, T. (2022). Overview of MXene and conducting polymer matrix composites for electromagnetic wave absorption. *Advanced Composites and Hybrid Materials*, 5(2), 704–754. <https://doi.org/10.1007/s42114-022-00510-6>
- Dassan, E. G. B., Anjang, A., Abidin, M. J. Z., & Akil, H. M. (2020). Carbon nanotube–reinforced polymer composite for electromagnetic interference application: A review. *Nanotechnology Reviews*, 9(1), 768–788. <https://doi.org/10.1515/ntrev-2020-0064>
- Dhanasekaran, A., Kannadassan, D., & Velmurugan, V. (2025). Challenges and Future Perspectives in the Development of Electromagnetic Interference Shielding Materials. *Advanced Engineering Materials*, 27(20). <https://doi.org/10.1002/adem.202500417>
- Dhand, V., Hyunsuk, C., Hassan, T., Koo, C. M., & Rhee, K. Y. (2024). Tailored eutectic alloy coating for enhanced EMI and X-ray protection by basalt fiber CNT/epoxy composite. *Journal of Materials Research and Technology*, 31, 689–697. <https://doi.org/10.1016/j.jmrt.2024.06.096>
- Domun, N., Hadavinia, H., Zhang, T., Sainsbury, T., Liaghat, G., & Vahid, S. (2015). Improving the fracture toughness and the strength of epoxy using nanomaterials – a review of the current status. *Nanoscale*, 7(23), 10294–10329. <https://doi.org/10.1039/c5nr01354b>
- Duncan, T. V., & Pillai, K. V. (2014). Release of Engineered Nanomaterials from Polymer Nanocomposites: Diffusion, Dissolution, and Desorption. *ACS Applied Materials & Interfaces*, 7(1), 2–19. <https://doi.org/10.1021/am5062745>
- Fallah, A., Fard, N. E., Aliyari, D., Ghamarpoor, R., & Ramezanzadeh, B. (2026). A review on conductive polymeric nanocomposites for advanced electromagnetic interference shielding: materials, mechanisms, and applications. *RSC Advances*, 16(31), 28643–28666. <https://doi.org/10.1039/d6ra03128e>
- Fallah, R., Hosseinabadi, S., & Pourtaghi, G. (2021). Influence of Fe₃O₄ and Carbon Black on the Enhanced Electromagnetic Interference (EMI) Shielding Effectiveness in the Epoxy Resin Matrix. *Journal of Environmental Health Science and Engineering*, 20(1), 113–122. <https://doi.org/10.1007/s40201-021-00759-x>
- Filipović, J. P., Milenković, M., Kepić, D., Dorontić, S., Yasir, M., Nardin, B., & Jovanović, S. (2025). Electromagnetic Interference in the Modern Era: Concerns, Trends, and Nanomaterial-Based Solutions. *Nanomaterials*, 15(20), 1558. <https://doi.org/10.3390/nano15201558>
- Gan, S., Chen, R. S., Flaifel, M. H., Yang, T., Shahdan, D., Hamad, M. K., Mhareb, M. H. A., Kong, I., Fan, X., Wong, J. W. C., & Ahmad, S. (2026). Sustainable magnetite reinforced PLA/Mater-Bi starch/PANi nanocomposites: toward flexible, magnetic, and radiation-protective materials. *Advanced Composites and Hybrid Materials*, 9(2). <https://doi.org/10.1007/s42114-026-01645-6>
- Ghag, S., Bhushan, S., Oommen, S., Nayak, S. Y., P, J. J., Suryanarayana, S. V., Prajapati, P. M., Shet, S., & KV, S. (2025). FABRICATION OF KEVLAR BASED SHIELDING MATERIAL FOR ATTENUATION OF IONIZING RADIATIONS. *Radiation Physics and Chemistry*, 112540. <https://doi.org/10.1016/j.radphyschem.2025.112540>
- G.M., M., Dixit, P., Krishna, R. H., & Kumar, S. G. (2024). Polymer based composites for electromagnetic interference (EMI) shielding: The role of magnetic fillers in effective attenuation of microwaves, a review. *Hybrid Advances*, 6, 100200. <https://doi.org/10.1016/j.hybadv.2024.100200>
- Gouda, M. M., El-Khatib, A. M., Khalil, M. M., Zaher, M. A., & Abbas, M. I. (2024). Comparative study between micro- and nano-carbon with epoxy for gamma shielding applications. *Carbon Letters*, 34(4), 1129–1141. <https://doi.org/10.1007/s42823-023-00673-2>
- Hareesh, M. S., Joseph, P., & George, S. (2025). Electromagnetic interference shielding: a comprehensive review of materials, mechanisms, and applications. *Nanoscale Advances*, 7(15), 4510–4534. <https://doi.org/10.1039/d5na00240k>

- Hashim, A., Al-Attayah, K. H. H., Obaid, S. F., Kumar, A., Kaur, K., Sharma, S., Ruhail, A., Rana, J., Ruhail, P., Kumar, A., Ruhil, M., Jhansi, K., Chandralingam, S., Reddy, N., Suvarna, P., Chinthakuntla, A., Rao, K., Sh, Kaushik, ... Shujatullah, F. (2019). Modern Developments of Polymer Blend/ OxideNanocomposites for Biomedical Applications asAntibacterial and Radiation Shielding Materials: A Review. *Research Journal of Agriculture and Biological Sciences*. <https://doi.org/10.22587/rjabs.2019.14.1.2>
- He, P., Cao, M., Cao, W., & Yuan, J. (2021). Developing MXenes from Wireless Communication to Electromagnetic Attenuation. *Nano-Micro Letters*, 13(1), 115. <https://doi.org/10.1007/s40820-021-00645-z>
- Hosseini, M. A., Malekie, S., & Keshavarzi, M. A. (2021). Analysis of Radiation Shielding Characteristics of Magnetite/High Density Polyethylene Nanocomposite at Diagnostic Level Using the MCNPX, XCOM, XMuDat and Auto-Zeff Programs. *Moscow University Physics Bulletin*, 76. <https://doi.org/10.3103/s0027134922010040>
- Idumah, C. I. (2021). Novel Trends in Magnetic Polymeric Nanoarchitectures. *Polymer-Plastics Technology and Materials*, 60(8), 830–848. <https://doi.org/10.1080/25740881.2020.1869780>
- Isari, A. A., Ghaffarkhah, A., Hashemi, S. A., Wuttke, S., & Arjmand, M. (2024). Structural Design for EMI Shielding: From Underlying Mechanisms to Common Pitfalls. *Advanced Materials*, 36(24). <https://doi.org/10.1002/adma.202310683>
- Jayakumar, S., Saravanan, T., & Philip, J. (2023). A review on polymer nanocomposites as lead-free materials for diagnostic X-ray shielding: Recent advances, challenges and future perspectives. *Hybrid Advances*, 4, 100100. <https://doi.org/10.1016/j.hybadv.2023.100100>
- Jiang, D., Murugadoss, V., Wang, Y., Lin, J., Ding, T., Wang, Z., Shao, Q., Wang, C., Liu, H., Lü, N., Wei, R., Angaiah, S., & Guo, Z. (2019). Electromagnetic Interference Shielding Polymers and Nanocomposites - A Review. *Polymer Reviews*, 59(2), 280–337. <https://doi.org/10.1080/15583724.2018.1546737>
- Jones, C. F., Resina, L., Ferreira, F. C., Sanjuan-Alberte, P., & Esteves, T. (2024). Conductive Core–Shell Nanoparticles: Synthesis and Applications. *QRU Quaderns de Recerca En Urbanisme*, 128(27), 11083–11100. <https://doi.org/10.1021/acs.jpcc.4c02012>
- Kara, H., Karabul, Y., Kılıç, M., İçelli, O., & Özdemir, Z. G. (2019). Gama Işını Koruması için Volkanik Kaya İle Güçlendirilmiş Epoksi Kompozitler. *European Journal of Science and Technology*, 552–560. <https://doi.org/10.31590/ejosat.521516>
- Keykavous-Amand, S., & Peymanfar, R. (2021). Fabrication of clay soil/CuFe₂O₄ nanocomposite toward improving energy and shielding efficiency of buildings. *Scientific Reports*, 11(1), 20832. <https://doi.org/10.1038/s41598-021-00347-x>
- Khalil, M. M., Gouda, M. M., Abbas, M. I., Zaher, M. A., & El-Khatib, A. M. (2024). Impact of nano Fe₂O₃ on radiation parameters of epoxy reinforced with nano carbon. *Scientific Reports*, 14(1), 21940. <https://doi.org/10.1038/s41598-024-73139-8>
- Kim, S.-C. (2026). Fabrication of medical radiation shielding sheets using reactive densification–based tungsten/PE porous composite materials. *Scientific Reports*. <https://doi.org/10.1038/s41598-026-55041-7>
- Kolanowska, A., Janas, D., Herman, A. P., Jędrysiak, R. G., Giżewski, T., & Boncel, S. (2017). From blackness to invisibility – Carbon nanotubes role in the attenuation of and shielding from radio waves for stealth technology. *Carbon*, 126, 31–52. <https://doi.org/10.1016/j.carbon.2017.09.078>
- Krakow, K., Allen, P. J., Symms, M. R., Lemieux, L., Josephs, O., & Fish, D. R. (2000). EEG recording during fMRI experiments: Image quality. *Human Brain Mapping*, 10(1), 10–15. [https://doi.org/10.1002/\(sici\)1097-0193\(200005\)10:1<10::aid-hbm20>3.0.co;2-t](https://doi.org/10.1002/(sici)1097-0193(200005)10:1<10::aid-hbm20>3.0.co;2-t)
- Kruželák, J., Kvasničáková, A., Hložeková, K., & Hudec, I. (2020). Progress in polymers and polymer composites used as efficient materials for EMI shielding. *Nanoscale Advances*, 3(1), 123–172. <https://doi.org/10.1039/d0na00760a>
- Kumar, S., Walia, R., Kumar, A., & Verma, V. (2021). Hybrid structure of MWCNT/ferrite and GO incorporated composites for microwave shielding properties and their practical applications. *RSC Advances*, 11(17), 9775–9787. <https://doi.org/10.1039/d1ra01129d>
- Kumari, S., Dalal, J., Kumar, A., Pal, R., Chahal, R., & Ohlan, A. (2024). Enhanced microwave absorption properties of conducting polymer@graphene composite to counteract electromagnetic radiation pollution: green EMI shielding. *RSC Advances*, 14(1), 662–676. <https://doi.org/10.1039/d3ra07245b>
- Lee, H., Ryu, S. H., Kwon, S. J., Choi, J. R., Lee, S., & Park, B. (2023). Absorption-Dominant mmWave EMI Shielding Films with Ultralow Reflection using Ferromagnetic Resonance Frequency Tunable M-Type Ferrites. *Nano-Micro Letters*, 15(1), 76. <https://doi.org/10.1007/s40820-023-01058-w>
- Lee, J., Kim, Y.-S., Ru, H.-J., Lee, S., & Park, S. (2022). Highly Flexible Fabrics/Epoxy Composites with Hybrid Carbon Nanofillers for Absorption-Dominated Electromagnetic Interference Shielding. *Nano-Micro Letters*, 14(1), 188. <https://doi.org/10.1007/s40820-022-00926-1>

- Li, X., Yao, H., Zhao, Y., Yuan, B., Zhai, J., Li, L., Li, H., & Li, X. (2025). Polymer-based nuclear radiation shielding materials: state-of-the-art and emerging trends for engineering applications. *Frontiers in Materials*, 12. <https://doi.org/10.3389/fmats.2025.1672938>
- Lim, K., Seo, H., Chung, W. G., Song, H., Oh, M., Ryu, S. Y., Kim, Y., & Park, J. (2024). Material and structural considerations for high-performance electrodes for wearable skin devices. *Communications Materials*, 5(1). <https://doi.org/10.1038/s43246-024-00490-8>
- Liu, J., Yu, M.-Y., Yu, Z., & Nicolosi, V. (2023). Design and advanced manufacturing of electromagnetic interference shielding materials. *Materials Today*, 66, 245–272. <https://doi.org/10.1016/j.mattod.2023.03.022>
- Lopes, C., Ferreira, A., Corrêa, M. A., Rodrigues, A. M., Mendes, P. M., & Vaz, F. (2023). EMI Shielding and Conductive Textiles Functionalized with (Ti,Cu) Nanomaterials for Biomedical Applications. *ACS Applied Materials & Interfaces*, 15(33), 39872–39882. <https://doi.org/10.1021/acsami.3c07971>
- Lopresti, M., Alberto, G., Cantamessa, S., Cantino, G., Conterposito, E., Palin, L., & Milanesio, M. (2020). Light Weight, Easy Formable and Non-Toxic Polymer-Based Composites for Hard X-ray Shielding: A Theoretical and Experimental Study. *International Journal of Molecular Sciences*, 21(3), 833. <https://doi.org/10.3390/ijms21030833>
- Lv, H., Cui, J., Li, B., Yuan, M., Liu, J., & Che, R. (2024). Insights into Civilian Electromagnetic Absorption Materials: Challenges and Innovative Solutions. *Advanced Functional Materials*, 35(18). <https://doi.org/10.1002/adfm.202315722>
- Ma, L., Hamidinejad, M., Zhao, B., Liang, C., & Park, C. B. (2021). Layered Foam/Film Polymer Nanocomposites with Highly Efficient EMI Shielding Properties and Ultralow Reflection. *Nano-Micro Letters*, 14(1), 19. <https://doi.org/10.1007/s40820-021-00759-4>
- Ma, Z., Jiang, R., Jing, J., Kang, S., Ma, L., Zhang, K., Li, J., Zhang, Y., Qin, J., Yun, S., & Zhang, G. (2024). Lightweight Dual-Functional Segregated Nanocomposite Foams for Integrated Infrared Stealth and Absorption-Dominant Electromagnetic Interference Shielding. *Nano-Micro Letters*, 16(1), 223. <https://doi.org/10.1007/s40820-024-01450-0>
- Mai, T., Chen, L., Wang, P., Liu, Q., & Ma, M. (2024). Hollow Metal–Organic Framework/MXene/Nanocellulose Composite Films for Giga/Terahertz Electromagnetic Shielding and Photothermal Conversion. *Nano-Micro Letters*, 16(1), 169. <https://doi.org/10.1007/s40820-024-01386-5>
- Mehrara, R., Malekie, S., Kotahi, S. M. S., & Kashian, S. (2021). Introducing a novel low energy gamma ray shield utilizing Polycarbonate Bismuth Oxide composite. *Scientific Reports*, 11(1), 10614. <https://doi.org/10.1038/s41598-021-89773-5>
- Mikinka, E., & Siwak, M. (2021). Recent advances in electromagnetic interference shielding properties of carbon-fibre-reinforced polymer composites—a topical review. *Journal of Materials Science Materials in Electronics*, 32(20), 24585–24643. <https://doi.org/10.1007/s10854-021-06900-8>
- Musa, A. A., Bello, A., Adams, S. M., Onwualu, A. P., Anye, V. C., Bello, K. A., & Obianyo, I. I. (2025). Nano-Enhanced Polymer Composite Materials: A Review of Current Advancements and Challenges. *Polymers*, 17(7), 893. <https://doi.org/10.3390/polym17070893>
- Nan, Z., Wei, W., Lin, Z., Chang, J., & Hao, Y. (2023). Flexible Nanocomposite Conductors for Electromagnetic Interference Shielding. *Nano-Micro Letters*, 15(1), 172. <https://doi.org/10.1007/s40820-023-01122-5>
- Orasugh, J. T., Bothoko, O. J., Temane, L. T., & Ray, S. S. (2024). Progress in polymer nonwoven textile materials in electromagnetic interference shielding applications. *Functional Composite Materials*, 5(1). <https://doi.org/10.1186/s42252-024-00054-6>
- Orasugh, J. T., & Ray, S. S. (2023). Functional and Structural Facts of Effective Electromagnetic Interference Shielding Materials: A Review. *PubMed Central*, 8(9), 8134–8158. <https://doi.org/10.1021/acsomega.2c05815>
- Park, B., Hwang, S., Lee, H., Jung, Y., Kim, T., Kwon, S. J., Jung, D., & Lee, S. (2024). Absorption-Dominant Electromagnetic Interference (EMI) Shielding across Multiple mmWave Bands Using Conductive Patterned Magnetic Composite and Double-Walled Carbon Nanotube Film. *Advanced Functional Materials*, 34(40). <https://doi.org/10.1002/adfm.202406197>
- Paul, I. C., & Rajan, S. C. (2026). *Electromagnetic Interference Shielding of Medical Equipment from a Mathematical Modelling Perspective* (pp. 139–162). <https://doi.org/10.1201/9781003512363-7>
- Peng, Y., Dong, J., Long, J., Zhang, Y., Tang, X., Lin, X., Liu, H., Liu, T., Fan, W. J., Liu, T., & Huang, Y. (2024). Thermally Conductive and UV-EMI Shielding Electronic Textiles for Unrestricted and Multifaceted Health Monitoring. *Nano-Micro Letters*, 16(1), 199. <https://doi.org/10.1007/s40820-024-01429-x>
- Pham, A.-T., Mai, Q.-D., Loan, N. T., Huy, N. T., Anh, N. T. P., Thanh, P. C., Trang, N. T., Quang, L. M., Quyet, N. V., Bach, T. N., & Le, A.-T. (2026). Covalently silane-bridged e-graphene oxide nanosheets toward year-long dispersion-stable epoxy nanocomposites with superior corrosion protection. *RSC Advances*, 16(30), 27818–27836. <https://doi.org/10.1039/d6ra02282k>
- Posada, A. O. G., Téllez, D. A. L., Roa-Rojas, J., & Ramos-Barrado, J. R. (2020). Electromagnetic shielding response of magnetite elastomeric composites: Source and filler content dependence. *Journal of Materials Research and Technology*,

9(5), 10597–10607. <https://doi.org/10.1016/j.jmrt.2020.07.081>

Prabhu, S., Bubbly, S. G., & Gudennavar, S. B. (2022). X-Ray and γ -Ray Shielding Efficiency of Polymer Composites: Choice of Fillers, Effect of Loading and Filler Size, Photon Energy and Multifunctionality. *Polymer Reviews*, 63(1), 246–288. <https://doi.org/10.1080/15583724.2022.2067867>

Qi, Q., Lu-wu, H., Ye, H., Wang, C., Hu, P., & Liu, Y. (2025). From Bench to Use: The Status of Gamma-Shielding Nanomaterials and the Prospects for Lead-Free Wearables. *Nanomaterials*, 15(23), 1799. <https://doi.org/10.3390/nano15231799>

Raveendran, A., Sebastian, M. T., & Raman, S. (2019). Applications of Microwave Materials: A Review. *Journal of Electronic Materials*, 48(5), 2601–2634. <https://doi.org/10.1007/s11664-019-07049-1>

Reddy, S. B., & Bharath., V. (2024). A Comprehensive Review on the Characterization of Nanomaterials for the Suppression of Electromagnetic Interference Across Diverse Frequency bands. *Polymer-Plastics Technology and Materials*, 63(14), 1917–1958. <https://doi.org/10.1080/25740881.2024.2363266>

Ribadeneyra, M. C., Méndez-Lozano, N., González, M. G., Baselga, J., & Pozuelo, J. (2014). Synergistic effect of magnetite nanoparticles and carbon nanofibres in electromagnetic absorbing composites. *Carbon*, 74, 63–72. <https://doi.org/10.1016/j.carbon.2014.02.082>

Safari, A., Rafie, P., Taeb, S., Najafi, M., & Mortazavi, S. M. J. (2024). Development of Lead-Free Materials for Radiation Shielding in Medical Settings: A Review. *Journal of Biomedical Physics and Engineering*, 14(3), 229–244. <https://doi.org/10.31661/jbpe.v0i0.2404-1742>

Saini, P., & Aror, M. (2012). Microwave Absorption and EMI Shielding Behavior of Nanocomposites Based on Intrinsically Conducting Polymers, Graphene and Carbon Nanotubes. In *InTech eBooks*. <https://doi.org/10.5772/48779>

Saiyad, M., & Devashrayee, N. M. (2020). Lifetime estimation of epoxy based composite materials on irradiating with gamma radiation for shielding applications. *Polymer Testing*, 93, 106929. <https://doi.org/10.1016/j.polymertesting.2020.106929>

Sayyadi, E., Mesbahi, A., Zamiri, R. E., & Nejad, F. S. (2021). A comprehensive Monte Carlo study to design a novel multi-nanoparticle loaded nanocomposites for augmentation of attenuation coefficient in the energy range of diagnostic X-rays. *Polish Journal of Medical Physics And Engineering*, 27(4), 279–289. <https://doi.org/10.2478/pjmpe-2021-0033>

Seyed, H. H., & Falsafi, A. (2025). Preparation of soft-hard X-ray absorption nanocomposites using PbS, PbSe coated on SWCNTs based polyaniline. *International Journal of the Physical Sciences*, 20(1), 12–25. <https://doi.org/10.5897/ijps2024.5089>

Shabib, M., Tawfik, E. K., Reheem, A. M. A., Nada, A., & Ashry, H. A. (2026). A comparative analysis of gamma and neutron radiation shielding properties of Gd₂O₃ nanoparticles within HDPE composites irradiated with argon ion beam. *Scientific Reports*, 16(1). <https://doi.org/10.1038/s41598-026-40153-x>

Shi, S., Jiang, Y., Ren, H., Deng, S., Sun, J., Cheng, F., Jing, J., & Chen, Y. (2024). 3D-Printed Carbon-Based Conformal Electromagnetic Interference Shielding Module for Integrated Electronics. *Nano-Micro Letters*, 16(1), 85. <https://doi.org/10.1007/s40820-023-01317-w>

Shivamurthy, B., Sachidananda, H. K., Shivamurthy, B., George, G., & Parasuram, S. (2025). Structural properties and electromagnetic shielding performance of bidirectional carbon fabric and Fe₂O₃ nano filler reinforced epoxy composites. *RSC Advances*, 15(47), 40252–40266. <https://doi.org/10.1039/d5ra06245d>

Shukla, V. (2019). Review of electromagnetic interference shielding materials fabricated by iron ingredients. *Nanoscale Advances*, 1(5), 1640–1671. <https://doi.org/10.1039/c9na00108e>

Si, H., Zhang, Y., Li, M., Chai, Z., Zhang, J., Li, C., & Gong, C. (2026). A synergistic design model for ultrathin broadband microwave absorbers using electromagnetic frequency dispersion coefficients. *Nature Communications*, 17(1). <https://doi.org/10.1038/s41467-026-69591-x>

Song, P., Ma, Z., Qiu, H., Ru, Y., & Gu, J. (2022). High-Efficiency Electromagnetic Interference Shielding of rGO@FeNi/Epoxy Composites with Regular Honeycomb Structures. *Nano-Micro Letters*, 14(1), 51. <https://doi.org/10.1007/s40820-022-00798-5>

Sparavigna, A. C. (2023). Iron Oxide Fe₃O₄ Nanoparticles with Intrinsic Conducting Polymers and Biochar to Improve the Electromagnetic Shielding Performance of Light Weight Absorption-Type Materials. *International Journal of Sciences*, 12(8), 5–23. <https://doi.org/10.18483/ijsci.2709>

Srivastava, S. K., & Manna, K. (2022). Recent advancements in the electromagnetic interference shielding performance of nanostructured materials and their nanocomposites: a review. *Journal of Materials Chemistry A*, 10(14), 7431–7496. <https://doi.org/10.1039/d1ta09522f>

Sushmita, K., Madras, G., & Bose, S. (2020). Polymer Nanocomposites Containing Semiconductors as Advanced Materials for EMI Shielding. *ACS Omega*, 5(10), 4705–4718. <https://doi.org/10.1021/acsomega.9b03641>

Tang, X., Li, K., Li, S., Li, F., & Hang, C. (2025). Multifunctional Epoxy Nanocomposites Incorporating Fe₃O₄@Ti₃C₂T_x for Next-Generation Device Packaging. 1–3.

<https://doi.org/10.1109/icept67137.2025.11156955>

Tochaikul, G., & Moonkum, N. (2024). Eggshell-derived particle composites with epoxy resin for enhanced radiation shielding applications. *Radiation and Environmental Biophysics*, 64(1), 163–178. <https://doi.org/10.1007/s00411-024-01101-3>

Wang, M., Wang, F., Xu, Y., He, Y., Hu, Y., Chang, Y., Zhou, X., Wang, Z., Yao, X., Li, W., Chen, Z., & Guan, J. (2026). Enhancing Mechanical Performance of Microwave Absorbing Coatings by Controlled Fluorosilane Modification of Absorbents. *ACS Applied Materials & Interfaces*, 18(7), 12143–12155. <https://doi.org/10.1021/acsami.5c23796>

Wang, T., Kong, W., Yu, W.-C., Gao, J., Dai, K., Yan, D., & Li, Z. (2021). A Healable and Mechanically Enhanced Composite with Segregated Conductive Network Structure for High-Efficient Electromagnetic Interference Shielding. *Nano-Micro Letters*, 13(1), 162. <https://doi.org/10.1007/s40820-021-00693-5>

Wang, Y., Cheng, R., Cui, W.-G., Lu, Z., Yang, Y., Pan, H., & Che, R. (2023). Heterostructure design of 3D hydrangea-like Fe₃O₄/Fe₇S₈@C core-shell composite as a high-efficiency microwave absorber. *Carbon*, 210, 118043. <https://doi.org/10.1016/j.carbon.2023.118043>

Wei, Y., Bhuyan, P., Kwon, S. J., Kim, S., Bae, Y., Singh, M. K., Tran, D. T., Ha, M., Jeong, K., Ma, X., Park, B., & Park, S. (2024). Liquid Metal Grid Patterned Thin Film Devices Toward Absorption-Dominant and Strain-Tunable Electromagnetic Interference Shielding. *Nano-Micro Letters*, 16(1), 248. <https://doi.org/10.1007/s40820-024-01457-7>

Wu, M., Sadhukhan, J., Murphy, R., Bharadwaj, U., & Cui, X. (2023). A novel life cycle assessment and life cycle costing framework for carbon fibre-reinforced composite materials in the aviation industry. *The International Journal of Life Cycle Assessment*, 28(5), 566–589. <https://doi.org/10.1007/s11367-023-02164-y>

Wu, S., Zhang, W., & Yang, Y. (2024). Progress in Flexible and Wearable Lead-Free Polymer Composites for Radiation Protection. *Polymers*, 16(23), 3274. <https://doi.org/10.3390/polym16233274>

Xiang, Z., Shi, Y., Zhu, X., Cai, L., & Lü, W. (2021). Flexible and Waterproof 2D/1D/0D Construction of MXene-Based Nanocomposites for Electromagnetic Wave Absorption, EMI Shielding, and Photothermal Conversion. *Nano-Micro Letters*, 13(1), 150. <https://doi.org/10.1007/s40820-021-00673-9>

Xue, B., Li, Y., Cheng, Z., Yang, S., Xie, L., Qin, S., & Zheng, Q. (2021). Directional Electromagnetic Interference Shielding Based on Step-Wise Asymmetric Conductive Networks. *Nano-Micro Letters*, 14(1), 16. <https://doi.org/10.1007/s40820-021-00743-y>

Yan, R., Lin, Q., You, K.-I., Zhang, L., Chen, Y., Huang, Z., & Sheng, X. (2025). Construction strategies and recent advances of flexible EMI phase change composites. *Soft Science*, 5(1). <https://doi.org/10.20517/ss.2024.66>

Yang, J., Wang, H., Zhang, Y., Zhang, H., & Gu, J. (2023). Layered Structural PBAT Composite Foams for Efficient Electromagnetic Interference Shielding. *Nano-Micro Letters*, 16(1), 31. <https://doi.org/10.1007/s40820-023-01246-8>

Zecchi, S., Cristoforo, G., Bartoli, M., Tagliaferro, A., Torsello, D., Rosso, C., Boccaccio, M., & Acerra, F. (2024). A Comprehensive Review of Electromagnetic Interference Shielding Composite Materials [Review of *A Comprehensive Review of Electromagnetic Interference Shielding Composite Materials*]. *Micromachines*, 15(2), 187. Multidisciplinary Digital Publishing Institute. <https://doi.org/10.3390/mi15020187>

Zhang, S., Liu, X., Jia, C., Sun, Z., Jiang, H., Jia, Z., & Wu, G. (2023). Integration of Multiple Heterointerfaces in a Hierarchical 0D@2D@1D Structure for Lightweight, Flexible, and Hydrophobic Multifunctional Electromagnetic Protective Fabrics. *Nano-Micro Letters*, 15(1). <https://doi.org/10.1007/s40820-023-01179-2>

Zhang, Y., & Gu, J. (2022). A Perspective for Developing Polymer-Based Electromagnetic Interference Shielding Composites. *Nano-Micro Letters*, 14(1), 89. <https://doi.org/10.1007/s40820-022-00843-3>

Zheng, W., Wen-xian, Y., Yang, P., Wang, D., Xiong, Y., Li, X., Qi, J., & Zhang, Y. (2022). Recent Progress in Iron-Based Microwave Absorbing Composites: A Review and Prospective. *Molecules*, 27(13), 4117. <https://doi.org/10.3390/molecules27134117>

Zhou, M., Tan, S., Wang, J., Wu, Y., Liang, L., & Ji, G. (2023). “Three-in-One” Multi-Scale Structural Design of Carbon Fiber-Based Composites for Personal Electromagnetic Protection and Thermal Management. *Nano-Micro Letters*, 15(1), 176. <https://doi.org/10.1007/s40820-023-01144-z>

Zhou, X., Min, P., Liu, Y., Jin, M., Yu, Z., & Zhang, H. (2024). Insulating electromagnetic-shielding silicone compound enables direct potting electronics. *Science*, 385(6714), 1205–1210. <https://doi.org/10.1126/science.adp6581>

Zolochovska, K., Šafařík, I., Rajňák, M., Dolník, B., Maslyuk, V. T., Свaтюк, H. I., & Kopčanský, P. (2025). Shielding Properties and Radiation Modification of Magnetic Nanoparticle-Functionalized Textiles. *Acta Electrotechnica et Informatica*, 25(3), 3–9. <https://doi.org/10.2478/aei-2025-0009>

Zou, L., Lan, C., Zhang, S., Zheng, X., Xu, Z., Li, C., Yang, L., Ruan, F., & Tan, S. C. (2021). Near-Instantaneously Self-Healing Coating toward Stable and Durable Electromagnetic Interference Shielding. *Nano-Micro Letters*, 13(1), 190. <https://doi.org/10.1007/s40820-021-00709-0>