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A Systematic Review of Mathematical Modelling of Electromagnetic Shielding Effectiveness: Methods, Architectures, and Future Research Directions

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Abstract

Electromagnetic shielding effectiveness (EMSE) is a critical parameter in evaluating the ability of materials and structures to attenuate electromagnetic interference (EMI) across a wide range of frequencies. Mathematical modelling plays a fundamental role in understanding and predicting shielding performance by quantifying mechanisms such as reflection, absorption, and multiple reflections. Recent advancements between 2018 and 2023 have significantly enhanced EMSE modelling through the integration of computational electromagnetics, machine learning, stochastic approaches, and multi-scale modelling frameworks. Traditional models based on Maxwell's equations and transmission line theory provide analytical insights but often fail to capture complex material heterogeneity and frequency-dependent behaviour. Modern approaches incorporate numerical techniques such as finite element method (FEM), finite-difference time-domain (FDTD), and Monte Carlo simulations, enabling accurate modelling of composite and nanostructured shielding materials. Additionally, hybrid AI-driven models have emerged to improve prediction accuracy and reduce computational complexity. This review systematically analyses recent developments in EMSE mathematical modelling, focusing on modelling techniques, architectural frameworks, and real-world applications. It also identifies key challenges, including model validation, computational cost, and multi-physics integration. Finally, the paper highlights future research directions toward intelligent, adaptive, and scalable electromagnetic shielding solutions for next-generation communication and electronic systems.

Introduction

Electromagnetic interference (EMI) has become a critical concern in modern electronic and communication systems due to the rapid proliferation of wireless devices, high-frequency circuits, and densely integrated electronic components. EMI can degrade system performance, cause signal distortion, and even lead to complete system failure in sensitive applications such as aerospace, medical devices, and defence systems. To mitigate these effects, electromagnetic shielding is employed, which involves the use of materials or structures designed to attenuate electromagnetic waves. The effectiveness of such shielding is quantified using electromagnetic shielding effectiveness (EMSE), typically expressed in decibels (dB).

Mathematical modelling plays a central role in understanding and predicting EMSE by enabling the analysis of electromagnetic wave interactions with materials and structures. Classical EMSE models are derived from Maxwell's equations and are often simplified using transmission line theory and plane wave approximations. These models decompose shielding effectiveness into three fundamental components: reflection loss, absorption loss, and multiple reflection loss. This decomposition provides a theoretical foundation for analysing shielding mechanisms and designing effective shielding materials.

Traditional analytical models, such as the Schelkunoff theory, assume homogeneous materials and idealized boundary conditions. While these models are computationally efficient and provide valuable insights, they are often inadequate for modelling complex materials such as polymer nanocomposites, multilayer structures, and porous media. These materials exhibit heterogeneous electrical conductivity, dielectric properties, and frequency-dependent behaviour, which cannot be accurately captured using simple analytical approaches.

To address these limitations, researchers have developed numerical modelling techniques based on computational electromagnetics (CEM). Methods such as the finite element method (FEM), finite-difference time-domain (FDTD), and method of moments (MoM) allow for detailed simulation of electromagnetic wave propagation and interaction with complex geometries. These techniques enable accurate modelling of shielding performance across a wide frequency range and are widely used in the design and optimization of shielding materials and structures.

Between 2018 and 2023, significant progress has been made in advancing mathematical models for EMSE. One notable trend is the integration of multi-scale modelling approaches, which combine microscopic material properties with macroscopic electromagnetic behaviour. For example, models for nanocomposite materials incorporate filler distribution, particle size, and interfacial effects to predict shielding performance more accurately.

Another important development is the incorporation of stochastic modelling techniques to account for randomness in material properties and structural configurations. Real-world shielding materials often exhibit variability due to manufacturing processes, material defects, and environmental conditions. Stochastic models provide a probabilistic framework for analysing such uncertainties, leading to more robust and reliable predictions.

Recent studies have also explored the use of machine learning and artificial intelligence to enhance EMSE modelling. Data-driven models can learn complex relationships between material properties, structural parameters, and shielding performance, enabling rapid prediction and optimization. These approaches are particularly useful for high-dimensional problems where traditional numerical methods become computationally expensive.

In addition to modelling techniques, architectural advancements in shielding design have gained significant attention. Multilayered structures, metamaterials, and conductive polymer composites have been widely studied for their superior shielding performance. Advanced fabrication techniques, such as 3D printing and nano-engineering, enable precise control over material structure, further enhancing EMSE.

Despite these advancements, several challenges remain in the field of EMSE modelling. One of the primary challenges is the high computational cost associated with numerical simulations, particularly for large-scale and high-frequency problems. Another challenge is the lack of standardized modelling frameworks and validation methodologies, which hinders the comparison and reproducibility of results. Additionally, integrating multi-physics effects, such as thermal and mechanical interactions, remains an open research problem.

This systematic review aims to provide a comprehensive overview of mathematical modelling approaches for EMSE, focusing on recent developments from 2018 to 2023. It examines various modelling techniques, including analytical, numerical, stochastic, and AI-driven approaches, as well as architectural innovations in shielding materials. Furthermore, the review identifies key challenges and future research directions,

Literature Review

Ganguly et al. (2018) conducted an extensive investigation into the electromagnetic shielding effectiveness (EMSE) of polymer nanocomposites, focusing particularly on the role of conductive filler networks and percolation theory. The study emphasized that traditional homogeneous models are insufficient to capture the complex electrical behavior of nanocomposites, where conductive fillers such as carbon nanotubes (CNTs), graphene, and metallic nanoparticles form interconnected networks within an insulating polymer matrix. The authors developed a mathematical framework based on percolation thresholds, where electrical conductivity sharply increases once a critical filler concentration is reached. This transition significantly enhances shielding effectiveness by improving absorption losses due to increased dielectric polarization and conduction mechanisms. Furthermore, the study integrated Maxwell–Garnett and Bruggeman effective medium theories to estimate composite permittivity and conductivity, enabling prediction of EMSE across different frequency bands. The results demonstrated that microstructural parameters such as filler dispersion, aspect ratio, and inter-particle distance play a crucial role in determining shielding performance. The authors concluded that multi-scale modelling—linking nanoscale conductive networks with macroscopic electromagnetic behaviour—is essential for accurately predicting EMSE in advanced composite materials. However, they also highlighted challenges in modelling randomness and agglomeration effects, which introduce variability in real-world materials.

Wanasinghe et al. (2019) focused on analytical modelling of electromagnetic shielding effectiveness in metallic and composite materials using classical electromagnetic theory derived from Maxwell's equations. The study revisited the fundamental components of shielding effectiveness, namely reflection loss (SE_R), absorption loss (SE_A), and multiple reflection loss (SE_M), and provided detailed mathematical formulations for each component. The authors demonstrated that reflection loss is primarily governed by impedance mismatch between free space and the shielding material, while absorption loss depends on material thickness, conductivity, and magnetic permeability. The study also introduced frequency-dependent modelling, highlighting that shielding effectiveness varies significantly across different frequency ranges due to skin depth effects. At higher frequencies, reduced skin depth leads to increased absorption, enhancing overall shielding performance. The authors validated their analytical models through experimental measurements, showing strong agreement for homogeneous metallic shields. However, the study noted limitations when extending these models to heterogeneous or multilayered materials, where complex boundary conditions and interfacial effects must be considered. This work reinforced the importance of classical models as a baseline for EMSE analysis while highlighting the need for more advanced approaches in complex systems.

Zeng et al. (2020) explored electromagnetic shielding through microwave absorption theory and transmission line modelling, particularly focusing on carbon-based materials such as graphene and carbon fibres. The study developed a comprehensive mathematical model using transmission line theory (TLT) to analyse wave propagation through shielding materials. The model treated the shielding material as a lossy transmission medium, where impedance matching and attenuation constants determine shielding performance. A key contribution of this work was the formulation of reflection and absorption losses in terms of complex permittivity and permeability, enabling accurate modelling of frequency-dependent behaviour. The authors showed that optimal shielding performance can be achieved by balancing impedance matching (to minimize reflection) and high attenuation (to maximize absorption). The study also demonstrated that carbon-based materials exhibit superior shielding properties due to their high electrical conductivity and dielectric loss characteristics. Additionally, Zeng et al. highlighted the importance of thickness optimization and multi-layer configurations in enhancing EMSE. Their results indicated that single-layer materials often suffer from impedance mismatch, while multi-layer structures can achieve broadband shielding performance. However, the study also pointed out computational challenges in modelling multilayer systems with varying material properties.

Kumar et al. (2021) introduced a multi-scale modelling approach for electromagnetic shielding in carbon-based composite materials. The study addressed a key limitation of traditional models, which often fail to capture the hierarchical structure of nanocomposites. The authors proposed a framework that integrates nanoscale modelling of filler distribution with macroscale electromagnetic simulations using finite element methods (FEM). At the nanoscale, the model accounted for particle dispersion, orientation, and interaction effects, which influence electrical conductivity and dielectric properties. At the macroscale, FEM simulations were used to analyse electromagnetic wave propagation and attenuation within the composite material. The integration of these scales enabled accurate prediction of shielding effectiveness across a wide frequency range. The study demonstrated that multi-scale modelling significantly improves prediction accuracy compared to conventional analytical models, particularly for heterogeneous materials. It also highlighted the role of interfacial polarization and tunnelling effects in enhancing EMSE. However, the authors noted that the computational cost of multi-scale modelling is high, and efficient algorithms are required to make such models practical for large-scale applications.

Morales et al. (2023) developed an advanced mathematical model for electromagnetic shielding effectiveness in metallized nonwoven fabrics, which are increasingly used in wearable electronics and flexible shielding applications. The study introduced a novel parameter transformation technique to account for the anisotropic and porous nature of textile-based materials. Unlike conventional solid materials, nonwoven fabrics exhibit complex structural properties, including fibre orientation, porosity, and variable conductivity. The authors extended classical EMSE models by incorporating effective conductivity and permittivity values derived from experimental measurements and microstructural analysis. The model also considered multiple scattering and absorption effects within the porous structure, providing a more realistic representation of electromagnetic wave interaction. The results showed that textile-based shielding materials can achieve high EMSE while maintaining flexibility and lightweight properties, making them suitable for wearable applications. The study also emphasized the importance of integrating experimental validation with mathematical modelling to ensure accuracy. However, challenges remain in modelling dynamic deformation and environmental effects, which can influence shielding performance in real-world conditions.

Li et al. (2018) investigated electromagnetic shielding effectiveness (EMSE) using numerical modelling techniques, particularly focusing on the finite element method (FEM) for complex geometries. The study addressed limitations of analytical models when dealing with irregular structures and heterogeneous materials. By solving Maxwell's equations in discretized domains, the FEM approach enabled precise simulation of electromagnetic wave propagation, reflection, and absorption within shielding materials. The authors developed a mathematical framework that integrates material properties such as conductivity, permittivity, and permeability into FEM simulations. This allowed for accurate modelling of shielding performance in multilayered composites and nanostructured materials. The study demonstrated that FEM-based models can capture edge effects, boundary conditions, and localized field variations, which are often neglected in simplified analytical approaches. Furthermore, Li et al. validated their model using experimental data, showing strong agreement across a wide frequency range. However, they highlighted that FEM simulations are computationally intensive, particularly for high-frequency applications and large-scale structures. The study concluded that while FEM provides high accuracy, optimization techniques and reduced-order models are necessary to improve computational efficiency for practical applications.

Kwon et al. (2019) explored the finite-difference time-domain (FDTD) method for modelling electromagnetic shielding in complex materials and structures. Unlike frequency-domain approaches, FDTD operates in the time domain, enabling broadband analysis of electromagnetic wave interactions. The study developed a mathematical model that discretizes both space and time to simulate wave propagation through shielding materials. A key contribution of this work was the ability to analyse transient electromagnetic responses and frequency-dependent shielding behaviour simultaneously. The authors demonstrated that FDTD is particularly effective for modelling layered structures, metamaterials, and frequency-selective surfaces. The study also highlighted the role of grid resolution and time-step stability in ensuring accurate simulations. Kwon et al. showed that FDTD models can capture multiple reflection effects and nonlinear material responses, making them suitable for advanced shielding applications. However, the method requires significant memory and computational resources, especially for three-dimensional simulations. The authors suggested hybrid approaches combining FDTD with analytical models to reduce computational overhead while maintaining accuracy.

Zhang et al. (2020) proposed a stochastic modelling approach for electromagnetic shielding effectiveness to account for uncertainties in material properties and structural configurations. The study recognized that real-world shielding materials often exhibit variability due to manufacturing inconsistencies, environmental factors, and material defects. To address this, the authors developed a probabilistic framework based on Monte Carlo simulations. The model incorporated random variations in parameters such as conductivity, thickness, and dielectric properties, generating a distribution of shielding effectiveness values rather than a single deterministic result. This approach provided insights into the reliability and robustness of shielding materials under uncertain conditions. The study demonstrated that stochastic models are particularly useful for quality control and risk assessment in shielding design. By quantifying uncertainty, designers can identify worst-case scenarios and optimize material properties accordingly. However, the authors noted that Monte Carlo simulations require a large number of iterations, leading to increased computational cost. They suggested the use of variance reduction techniques and surrogate models to improve efficiency.

Chen et al. (2021) introduced a machine learning-based approach for predicting electromagnetic shielding effectiveness in composite materials. The study leveraged artificial neural networks (ANNs) to model complex relationships between material properties, structural parameters, and shielding performance. Unlike traditional physics-based models, the ANN approach does not require explicit mathematical equations, making it suitable for high-dimensional and nonlinear problems. The authors trained the model using a dataset of experimentally measured EMSE values for various composite materials. Input parameters included filler concentration, frequency, thickness, and conductivity, while the output was shielding effectiveness. The results showed that the ANN model achieved high prediction accuracy and significantly reduced computation time compared to numerical simulations. The study also highlighted the potential of machine learning for material design and optimization. By rapidly predicting EMSE, designers can explore a wide range of material configurations without performing expensive simulations or experiments. However, the authors emphasized that the accuracy of machine learning models depends on the quality and size of the training dataset. Additionally, the lack of interpretability in black-box models remains a challenge for scientific understanding.

Gupta et al. (2022) developed a hybrid modelling framework combining analytical electromagnetic theory with numerical and data-driven approaches to improve EMSE prediction. The study integrated classical transmission line models with machine learning algorithms, creating a hybrid system that balances physical interpretability and predictive accuracy. The analytical component provided a baseline understanding of reflection and absorption mechanisms, while the machine learning component captured nonlinear interactions and complex dependencies. The authors demonstrated that this hybrid approach outperforms both purely analytical and purely data-driven models, particularly in heterogeneous and multilayer shielding materials. The study also introduced optimization techniques to identify optimal material configurations for maximum shielding effectiveness. By combining modelling and optimization, the framework enables efficient design of advanced shielding materials for applications such as 5G communication systems and aerospace electronics. However, the authors noted that integrating different modelling approaches requires careful calibration and validation to ensure consistency and accuracy.

Maiti et al. (2018) investigated electromagnetic shielding effectiveness (EMSE) in graphene-based polymer nanocomposites, emphasizing the role of electrical conductivity and dielectric loss mechanisms. The study developed a mathematical model based on effective medium theory (EMT), which considers the composite material as an equivalent homogeneous medium with averaged electrical properties. By incorporating filler concentration, aspect ratio, and dispersion quality into the model, the authors demonstrated that graphene significantly enhances shielding performance due to its high conductivity and large surface area. The study further analysed the frequency-dependent behaviour of shielding effectiveness, showing that dielectric relaxation and polarization mechanisms contribute significantly to absorption loss at higher frequencies. The authors also introduced percolation theory to explain the transition from insulating to conductive behaviour, which is critical for achieving high EMSE. However, the model assumed uniform filler distribution, which may not accurately represent real-world composites with agglomeration effects. The study concluded that combining EMT with microstructural modelling can improve prediction accuracy.

Zhao et al. (2019) focused on multilayer electromagnetic shielding structures and developed a mathematical model based on transmission line theory and impedance matching principles. The study treated each layer as a transmission medium with specific impedance, allowing analysis of wave propagation across multiple interfaces. By optimizing layer thickness and material properties, the authors demonstrated that multilayer structures can achieve broadband shielding performance. A key contribution of this study was the identification of impedance matching as a critical factor in minimizing reflection loss and enhancing absorption. The authors showed that improper impedance matching leads to high reflection at interfaces, reducing overall shielding effectiveness. The model was validated through experimental measurements on layered composite materials, showing strong agreement with theoretical predictions. However, the complexity of multilayer modelling increases significantly with the number of layers, requiring efficient computational techniques for practical implementation.

Liu et al. (2020) explored electromagnetic shielding using metamaterials and developed a mathematical framework based on effective permittivity and permeability. Metamaterials are engineered structures with unique electromagnetic properties, such as negative refractive index and tuneable impedance. The study modelled these properties using homogenization techniques, allowing complex periodic structures to be represented as equivalent continuous media. The authors demonstrated that metamaterials can achieve superior shielding performance by enabling strong absorption and minimal reflection across a wide frequency range. The model also accounted for resonance effects, which play a critical role in enhancing EMSE. The study highlighted the potential of metamaterials for advanced shielding applications in high-frequency communication systems. However, challenges remain in accurately modelling complex geometries and scaling these materials for practical use.

Singh et al. (2021) developed a finite-difference time-domain (FDTD)-based model to analyse electromagnetic shielding in nanocomposite materials. The study focused on time-domain simulation of electromagnetic wave propagation, enabling broadband analysis of shielding performance. By incorporating frequency-dependent material properties into the FDTD framework, the authors were able to capture complex interactions between electromagnetic waves and composite materials. The study demonstrated that nanocomposites exhibit enhanced shielding performance due to multiple scattering and absorption mechanisms at the nanoscale. The FDTD model also allowed visualization of electromagnetic field distribution within the material, providing insights into shielding mechanisms. However, the authors noted that FDTD simulations require fine spatial discretization and small-time steps, leading to high computational cost. Despite these challenges, the study confirmed the effectiveness of time-domain modelling for complex shielding systems.

Park et al. (2022) investigated the use of machine learning techniques for optimizing electromagnetic shielding materials. The study developed a predictive model using support vector machines (SVM) and regression algorithms to estimate shielding effectiveness based on material properties and structural parameters. By training the model on experimental data, the authors demonstrated that machine learning can significantly reduce the time required for material design and optimization. The study also introduced feature selection techniques to identify the most influential parameters affecting EMSE, such as conductivity, thickness, and filler concentration. This insight enables more efficient material design by focusing on key variables. Additionally, the model was used to optimize multilayer structures for maximum shielding performance. However, the authors emphasized that machine learning models require large datasets for training and may lack interpretability compared to physics-based models.

Zhang et al. (2018) investigated electromagnetic shielding effectiveness (EMSE) in carbon nanotube (CNT)-based composites using a multi-scale mathematical modelling approach. The study combined nanoscale modelling of CNT dispersion with macroscale electromagnetic simulations to evaluate shielding performance. At the nanoscale, the authors modelled the formation of conductive networks using percolation theory, highlighting the critical role of CNT alignment and distribution in determining electrical conductivity. At the macroscale, the model incorporated Maxwell's equations to simulate electromagnetic wave attenuation within the composite material. The results demonstrated that CNT alignment significantly enhances shielding effectiveness by improving electrical pathways and increasing absorption loss. Additionally, the study emphasized the importance of interfacial interactions between CNTs and the polymer matrix, which influence dielectric properties and polarization effects. However, the authors noted that accurately modelling CNT dispersion remains challenging due to the randomness and agglomeration of nanoparticles. The study concluded that multi-scale modelling is essential for designing high-performance nanocomposite shielding materials.

Ahmed et al. (2019) focused on numerical modelling of electromagnetic shielding in conductive polymer composites using the method of moments (MoM). The study developed a mathematical framework to analyse electromagnetic wave scattering and absorption in complex geometries. By discretizing the surface currents induced by incident electromagnetic waves, the MOM approach provided accurate solutions for shielding effectiveness in irregular structures. The authors demonstrated that MoM is particularly effective for thin conductive layers and frequency-selective surfaces, where traditional volumetric methods such as FEM may be less efficient. The study also highlighted the influence of material conductivity and surface roughness on shielding performance. Experimental validation showed strong agreement with simulation results, confirming the accuracy of the model. However, the computational complexity of MoM increases significantly with problem size, limiting its application to large-scale systems.

Wang et al. (2020) proposed a hybrid electromagnetic modelling approach combining finite element method (FEM) and transmission line theory (TLT) to analyse multilayer shielding structures. The study addressed the limitations of using a single modelling technique by integrating the strengths of both approaches. FEM was used to model complex geometries and material properties, while TLT provided analytical insights into wave propagation and impedance matching across layers. The authors demonstrated that this hybrid approach improves computational efficiency while maintaining high accuracy. The model was applied to multilayer nanocomposites and metamaterials, showing enhanced shielding performance across a broad frequency range. The study also highlighted the importance of optimizing layer thickness and material composition to achieve maximum absorption and minimal reflection. However, the integration of different modelling techniques requires careful calibration to ensure consistency between numerical and analytical results.

Kim et al. (2021) explored the use of deep learning techniques for electromagnetic shielding prediction and optimization. The study developed a convolutional neural network (CNN) model trained on simulated and experimental data to predict EMSE for various material configurations. Unlike traditional machine learning models, CNNs can capture spatial patterns and complex relationships within the data, making them suitable for modelling heterogeneous materials. The results showed that the CNN model achieved high prediction accuracy and significantly reduced computation time compared to conventional numerical simulations. The study also demonstrated the potential of deep learning for inverse design, where desired shielding performance is specified, and the model predicts optimal material configurations. However, the authors noted that deep learning models require large datasets and may lack physical interpretability, which can limit their acceptance in engineering applications.

Li et al. (2022) investigated electromagnetic shielding in flexible and wearable materials, focusing on textile-based composites. The study developed a mathematical model that incorporates anisotropic conductivity and structural porosity, which are key characteristics of textile materials. By extending classical EMSE equations, the authors accounted for multiple scattering and absorption effects within the porous structure. The results demonstrated that textile-based shielding materials can achieve high EMSE while maintaining flexibility and lightweight properties, making them suitable for wearable electronics. The study also highlighted the importance of fibre orientation and coating techniques in enhancing shielding performance. However, modelling dynamic deformation and environmental effects, such as humidity and temperature, remains a challenge. The authors concluded that future models should incorporate multi-physics effects to improve accuracy in real-world applications.

Al-Saleh et al. (2018) investigated electromagnetic shielding effectiveness (EMSE) in polymer composites filled with carbon-based nanomaterials, focusing on the influence of filler morphology and dispersion on electrical conductivity. The study developed a mathematical model based on percolation theory and tunnelling conduction mechanisms, where electrons can transfer between adjacent conductive particles even without direct contact. This tunnelling effect becomes significant at nanoscale distances and plays a crucial role in enhancing shielding performance. The authors demonstrated that the aspect ratio and orientation of fillers such as carbon nanotubes and graphene significantly affect the formation of conductive networks. The model incorporated statistical distribution functions to account for random dispersion of fillers, enabling more realistic prediction of EMSE. The results showed that optimizing filler alignment and reducing agglomeration can significantly improve shielding effectiveness. However, the study highlighted challenges in accurately modelling inter-particle interactions and variability in composite structures.

Seo et al. (2019) focused on electromagnetic shielding in hybrid nanocomposites and developed a mathematical framework combining effective medium theory (EMT) with frequency-dependent dielectric modelling. The study analysed composites containing multiple fillers, such as metallic nanoparticles and carbon-based materials, which exhibit synergistic effects in enhancing shielding performance. The authors demonstrated that hybrid composites provide improved EMSE due to combined reflection and absorption mechanisms. The model incorporated complex permittivity and permeability to capture frequency-dependent behaviour, showing that dielectric loss plays a significant role at higher frequencies. Additionally, the study emphasized the importance of interfacial polarization, where charge accumulation at material interfaces enhances absorption. However, the complexity of modelling multiple fillers and their interactions increases computational requirements and necessitates advanced simulation techniques.

Huang et al. (2020) investigated electromagnetic shielding using graphene-based metamaterials and developed a mathematical model based on effective parameter retrieval methods. The study focused on engineered structures with periodic patterns that exhibit unique electromagnetic properties, such as negative permittivity and tuneable impedance. The authors used homogenization techniques to represent complex metamaterial structures as equivalent continuous media, simplifying the analysis of electromagnetic wave interaction. The model demonstrated that metamaterials can achieve near-perfect absorption by minimizing reflection and maximizing energy dissipation within the material. The study also highlighted the role of resonance effects in enhancing shielding performance across specific frequency bands. However, accurately modelling these effects requires precise control over material geometry and fabrication processes, which can be challenging in practical applications.

Reddy et al. (2021) developed a numerical modelling framework using the finite element method (FEM) to analyse electromagnetic shielding in multilayer composite structures. The study focused on optimizing layer configurations to achieve broadband shielding performance. By varying material properties and thickness of each layer, the authors demonstrated that multilayer structures can significantly enhance absorption and reduce reflection losses. The model incorporated boundary conditions and electromagnetic field interactions at layer interfaces, providing detailed insights into wave propagation within the structure. The study also explored the effect of impedance matching between layers, which is critical for minimizing reflection at interfaces. The results showed that properly designed multilayer systems can achieve high EMSE across a wide frequency range. However, the computational complexity increases with the number of layers, making optimization challenging for large-scale systems.

Choi et al. (2022) explored the application of artificial intelligence for optimizing electromagnetic shielding materials and structures. The study developed a deep learning-based predictive model that integrates material properties, structural parameters, and frequency characteristics to estimate EMSE. The model was trained using a large dataset generated from numerical simulations and experimental measurements. The authors demonstrated that AI-based models can rapidly predict shielding performance and identify optimal material configurations, significantly reducing design time. Additionally, the study introduced an inverse design approach, where desired shielding performance is specified, and the model predicts suitable material combinations. This approach is particularly useful for designing advanced shielding materials for high-frequency applications such as 5G and IoT devices. However, the study noted that AI models require extensive training data and may lack interpretability compared to physics-based models.

Verma et al. (2020) proposed a comprehensive hybrid modelling approach for electromagnetic shielding effectiveness (EMSE) that integrates analytical formulations with numerical simulations. The study combined classical transmission line theory (TLT) with finite element method (FEM) simulations to capture both theoretical and practical aspects of electromagnetic wave interaction with shielding materials. The analytical component provided insights into reflection and absorption losses, while the FEM component accounted for complex geometries and heterogeneous material properties. The authors demonstrated that hybrid modelling significantly improves prediction accuracy compared to standalone analytical or numerical methods. The model was applied to polymer nanocomposites and multilayer shielding systems, showing strong agreement with experimental results. Additionally, the study introduced optimization techniques for tuning material properties and layer thickness to maximize shielding performance. However, the integration of multiple modelling techniques requires careful parameter calibration and validation to ensure consistency.

Nguyen et al. (2021) investigated electromagnetic shielding in porous and foam-based materials, which are increasingly used for lightweight and flexible shielding applications. The study developed a mathematical model incorporating porosity, tortuosity, and effective conductivity to represent the complex internal structure of foam materials. The authors extended classical EMSE equations by introducing correction factors for multiple scattering and absorption within the porous medium. The model showed that increased porosity enhances absorption due to longer wave propagation paths, while excessive porosity reduces conductivity and reflection loss. This trade-off was analysed using parametric studies, providing guidelines for optimizing foam-based shielding materials. However, accurately modelling the random structure of porous materials remains challenging, and the study suggested using stochastic approaches for further improvement.

Singh et al. (2022) introduced a fractional-order mathematical model for electromagnetic shielding effectiveness, extending traditional integer-order differential equations to capture complex wave-material interactions. The study emphasized that classical models often fail to represent memory effects and anomalous diffusion phenomena observed in advanced materials such as nanocomposites and metamaterials. By incorporating fractional calculus, the model provided a more accurate representation of frequency-dependent shielding behaviour. The authors demonstrated that fractional-order models outperform conventional approaches in predicting EMSE across a wide frequency range. The study also highlighted the potential of fractional modelling in capturing multi-scale interactions within heterogeneous materials. However, the complexity of fractional equations and the lack of standardized solution methods pose challenges for practical implementation.

Zhao et al. (2022) developed an Internet of Things (IoT)-enabled framework for real-time monitoring and prediction of electromagnetic shielding effectiveness. The study integrated sensor data with mathematical models to dynamically evaluate shielding performance in real-world environments. The framework used data-driven algorithms to update model parameters based on real-time measurements, enabling adaptive shielding systems. The authors demonstrated that this approach is particularly useful in applications such as smart buildings, wearable electronics, and industrial systems, where environmental conditions can affect shielding performance. The model also incorporated machine learning techniques to improve prediction accuracy and reduce computational overhead. However, the study highlighted challenges related to data security, sensor reliability, and integration with existing systems.

Patel et al. (2023) presented a comprehensive AI-driven modelling framework for electromagnetic shielding effectiveness, combining deep learning, optimization algorithms, and multi-physics simulations. The study emphasized the transition toward intelligent and automated design systems capable of predicting and optimizing shielding performance in complex environments. The model integrated electromagnetic, thermal, and mechanical effects, providing a holistic approach to shielding design. The authors demonstrated that AI-driven models can significantly reduce design time and improve performance by exploring a large design space efficiently. Additionally, the study introduced explainable AI techniques to enhance model interpretability, addressing one of the key limitations of traditional machine learning models. However, the implementation of such systems requires extensive datasets and computational resources, which may limit their accessibility in some applications.

Comparative Table

Study No.	**Author (Year)**	**Model Type**	**Technique Used**	**Material/Structure**	**Key Contribution**	**Limitation**
1	Ganguly (2018)	Percolation Model	EMT + Percolation	Polymer nanocomposites	Conductive network modelling	Ignores agglomeration
2	Wanasinghe (2019)	Analytical	Maxwell-based	Metallic materials	Reflection & absorption modelling	Limited for complex systems
3	Zeng (2020)	Transmission Line	TLT	Carbon materials	Frequency-based EMSE modelling	Multilayer complexity
4	Kumar (2021)	Multi-scale	FEM + Nano modelling	Carbon composites	Micro–macro integration	High computational cost
5	Morales (2023)	Extended Analytical	Parameter transformation	Textile materials	Porosity-based modelling	Environmental effects ignored
6	Li (2018)	Numerical	FEM	Multilayer composites	Accurate geometry modelling	High computation
7	Kwon (2019)	Time-domain	FDTD	Metamaterials	Broadband analysis	Memory intensive

8	Zhang (2020)	Stochastic	Monte Carlo	Random composites	Uncertainty modelling	High iterations
9	Chen (2021)	AI-based	ANN	Composite materials	Fast prediction	Data dependency
10	Gupta (2022)	Hybrid	TLT + ML	Multilayer structures	High accuracy	Complex integration
11	Maiti (2018)	EMT	Effective medium	Graphene composites	Conductivity modelling	Uniform assumption
12	Zhao (2019)	Multilayer	TLT	Layered structures	Impedance optimization	High complexity
13	Liu (2020)	Metamateri al	Homogenizatio n	Metamaterials	Resonance modelling	Fabrication challenges
14	Singh (2021)	Numerical	FDTD	Nanocomposites	Field visualization	High cost
15	Park (2022)	ML-based	SVM	Composite materials	Parameter optimization	Data requirement
16	Zhang (2018)	Multi-scale	Percolation + Maxwell	CNT composites	CNT alignment modelling	Dispersion issues
17	Ahmed (2019)	Numerical	MoM	Thin structures	Surface current modelling	Large system limitation
18	Wang (2020)	Hybrid	FEM + TLT	Multilayer composites	Efficiency improvement	Calibration required
19	Kim (2021)	Deep Learning	CNN	Heterogeneous materials	High accuracy	Black-box nature
20	Li (2022)	Analytical + Numerical	Extended EMSE	Textile composites	Flexible shielding	Environment al impact
21	Al-Saleh (2018)	Percolation	Tunnelling model	Polymer composites	Nano conduction modelling	Complex interactions
22	Seo (2019)	EMT	Hybrid fillers	Hybrid composites	Synergistic effects	High complexity
23	Huang (2020)	Metamateri al	Homogenizatio n	Graphene metamaterials	Perfect absorption	Scaling issues
24	Reddy (2021)	Numerical	FEM	Multilayer systems	Broadband optimization	Computation heavy
25	Choi (2022)	AI-based	Deep Learning	Advanced materials	Inverse design	Data dependency
26	Verma (2020)	Hybrid	FEM + TLT	Nanocomposites	Improved accuracy	Calibration complexity
27	Nguyen (2021)	Analytical	Porosity modelling	Foam materials	Lightweight shielding	Random structure modelling
28	Singh (2022)	Fractional	Fractional calculus	Advanced materials	Memory effect modelling	Mathematica l complexity
29	Zhao (2022)	IoT-based	Data-driven	Smart systems	Real-time adaptation	Security issues
30	Patel (2023)	AI + Multi-physics	Deep learning	Complex systems	Intelligent design	High resource requirement

Comparative Analysis

The comparative analysis of the 30 reviewed studies reveals a clear evolution in electromagnetic shielding effectiveness (EMSE) modelling from traditional analytical approaches toward advanced hybrid, intelligent, and multi-scale frameworks. Early studies primarily relied on analytical models derived from Maxwell's equations and transmission line theory, which provided a fundamental understanding of shielding mechanisms such as reflection, absorption, and multiple reflections. While these models (Studies 2, 3, and 11) offer simplicity and computational efficiency, they are limited in their ability to accurately represent complex materials such as nanocomposites, multilayer structures, and metamaterials. To overcome these limitations, numerical methods such as finite element method (FEM), finite-difference time-domain (FDTD), and method of moments (MoM) have been widely adopted (Studies 6, 7, 14, 17, and 24). These methods enable precise modelling of electromagnetic wave interactions with complex geometries and heterogeneous materials. However, they come at the cost of high computational complexity and resource requirements, particularly for high-frequency and large-scale problems. This trade-off between accuracy and computational efficiency remains a central challenge in EMSE modelling.

Another significant trend is the emergence of multi-scale and hybrid modelling approaches (Studies 4, 16, 18, and 26), which integrate nanoscale material behaviour with macroscale electromagnetic analysis. These models are particularly effective in capturing the hierarchical structure of advanced materials such as carbon nanotube composites and graphene-based systems. By combining different modelling techniques, hybrid approaches achieve improved accuracy while maintaining manageable computational costs. However, they require careful calibration and validation to ensure consistency across different modelling domains. The incorporation of stochastic and probabilistic methods (Study 8) represents another important advancement, addressing uncertainties in material properties and structural configurations. These models provide a more realistic representation of real-world conditions, enabling robust design and risk assessment. However, their reliance on extensive simulations and large datasets increases computational overhead.

Artificial intelligence and machine learning have emerged as transformative tools in EMSE modelling (Studies 9, 15, 19, 25, and 30). These approaches enable rapid prediction and optimization of shielding performance by learning complex relationships between input parameters and output responses. Deep learning models, in particular, have demonstrated high accuracy and efficiency, making them suitable for inverse design and real-time applications. However, challenges related to data dependency, interpretability, and generalization remain significant barriers to widespread adoption. Recent studies also highlight the growing importance of advanced materials and architectures, including metamaterials, multilayer structures, and flexible textiles (Studies 13, 20, 23, and 27). These materials offer enhanced shielding performance through mechanisms such as resonance, impedance matching, and multiple scattering. Mathematical models have been extended to account for these complex behaviours, enabling more accurate prediction and optimization.

Finally, the integration of EMSE modelling with digital technologies such as IoT and smart systems (Study 29) represents a new frontier in electromagnetic shielding. These systems enable real-time monitoring and adaptive shielding, paving the way for intelligent and responsive environments. However, issues related to data security, system integration, and scalability must be addressed. Overall, the comparative analysis indicates a strong shift toward intelligent, hybrid, and multi-physics modelling approaches. Future research is expected to focus on improving computational efficiency, enhancing model interpretability, and integrating real-time data for adaptive shielding systems. This evolution will play a crucial role in addressing the challenges of electromagnetic interference in next-generation technologies such as 5G, IoT, and advanced electronic systems.

Discussion

The systematic review of mathematical modelling approaches for electromagnetic shielding effectiveness (EMSE) from 2018 to 2023 highlights a significant transition from conventional analytical models toward advanced computational and intelligent frameworks. Traditional models based on Maxwell's equations and transmission line theory have served as the foundation for understanding shielding mechanisms such as reflection, absorption, and multiple reflections. These models remain valuable due to their simplicity and ability to provide theoretical insights into electromagnetic wave behaviour. However, their limitations in handling complex materials, heterogeneous structures, and frequency-dependent properties have necessitated the development of more sophisticated modelling techniques. Numerical methods such as finite element method (FEM), finite-difference time-domain (FDTD), and method of moments (MoM) have become widely adopted for modelling EMSE in complex geometries and advanced materials. These methods allow accurate simulation of electromagnetic wave interactions by solving Maxwell's equations in discretized domains. They are particularly effective in analysing multilayer structures, metamaterials, and nanocomposites, where analytical solutions are not feasible. Despite their accuracy, these methods are computationally intensive and require significant processing power, especially for high-frequency and large-scale applications.

The emergence of multi-scale and hybrid modelling approaches represents a major advancement in EMSE analysis. By integrating nanoscale material behaviour with macroscale electromagnetic simulations, these models provide a comprehensive understanding of shielding performance. For example, percolation-based models combined with FEM simulations enable accurate prediction of conductivity networks in nanocomposites. Hybrid approaches that combine analytical models with machine learning further enhance prediction accuracy while reducing computational cost. These developments demonstrate the importance of combining physics-based and data-driven methods for effective EMSE modelling. Artificial intelligence and machine learning have introduced a new dimension to EMSE modelling by enabling rapid prediction and optimization of shielding performance. Techniques such as artificial neural networks (ANN), support vector machines (SVM), and deep learning models have shown remarkable ability to capture complex nonlinear relationships between material properties and shielding effectiveness. These models significantly reduce computation time and facilitate inverse design, where optimal material configurations are identified based on desired performance criteria. However, challenges such as data dependency, lack of interpretability, and generalization issues must be addressed to ensure reliability in practical applications.

Another important trend is the development of advanced materials and architectures, including metamaterials, multilayer composites, and flexible textile-based shielding systems. These materials exhibit unique electromagnetic properties, such as tenable permittivity and permeability, enabling superior shielding performance across a wide frequency range. Mathematical models have been extended to incorporate these properties, allowing accurate prediction of EMSE in complex systems. Additionally, stochastic modelling approaches have been introduced to account for variability in material properties and manufacturing processes, providing a more realistic representation of real-world conditions. The integration of EMSE modelling with digital technologies, such as IoT and smart sensing systems, represents a transformative step toward adaptive and intelligent shielding solutions. Real-time monitoring of electromagnetic environments and dynamic adjustment of shielding parameters can significantly enhance system performance and reliability. However, challenges related to data security, system integration, and scalability must be addressed to fully realize the potential of these technologies.

Conclusion

The systematic review of mathematical modelling approaches for electromagnetic shielding effectiveness (EMSE) from 2018 to 2023 demonstrates a substantial evolution in both theoretical and applied research domains. Electromagnetic shielding remains a critical requirement in modern electronic systems due to the increasing density of devices, high-frequency operations, and the growing complexity of communication technologies such as 5G, IoT, and advanced embedded systems. Mathematical modelling serves as a cornerstone in understanding, predicting, and optimizing shielding performance, enabling efficient design and deployment of shielding materials and structures. Traditional analytical models, grounded in Maxwell's equations and transmission line theory, have provided the foundational framework for EMSE analysis. These models effectively describe key shielding mechanisms, including reflection, absorption, and multiple reflections, and offer valuable insights into the influence of material properties such as conductivity, permeability, and thickness. However, their reliance on simplifying assumptions, such as material homogeneity and ideal boundary conditions, limits their applicability in modelling modern complex materials such as nanocomposites, multilayer systems, and metamaterials.

To overcome these limitations, numerical modelling techniques such as finite element method (FEM), finite-difference time-domain (FDTD), and method of moments (MoM) have been extensively adopted. These methods enable precise simulation of electromagnetic wave interactions with complex geometries and heterogeneous materials. They are particularly effective in capturing frequency-dependent behaviour and multi-layer interactions, which are critical for designing advanced shielding systems. Despite their advantages, numerical methods are computationally intensive and require significant resources, making them less suitable for rapid design and optimization. The emergence of multi-scale and hybrid modelling approaches represents a significant advancement in EMSE research. By integrating nanoscale material behaviour with macroscale electromagnetic simulations, these models provide a comprehensive understanding of shielding mechanisms. Hybrid frameworks that combine analytical models with numerical simulations and machine learning techniques have demonstrated improved accuracy and efficiency. These approaches bridge the gap between theoretical understanding and practical application, enabling the design of high-performance shielding materials.

Artificial intelligence and machine learning have further transformed EMSE modelling by introducing data-driven methodologies capable of handling complex, nonlinear relationships. Techniques such as artificial neural networks, support vector machines, and deep learning models enable rapid prediction and optimization of shielding effectiveness. These methods are particularly valuable in exploring large design spaces and performing inverse design, where desired performance characteristics are used to determine optimal material configurations. However, challenges related to data availability, model interpretability, and generalization must be addressed to ensure their reliability in engineering applications. In addition to modelling techniques, significant advancements have been made in shielding materials and architectures. Metamaterials, multilayer composites, and flexible textile-based materials have emerged as promising solutions for next-generation shielding applications. These materials offer enhanced performance through mechanisms such as impedance matching, resonance, and multiple scattering. Mathematical models have been extended to incorporate these complex behaviours, enabling accurate prediction and optimization of shielding effectiveness across a wide frequency range.

The integration of EMSE modelling with digital technologies, including IoT and smart sensing systems, represents a new frontier in electromagnetic shielding. These systems enable real-time monitoring and adaptive control of shielding performance, paving the way for intelligent and responsive environments. Such advancements are particularly relevant in applications such as smart buildings, wearable electronics, and autonomous systems. However, issues related to data security, system integration, and scalability must be carefully addressed. Despite these advancements, several challenges remain. High computational cost, lack of standardized modelling frameworks, and difficulties in experimental validation continue to hinder progress. Additionally, integrating multi-physics effects, such as thermal and mechanical interactions, into EMSE models remains an open research area. Addressing these challenges will require interdisciplinary collaboration among researchers in electromagnetics, materials science, data science, and engineering. In conclusion, the evolution of EMSE modelling reflects a shift toward intelligent, hybrid, and multi-scale approaches that combine physics-based understanding with data-driven techniques. These advancements have the potential to significantly enhance the design and performance of electromagnetic shielding systems, enabling robust and efficient solutions for modern technological applications. Future research should focus on improving model efficiency, enhancing interpretability, and integrating real-time data to develop adaptive and intelligent shielding systems for next-generation technologies.

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