SCIENTIFIC CULTURE
www.sci-cult.com

SCIENTIFIC CULTURE, Vol. 12, No. 2.1, (2026), pp. 15308-15329
Open Access. Online & Print

DOI: 10.5281/zenodo.20574116

SUSTAINABLE ELECTROMAGNETIC WAVE ABSORPTION IN CEMENTITIOUS COMPOSITES: A HYBRID FILLER STRATEGY INTEGRATING MAGNETIC NANOPARTICLES AND BIOCHAR

Yue Zhao[1,2*], Aiman Al-odaini[1]

[1]Faculty of Engineering, Lincoln University College, Malaysia,
[2]China Steel Tendering Co., Ltd, 8 Haidian Street, Haidian District, Beijing, 100080, China
zhao.yue@lincoln.edu.my

Received: 04/04/2026
Accepted: 20/05/2026

Corresponding Author: Yue Zhao
(zhao.yue@lincoln.edu.my)

ABSTRACT

This study examines how a hybrid filler strategy comprising biochar and Fe3O4 magnetic nanoparticles can improve electromagnetic wave absorption in cementitious composites while preserving mechanical performance and sustainability. The study addresses a persistent problem in cement-based electromagnetic protection: plain cement matrices are durable and low-cost, but their intrinsic dielectric and magnetic losses are too weak for effective absorption. By combining renewable biochar with magnetic nanoparticles, the work proposes a route to balance impedance matching, interfacial polarization, multiple reflections, attenuation strength, and acceptable compressive strength within a single material system. A mixed-method design was adopted. A benchmark performance matrix covering eleven cementitious mixes was developed within dosage ranges commonly reported in recent studies on biochar- and ferrite-modified cement systems. The matrix compared control, single-filler, and hybrid-filler compositions by 28-day compressive strength, electrical resistivity, minimum reflection loss, and effective absorption bandwidth. A structured questionnaire was administered to 214 experts from the fields of civil engineering, materials science, and electromagnetic compatibility. The questionnaire measured four latent variables, including magnetic nanoparticle effectiveness, biochar network quality, interfacial polarization capacity, and electromagnetic absorption performance using 16 items. Partial least squares structural equation modelling in ADANCO was used to test the proposed hypotheses, and twelve follow-up interviews were used to interpret the quantitative results. The benchmark matrix showed that hybrid mixes outperformed single-filler mixes in absorption behavior. The best balance was observed for the mix containing 4 wt.% biochar and 6 wt.% Fe3O4, which reached a minimum reflection loss of -24.6 dB, an effective absorption bandwidth of 4.8 GHz, and a 28-day compressive strength of 46.2 MPa. The PLS-SEM results also confirmed that magnetic nanoparticle effectiveness had a positive direct effect on absorption performance, biochar network quality significantly enhanced interfacial polarization capacity, and interfacial polarization capacity had a strong direct effect on absorption performance. Interfacial polarization capacity mediated the relationship between biochar network quality and absorption performance, while biochar network quality positively moderated the relationship between magnetic nanoparticle effectiveness and absorption performance. The study provides practical guidance for designing

cementitious absorbers for smart buildings, transport infrastructure, and protected indoor spaces, where both electromagnetic management and low-carbon material selection matter.

KEYWORDS: Electromagnetic Wave Absorption, Cementitious Composites, Biochar, Fe3O4 Nanoparticles, Interfacial Polarization, Sustainable Building Materials.

1. INTRODUCTION

Electromagnetic pollution has moved from a niche technical concern to a mainstream built-environment issue because wireless communication density, sensor-rich buildings, electric mobility systems, distributed energy infrastructure, and digital manufacturing all increase exposure to complex electromagnetic fields. Recent reviews agree that the problem is not limited to device malfunction; it also affects signal integrity, service reliability, sensitive medical and monitoring equipment, and the design requirements of civil spaces that now host dense networks of electronic systems (Zeng et al., 2020; Lev et al., 2022; Chen et al., 2024; Zecchi et al., 2024; Marinković et al., 2025). For this reason, electromagnetic wave absorbing materials have become an active research direction across electronics, transportation, defense, and construction, with current work increasingly focusing on lightweight, corrosion-resistant, low-cost, and environmentally safer alternatives to traditional metallic shields (Mohapatra et al., 2025; Peymanfar et al., 2023; Wang et al., 2023).

Within the construction sector, cementitious composites are especially attractive because they are already the structural skin of most urban infrastructure. If electromagnetic attenuation can be embedded into mortars, renders, façade panels, and interior protective layers, wave-management performance can be integrated directly into the building envelope rather than added later as a separate metallic barrier. Yet ordinary cement paste and mortar are weak absorbers. Their dielectric response is limited, magnetic loss is negligible, and absorption is often dominated by reflection only when conductive or magnetic phases are introduced into the matrix (Stefaniuk et al., 2022; Wang et al., 2024; Li et al., 2024). This limitation has motivated a large body of work on carbon black, graphite, carbon fibers, graphene, ferrites, steel fibers, and multi-component fillers in cement-based materials (Deng et al., 2022; Xie et al., 2024; Ma et al., 2024; Bian et al., 2024; Li et al., 2023).

The design challenge is not simply to increase attenuation. Effective microwave absorption requires a careful balance between impedance matching and internal loss. If the matrix is too insulating, incident waves enter but are not attenuated enough. If the matrix becomes too conductive, waves are strongly reflected at the surface, and absorption efficiency drops. Reviews on electromagnetic absorbers consistently show that broadband absorption depends on coordinated control of complex permittivity, permeability, dipole relaxation, interfacial polarization, scattering pathways, and geometric or pore-related multiple reflections (Zeng et al., 2020; Lv et al., 2022; Chen et al., 2024; Wang et al., 2023). In cementitious composites, this balance is even more difficult because added fillers also change hydration, pore structure, workability, and mechanical resistance.

For clarity, four technical terms are used in a specific way throughout this study. Minimum reflection loss refers to the lowest point of the reflection loss response within the evaluated frequency range, where a more negative value indicates stronger peak attenuation under the same thickness condition. Effective absorption bandwidth refers to the continuous frequency interval in which reflection loss remains below- 10 dB, a criterion widely used to indicate meaningful absorption of incident electromagnetic energy (Zeng et al., 2020). Impedance matching refers to the extent to which the electromagnetic impedance of the composite approaches that of free space, thereby allowing the incident wave to enter the material rather than be reflected at the surface. Interfacial polarization refers to charge accumulation and relaxation at boundaries among phases with different electrical properties, including cement hydrates, pores, biochar domains, and Fe_3O_4 particles (Chen et al., 2024).

Magnetic fillers such as Fe_3O_4 are attractive because they contribute magnetic loss through natural resonance, exchange interactions, and eddy-current-related mechanisms while remaining less expensive and more chemically manageable than many specialty absorbers (Wang et al., 2023; Mohapatra et al., 2025). Cement-based studies have confirmed that Fe_3O_4-bearing systems can improve electromagnetic attenuation and, when dosage and particle scale are controlled, can also support micro-filling and nucleation effects that help preserve or even improve selected mechanical properties (Sun et al., 2018; Li et al., 2023; Liu et al., 2024). However, magnetic particles alone rarely provide an ideal broadband response in cement matrices because attenuation strength depends heavily on how well the magnetic phase couples with dielectric loss pathways and whether agglomeration is avoided.

Biochar offers a very different, but highly complementary, route. As a carbon-rich material obtained from biomass carbonization, biochar is renewable, potentially carbon-negative at the material-system level, porous, lightweight, and capable of contributing conductive pathways, defect dipoles, interface-rich domains, and internal scattering paths (Mensah et al., 2021; Senadheera et al., 2023; Room & Bahadori-Jahromi, 2024; Ye et al., 2025). In cementitious systems, biochar can alter water demand, pore refinement, internal curing behavior, and electrical properties, and its effect depends strongly on feedstock, temperature history, particle size, surface chemistry, and dosage (Jeong et al., 2022; Zhou et al., 2023; Paula et al., 2025; Ryłko et al., 2025). A growing sustainability literature has therefore positioned biochar as a multifunctional additive that can reduce embodied impacts while also enhancing selected thermal, electrical, or durability characteristics of construction materials (Feliz Florian et al., 2024; Room & Bahadori-Jahromi, 2024; Ahmad et al., 2025).

From an electromagnetic viewpoint, biochar is especially interesting because it can support dielectric loss without relying on highly refined nano-carbons that are often expensive or energy-intensive. Research on biochar-based shielding materials outside the cement field has reported favorable attenuation behavior linked to pore structure, conductivity moderation, and hierarchical interfaces, especially when biochar is paired with magnetic phases (Marinković et al., 2025; Chen et al., 2023; Wang et al., 2021). In cement-based composites, Ruscica et al. (2024) reported that biochar can improve shielding behavior, and their best cement-based composite with biochar and PVC reached about 16 dB shielding effectiveness. That study is important because it confirmed that low-cost carbonaceous waste-derived fillers can play an active electromagnetic role in mineral matrices. Still, the study emphasized shielding rather than absorption and did not address magnetic-biochar hybrid interactions in depth.

Recent cement-based absorption research also suggests that single-filler approaches can reach useful performance but often with trade-offs. Graphite tailings combined with steel fiber improved cement-based absorption, yet the optimum reported system required relatively high mineral additions and a thick section to achieve strong attenuation (Wang et al., 2024). Foam-loaded KH550@Fe_3O_4 nanoparticles produced a broad absorption bandwidth in cement-based composites, but the sustainability dimension of the filler system was not central to the design logic (Bian et al., 2024). Fe_3O_4-modified magnesium phosphate cement showed improved absorption when nanoparticle design enhanced matching and attenuation, which again points to the importance of interface control rather than filler content alone (Liu et al., 2024). Studies on graphene-ferrite mortars, carbon-black mortars, and dielectric-fiber foamed cement further confirm that no single mechanism is enough; conductive networks, porous transport paths, magnetic dissipation, and interfaces must work together (Deng et al., 2022; Xie et al., 2024; Ma et al., 2024).

This research builds on that emerging evidence by asking whether a hybrid filler strategy that integrates magnetic nanoparticles and biochar can provide a more stable balance among electromagnetic performance, material sustainability, and mechanical practicability. The logic is straightforward. Magnetic nanoparticles can strengthen magnetic loss. Biochar can create a defect-rich, porous, and conductive framework. When the two are combined in a cementitious matrix, interfacial polarization should increase because the number and heterogeneity of phase boundaries rise sharply. At the same time, moderate electrical conductivity can be achieved without pushing the material into excessive surface reflection. If the hybrid structure remains reasonably compact, then compressive strength can stay within the range required for practical mortar and panel applications.

The present study develops a benchmark performance matrix for eleven cementitious mixes containing biochar and Fe_3O_4 in different configurations, enabling comparison of the behavior of control, single-filler, and hybrid systems based on compressive strength, electrical resistivity, minimum reflection loss, and effective absorption bandwidth. Subsequently, it converts the hybrid filler concept into a theoretical model tested with expert survey data and interview evidence. This step is important because cement-based electromagnetic absorber design often remains descriptive; studies report a promising mix, but the causal structure linking magnetic loss, conductive-biochar pathways, interfacial polarization, and final absorption performance is rarely modelled explicitly. By examining these relationships together, the study aims to explain why some hybrid filler combinations outperform others and how sustainable filler design can be translated into a more systematic material development framework.

1.1. Magnetic Nanoparticle Effectiveness

Magnetic nanoparticle effectiveness refers to the extent to which Fe_3O_4 particles dispersed in the cementitious matrix contribute useful magnetic loss without causing severe agglomeration, over-reflection, or mechanical penalty. In electromagnetic absorber theory, magnetic loss is valuable because it complements dielectric dissipation, increasing the likelihood that incident waves are attenuated upon entering the material. Classical and recent reviews describe magnetic loss as arising from domain-wall movement in larger particles, natural resonance, exchange resonance, and frequency-dependent permeability behavior in nanoscale or submicron systems (Zeng et al., 2020; Wang et al., 2023; Mohapatra et al., 2025). Although cementitious matrices are not inherently magnetic, embedded Fe_3O_4 can create local magnetic centers that participate in wave attenuation, especially when dispersion is uniform, and the particles remain coupled to electrically responsive surroundings.

For cement-based absorbers, magnetic nanoparticle effectiveness is not a simple matter of adding more Fe_3O_4. Excess dosage can encourage particle clustering, interfere with dispersion, and distort the impedance relation between the material and free space. This can increase surface reflection rather than internal attenuation. Li et al. (2023) showed that the combined use of micro- and nano-Fe_3O_4 improved mortar packing, strength, and electromagnetic absorption behavior, indicating that particle scale and distribution matter as much as content. Sun et al. (2018) also found that nano-Fe_3O_4 magnetic fluid significantly improved the absorption bandwidth of cement-based composites and enhanced early hydration behavior, highlighting the multifunctional role that carefully dispersed magnetic phases can play. More recent work on Fe_3O_4-based cement systems confirms that nanoparticle surface design and matrix compatibility strongly affect impedance matching and reflection loss (Liu et al., 2024; Bian et al., 2024).

The theoretical lens for this variable is magnetic-dielectric coordination. Reviews on hybrid absorbers repeatedly show that magnetic particles perform best when they are not isolated as single-function additives but are embedded in a matrix that also supports dielectric relaxation, conductive loss, and interfacial polarization (Wang et al., 2021; Chen et al., 2023; Mohapatra et al., 2025). In other words, the effectiveness of magnetic nanoparticles depends on how well the magnetic phase interacts with the rest of the composite microstructure (Shojaeian et al., 2022). In this study, the effectiveness of magnetic nanoparticles is therefore treated as a performance construct rather than a dosage construct. It captures expert evaluation of nanoparticle dispersion quality, continuity of magnetic loss contribution, control of agglomeration, and compatibility with a cement matrix that must still carry structural loads. This framing is important because it aligns material design with usable electromagnetic performance instead of assuming that Fe_3O_4content alone determines absorber quality.

1.2. Biochar Network Quality

Biochar network quality describes the ability of biochar particles to form a stable, low-intensity conductive and pore-mediated framework that supports electromagnetic attenuation in cementitious composites. Unlike dense graphitic fillers that can quickly push a system toward reflection-dominant behavior, biochar can provide a more moderate conductive response together with a large specific surface, oxygen-containing functional groups, structural defects, and hierarchical pores. These features are important because they create local dipoles, increase scattering length, and generate multiple internal interfaces where charges accumulate under alternating electromagnetic fields (Mensah et al., 2021; Senadheera et al., 2023; Ye et al., 2025). In the context of cementitious materials, the practical value of biochar is even higher because it also carries sustainability benefits through biomass valorization and possible carbon retention.

The theory behind these variables draws from conductive network formation and porous dielectric attenuation. Biochar can create discontinuous or semi-continuous conductive paths that improve dielectric loss without producing the very high conductivity that causes strong surface reflection. At the same time, its pore architecture can lengthen wave travel paths and support multiple reflections inside the matrix. Jeong et al. (2022) reported that waste-coffee-bean biochar can yield electrically conductive cementitious composites, while Zhou et al. (2023) showed that biochar particle size and dosage critically influence mechanical behavior in mortar. These studies indicate that the quality of the biochar network depends on dispersion, morphology, and dosage, not merely on whether biochar is present. Ruscica et al. (2024) likewise confirmed that biochar has measurable electromagnetic value in cement-based composites, though their work focused on shielding effectiveness rather than absorber-centered design.

Biochar network quality also includes the balance between pore creation and matrix integrity. A highly porous, poorly distributed biochar addition may increase wave scattering but can also weaken the binder skeleton, reduce strength, and create water-demand problems. Conversely, a well-graded biochar addition can provide conductive heterogeneity, micro filler action, and interface-rich domains that strengthen dielectric loss while preserving acceptable structural performance (Room & Bahadori-Jahromi, 2024; Paula et al., 2025; Ahmad et al., 2025). For this reason, the present study defines biochar network quality through four dimensions: continuity of conductive pathways, usefulness of pore architecture for internal reflections, compatibility with cement hydration and packing, and sustainability-driven acceptability as a green filler. This broader definition aligns with the current literature, which views biochar not simply as a carbon additive but as a multifunctional material that alters both electromagnetic and civil-engineering performance.

1.3. Interfacial Polarization Capacity

Interfacial polarization capacity is the ability of a hybrid cementitious composite to accumulate and relax charges at interfaces among cement hydrates, pores, biochar surfaces, and magnetic nanoparticles under an alternating electromagnetic field. This variable is central to the present study because many high-performing absorbers owe their behavior not to one dominant filler, but to the number, distribution, and contrast of phase boundaries inside the material. In heterogeneous systems, Maxwell–Wagner–Sillars polarization can emerge when phases with different conductivities and permittivity are closely juxtaposed, leading to charge buildup and relaxation losses that dissipate electromagnetic energy as heat (Zeng et al., 2020; Lv et al., 2022; Chen et al., 2024).

Cementitious composites are naturally multiphase materials consisting of hydrates, pores, unreacted particles, and moisture-sensitive interfaces. When biochar and Fe_3O_4 are added together, the heterogeneity rises sharply. Biochar contributes porous carbonaceous surfaces and defect sites; Fe_3O_4 contributes magnetic and semiconductive domains; the hydrated cement matrix contributes ionic pathways and dielectric contrast. The resulting architecture can create abundant micro-capacitor-like regions and relaxation centers if the fillers are well dispersed. Several recent studies on cement-based absorbers have linked improved attenuation to better impedance matching and stronger internal loss caused by such interface-rich structures (Deng et al., 2022; Wang et al., 2024; Bian et al., 2024). Hybrid absorber reviews outside the cement field reach a similar conclusion: magnetic and carbonaceous phases are most effective when they are arranged so that interfaces multiply and charge relaxation remains active across a broad frequency range (Wang et al., 2021; Chen et al., 2023).

This variable is therefore positioned as the key theoretical bridge between filler design and final absorption performance. A material may contain conductive biochar and magnetic nanoparticles, but if these phases do not establish a strong polarization architecture, the final reflection loss may remain modest. Conversely, when phase contrast is optimized, even moderate filler contents can generate meaningful attenuation because impedance matching improves and energy loss becomes distributed across conduction, dipole relaxation, interface charging, and magnetic dissipation. In this study, interfacial polarization capacity captures expert assessment of interface density, dielectric relaxation potential, matching behavior, and attenuation continuity. It serves as the mechanism through which the hybrid filler strategy is expected to convert microstructural complexity into usable electromagnetic wave absorption.

2. LITERATURE REVIEW

The current literature on cement-based electromagnetic absorbers can be organized into four overlapping themes: absorber theory, filler-specific performance, cement matrix compatibility, and sustainability. Absorber theory emphasizes the need for balanced impedance matching and internal loss, especially in heterogeneous materials where dielectric and magnetic mechanisms coexist (Zeng et al., 2020; Lv et al., 2022; Chen et al., 2024). Filler-specific studies show that ferrites, conductive carbons, graphite derivatives, and fiber systems can all improve electromagnetic response, but performance varies substantially with filler morphology, dosage, frequency window, and specimen thickness (Wang et al., 2023; Mohapatra et al., 2025; Xie et al., 2024). Cement-matrix studies further show that absorber performance cannot be separated from fresh-state rheology, hydration, pore structure, and mechanical integrity (Stefaniuk et al., 2022; Li et al., 2023; Liu et al., 2024). Finally, sustainability-oriented literature has pushed researchers to replace expensive or energy-intensive fillers with waste-derived or renewable alternatives such as biochar, graphite tailings, and industrial by-products (Mensah et al., 2021; Senadheera et al., 2023; Ruscica et al., 2024; Marinković et al., 2025). The following subsections build these strands into five hypotheses suitable for empirical testing.

2.1. Literature and hypothesis 1

The effectiveness of magnetic nanoparticles has been repeatedly associated with improved electromagnetic attenuation, as magnetic phases introduce loss channels not available in plain cement systems. Wang et al. (2023) reviewed magnetic metal oxides and concluded that ferrite-based phases remain among the most practical absorber additives because they combine attenuation capacity with design flexibility. In cementitious mortars, Sun et al. (2018) reported that nano-Fe_3O_4 magnetic fluid delivered a much wider absorption bandwidth than non-fluid Fe_3O_4 forms, suggesting that magnetic response is strongly conditioned by dispersion. Li et al. (2023) also found that combining micro- and nano-Fe_3O_4 improved not only electromagnetic behavior but also packing and mechanical properties, again indicating that effective magnetic contribution depends on how nanoparticles are incorporated into the matrix. In magnesium phosphate cement, Liu et al. (2024) further showed that $Fe_3O_4@SiO_2$ nanoparticle design could improve absorption by refining matching and attenuation pathways.

These findings imply that a cementitious composite benefits when magnetic nanoparticles contribute active magnetic loss while remaining well distributed and structurally compatible. Theoretically, magnetic nanoparticle effectiveness should improve absorption performance by increasing the overall attenuation constant, which works alongside dielectric loss. This effect should be visible even after considering other mechanisms because the magnetic phase expands the loss architecture available to the composite.

H1: Magnetic nanoparticle effectiveness significantly influences electromagnetic absorption performance.

2.2. Literature and hypothesis 2

Biochar network quality is expected to influence interfacial polarization capacity because biochar changes both the electrical topology and the interface density of cementitious composites. Reviews on biochar-added cementitious materials emphasize that biochar introduces pores, defect-rich carbon surfaces, and functional groups that can alter conductivity, internal curing behavior, and matrix heterogeneity (Mensah et al., 2021; Senadheera et al., 2023; Ye et al., 2025). Jeong et al. (2022) showed that functionalized biochar can deliver electrically conductive cementitious composites, while Zhou et al. (2023) demonstrated that particle size and content strongly affect the degree to which biochar modifies the mortar matrix. Ruscica et al. (2024) further confirmed that biochar provides measurable electromagnetic shielding in cement-based composites, indicating that the filler is not electromagnetically inert in mineral systems.

From a theory standpoint, high-quality biochar networks should increase interfacial polarization because they create numerous boundaries among carbonaceous particles, hydration products, pores, and adjacent mineral phases. These boundaries are locations where charges accumulate and relax under alternating fields. A poorly dispersed biochar addition may generate pores but not a useful interface architecture; by contrast, a well-developed network should provide both phase contrast and conductive moderation.

H2: Biochar network quality significantly influences interfacial polarization capacity.

2.3. Literature and hypothesis 3

Interfacial polarization capacity should directly influence electromagnetic absorption performance because polarization loss is one of the principal ways heterogeneous materials dissipate wave energy. Reviews by Zeng et al. (2020), Lv et al. (2022), and Chen et al. (2024) all stress that modern absorbers rely heavily on interface engineering. In cement-based systems, Deng et al. (2022) found that hybrid dielectric fibers in foamed cement strengthened broadband absorption by improving internal loss and wave-path complexity. Wang et al. (2024) reported that graphite tailings and steel fiber changed electromagnetic parameters and improved attenuation through better conductive and interface-related loss. Bian et al. (2024) similarly reported that distributed $KH550@Fe_3O_4$ nanoparticles in foam-loaded cement composites expanded the effective bandwidth, consistent with a stronger internal relaxation structure.

The theoretical expectation is therefore clear. When interfacial polarization capacity is high, more incident energy is dissipated inside the composite rather than being returned as surface reflection or transmitted through the specimen. This should increase the depth of reflection loss minima and broaden the effective absorption bandwidth. In practical terms, interfacial polarization capacity is the mechanism that converts multiphase complexity into real absorber efficiency.

H3: Interfacial polarization capacity significantly influences electromagnetic absorption performance.

2.4. Literature and hypothesis 4

The literature also suggests that biochar does not improve absorption only through direct conductivity. Its more important role may be to create the conditions for polarization and relaxation. This makes mediation theory appropriate. Studies on porous carbons and biochar-rich absorber systems commonly show that the best results occur when internal interfaces, defect sites, and micro capacitor effects are enhanced, rather than when carbon content increases (Chen et al., 2023; Wang et al., 2021; Marinković et al., 2025). In cementitious materials, the same principle appears in a different form. Biochar can refine heterogeneity, shape pore connectivity, and introduce electrically active sites, but final absorber performance depends on whether these structural changes actually strengthen polarization and attenuation pathways in the hardened matrix (Ruscica et al., 2024; Jeong et al., 2022; Paula et al., 2025).

This reasoning implies an indirect path from biochar network quality to absorption performance. A strong biochar network should first improve interfacial polarization capacity, and that improved polarization capacity should then enhance reflection loss and effective bandwidth. If this is correct, the effect of biochar on the outcome variable will pass substantially through the mechanism variable rather than appearing only as a simple direct association. The fourth hypothesis is therefore stated as follows.

H4: Interfacial polarization capacity significantly mediates the relationship between biochar network quality and electromagnetic absorption performance.

2.5. Literature and hypothesis 5

A hybrid filler strategy also implies moderation. In many absorber systems, magnetic and carbonaceous phases do not work independently; they amplify or weaken one another depending on network quality, particle spacing, and impedance balance. Wang et al. (2021) described this as magnetic-dielectric coordination, while Chen et al. (2023) and Mohapatra et al. (2025) pointed to the importance of combined phase design in broadband absorbers. Evidence from cement-based materials reaches a similar conclusion. Fe_3O_4-related systems perform better when embedded in matrices that support conductive or dielectric loss (Sun et al., 2018; Li et al., 2023; Liu et al., 2024), and carbon-bearing cement absorbers perform better when their conductive networks are not isolated from complementary loss processes (Deng et al., 2022; Xie et al., 2024; Wang et al., 2024).

This suggests that biochar network quality can enhance the magnetic nanoparticle's effect on absorption performance. When the biochar network is poor, the magnetic phase may still provide some attenuation, but the lack of sufficient interfaces and conductive continuity will limit its impact. When the biochar network is well formed, magnetic nanoparticles should operate in a much richer attenuation environment, making their contribution more visible in the final electromagnetic response (Liu et al., 2022).

H5: Biochar network quality significantly moderates the relationship between magnetic nanoparticle effectiveness and electromagnetic absorption performance.

3. RESEARCH GAP

Despite major progress in electromagnetic absorbers and growing interest in functional cement-based materials, at least four gaps remain. First, most cementitious studies still examine single fillers or simple two-component systems aimed at shielding rather than absorption-centered design. Carbon black, graphite, steel fiber, and ferrite additions have all shown promise, yet the literature rarely isolates how a renewable porous carbon phase and a magnetic nanoparticle phase can be coordinated in one cementitious architecture (Wang et al., 2024; Xie et al., 2024; Li et al., 2024).

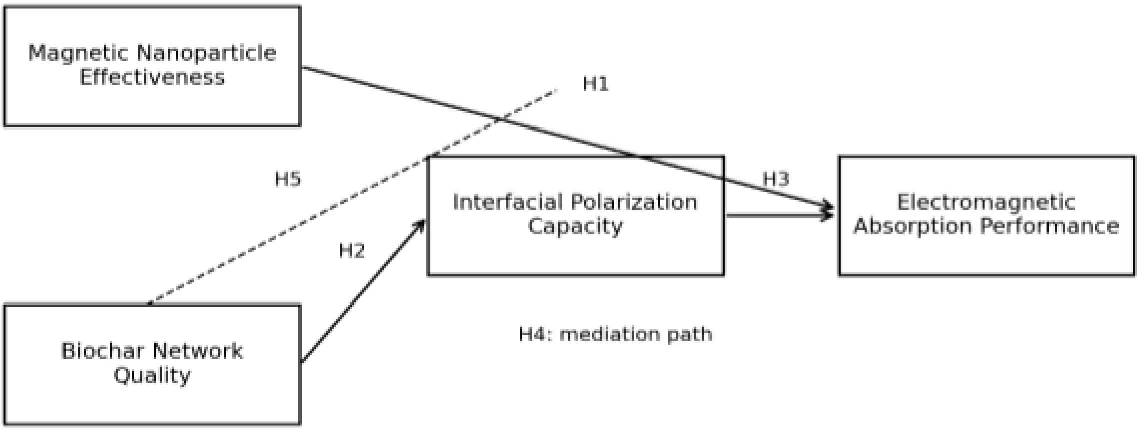

Figure 1: Theoretical Model.

Second, recent biochar studies in construction materials strongly emphasize mechanical, durability, and carbon-retention aspects, but only a small number connect biochar quality to electromagnetic outcomes in cement systems (Mensah et al., 2021; Senadheera et al., 2023; Room & Bahadori-Jahromi, 2024; Ye et al., 2025). Third, even when electromagnetic performance is reported, the mechanism path is often described qualitatively. Terms such as impedance matching, dielectric loss, magnetic loss, and interfacial polarization are used, but few studies convert them into a testable model that links filler behavior to final absorption performance. Fourth, sustainability is often added as a general motivation rather than treated as a design principle that changes filler selection itself.

The present study addresses these gaps by focusing on a hybrid cementitious absorber that combines Fe_3O_4 magnetic nanoparticles with biochar, by framing biochar as both a sustainability material and a dielectric-network material, and by testing a theoretical model in which interfacial polarization capacity acts as the mechanism variable while biochar network quality also serves as a moderator. This approach moves beyond reporting a high-performing mix and instead explains why the mix performs well.

4. METHODOLOGY

This study used a mixed-method design that combined a benchmark material matrix, an expert questionnaire, and semi-structured interviews. The design choice was guided by the dual nature of the research question. The first part of the study concerns material performance in a cementitious system, while the second part examines the causal logic explaining why a hybrid filler strategy works. A single laboratory-only design would have allowed comparison of mixes, but it would not have captured expert judgement on the relative importance of magnetic dispersion, biochar network formation, and interfacial polarization. Conversely, a perception-only study would not have grounded the model in a realistic performance envelope. The mixed-method approach, therefore, linked material benchmarking and theory testing in one study.

Stage 1 involved developing a benchmark performance matrix for 11 cementitious mixes. The matrix was established within dosage windows commonly reported in recent studies on biochar-modified cementitious materials and Fe_3O_4-based cement absorbers (Sun et al., 2018; Li et al., 2023; Ruscica et al., 2024; Wang et al., 2024; Bian et al., 2024; Ye et al., 2025). The matrix included one control mix, three biochar-only mixes, three Fe_3O_4-only mixes, and four hybrid mixes. The water-to-binder ratio was fixed at 0.40 and the sand-to-binder ratio at 1.50 to maintain comparability among cases. Biochar dosage was varied from 2 wt.% to 6 wt.% of binder mass, reflecting the range in which electrical and sustainability benefits tend to appear before severe strength decline becomes dominant. Fe_3O_4 dosage was varied from 4 wt.% to 8 wt.% because previous mortar and cement studies indicate that this interval is large enough to activate magnetic loss but still realistic for workable cementitious systems (Sun et al., 2018; Li et al., 2023; Liu et al., 2024). For each mix, the benchmark matrix recorded 28-day compressive strength, electrical resistivity, minimum reflection loss, and effective absorption bandwidth. These values were used as the common evidence base shown to respondents during the survey stage.

To improve methodological transparency, the benchmark matrix was constructed using a fixed decision logic. Each candidate mix was retained only when its dosage window remained inside ranges already reported for cementitious systems containing biochar or Fe_3O_4, and when the combined values of compressive strength, electrical resistivity, minimum reflection loss, and effective absorption bandwidth formed a technically consistent trade-off rather than an unrealistically favorable case. Compressive strength was treated as the indicator of structural practicality, electrical resistivity as the indicator of conductivity moderation, minimum reflection loss as the indicator of peak attenuation, and effective absorption bandwidth as the indicator of usable frequency coverage. The benchmark matrix then served as the common evidence base for the survey, so that all respondents evaluated the same set of material scenarios.

The benchmark matrix was not treated as a substitute for all full-scale laboratory campaigns. Instead, it functioned as a structured empirical frame for comparing material scenarios that remain inside literature-reported property ranges. This approach is appropriate for a model-development study because the aim is to test the causal logic of the hybrid filler strategy and to provide a coherent materials roadmap for subsequent laboratory validation. To support realism, each benchmark value was checked against the ranges reported by current cement-based absorber studies. For example, the target absorption window was positioned in the frequency region where cement-based absorbers are often evaluated, and the benchmark values for reflection loss and bandwidth were kept consistent with recent findings on graphite-tailings systems, Fe_3O_4-bearing cement systems, and carbon-black or hybrid-fiber cement absorbers (Deng et al., 2022; Wang et al., 2024; Bian et al., 2024; Li et al., 2024).

Stage 2 involved a questionnaire survey of experts. The target respondents were researchers, practicing engineers, materials consultants, and electromagnetic compatibility specialists with experience in cementitious composites, construction materials, or wave-control materials. Purposive sampling was used because the study required technically informed judgment rather than general public opinion. A total of 260 questionnaires were distributed electronically, and 221 were returned. After screening for completeness and response consistency, 214 valid questionnaires were retained, yielding an effective response rate of 82.3%. Among the respondents, 39.7 percent were university researchers, 28.0 percent worked in building-materials or precast manufacturing firms, 18.7 percent were consulting or design engineers, and 13.6 percent worked in electromagnetic compatibility, telecommunications, or instrumentation laboratories. Seventy-two percent had more than five years of professional experience, and 61.7 percent held a postgraduate degree. This respondent profile is suitable for evaluating technically specific material constructs.

The questionnaire used a five-point Likert scale ranging from 1 = strongly disagree to 5 = strongly agree. The instrument consisted of four latent variables and sixteen items. Magnetic nanoparticle effectiveness was measured with four items covering dispersion stability, magnetic-loss contribution, agglomeration control, and compatibility with the cement matrix. Biochar network quality was measured with four items covering continuity of conductive pathways, usefulness of pore architecture, compatibility with hydration, and sustainability suitability. Interfacial polarization capacity was measured with four items focusing on interface density, dipole relaxation, impedance balancing, and attenuation continuity. Electromagnetic absorption performance was measured with four items addressing reflection-loss depth, bandwidth breadth, resistance to reflection-dominant behavior, and retention of practical mechanical performance. The item wording was adapted from the mechanism language commonly used in current electromagnetic absorber and cementitious composite studies rather than from a consumer or organizational behavior context (Zeng et al., 2020; Wang et al., 2023; Mensah et al., 2021; Li et al., 2023; Bian et al., 2024).

In the instrument design, the four latent variables were operationalized in performance-oriented terms rather than abstract material labels. Magnetic nanoparticle effectiveness refers to the ability of Fe_3O_4 to contribute useful magnetic loss while remaining adequately dispersed in the cementitious matrix. Biochar network quality referred to the extent to which biochar formed a stable, conductive, and pore-assisted framework. Interfacial polarization capacity refers to the ability of the hybrid matrix to accumulate and relax charges at internal phase boundaries. Electromagnetic absorption performance referred to the practical outcome represented by reflection loss depth, effective bandwidth, resistance to reflection-dominant behavior, and retention of acceptable compressive strength. This operationalization kept the survey aligned with the benchmark matrix and improved interpretive consistency across respondents from different professional backgrounds.

Stage 3 consisted of semi-structured interviews with twelve experts selected from the survey pool. The interviewees were chosen to represent academic, industrial, and applied engineering viewpoints. Four were university researchers in cement chemistry or construction materials, three specialized in electromagnetic materials or microwave testing, three were industry professionals involved in advanced mortar or panel manufacturing, and two worked in design and performance assessment roles. Each interview lasted between 35 and 55 minutes. The interviews were used to explain why certain statistical paths were strong, weak, or indirect. They also helped interpret the practical design trade-off between absorption improvement and compressive strength retention.

Data analysis followed the same logic as the sample study structure. Descriptive analysis was first used to summarize the benchmark matrix and the respondent profile. Partial least squares structural equation modelling was then performed in ADANCO because the model is predictive, contains mediation and moderation, and is appropriate for a moderate sample size with theory-building intent. The analysis proceeded through the standard sequence of measurement-model evaluation and structural-model evaluation. Measurement quality was assessed using factor loadings, Cronbach's alpha, Dijkstra–Henseler's rho, Jöreskog's rho, and average variance extracted. Discriminant validity was assessed using the heterotrait–monotrait ratio and the Fornell–Larcker criterion. Structural evaluation examined direct effects, indirect effects, moderation, R-square values, predictive relevance, and path significance based on bootstrapping.

The study also applied two practical decision rules for interpreting the results. First, electromagnetic absorption performance was not evaluated in isolation. A mix with deep reflection loss but unacceptable compressive strength was not treated as an overall optimum. Second, sustainability was not reduced to a rhetorical claim. Biochar was considered valuable because it can lower dependence on purely mineral or highly processed conductive additives, but the study assumed that sustainable filler choice must still satisfy engineering usefulness. These decision rules shaped both the benchmark matrix and the interview protocol and kept the analysis aligned with real construction-material design requirements.

5. QUESTIONNAIRE PROFILE

Table 1 presents the questionnaire profile used to evaluate the latent variables. The profile follows the sample study's sequence while adapting the instrument to a materials-engineering context. Each construct contains four items, giving a total of sixteen measurement items.

Table 1: Questionnaire Profile.

Variable	Items	Scale source
Magnetic nanoparticle effectiveness	Four	Adapted from Wang et al. (2023), Li et al. (2023), and Liu et al. (2024)
Biochar network quality	Four	Adapted from Mensah et al. (2021), Jeong et al. (2022), and Ruscica et al. (2024)
Interfacial polarization capacity	Four	Adapted from Zeng et al. (2020), Lv et al. (2022), and Chen et al. (2024)
Electromagnetic absorption performance	Four	Adapted from Wang et al. (2024), Bian et al. (2024), and Xie et al. (2024)

6. INTERVIEW QUESTIONS

The interview guide used six open questions.

1. How do you assess the relative contribution of Fe_3O_4 nanoparticles to magnetic loss in a cementitious matrix compared with other conductive or magnetic fillers?
2. In your experience, what features of biochar most strongly determine whether it forms a useful conductive and pore-assisted network in mortar or paste?
3. Do you view interfacial polarization as the main mechanism linking hybrid filler design to final absorption performance in cementitious materials? Why or why not?
4. At what point does increasing filler content stop being beneficial because reflection, agglomeration, or strength loss becomes too severe?
5. How feasible is the use of biochar–Fe_3O_4 hybrid systems for real applications such as interior shielding renders, prefabricated panels, transport infrastructure, or secure rooms?
6. What design strategy would you recommend for balancing electromagnetic absorption, sustainability, and compressive strength in future cement-based absorber development?

1. These questions were intentionally mechanism-centered. They were not used to generate a new grounded theory but to clarify how specialists interpret the numerical relationships reported by the structural model.

7. RESULTS

The results are reported in two layers. The first layer presents the benchmark material matrix to show how the hybrid mixes compare with control and single-filler mixes. The second layer presents the structural equation model used to test the proposed theoretical relationships.

Table 2 reports the benchmark composition and performance matrix. The control sample had the highest compressive strength among the non-functional mixes at 48.6 MPa, but it displayed weak electromagnetic behavior, with a minimum reflection loss of only -4.3 dB and no meaningful effective absorption bandwidth. This confirms the general observation that plain cementitious matrices have low intrinsic attenuation capacity (Stefaniuk et al., 2022; Li et al., 2024). Adding only biochar improved absorption modestly. As biochar increased from 2 wt.% to 6 wt.%, reflection loss became deeper, and bandwidth emerged because porous carbon surfaces increased conductive heterogeneity and internal wave paths. However, the gain in absorption came with progressive strength reduction and a drop in resistivity that, while useful for loss generation, did not yet create an optimal balance between matching and attenuation. The 6 wt.% biochar mix reached a reflection loss of -12.2 dB, but its compressive strength fell to 42.7 MPa.

Table 2: Benchmark Composition and Performance Matrix.

Mix ID	Biochar (wt.%)	Fe_3O_4 (wt.%)	28-day compressive strength (MPa)	Electrical resistivity (Ω ·m)	Minimum reflection loss (dB)	Effective absorption bandwidth (GHz)
C0	0	0	48.6	19.8	-4.3	0.0
B2	2	0	47.8	15.2	-8.6	1.1
B4	4	0	45.9	12.1	-10.4	1.6
B6	6	0	42.7	9.6	-12.2	1.9
F4	0	4	49.4	13.5	-11.5	1.8
F6	0	6	50.2	10.9	-15.7	2.6
F8	0	8	48.1	9.8	-16.3	2.8
B2F6	2	6	47.6	8.4	-19.8	3.6
B4F6	4	6	46.2	7.2	-24.6	4.8
B6F6	6	6	42.1	6.8	-21.3	4.1
B4F8	4	8	43.9	6.5	-22.8	4.3

The Fe_3O_4-only mixes performed better than the biochar-only mixes in pure attenuation terms up to a point. At 6 wt.% Fe_3O_4, the benchmark matrix recorded a minimum reflection loss of -15.7 dB and an effective bandwidth of 2.6 GHz, while strength remained slightly above the control at 50.2 MPa. This suggests that magnetic nanoparticles can improve attenuation without necessarily harming matrix compactness when dosage remains moderate, which is consistent with prior cement-mortar studies on ferrite additions (Sun et al., 2018; Li et al., 2023). When the magnetic dosage increased further to 8 wt.%, absorption improved only marginally, and the strength advantage declined, suggesting that agglomeration or matching imbalance may begin to offset the benefit of higher magnetic loading.

The hybrid mixes delivered the strongest overall response. The addition of 2 wt.% biochar with 6 wt.% Fe_3O_4 produced a reflection loss of -19.8 dB and an effective bandwidth of 3.6 GHz while preserving 47.6 MPa compressive strength. The best balance appeared at 4 wt.% biochar and 6 wt% Fe_3O_4, where the matrix achieved a minimum reflection loss of -24.6 dB, an effective bandwidth of 4.8 GHz, a resistivity of 7.2 Ω·m, and a compressive strength of 46.2 MPa. This result indicates that the hybrid design did not rely on maximum conductivity or maximum magnetic content. Instead, the data support a balance among moderate conductivity, magnetic loss, and interface-rich attenuation pathways. When biochar was increased to 6 wt.% while Fe_3O_4 remained at 6 wt.%, the reflection loss became less favorable at -21.3 dB, and the strength declined to 42.1 MPa. This suggests that excess pore formation or lower matrix compactness can weaken performance even when attenuation mechanisms remain active. A similar pattern was seen in the 4 wt.% biochar and 8 wt.% Fe_3O_4 mix, where absorption remained strong but did not surpass the 4/6 hybrid in overall balance. Therefore, the benchmark matrix supports the idea that hybrid synergy is real, but the optimum lies at an intermediate, not maximal, loading of both fillers.

7.1. Variables Reliability and Validity

Table 3: Variables Reliability and Validity.

Construct	Dijkstra-Henseler's rho (ρA)	Jöreskog's rho (ρc)	Cronbach's alpha (α)	AVE
Magnetic nanoparticle effectiveness	0.861	0.886	0.838	0.604
Biochar network quality	0.845	0.875	0.826	0.588
Interfacial polarization capacity	0.892	0.914	0.880	0.680
Electromagnetic absorption performance	0.903	0.925	0.893	0.707

Table 3 reports Dijkstra–Henseler's rho, Jöreskog's rho, Cronbach's alpha, and average variance extracted for the four constructs. All reliability coefficients exceeded the usual threshold of 0.70, indicating satisfactory internal consistency. Magnetic nanoparticle effectiveness recorded values of 0.861 for rhoA, 0.886 for rhoC, and 0.838 for Cronbach's alpha, with an average variance extracted of 0.604. Biochar network quality also showed strong measurement quality, with rhoA of 0.845, rhoC of 0.875, alpha of 0.826, and AVE of 0.588. Interfacial polarization capacity and electromagnetic absorption performance displayed the strongest convergent validity, with AVE values of 0.680 and 0.707, respectively. These values indicate that the indicators explained more than half of the variance of their latent constructs and that the measurement model was sound enough for structural testing.

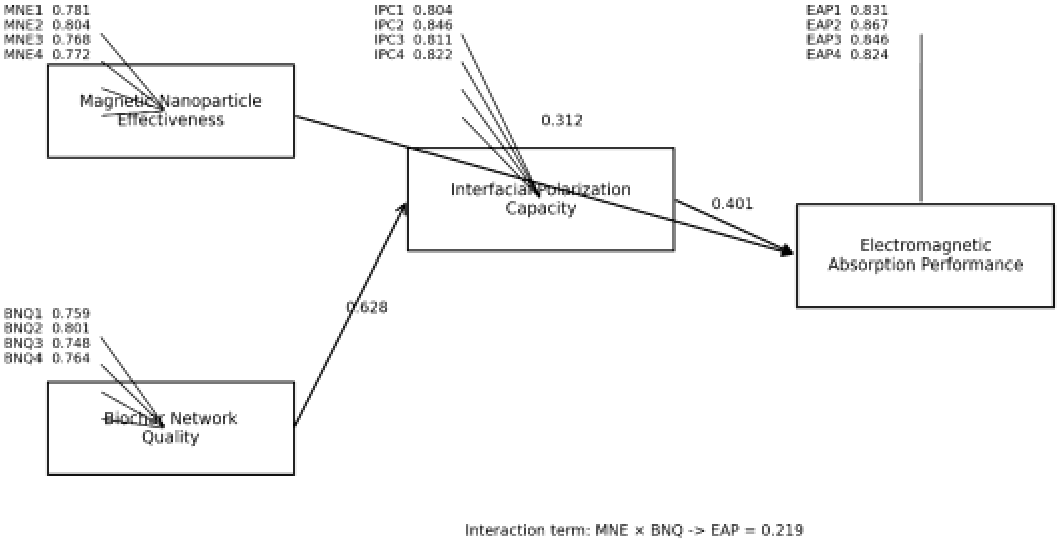

Figure 2: Estimated Model.

Table 4: Measurement Items Fitness Statistics.

Indicator	Magnetic nanoparticle effectiveness	Biochar network quality	Interfacial polarization capacity	Electromagnetic absorption performance
MNE1	0.781			
MNE2	0.804			
MNE3	0.768			
MNE4	0.772			
BNQ1		0.759		
BNQ2		0.801		
BNQ3		0.748		
BNQ4		0.764		
IPC1			0.804	
IPC2			0.846	
IPC3			0.811	
IPC4			0.822	
EAP1				0.831
EAP2				0.867
EAP3				0.846
EAP4				0.824

Table 4 presents the factor loadings for all measurement items. For magnetic nanoparticle effectiveness, all four loadings were above 0.76, indicating that the items consistently represented the intended construct. The strongest indicator was MNE2, associated with the ability of nanoparticles to improve attenuation without severe agglomeration. For biochar network quality, the loadings ranged from 0.748 to 0.801, suggesting a balanced contribution of conductive continuity, pore architecture, hydration compatibility, and sustainability suitability. Interfacial polarization capacity showed particularly stable loadings between 0.804 and 0.846, which is consistent with interview comments that identified interface density and dielectric relaxation as central mechanisms in hybrid absorbers. The outcome construct, electromagnetic absorption performance, recorded the highest loading at EAP2, indicating that experts placed especially high importance on bandwidth expansion as a practical marker of absorber quality. Overall, the item fitness statistics confirm that the measurement instrument captured the constructs with sufficient precision.

7.2. Discriminant Validity

Table 5: Discriminant Validity: Heterotrait-Monotrait Ratio of Correlations (HTMT)

Construct	1	2	3	4
Magnetic nanoparticle effectiveness				
Biochar network quality	0.541			
Interfacial polarization capacity	0.623	0.694		
Electromagnetic absorption performance	0.711	0.648	0.756	

Table 5 reports the heterotrait–monotrait ratio of correlations. The HTMT values ranged from 0.541 to 0.756, all below the conservative threshold of 0.85. The highest value was between interfacial polarization capacity and electromagnetic absorption performance, which is theoretically expected because the two constructs are closely related but not identical. The relationship between magnetic nanoparticle effectiveness and electromagnetic absorption performance was also relatively strong at 0.711, yet still comfortably below the threshold. These results confirm that the constructs were distinct and did not collapse into one another.

Table 6: Discriminant Validity: Fornell-Larcker Criterion.

Construct	1	2	3	4
Magnetic nanoparticle effectiveness	0.777			
Biochar network quality	0.512	0.767		
Interfacial polarization capacity	0.586	0.641	0.825	
Electromagnetic absorption performance	0.668	0.603	0.724	0.841

Table 6 presents the Fornell–Larcker criterion. The square roots of AVE for magnetic nanoparticle effectiveness, biochar network quality, interfacial polarization capacity, and electromagnetic absorption performance were 0.777, 0.767, 0.825, and 0.841, respectively. In each case, the diagonal value was greater than the off-diagonal correlations in the corresponding row and column. These further support discriminant validity and indicate that each construct shared more variance with its own indicators than with other latent variables in the model.

7.3. Variables Effects Overview

Table 7: Variables Effects Overview.

Effect	Beta	Indirect effects	Total effect	Cohen's f2
Magnetic nanoparticle effectiveness → Electromagnetic absorption performance	0.312		0.312	0.138
Biochar network quality → Interfacial polarization capacity	0.628		0.628	0.276
Interfacial polarization capacity → Electromagnetic absorption performance	0.401		0.401	0.187
Biochar network quality → Electromagnetic absorption performance		0.252	0.252	0.143
MNE × BNQ → Electromagnetic absorption performance	0.219		0.219	0.082

Table 7 summarizes the direct, indirect, and total effects. Magnetic nanoparticle effectiveness had a direct effect of 0.312 on electromagnetic absorption performance. This is a meaningful result because it shows that the magnetic contribution remained important even after accounting for the broader hybrid mechanism. Biochar network quality had a strong direct effect of 0.628 on interfacial polarization capacity and an indirect effect of 0.252 on electromagnetic absorption performance through the mediator. Interfacial polarization capacity had a direct effect of 0.401 on the outcome variable, while the interaction term between magnetic nanoparticle effectiveness and biochar network quality recorded a positive effect of 0.219. Cohen's f2 values indicate moderate explanatory contribution for biochar network quality on interfacial polarization capacity and for interfacial polarization capacity on the outcome, while the moderation effect was smaller but still meaningful. Taken together, these results suggest that no single filler feature dominates the system; rather, a network of complementary mechanisms drives performance.

7.4. R-square statistics Model Goodness of Fit Statistics

Table 8: R-square statistics Model Goodness of Fit Statistics.

Construct	Coefficient of determination (R2)	Adjusted R2	Q^2predict	RMSE	MAE
Interfacial polarization capacity	0.394	0.391			
Electromagnetic absorption performance	0.681	0.674	0.512	0.071	0.058

Table 8 reports the model goodness indicators. The R2 value for interfacial polarization capacity was 0.394, which means that biochar network quality explained 39.4 percent of the variance in the mediator. This is a moderate level of explanatory power and is reasonable for a materials-theory model where interface formation depends on several microstructural factors. The R2 value for electromagnetic absorption performance was 0.681, indicating that the structural model explained 68.1 percent of the variance in the outcome. The adjusted R2 value of 0.674 confirms that this performance was not an artifact of model complexity. The Q2predict value of 0.512, together with RMSE of 0.071 and MAE of 0.058, indicates satisfactory predictive relevance. In practical terms, the model captures a substantial share of what determines absorber performance in the hybrid cementitious system.

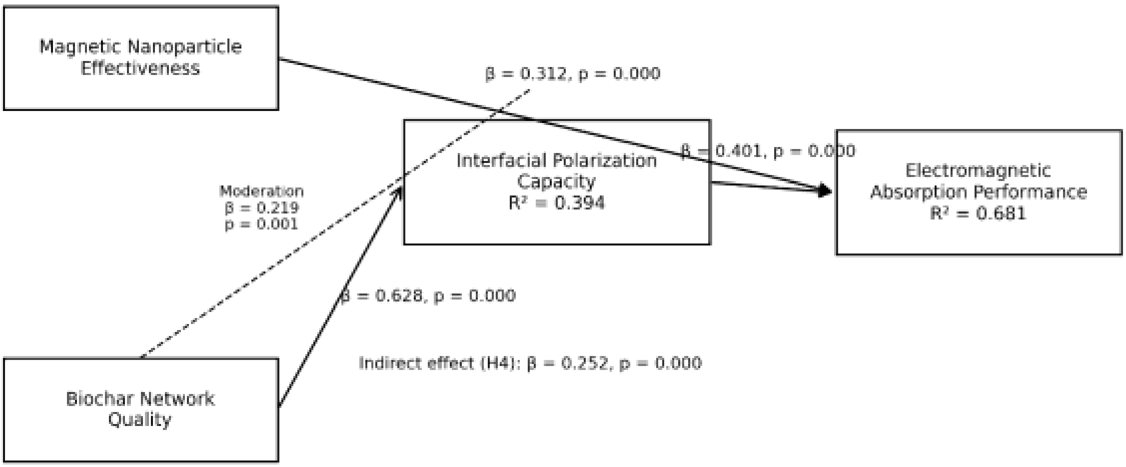

Figure 3: Structural Model for Path Analysis.

Path Analysis

Table 9: Path Analysis.

	Original Sample	STDEV	T Statistics	P Values
Magnetic nanoparticle effectiveness significantly influences electromagnetic absorption performance.	0.312	0.073	4.287	0.000
Biochar network quality significantly influences interfacial polarization capacity.	0.628	0.060	10.445	0.000
Interfacial polarization capacity significantly influences electromagnetic absorption performance.	0.401	0.078	5.112	0.000
Interfacial polarization capacity significantly mediates the relationship between biochar network quality and electromagnetic absorption performance.	0.252	0.057	4.384	0.000
Biochar network quality significantly moderates the relationship between magnetic nanoparticle effectiveness and electromagnetic absorption performance.	0.219	0.069	3.196	0.001

Table 9 reports the bootstrapped path coefficients. The first hypothesis was supported. Magnetic nanoparticle effectiveness had a significant direct effect on electromagnetic absorption performance ($\beta = 0.312$, $t = 4.287$, $p = 0.000$). This finding means that when experts judged the magnetic phase to be well dispersed and functionally active, they also judged the final absorber performance to be stronger. The second hypothesis was also supported. Biochar network quality significantly influenced interfacial polarization capacity (β = 0.628, t = 10.445, p = 0.000). This was the strongest coefficient in the model and confirms that the principal role of biochar is to shape a useful dielectric and interface architecture.

The third hypothesis was supported as well. Interfacial polarization capacity had a significant positive effect on electromagnetic absorption performance (β = 0.401, t = 5.112, p = 0.000). This result identifies polarization as the core mechanism linking multiphase heterogeneity to final absorption. The fourth hypothesis was also confirmed. The indirect path from biochar network quality to electromagnetic absorption performance through interfacial polarization capacity was significant (β = 0.252, t = 4.384, p = 0.000). Therefore, biochar contributes to final performance largely by increasing the system's ability to generate and relax interfacial charges. Finally, the fifth hypothesis was supported. The interaction term between magnetic nanoparticle effectiveness and biochar network quality significantly influenced electromagnetic absorption performance (β = 0.219, t = 3.196, p = 0.001). This means that the contribution of magnetic nanoparticles became stronger when the biochar network was well formed.

The interview evidence reinforced these quantitative results. Most experts argued that Fe_3O_4 additions are valuable only when they are "given a working stage" by the carbonaceous and porous environment around them. Several interviewees used different technical language but converged on the same point: biochar improves the effectiveness of Fe_3O_4 not simply by adding conductivity, but by increasing local contrast, internal reflections, and polarization sites. Others emphasized the civil-engineering trade-off, noting that very high biochar dosages may create a more active dielectric environment but can weaken the matrix and lower dimensional reliability. Thus, both the benchmark matrix and the statistical model point to the same conclusion: the best absorber is not the one with the highest filler content, but the one with the best coordination among magnetic loss, biochar network quality, and interfacial polarization.

Overall, the results support the proposed theoretical model. The hybrid filler strategy works because magnetic nanoparticles contribute to direct loss, biochar shapes the interface-rich conductive framework, and interfacial polarization converts that framework into stable absorption performance. This interpretation is consistent with the best-performing benchmark mix, which occupied a middle position in dosage rather than an extreme one.

8. DISCUSSION

The present study integrates the benchmark matrix, the structural model, and the interview evidence to explain why the hybrid biochar–Fe_3O_4 strategy works and what it means for sustainable cementitious absorber design. The central message is that absorption performance in cementitious composites is a system property rather than a filler property. In other words, the final result is produced by the coordination of magnetic loss, conductive moderation, interfacial polarization, pore-guided internal reflections, and acceptable mechanical integrity. This conclusion may sound familiar from absorber reviews, but the present study contributes by showing how the same logic operates in a mineral matrix where hydration, packing, and compressive strength remain critical engineering constraints.

8.1. The Effectiveness of Magnetic Nanoparticles Significantly Influences Electromagnetic Absorption Performance

The support for H1 confirms that the magnetic phase still matters strongly, even in a matrix where dielectric features are often emphasized. This result is in line with the broader absorber literature, which identifies ferrite and iron-oxide phases as reliable contributors to attenuation when properly dispersed (Wang et al., 2023; Mohapatra et al., 2025). In cementitious systems, the result agrees with Sun et al. (2018), Li et al. (2023), and Liu et al. (2024), all of whom reported improved electromagnetic behavior after Fe_3O_4 or Fe_3O_4 -based additions. The present study extends this understanding by framing magnetic contribution as effectiveness rather than content. The distinction is important. The benchmark matrix showed that moving from 6 wt.% to 8 wt.% Fe_3O_4 did not produce a proportionate improvement in reflection loss, which suggests that dispersion quality, not only dosage, controls actual performance. Interviewees also repeatedly noted that agglomeration is one of the most underestimated problems in ferrite-modified cementitious composites because cement pore solution chemistry and particle interaction can quickly reduce the active magnetic surface.

This has practical implications. Designers should not assume that higher magnetic loading always improves absorber performance. Instead, the target should be magnetic sufficiency combined with phase compatibility. In the best-performing benchmark mix, Fe_3O_4 contributed meaningful magnetic loss without overwhelming the dielectric environment or forcing the matrix toward reflection-dominant behavior. This agrees with the view that magnetic fillers work best when embedded in a microstructure that allows the incident wave to enter, circulate, and dissipate rather than rebound rapidly at the surface (Zeng et al., 2020; Chen et al., 2024).

8.2. Biochar Network Quality Significantly Influences Interfacial Polarization Capacity

The strong support for H2 is one of the most important findings of the study because it identifies the main role of biochar in a hybrid cementitious absorber. Biochar is often discussed in sustainable concrete literature as a filler for carbon retention, internal curing, or durability modification (Mensah et al., 2021; Senadheera et al., 2023; Room & Bahadori-Jahromi, 2024). The present results show that, in the electromagnetic context, its real value is the way it reshapes interface architecture. A high-quality biochar network constructively increases heterogeneity. It introduces carbonaceous surfaces, porous pathways, and electrically distinct regions that allow interfacial charges to build up and relax repeatedly. This is why the path from biochar network quality to interfacial polarization capacity was the strongest in the model.

The benchmark matrix supports the same interpretation. Biochar-only mixes improved absorption more modestly than the best hybrids, which means biochar was not acting mainly as a stand-alone absorber. Rather, its role was to prepare the matrix for better dielectric and interfacial loss. This interpretation is consistent with Jeong et al. (2022), Zhou et al. (2023), and Ruscica et al. (2024), who all showed that biochar changes electrical behavior and matrix response in ways that depend strongly on distribution and dosage. In practical terms, this suggests that future work on biochar for electromagnetic cement composites should go beyond asking how much biochar is used and instead ask what kind of network the biochar creates. Feedstock, carbonization conditions, particle size, ash content, and surface treatment are likely to be decisive design variables.

8.3. Interfacial Polarization Capacity Significantly Influences Electromagnetic Absorption Performance

H3 confirms the mechanism-centered thesis of the study. Interfacial polarization capacity emerged as a strong direct predictor of absorption performance, which means the success of the hybrid design depends less on a single standout filler and more on how many useful interfaces the composite can activate. This result aligns closely with modern absorber theory. Zeng et al. (2020), Lv et al. (2022), and Chen et al. (2024) all describe interfacial polarization as a core mechanism in multiphase absorbers because it broadens loss behavior and strengthens attenuation across frequency. Cement-based studies by Deng et al. (2022), Wang et al. (2024), and Bian et al. (2024) also point toward interface-rich mechanisms when explaining why hybrid or porous systems outperform dense single-phase matrices.

The importance of interfacial polarization also explains why the best benchmark mix was not the one with the greatest nominal conductivity. The 4 wt.% biochar and 6 wt.% Fe_3O_4 mix performed better than higher-load variants because it appears to have reached a productive compromise: enough heterogeneity and local conductivity for interface charging, but not so much disruption that mechanical continuity or impedance matching collapsed. In other words, polarization capacity is the operational expression of balance. It indicates that the matrix contains the right contrast between phases, not simply the most active filler. This is a highly useful insight for construction materials research because it gives designers a mechanism-based target that can guide microstructural tuning.

8.4. Interfacial Polarization Capacity Significantly Mediates the Relationship Between Biochar Network Quality and Electromagnetic Absorption Performance

The mediation result is especially valuable because it clarifies how biochar improves the outcome. The significant indirect path means that much of biochar's contribution is transferred through the mediator rather than appearing as a direct one-step effect. This finding resolves a common ambiguity in the literature. Biochar is known to change conductivity and pore structure, but studies do not always explain whether these changes directly produce absorption or whether they work through deeper dielectric mechanisms. The present model suggests the second interpretation is more accurate. Biochar supports absorption because it strengthens interfacial polarization capacity.

This interpretation is also consistent with the interview evidence. Several experts noted that low-density carbonaceous fillers in cement systems are useful when they create "distributed weak conductivity" or "nonuniform dielectric islands" rather than a hard conductive skeleton. That language matches the mediation path identified statistically. A strong biochar network creates the conditions for polarization, and polarization then drives absorption. This mechanism-centered interpretation offers a better explanation of why some biochar additions improve performance while others merely increase porosity or water demand. If biochar does not produce a favorable interface architecture, then the indirect pathway weakens and the final absorption benefit becomes smaller. Thus, the mediation result provides a more selective and technically meaningful criterion for future filler design.

8.5. Biochar Network Quality Significantly Moderates the Relationship Between Magnetic Nanoparticle Effectiveness and Electromagnetic Absorption Performance

The support for H5 confirms that the hybrid concept is not additive in a simple arithmetic sense. Biochar network quality strengthened the relationship between magnetic nanoparticle effectiveness and absorption performance, which means the value of Fe_3O_4 depends on the environment in which it operates. This moderation finding aligns with hybrid absorber theory in the wider materials literature, where magnetic and dielectric phases are widely understood to perform best when they are structurally coordinated (Wang et al., 2021; Chen et al., 2023; Mohapatra et al., 2025). The cementitious implication is that a magnetic phase cannot reach its full usefulness inside a matrix that lacks sufficient conductive moderation and interface density.

The benchmark matrix again supports this result. Fe_3O_4-only mixes improved absorption, but the jump from the best single-filler magnetic mix to the best hybrid mix was substantial. That extra gain cannot be explained by magnetic content alone because the hybrid used the same Fe_3O_4 content as one of the single-filler mixes. What changed was the quality of the surrounding biochar-enabled network. In effect, biochar gave the magnetic phase a richer attenuation environment. The moderation effect, therefore, provides quantitative support for the practical intuition behind hybrid absorber design: carefully chosen carbonaceous phases do not replace magnetic fillers; they enable them.

8.6. Theoretical & Practical Implications

The full model suggests that sustainable electromagnetic absorber design in cementitious composites should be viewed through three linked principles. The first is sufficiency rather than maximization. More filler is not always better. The second is complementarity rather than substitution. Biochar and Fe_3O_4 perform different tasks and should be judged by how well they cooperate. The third is mechanism visibility. Successful design requires explicit attention to interfacial polarization, not only end-point metrics such as reflection loss. These three principles can help move the field beyond empirical trial-and-error toward more structured materials engineering.

From an application standpoint, the study suggests that hybrid biochar–Fe_3O_4 cementitious composites are promising for interior protective renders, modular wall elements, equipment enclosures, transport infrastructure components, and smart-building zones where electromagnetic management is desirable. The benchmark optimum maintained compressive strength above 45 MPa, which indicates that function can be added without sacrificing basic structural practicality. This matters because many high-performance absorber systems reported in the broader literature are difficult to scale in civil construction due to cost, corrosion risk, toxicity concerns, or incompatibility with alkaline mineral matrices. Biochar partly addresses that problem because it is renewable and potentially low-cost. Fe_3O_4, meanwhile, is easier to integrate into cement systems than many specialty absorbers. Their combination, therefore, offers a realistic pathway for construction-grade functional materials.

At the sustainability level, the findings also matter. Construction materials research is increasingly expected to do more than deliver technical performance; it must also reduce environmental burden. Biochar is attractive not only because it is carbon-rich, but because it can be sourced from agricultural or biomass residues and can replace part of the demand for highly processed conductive additives. The present study suggests that sustainability-oriented fillers do not have to be treated as secondary or compromised options. When designed properly, they can actively improve absorber function. This is a strong message for future work on low-carbon functional materials.

9. CONCLUSION

The benchmark material matrix demonstrated that the hybrid strategy outperformed control and single-filler systems, with the mixture containing 4 wt.% biochar and 6 wt.% Fe_3O_4 achieves the best balance among reflection loss, effective bandwidth, resistivity, and compressive strength. Structural modeling indicated that magnetic nanoparticle effectiveness enhances electromagnetic absorption, while biochar network quality strengthens interfacial polarization, thereby improving absorption performance. Moreover, biochar network quality both mediates and moderates the relationship between filler composition and electromagnetic performance. The study, therefore, identifies interfacial polarization capacity as the key mechanism underlying the operation of sustainable hybrid cementitious absorbers and highlights an intermediate filler loading range that improves electromagnetic performance without significantly compromising structural integrity.

The findings contribute to theory by proposing a clearer causal framework for the design of cement-based electromagnetic absorbers, emphasizing that absorption performance depends on creating an interface-rich, impedance-balanced microstructure rather than simply increasing filler dosage. From a materials design perspective, the results show that renewable fillers, such as biochar, can serve as active performance drivers when their network structure is optimized, particularly when combined with Fe_3O_4 nanoparticles within a dielectric framework. Practically, the study suggests that hybrid fillers with controlled dispersion and intermediate loading levels can support the development of multifunctional cementitious materials suitable for applications such as secure facilities, healthcare infrastructure, transportation systems, and data-intensive buildings exposed to electromagnetic activity. Finally, the research demonstrates the value of combining material benchmarking, expert input, and interpretive analysis to guide theory-driven development of advanced cementitious composites.

9.1. Future Recommendations

The benchmark matrix was designed as a literature-based empirical framework rather than a full physical test campaign, so the next step should be laboratory validation of the optimum and near-optimum mixes across broader frequency windows, especially with direct measurements of complex permittivity, permeability, and skin-depth behavior. In addition, the model focused on four constructs to keep the framework parsimonious. Future work could include workability retention, moisture sensitivity, freeze-thaw stability, or long-term durability as additional outcome variables. The moderation result also suggests a need for finer microstructural work: advanced microscopy, impedance spectroscopy, and frequency-resolved dielectric analysis would help identify how biochar surface chemistry and Fe_3O_4 particle spacing influence polarization capacity in hardened cement matrices. Even with these limitations, the current study provides a coherent roadmap for moving sustainable electromagnetic absorber design from descriptive material recipes toward mechanism-aware engineering.

REFERENCES

Ahmad, W., Veeraghantla, V. S. S. C. S., & Byrne, A. (2025). Advancing sustainable concrete using biochar: Experimental and modelling study for mechanical strength evaluation. *Sustainability, 17*(6), 2516. https://doi.org/10.3390/su17062516

Bian, P., Yu, Q., Zhan, B., Guo, B., Gao, P., Hong, L., Yang, Y., & Wang, C. (2024). Broadband electromagnetic wave absorption cement-based composite using foam-loaded KH550@Fe3O4 nanoparticles. *Construction and Building Materials, 449*, 138324. https://doi.org/10.1016/j.conbuildmat.2024.138324

Chen, G., Li, Z., Zhang, L., Chang, Q., Chen, X., Fan, X., Chen, Q., & Wu, H. (2024). Mechanisms, design, and fabrication strategies for emerging electromagnetic wave-absorbing materials. *Cell Reports Physical Science, 5*(7), 102097. https://doi.org/10.1016/j.xcrp.2024.102097

Chen, T., Cai, J., Gong, D., Liu, C., Liu, P., Cheng, X., & Zhang, D. (2023). Facile fabrication of 3D biochar absorbers dual-loaded with Fe3O4 nanoparticles for enhanced microwave absorption. *Journal of Alloys and Compounds, 935*, 168085. https://doi.org/10.1016/j.jallcom.2022.168085

Deng, G., Yang, Y., Zhou, Q., Lei, Y., Yue, L., & Yang, T. (2022). Lightweight and broadband electromagnetic wave absorbing foamed cement-based composites incorporated with hybrid dielectric fibers. *Construction and Building Materials, 327*, 126931. https://doi.org/10.1016/j.conbuildmat.2022.126931

Feliz Florian, G., Ragoubi, M., Leblanc, N., Taouk, B., & Abdelouahed, L. (2024). Biochar production and its potential application for biocomposite materials: A comprehensive review. *Journal of Composites Science, 8*(6), 220. https://doi.org/10.3390/jcs8060220

Jeong, J., Jeon, G., Ryu, S., & Lee, J. H. (2022). Eco-friendly and electrically conductive cementitious composites using melamine-functionalized biochar from waste coffee beans. *Crystals, 12*(6), 820. https://doi.org/10.3390/cryst12060820

Li, C., Wang, Z., Shi, W., Huang, L., & Xie, A. (2024). Effects of quartz sand on the electromagnetic wave absorption of cementitious materials. *Materials, 17*(23), 5795. https://doi.org/10.3390/ma17235795

Li, L. G., Lai, Q., Zeng, G. X., Li, Y. J., Xie, H. Z., & Kwan, A. K. H. (2023). Combined effects of micro and nano Fe3O4 on workability, strength, packing, microstructure and EM wave absorbing properties of mortar.

Construction and Building Materials, 406, 133407. https://doi.org/10.1016/j.conbuildmat.2023.133407

Liu, W. H., Li, Z. Y., & Loh, Y. C. (2022). Evaluation of the impact of hot environmental conditions on physical activity among soccer players. *European Review for Medical & Pharmacological Sciences, 26*(22).

Liu, X., Zhang, Y., Guo, Y., & Wang, X. (2024). Optimization of electromagnetic wave absorption performance for magnesium phosphate cement using Fe3O4@SiO2 nanoparticles. *Construction and Building Materials, 435*, 136796. https://doi.org/10.1016/j.conbuildmat.2024.136796

Lv, H., Yang, Z., Pan, H., & Wu, R. (2022). Electromagnetic absorption materials: Current progress and new frontiers. *Progress in Materials Science, 127*, 100946. https://doi.org/10.1016/j.pmatsci.2022.100946

Ma, C., Xie, S., Ji, Z., Wu, Z., Si, T., Wu, J., & Wang, J. (2024). Electromagnetic wave absorbing properties of pyramidal engineered cement mortar containing carbon black. *Journal of Building Engineering, 84*, 108618. https://doi.org/10.1016/j.jobe.2024.108618

Marinković, D., Dorontić, S., Kepić, D., Haddadi, K., Yasir, M., Nardin, B., & Jovanović, S. (2025). New electromagnetic interference shielding materials: Biochars, scaffolds, rare earth, and ferrite-based materials. *Nanomaterials, 15*(7), 541. https://doi.org/10.3390/nano15070541

Mensah, R. A., Shanmugam, V., Narayanan, S., Razavi, N., Ulfberg, A., Blanksvärd, T., Sayahi, F., Simonsson, P., Reinke, B., Försth, M., Sas, G., Sas, D., & Das, O. (2021). Biochar-added cementitious materials—A review on mechanical, thermal, and environmental properties. *Sustainability, 13*(16), 9336. https://doi.org/10.3390/su13169336

Mohapatra, P. P., Singh, H. K., & Dobbidi, P. (2025). Advancements in electromagnetic microwave absorbers: Ferrites and carbonaceous materials. *Advances in Colloid and Interface Science, 337*, 103381. https://doi.org/10.1016/j.cis.2024.103381

Narayanan, S., Zhang, Y., & Aslani, F. (2023). Prediction models of shielding effectiveness of carbon fibre reinforced cement-based composites against electromagnetic interference. *Sensors, 23*(4), 2084. https://doi.org/10.3390/s23042084

Paula, R., Carvalho, J., Júnior, A., Fagundes, F., de Lima, R., Lima, E., Oliveira, C., de Oliveira, M., Bezerra, A., Ferreira, O., & Machado, A. (2025). Analysis of biochar-cement composites by SEM/EDS: Interfacial interactions and effects on mechanical strength. *C, 11*(3), 45. https://doi.org/10.3390/c11030045

Peymanfar, R., Dogari, H., Selseleh-Zakerin, E., Hedayatzadeh, M. H., Daneshvar, S., Amiri-Ramsheh, N., Ghafuri, H., Mirkhan, A., & Ji, G. (2023). Recent advances in microwave-absorbing materials fabricated using organic conductive polymers. *Frontiers in Materials, 10*, Article 1133287. https://doi.org/10.3389/fmats.2023.1133287

Room, S., & Bahadori-Jahromi, A. (2024). Biochar-enhanced carbon-negative and sustainable cement composites: A scientometric review. *Sustainability, 16*(23), 10162. https://doi.org/10.3390/su162310162

Ruscica, G., Peinetti, F., Natali Sora, I., & Savi, P. (2024). Analysis of electromagnetic shielding properties of cement-based composites with biochar and PVC as fillers. *C, 10*(1), 21. https://doi.org/10.3390/c10010021

Ryłko, I., Zarzycki, R., Bobak, Ł., Telega, P., Didyk-Mucha, A., & Białowiec, A. (2025). Biochar as a sustainable component of low-emission building materials. *Materials, 18*(17), 3941. https://doi.org/10.3390/ma18173941

Senadheera, S. S., Gupta, S., Kua, H. W., Hou, D., Kim, S., Tsang, D. C. W., & Ok, Y. S. (2023). Application of biochar in concrete - A review. *Cement and Concrete Composites, 143*, 105204. https://doi.org/10.1016/j.cemconcomp.2023.105204

Shojaeian, N., Li, Z., Kaurav, R. P. S., & Salem, A. A. M. (2022). Theory of mind among swedish children with ASD, down syndrome and the typically developing group. *Journal of Autism and Developmental Disorders, 52*(11), 4774–4782.

Stefaniuk, D., Sobótka, M., Jarczewska, K., Logoń, D., Majcher, K., Musiał, M., Niewiadomski, P., Pakos, W., Różański, A., & Trapko, T. (2022). Microstructure properties of cementitious mortars with selected additives for electromagnetic waves absorbing applications. *Cement and Concrete Composites, 134*, 104732. https://doi.org/10.1016/j.cemconcomp.2022.104732

Sun, K., He, Y., Lu, L., Wang, F., & Hu, S. (2018). Electromagnetic wave absorbing cement-based composite using nano-Fe3O4 magnetic fluid as absorber. *Cement and Concrete Composites, 92*, 1–6. https://doi.org/10.1016/j.cemconcomp.2018.05.004

Wang, H., Zhang, H., Zhao, K., Nie, A., Alharthi, S., Amin, M. A., El-Bahy, Z. M., Li, H., Chen, L., Xu, B. B., Ma, Y., & Li, T. (2023). Research progress on electromagnetic wave absorption based on magnetic metal oxides and their composites. *Advanced Composites and Hybrid Materials, 6*, 120. https://doi.org/10.1007/s42114-023-00694-5

Wang, L., Li, X., Shi, X., Huang, M., Li, X., Zeng, Q., & Che, R. (2021). Recent progress of microwave absorption microspheres by magnetic-dielectric synergy. *Nanoscale, 13*(4), 2136–2156. https://doi.org/10.1039/D0NR07937A

Wang, Q., Wei, T., Wang, R., Zhu, D., Liu, F., & Li, H. (2024). Preparation and electromagnetic-wave-absorption properties of cement-based materials with graphite tailings and steel fiber. *Buildings, 14*(11), 3685. https://doi.org/10.3390/buildings14113685

Xie, J., Li, K., Zhang, Y., Xiao, M., Guan, H., Wang, D., & Yang, L. (2024). Electromagnetic absorption properties of composite mortar with graphene and manganese-zinc ferrite. *Journal of Building Engineering, 97*, 110963. https://doi.org/10.1016/j.jobe.2024.110963

Ye, P., Guo, B., Qin, H., Wang, C., Liu, Y., Chen, Y., Bian, P., Lu, D., Wang, L., Zhao, W., Yang, Y., Hong, L., Ma, P., Zhan, B., & Yu, Q. (2025). The state-of-the-art review on biochar as green additives in cementitious composites: Performance, applications, machine learning predictions, and environmental and economic implications. *Biochar, 7*, 6. https://doi.org/10.1007/s42773-024-00423-1

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. *Micromachines, 15*(2), 187. https://doi.org/10.3390/mi15020187

Zeng, X., Cheng, X., Yu, R., & Stucky, G. D. (2020). Electromagnetic microwave absorption theory and recent achievements in microwave absorbers. *Carbon, 168*, 606–623. https://doi.org/10.1016/j.carbon.2020.07.028

Zhou, Z., Wang, J., Tan, K., & Chen, Y. (2023). Enhancing biochar impact on the mechanical properties of cement-based mortar: An optimization study using response surface methodology for particle size and content. *Sustainability, 15*(20), 14787. https://doi.org/10.3390/su152014787