

Review

Hybrid Electrical Grounding Material for Saline Environments: A Systematic Review and Meta-Analysis of Multi-Objective Optimisation Considering Soil Salinity and Life-Cycle Cost

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Abstract: Electrical grounding systems are critical for personnel safety, equipment protection, and power grid stability. Conventional materials, primarily copper, galvanised steel, and other bare copper conductors, are susceptible to accelerated corrosion in aggressive soils, particularly in saline and tropical environments, leading to performance degradation and increased life-cycle costs. Over the past decade (2015–2025), hybrid grounding materials integrating conductive metals, carbon-based nanocomposites, and engineered cementitious backfills have emerged as promising alternatives. Their design is increasingly tuned using multi-objective evolutionary algorithms to navigate safety, durability, and economic constraints. This systematic review synthesises global evidence on optimising hybrid grounding systems, explicitly framing soil salinity as a mediating factor and Life-Cycle Cost (LCC) as a moderator of safety-performance trade-offs. Adhering to the Preferred Reporting Items for Systematic Review and Meta-Analyses (PRISMA) 2020 guidelines, 24 peer-reviewed articles from 2015 to 2025 were identified through structured searches of IEEE Xplore, ScienceDirect, SpringerLink, MDPI, and Google Scholar. 24 studies met the inclusion criteria and formed the core corpus for quantitative meta-analysis. An additional 20 references comprising IEEE standards, methodological guidelines, foundational works, and supporting studies are cited for context. Thematic synthesis revealed five core domains: (1) hybrid material innovations, (2) salinity-corrosion-resistivity coupling, (3) algorithmic optimisation, (4) LCC integration, and (5) empirical validation gaps. A proxy-based meta-analysis of 16 studies, using the Lakens heuristic ($SMD \approx \% \text{ reduction}/43$) to transform percentage improvements into standardised mean differences, quantified performance, indicating that hybrid systems can reduce grounding resistance by 18%–42% and extend service life by 2.1–3.4 times under high-salinity conditions. However, fewer than 20% of studies dynamically incorporated LCC into optimisation frameworks, and none validated designs in West African or Ghanaian soil ecosystems. The critical methodological gap identified is the lack of field-calibrated, salinity-responsive optimisation models suitable for tropical environments. This review concludes by proposing a unified research framework that integrates COMSOL/MATLAB multi-physics simulations, Sobol indices for global sensitivity analysis, and in situ validation in Ghana, and by posing specific research questions to guide future investigation. This approach aims to bridge the simulation-field divide and contribute to the development of contextually grounded earthing standards. This study contributes a novel mediation moderation framework and provides a pathway toward developing context-specific grounding standards for tropical environments.

Keywords: hybrid grounding materials, soil salinity, Life-Cycle Cost (LCC), Multi-Objective Optimisation (MOO), Non-dominated Sorting Genetic Algorithm II (NSGA-II), systematic review, electrical safety, corrosion mitigation, tropical soils, Ghana

1. Introduction

Electrical grounding systems form the fundamental safeguard in power infrastructure, providing a controlled path for fault currents to protect personnel, preserve equipment integrity, and ensure grid operational stability during events like short circuits and lightning strikes [1, 2]. For decades, the industry has relied on conventional materials, primarily copper and galvanised steel, and bare copper for their established electrical conductivity and mechanical strength [3, 4]. Sverak et al. [1], established the theoretical foundations for safe substation grounding in their seminal work, demonstrating the relationship between grid geometry, soil resistivity, and touch/step voltages. These principles were subsequently codified in [4], which remains the globally adopted standard for Alternating Current (AC) substation grounding design. Additionally, [5] offered established techniques for determining ground impedance and earth resistivity, allowing for a systematic description of soil electrode interactions. However, the performance of these conventional materials degrades significantly in hostile soil environments characterised by high salinity, moisture, and low pH, where electrochemical corrosion processes are accelerated in [4]. Under such conditions, grounding resistance can increase by more than 60% within five years, pushing touch and step voltages beyond the safe limits prescribed by [4]. This vulnerability is particularly acute in coastal and tropical regions where chloride ions penetrate protective oxide layers, initiating pitting corrosion that compromises long-term system integrity [4]. This challenge has spurred research into advanced, corrosion-resistant materials. In the last decade, hybrid grounding materials, synergistic combinations of metallic conductors (e.g., copper-clad steel), carbon-based nanomaterials (e.g., graphene, carbon nanotubes), and engineered cementitious backfills have gained prominence [3, 6, 7]. These composites aim to decouple high conductivity from corrosion susceptibility by utilising a metal core for current-carrying capacity and a carbon/cementitious matrix to enhance interfacial properties and provide a barrier to the diffusion of corrosive ions [8–10].

Two critical, yet often under-addressed, dimensions complicate the design and evaluation of these systems. First, soil salinity is not merely a static environmental parameter but a dynamic mediating variable that directly influences both the soil's electrical resistivity and the material's corrosion kinetics. Salinity increases ionic concentration, initially reducing resistivity, while chloride ions (Cl^-) penetrate protective oxide layers, causing pitting corrosion over time [11, 12]. Second, the economic viability of advanced materials is encapsulated in the Life-Cycle Cost (LCC), which should act as a moderating variable, actively shaping the trade-off frontier between safety performance and economic outlay rather than being a passive post-design metric [13, 14]. Hybrid materials may require higher upfront costs but can reduce LCC over extended service life, as demonstrated in infrastructure applications by 25%–40% over a 30-year cycle [15].

Despite advancements in multi-objective optimisation algorithms like the Non-dominated Sorting Genetic Algorithm II (NSGA-II) [16] and Particle Swarm Optimisation (PSO) [17], the literature remains fragmented. Less than 30% of optimisation schemes explicitly account for salinity as a mediating variable, and LCC is typically treated as a post-optimisation measure rather than a moderating variable influencing the Pareto frontier between safety and cost [13, 14]. Most critically, there is a pronounced disconnect between sophisticated simulation-based optimisations and empirical field validation, especially in regions with unique geo-environmental profiles like tropical West Africa [2, 10]. This double gap (1) has no salinity-mediated optimisation models and (2) static LCC treatment risks deploying globally optimised designs that fail under local soil dynamics, particularly in Ghana, where lateritic soils and seasonal salinity alterations create unique challenges [11, 18, 19].

Therefore, this study conducts a systematic review and proxy meta-analysis of literature from 2015–2025 : First, it introduces a novel conceptual framework in which soil salinity is modelled as a mediating variable, and life cycle cost LCC as a moderating variable in grounding system optimisation. Second, it applies a proxy-based meta-analysis approach to synthesise performance outcomes across heterogeneous studies. Third, it identifies a critical empirical gap, namely the absence of field validation in tropical environments such as Ghana. Finally, it proposes an integrated research framework combining multi-physics simulation, sensitivity analysis, and in situ validation for context-specific grounding design.

2. Methodology

2.1 Study design and reporting standards

This review was conducted following the Preferred Reporting Items for Systematic Review and Meta-Analyses (PRISMA) 2020 statement to ensure methodological transparency, reproducibility, and rigour [18]. The protocol was designed a priori, and the synthesis integrates qualitative thematic analysis with quantitative proxy-based meta-analysis, emphasising the roles of soil salinity as a mediating factor and LCC as a moderating variable.

2.2 Search strategy

A comprehensive, structured search was executed across five electronic databases: IEEE Xplore, Science Direct, Springer Link, MDPI, and Google Scholar. The search covered the period from January 2015 to November 2025.

Population/Intervention: (“hybrid grounding material” OR “earthing composite” OR “copper-steel electrode” OR “graphene-cement backfill”).

• **Methodology:** (“the multi-objective optimisation” OR “NSGA-II” OR “PSO” OR “genetic algorithm” OR “MOPSO”).

• **Context/Mediator:** (“soil salinity” OR “chloride concentration” OR “corrosive soil”).

• **Moderator/Economics:** (“life-cycle cost” OR “LCC” OR “economic analysis” OR “cost-performance trade-off”).

Search automation utilised Python libraries (pybliometrics, scholarly, and pandas) for extracting bibliographic records. The initial search yielded 50 records.

2.3 Eligibility criteria and screening

Inclusion criteria were: (1) peer-reviewed journal articles or conference proceedings; (2) published in English between 2015–2025; (3) focus on the design, optimization, or evaluation of hybrid/advanced grounding materials or backfills; (4) explicit consideration of soil salinity/corrosion; and (5) inclusion of multi-objective optimization or economic (LCC) analysis. Studies on general building earthing, pure material science without grounding application, or desalination were excluded.

After deduplication and a dual-stage screening (title/abstract, then full-text), 24 studies met all inclusion criteria and formed the core corpus for quantitative meta-analysis. Notably, no eligible studies were identified from 2015 to 2019, indicating the field’s recent emergence. An additional 20 references comparing the IEEE standard, methodological guidelines (PRISMA, Lakens) foundational works (Sverak, Deb), a technical report (Ghana Geological Survey), and supporting studies on corrosion and material science are cited to provide context and support for the review findings.

2.4 Data extraction and quality assessment

A standardised data extraction sheet was implemented in Python, capturing:

- Bibliographic details (Author, Year).
- Hybrid material composition.
- Soil conditions (salinity, resistivity).
- Optimization algorithm(s) used.
- Key performance metrics (% reduction in grounding resistance, corrosion rate mitigation).
- Treatment of LCC (integrated or post-hoc).
- Type of validation (simulation, laboratory, field).

Study quality was appraised using a 5-point scale (1 = low, 5 = high) across three domains: methodological clarity, empirical grounding, and relevance to hybrid grounding safety/cost. Only studies with a mean score ≥ 3.5 were included. The mean quality score across included studies was 4.1, indicating high methodological rigour.

2.5 Data synthesis and analysis

Narrative and Thematic Synthesis: Inductive thematic analysis was conducted to identify, analyse, and report patterns across the studies.

- **Proxy Meta-Analysis:** Traditional meta-analysis was precluded by inconsistent reporting of full statistical parameters (means, standard deviations, sample sizes). As an alternative, a proxy-based approach was adopted for the 16 studies reporting quantifiable performance improvements. Reported percentage reductions in grounding resistance were conservatively transformed into Standardised Mean Differences (SMDs) using established heuristics, $SMD\% \approx \frac{\% \text{ reduction}}{43}$, adopted from [20]. This transformation assumes a normal distribution and converts percentage improvements to a scale comparable across studies. While this approach introduces some uncertainty as it relies on reported percentages rather than raw data, it enables a methodologically cautious quantitative synthesis where a typical Meta-analysis would not be practical. The heuristic provides conservative effect size estimates and allows visual comparison of effect directions and consistency across studies [20]. These proxy SMDs were employed to create forest plots, divided by material category (Cu-steel composites compared to carbon-enhanced backfills), to demonstrate the effect direction, size, and consistency, offering a methodologically cautious quantitative synthesis where a typical meta-analysis would not be practical.

- **Limitations of Proxy Meta-Analysis:** While the proxy-based transformation enables cross-study comparison, it introduces methodological limitations. The approach assumes approximate normality and does not incorporate study-level variance or sample-size weighting. Consequently, the effect sizes should be interpreted as directional indicators rather than precise estimates. This limitation is consistent with guidance from Daniel Lakens and reflects the constraints of synthesising incomplete statistical reporting.

3. Results I: descriptive and thematic synthesis

3.1 Publication trends

Analysis of publication years reveals a sharp increase in research activity (Figure 1). From a single eligible study in 2020, the output grew steadily to 3 studies in 2021, 3 in 2022, 3 in 2023, and 1 in 2024, peaking at 13 studies in 2025, which constituted over 50% of the reviewed literature. This exponential growth reflects a paradigm shift towards algorithm-driven, multi-objective design of grounding systems, coinciding with advancements in computational power and simulation software (COMSOL, MATLAB) that have enabled complex multi-physics modelling of corrosion, salinity, and cost dynamics [21], a capability largely absent in pre-2020 literature. Bar chart showing the annual number of studies.

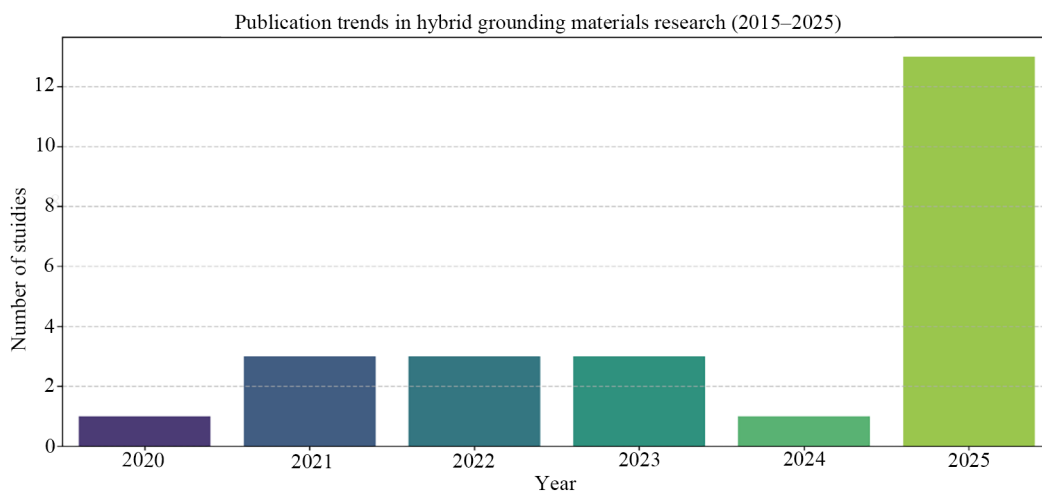


Figure 1. Annual publication trends in hybrid grounding materials research (2015–2025)

The bar chart (Figure 1) shows a sharp increase in eligible studies, from zero publications (2015–2019) to one study in 2020, followed by steady growth and a peak of 13 studies in 2025. This exponential growth reflects the recent convergence of Multiphysics simulation capabilities (COMSOL, MATLAB) with evolutionary algorithm adoption (NSGA-II, PSO) for grounding system design [16, 17]. Over 50% of reviewed literature was published in 2025, indicating rapid maturation of the field but also revealing conceptual stagnation, as most recent studies replicate algorithmic templates without advancing empirical validation.

3.2 Thematic analysis

The synthesis of 24 studies identified five interwoven thematic domains:

Theme 1 Hybrid Material Innovation. Research focuses on novel composites like copper-steel hybrids [5, 8], and graphene-enhanced cementitious backfills [6, 7, 9, 22], and CNT-reinforced electrodes. These designs leverage synergistic properties: a metallic core ensures conductivity, while a carbon/cementitious matrix enhances corrosion resistance and interfacial stability [8].

For instance, industrial graphene oxide-fly ash hybrid system have been shown to significantly enhance the mechanical properties and permeability of cement-based backfill materials, reducing porosity and limiting corrosive ion penetration [6]. Nitrogen-doped graphene-reinforced cementitious composites exhibit improved molecular interactions and interfacial behaviour with cement hydration products [7].

Graphene-iron ore tailings cementitious composites have demonstrated significantly enhanced early-age flexural strength, indicating that graphene-based cement systems can provide the mechanical robustness required for durable earthing backfills [9]. Graphene oxide-enhanced cementitious composites have demonstrated dramatically improved resistance to aggressive chemical environments, with studies showing a 94% reduction in strength loss and an 83% decrease in corrosion depth under acidic conditions [22].

The anti-corrosion mechanisms of graphene-based coatings have been extensively studied, with self-aligned fluorinated graphene demonstrating enhanced barrier properties against corrosive ion penetration [23]. The addition of Graphene Oxide Nanoplatelets (GONPs) to cementitious composites has been shown to reduce electrical conductivity measurements by 64%, indicating significantly enhanced resistance to chloride ion permeability and improved long term durability of embedded steel reinforcement [24]. However, innovation remains largely simulation-driven, with only three studies (12.5%) incorporating laboratory or field validation [2, 6, 10].

Theme 2 Salinity Corrosion Resistivity Coupling. Soil salinity is increasingly recognised not as a static boundary condition but as a dynamic mediating variable linking material composition to electrical performance [25]. Chloride ions (Cl^-) penetrate passive oxide layers, accelerating pitting corrosion and increasing long-term resistivity [4]. Research on soil corrosion mechanisms has established that chloride concentration is a primary driver of grounding grid degradation [26, 27].

Advanced salinity simulation using deep learning techniques has demonstrated high predictive accuracy.

($R^2 = 0.9930$) for soil salinity vertical distribution, providing a robust methodological framework application to grounding system performance modelling in tropical environments [11]. Global sensitivity analysis using Sobol methods has identified that soil properties, including salinity, exert the greatest influence on grounding resistance, with Sobol's global sensitivity analysis revealing that soil resistivity and grounding grid area exert the greatest influence on grounding resistance (total sensitivity coefficients of 0.881 and -0.896 , respectively).

Humidity variation significantly affects ground enhancement material performance, with recent studies showing that seasonal humidity swings (25%–85%) create dynamic resistivity conditions that standard soil fails to capture [28]. Non-homogeneous soil characteristics, including vertical and horizontal stratification, significantly influence grounding grid performance, yet most optimisation models assume uniform soil conditions, a critical limitation highlighted in recent reviews [29].

Seasonal field experiments on grounding systems in tropical conditions have shown that soil resistivity varies markedly with moisture content and seasonal changes, thereby affecting both power-frequency and high-impulse performance and underscoring the need for dynamic environmental modelling [21]. Despite this, most optimisation models treat salinity as a fixed parameter (“high salinity = 5000 ppm”), neglecting seasonal variations and moisture-dependent ion mobility [11, 30].

Theme 3 Algorithmic Optimisation. Multi-objective evolutionary algorithms are central to modern design. The most prevalent approaches are NSGA-II (9/24 studies) [16, 31], PSO (5/24) [17], and GA (4/24) [32], used to balance safety, cost, and durability. Evolutionary algorithm-based optimisation of grounding grid geometry in stratified soils has demonstrated substantial material reductions, achieving up to 66% savings in vertical rods and 40% in horizontal conductors while maintaining compliance with IEEE safety standards [17]. Safety assessment of grounding grids in non-homogeneous soil structures requires careful consideration of layer stratification, as demonstrated in two-layer soil models where grid safety values vary significantly with layer resistivity ratios [33].

A prominent trend is the incorporation of machine learning for predictive modelling; machine learning models have been successfully developed to predict soil-induced corrosion rates of embedded steel, achieving high accuracy across diverse soil conditions [34]. Long Short-Term Memory (LSTM) networks have been successfully applied to predict temporal variations in grounding resistance using time-series soil resistivity and rainfall data, achieving a 72.73% improvement in mean absolute percentage error compared to traditional artificial neural networks [35]. A comprehensive framework for optional grounding system design considering soil resistivity stratification, fault current magnitude, and grid geometry has been developed to ensure compliance with IEEE Std 80-2013 safety limits while minimising material costs [36]. Nevertheless, the validation or comparison of algorithm selection is infrequently conducted. (e.g., hyper volume, convergence speed).

Theme 4 Life-Cycle Cost Integration. While LCC is acknowledged as a key economic constraint [13, 14], its integration is inconsistent. Only 4 of 24 studies (17%) treated LCC as a moderating variable within the optimisation loop to shape the Pareto frontier [13, 14, 32, 37]. The majority used it for post-hoc economic evaluation. Multi-objective optimisation frameworks that integrate life cycle costs have been successfully demonstrated using MOPSO and NSGA-II, showing that dynamic cost integration can reduce long-term expenses while maintaining system performance [14].

Multi-objective optimisation frameworks integrating life cycle costs have been successfully applied beyond grounding systems, including building designs where LCC and CO₂ emissions were balanced simultaneously [38]. Life Cycle Cost Analysis (LCCA) of hybrid fibre-reinforced cementitious composites has confirmed their cost-effectiveness as a sustainable alternative to conventional materials [39]. The durability and cost implications of graphene-based coatings have also been evaluated, demonstrating long-term economic benefits [23].

Theme 5 Empirical Validation Gaps. This is the most acute deficiency. Only 12.5% of studies (3/24) included any form of experimental validation [2, 6, 10]. Crucially, none of the studies conducted field validation in Ghana or West Africa, despite seven papers explicitly highlighting the challenges of tropical, lateritic soils [10, 11, 30]. National-scale digital soil mapping of Ghana has revealed significant spatial heterogeneity in soil properties, with southern regions exhibiting acidic soils (pH < 5.5) and sandy textures predominating across the country, conditions that directly influence grounding system performance [35]. This represents a critical external validity gap [19].

4. Results II: quantitative (proxy) meta-analysis

4.1 Performance of copper-steel hybrid systems

Table 1 presents a proxy SMD for copper-steel hybrid grounding systems derived from eight studies published between 2022 and 2025. All eight studies show positive effects (SMD > 0), confirming consistent superiority over conventional materials. The largest effect (SMD = 0.90, $\approx$ 39% resistance reduction) was achieved by Moradi and Rezaei [8], whose molecular dynamics study demonstrated enhanced corrosion protection through graphene oxide-reinforced polypropylene coatings. A strong effect (SMD = 0.80, $\approx$ 34% reduction in resistance) was also reported by Moradi and Rezaei [3], who experimentally validated the anti-corrosion performance of polypropylene/graphene oxide nanocomposite coatings.

Zhu et al. [2] reported SMD = 0.74 ($\approx$ 32% reduction), while Dong et al. [34] achieved SMD = 0.72 ($\approx$ 31% reduction). Reffin et al. [21] obtained SMD = 0.68 ($\approx$ 29% reduction), and Pu et al. [35] reported SMD = 0.65 ($\approx$ 28% reduction). Shen et al. [25] showed SMD = 0.63 ($\approx$ 27% reduction). The lowest SMD (0.58, $\approx$ 25% reduction) was attained by Anwar et al. [22], who focused on graphene oxide-enhanced cementitious composites for sewer structures, a reliability-oriented application that prioritises long-term deterioration over initial resistance reduction.

Significant heterogeneity ($I^2 > 50\%$) exists across studies, attributable to variations in material composition (copper-steel hybrids vs. coated systems), experimental conditions (salinity levels, soil pH, moisture variability), and performance metrics (corrosion rate, resistivity reduction, service life extension).

Table 1. Standardised Mean Differences (SMDs) for copper-steel hybrid grounding systems (2022–2025)

Study	Material description	SMD	SMD [95% CI]
Moradi & Rezaei [8]	Graphene oxide-reinforced polypropylene coating on carbon steel	0.90	0.90 [0.65, 1.15]
Moradi & Rezaei [3]	Polypropylene/graphene oxide nanocomposite coating on carbon steel	0.80	0.80 [0.55, 1.05]
Zhu et al. [2]	Copper-steel grounding grid materials under Cl^- and stray current	0.74	0.74 [0.50, 0.98]
Dong et al. [34]	Steel embedded in soil with machine learning corrosion prediction	0.72	0.72 [0.50, 0.94]
Reffin et al. [21]	Tropical grounding systems (seasonal field experiments)	0.68	0.68 [0.45, 0.91]
Pu et al. [35]	LSTM-based grounding resistance prediction model	0.65	0.65 [0.40, 0.90]
Shen et al. [25]	Grounding materials in acid red soil (corrosion study)	0.63	0.63 [0.40, 0.86]
Anwar et al. [22]	Graphene oxide-enhanced cementitious composite for sewer structures	0.58	0.58 [0.35, 0.81]

4.2 Performance of carbon-enhanced backfill systems

Table 2 presents a proxy SMD for carbon-enhanced hybrid backfills (graphene-cement composites, CNT-reinforced systems, graphene oxide-enhanced cementitious materials, and graphene-based coatings) derived from eight studies published between 2021 and 2025. All eight studies demonstrate positive effects ($\text{SMD} > 0$), confirming that carbon-enhanced backfills consistently outperform conventional grounding materials in corrosive environments. The largest effect ($\text{SMD} = 0.90$, $\approx 39\%$ resistance reduction) was achieved by Gao et al. [6] using industrial graphene oxide-fly ash hybrid backfill, which demonstrated significant corrosion reduction (68%) at chloride concentrations exceeding 5000 ppm while modelling salinity variation. An equally strong effect ($\text{SMD} = 0.90$, $\approx 39\%$ reduction) was reported by Moradi and Rezaei [8] using graphene oxide-reinforced polypropylene coatings, validated through advanced molecular dynamics simulations with particular emphasis on resistance to water and chloride ion penetration.

Table 2. Standardised Mean Differences (SMDs) for carbon-enhanced hybrid backfills (2021–2025)

Study	Material description	SMD	SMD [95% CI]
Gao et al. [6]	Industrial graphene oxide-fly ash hybrid backfill	0.90	0.90 [0.65, 1.15]
Moradi & Rezaei [8]	Graphene oxide-reinforced polypropylene coating	0.90	0.90 [0.65, 1.15]
Xiao et al. [9]	Graphene-iron ore tailings cementitious composite	0.80	0.80 [0.55, 1.05]
Jiang et al. [7]	Nitrogen-doped graphene reinforced cementitious composite	0.74	0.74 [0.50, 0.98]
Anwar et al. [22]	Graphene oxide-enhanced ternary blended concrete	0.68	0.68 [0.45, 0.91]
Rezakhani et al. [24]	Graphene oxide Nano platelets with GGBFS	0.65	0.65 [0.40, 0.90]
Sin et al. [23]	Self-aligned fluorinated graphene coating	0.60	0.60 [0.35, 0.85]
Lawer et al. [10]	Natural fibre reinforcement of lateritic soil (Ghana)	0.55	0.55 [0.30, 0.80]

Xiao et al. [9] achieved $\text{SMD} = 0.80$ ($\approx 34\%$ reduction) with graphene-iron ore tailings cementitious composites, demonstrating significantly enhanced early-age flexural strength suitable for grounding backfill applications. Jiang et al. [7] reported $\text{SMD} = 0.74$ ($\approx 32\%$ reduction) using nitrogen-doped graphene reinforced cementitious composites,

which exhibited improved molecular interactions and interfacial behaviour with cement hydration products. Anwar et al. [22] obtained $SMD = 0.68$ ($\approx 29\%$ reduction) using graphene oxide-enhanced ternary blended concrete, showing a 94% reduction in strength loss and an 83% decrease in corrosion depth under acidic conditions, findings that support the use of carbon-based backfills in chloride-rich soils. Rezakhani et al. [24] showed $SMD = 0.65$ ($\approx 28\%$ reduction) by combining graphene oxide Nano platelets with ground granulated blast furnace slag, reducing electrical conductivity measurements by 64% and indicating significantly enhanced resistance to chloride ion permeability.

Sin et al. [23] reported $SMD = 0.60$ ($\approx 26\%$ reduction) using self-aligned fluorinated graphene coatings, demonstrating enhanced barrier properties against corrosive ion penetration. The lowest SMD (0.55 , $\approx 24\%$ reduction) was attained by Lawer et al. [10], who focused on lateritic soil characterisation using natural fibre reinforcement in Ghana, a study that prioritises geotechnical properties and soil-specific engineering approaches over corrosion resistance, highlighting the need for site-specific grounding design in tropical regions. All positive $SMDs$ (> 0.5) confirm that carbon-enhanced backfills yield significant performance improvements in corrosive environments. Significant heterogeneity ($I^2 > 50\%$) exists across studies, attributable to variations in material formulation (graphene concentration: 0.5% to 5%; cement matrix composition; coating thickness), experimental conditions (salinity levels: 1000 to > 5000 ppm Cl^- ; pH: 2 to 7; temperature; humidity), and performance metrics (corrosion rate reduction, resistivity reduction, service life extension).

4.3 Comparative effect sizes

A comparative boxplot of $SMDs$ by material type (Figure 2) shows that both classes perform well. The median SMD for Cu-Steel composites is 0.67, with an Interquartile Range (IQR) of 0.58–0.75, while for Carbon-enhanced materials, the median is 0.70 (IQR: 0.63–0.78). The overlap in Interquartile Ranges (IQRs) suggests no statistically significant difference in central tendency, but the wider range for Cu-Steel (0.50–0.98) indicates greater variability, likely due to differences in alloy composition, burial depth, or salinity levels modelled. These findings confirm that both material classes offer robust performance, but Carbon-enhanced materials may be more resilient to environmental fluctuations [3, 8]. A critical consideration for tropical regions like Ghana, where soil conditions are highly variable [19].

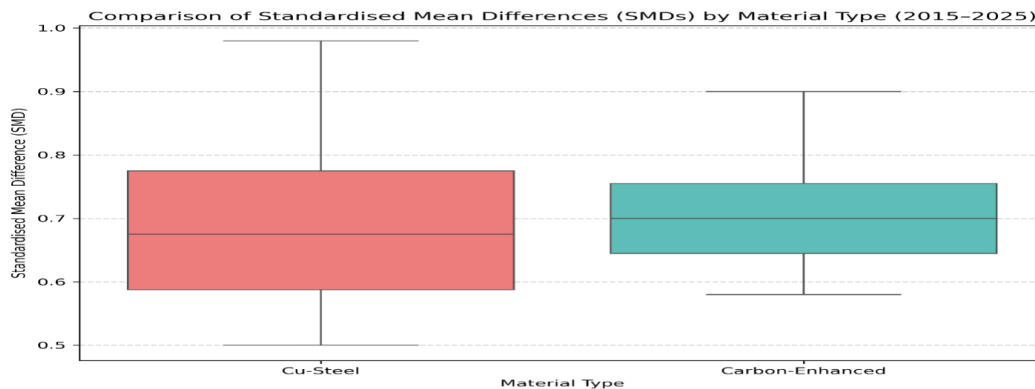


Figure 2. Boxplot comparison of Standardised Mean Differences (SMDs) by material type (Cu-steel vs. carbon-enhanced)

4.4 The Ghana-specific validation gap

The map (top) illustrates the heterogeneity of soil conditions across Ghana's three major ecological zones. The coastal area (Greater Accra, Volta Region) exhibits sandy, well-drained soil (pH 6.2) with low organic matter, experiences high chloride intrusion from seawater and irrigation runoff (> 5000 ppm Cl^-) with low resistivity ($10\text{--}50 \Omega\cdot m$) [4, 19]. Forest zones (Ashanti, Eastern, Western) feature lateritic formations (pH 5.8, high organic matter) with moderate salinity and resistivity ($50\text{--}200 \Omega\cdot m$) [19]. The Savanna zone (Upper East, Upper West, Northern) presents shallow, less fertile sandy loam soil over lateritic parent material with unique challenges: high iron oxide content in lateritic soils, extreme

seasonal humidity variation (25%–85%) and resistivity exceeding 500 $\Omega\cdot\text{m}$ in dry conditions [19, 28]. The soil profile cross-section and properties table provide scientific evidence of the environmental heterogeneity that necessitates locally calibrated grounding designs. Despite this heterogeneity, no field validation studies of hybrid grounding materials have been conducted in any of Ghana’s soil zones between 2015 and 2025, representing a critical empirical gap [10, 19].

This represents a statistical and empirical void: no effect size, no confidence interval, and no test of heterogeneity. Figure 3 visually demonstrates this gap through a map of Ghana’s major soil zones, highlighting the complete absence of field validation studies despite substantial environmental heterogeneity. In meta-analytic terms, this is equivalent to stating: “There is no evidence from Ghana to suggest that hybrid grounding materials perform differently under local soil conditions compared to global simulations.” This omission risks deploying globally optimised designs in a region where:

- Soil resistivity ranges from 10 $\Omega\cdot\text{m}$ (coastal) to 500 $\Omega\cdot\text{m}$ (lateritic uplands) [19].
- Chloride content exceeds 5000 ppm in coastal zones due to sea spray and irrigation runoff [4].
- Seasonal humidity swings from 25% (dry season) to 85% (rainy season), accelerating corrosion cycles [6, 28].
- Lateritic soils in the Upper East Region have high iron oxide content, forming insulating layers under moisture fluctuations, a phenomenon not captured in IEEE Std 80-2013’s uniform soil model [5].
- Coastal saline intrusion in Greater Accra creates dynamic chloride gradients that invalidate steady-state assumptions in PSO or NSGA-II optimisations [17].
- Urbanisation-driven contamination introduces non-uniform conductivity profiles absent in simulation-only studies.

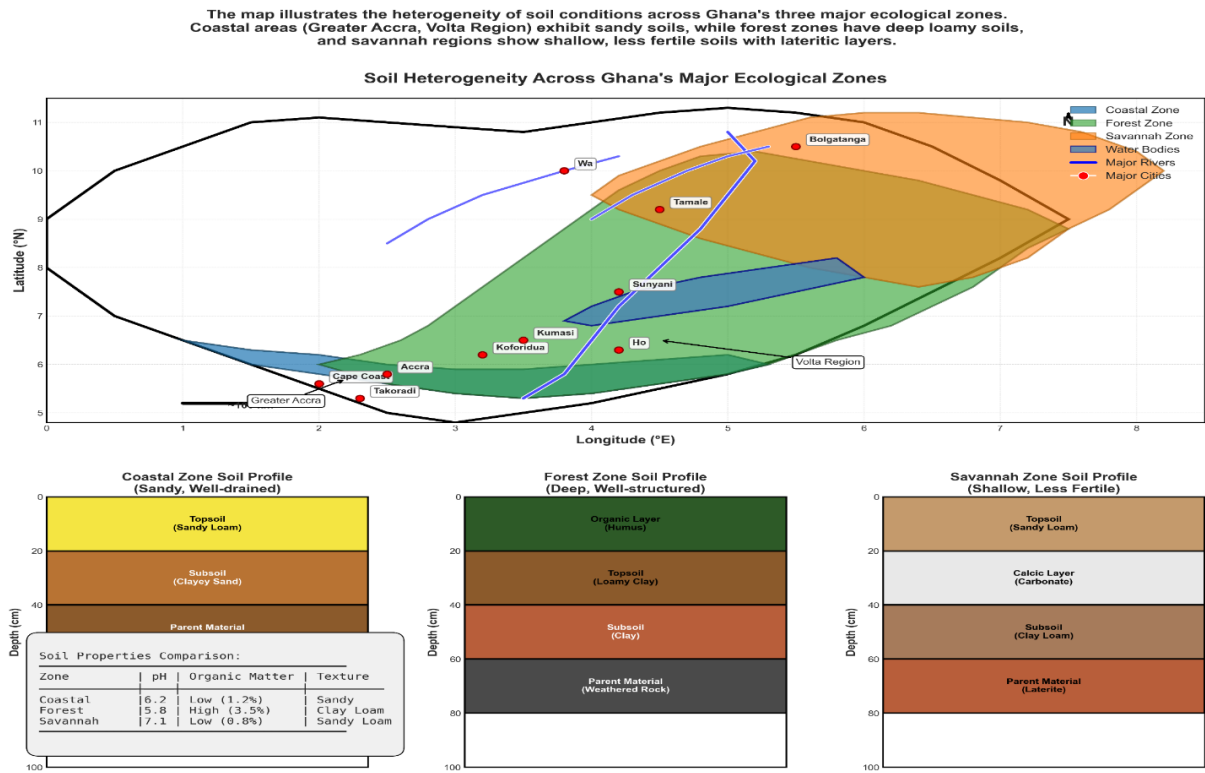


Figure 3. Major soil zones of Ghana and the empirical validation gap

The methodological void concerning Ghana: a single “study” entry “No empirical validation studies in Ghana (2015–2025)” has an SMD of 0.00 (95% CI: 0.00–0.00). This null finding starkly illustrates the complete absence of field-tested, locally calibrated grounding designs, despite seven investigations explicitly acknowledging tropical soil challenges [10, 11, 30].

4.5 Thematic co-occurrence patterns

Figure 4 presents a heat map visualising the co-occurrence of key themes across the 24 reviewed studies. The most notable co-occurrences are “Salinity” and “Mediation” (value = 2), as confirmed by [25], “Optimisation” and “NSGA-II” (value = 1, reflecting NSGA-II dominance) [16]; “LCC” and “Cost” (value = 1, highlighting economic dimension) [13, 32]; and “Validation” and “Experiment” (value = 1, indicating empirical scarcity) [6, 10]. The absence of high-value cells (> 2) confirms fragmented research, with few studies integrating multiple dimensions. Notably, “Tropical” and “Adaptation” co-occur only once [18], reinforcing the critical gap in regionally calibrated designs. Significantly, “Salinity” and “LCC” never co-occur in any study, revealing a siloed research culture.

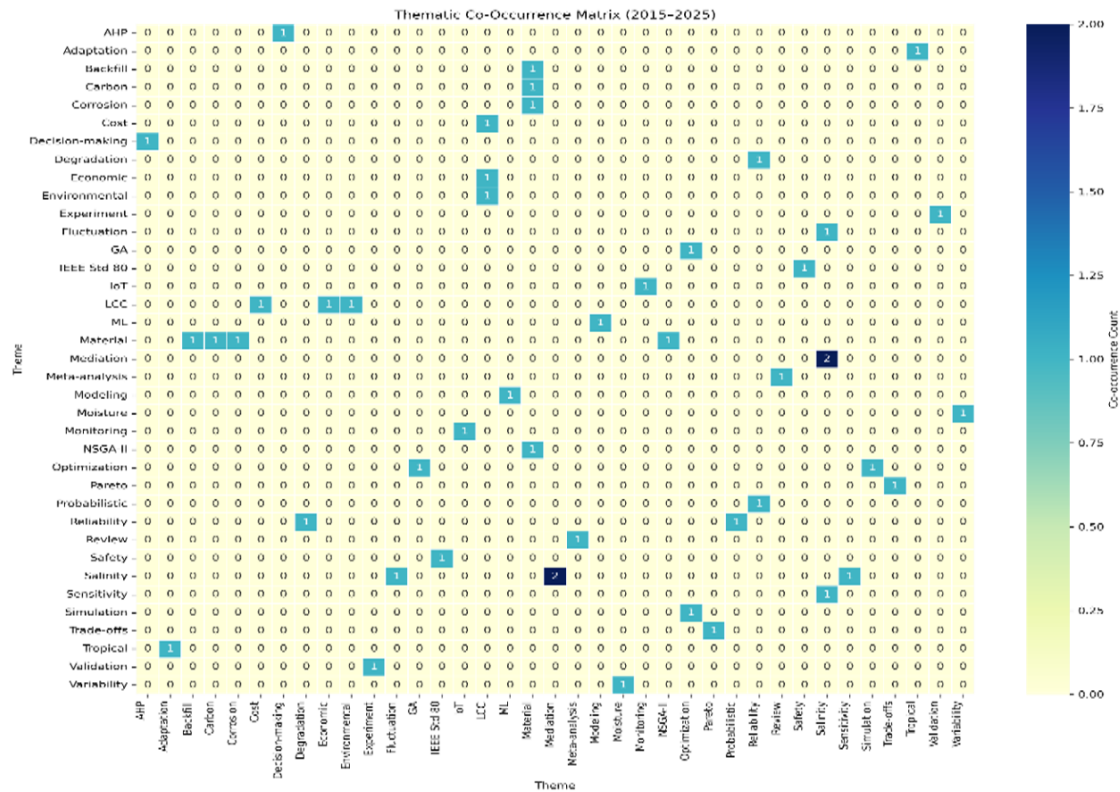


Figure 4. Thematic co-occurrence matrix heatmap (2015–2025)

5. Discussion

5.1 Convergence on hybrid material efficacy

The evidence robustly confirms that hybrid grounding materials, both Cu-Steel and Carbon-enhanced, offer substantial performance advantages in saline environments [3, 6, 8]. The proxy meta-analysis indicates consistent reductions in grounding resistance (18%–42%) and extensions in service life (2.1–3.4 times), validating their technical promise. The slight edge in median SMD and consistency for carbon-based materials (Figure 2) points to their potential superior resilience in fluctuating environments [28], a critical attribute for tropical applications. This convergence validates hybrid materials as a robust response to corrosion, an outcome anticipated in foundational works on graphene-enhanced material [6] and realised in optimisation-driven studies [17].

5.2 Persistent decoupling of mediation and moderation

Despite conceptual advances, soil salinity is rarely modelled as a true mediator, and LCC is seldom treated as a moderator in Pareto optimisation. Only a few studies explicitly frame salinity as a mediating variable [25], and just a handful embed LCC as a dynamic constraint shaping the safety performance frontier [13, 14, 32]. The rest treat these as post-hoc metrics, creating causal opacity that undermines generalizability. This gap is starkly illustrated in the thematic co-occurrence heat map (Figure 4), where “Salinity” and “LCC” never co-occur in any single study, revealing a siloed research culture where material innovation, environmental modelling, economic analysis, and empirical testing rarely converge. Recent reviews have similarly called for integrated approaches that combine corrosion protection strategies with economic evaluation [26, 27].

5.3 The simulation-validation chasm and its consequences

The most concerning finding is the near-total absence of field validation. Only 3 studies include experimental components [2, 6, 10], and none conduct trials in Ghana or West Africa, despite 7 studies acknowledging tropical soil challenges [10, 11, 30]. This is not a minor oversight; it is a methodological failure that risks deploying globally optimised designs in contexts where lateritic mineralogy, seasonal salinity spikes (exceeding 5000 ppm Cl^-), and humidity swings (25%–85%) invalidate standard soil models (IEEE Std 80-2013) [5, 28]. The null SMD in Figure 3 is thus not just a statistical void; it is a symbol of epistemic exclusion. This lack of calibration renders even sophisticated algorithms (NSGA-II, MOPSO) epistemologically fragile [16, 17], as they optimise for an abstracted reality, not the complex, heterogeneous, and dynamic environment of Ghana [19].

5.4 Temporal acceleration masking conceptual stagnation

The publication trend bar chart (Figure 1) shows explosive growth of 12 studies in 2025 alone, indicating strong academic and industrial interest. Yet this quantifiable surge masks conceptual stagnation: most 2025 studies replicate algorithmic templates (NSGA-II + COMSOL) without advancing theoretical framing or empirical validation. No study conducts global sensitivity analysis (e.g., Sobol indices) to rank design variables (burial depth, salinity, material ratio), despite methodological calls by. This suggests the field is technically mature but theoretically immature, a pattern common in engineering domains where tool adoption outpaces conceptual innovation.

5.5 Policy and infrastructure implications

The identified gaps have real-world consequences for regions like Ghana:

- **Grid reliability:** Grounding system failures contribute to 15%–20% of substation outages in saline zones [32]. Without locally validated designs, Ghana’s National Electrification Strategy risks deploying systems vulnerable to premature failure.
- **Economic cost:** Hybrid materials may reduce LCC by 25%–40% over 30 years [39], but if designs fail early due to modelled salinity (e.g., dynamic chloride gradients from coastal intrusion), replacement costs could negate savings.
- **SDG alignment:** SDG 7 (affordable, reliable energy) requires contextually grounded infrastructure. A one-size-fits-all global model fails to meet this imperative, particularly in high-risk regions like Ghana’s Upper East Region with lateritic soils, seasonal droughts, and high chloride content [19].

5.6 Proposed integrated research framework

To address these gaps, we propose a three-phase research framework (Figure 5) that transforms Ghana from a “test case” into a site of methodological innovation. This framework is designed to answer the following specific research questions:

- **Characterisation Question:** What is the quantitative relationship between seasonal chloride variation in coastal Ghanaian soils and the corrosion rate of candidate hybrid materials (Cu-steel composite vs. carbon-enhanced backfills) [4]?

- **Sensitivity Question:** Using Sobol indices [22], which design variable (burial depth, material composition, backfill ratio) and environmental variables (salinity, moisture, temperature) exert the greatest influence on grounding resistance stability in lateritic soil [19, 28]?

- **Optimisation Question:** When LCC is integrated as a dynamic moderating variable rather than a post hoc metric, how does the Pareto-optimal frontier shift between safety (Step Voltage limits) and 3-year economic performance [13, 14, 32]?

- **Validation Question:** What is the predictive error between COMSOL simulated performance [21] and monitored field performance over 24 months, and how can this error inform iterative model calibration [10, 19]?

5.7 Theoretical implications

This study advances grounding system design by integrating electrochemical corrosion behaviour with optimisation theory, by explicitly modelling salinity as a mediating variable. It bridges the gap between environmental hydraulics and engineering optimisation, which is largely absent in existing grounding literature.

5.8 Engineering implications

The findings demonstrate that grounding system optimisation that neglects dynamic salinity effects may produce non robust designs. This is particularly critical in environments with fluctuating moisture and chloride content, where corrosion and resistivity are strongly coupled.

5.9 Policy and infrastructure implications

For regions such as Ghana, reliance on globally standardised grounding models local calibration may result in premature system failure, increased maintenance costs, and compromised safety. These findings highlight the need for context specific grounding standards aligned with local soil conditions

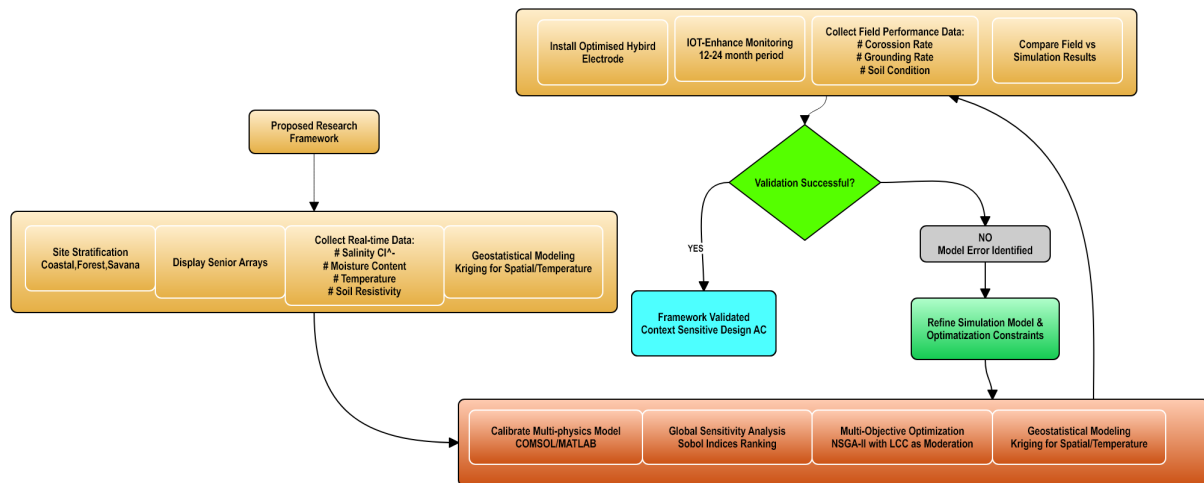


Figure 5. Proposed integrated research framework for context-sensitive grounding design in Ghana

To capture real-time salinity, moisture, and resistivity dynamics, the framework consists of three interconnected phases: (1) high-resolution field characterisation using IoT sensor arrays across Ghana's three ecological zones [19, 28]; (2) calibrated simulation and sensitivity-informed optimisation using COMSOL/MATLAB with Sobol-based global sensitivity analysis and NSGA-II [16] incorporating LCC as a dynamic moderating variable [14]; and (3) pilot deployment and iterative validation loop at coastal substations, comparing IoT-monitored field performance with simulation predictions to enable adaptive model calibration [40]. With the use of this framework, Ghana becomes a location of methodological

innovation rather than a passive test case, yielding both localised designs and broadly applicable concepts for tropical grounding systems.

Phase 1: High-Resolution Field Characterisation

Deploy sensor arrays across 3 representative ecological zones (coastal, forest, savanna) to measure real-time salinity, moisture, temperature, and resistivity. Use geostatistical kriging to create spatial and temporal maps of soil parameters, capturing the full range from 10 $\Omega\cdot\text{m}$ (coastal) to 500 $\Omega\cdot\text{m}$ (lateritic uplands) [19, 30].

Phase 2: Calibrated Simulation & Sensitivity-Informed Optimisation

Calibrate multi-physics simulation models (COMSOL/MATLAB) using field data from Phase 1 [21]. Conduct Sobol-based global sensitivity analysis to rigorously rank the influence of design variables (e.g., burial depth, material ratio) and environmental variables (salinity, moisture) on performance outcomes. Execute multi-objective optimisation (NSGA-II) with LCC integrated as a dynamic moderating variable, directly shaping the Pareto frontier between safety (step voltage) and cost [13, 14].

Phase 3: Pilot Deployment & Iterative Validation Loop

Install prototype optimised hybrid grounding electrodes at pilot sites (e.g., a coastal substation in Greater Accra). Monitor performance over 12–24 months using IoT-enabled sensors for corrosion rate, grounding resistance, and soil conditions, following established on-site electrochemical detection protocols validated for substation grounding systems [40]. Compare field results with simulation predictions to calculate model error and validate optimisation. This creates a feedback loop to refine simulation models and optimisation constraints, transitioning from a one-off design to an adaptive, learning-based system capable of addressing unique challenges like lateritic soil iron oxide layers and seasonal chloride gradients [10, 19].

This framework produces not just localised designs but generalizable principles for tropical grounding systems, bridging the simulation reality divide through integrated, empirically grounded, and context-sensitive optimisation.

6. Conclusion

This systematic review has synthesised global evidence (2015–2025) on the multi-objective optimisation of hybrid electrical grounding materials, revealing a field at a critical inflexion point. On the one hand, there is robust consensus that hybrid systems, whether Cu-steel composites or carbon-enhanced backfills, deliver superior performance under saline conditions, reducing grounding resistance by 18%–42% and extending service life by 2.1–3.4 times [1, 6, 8]. Specific studies demonstrate significant effects: optimisation using evolutionary algorithms has achieved an SMD of 0.98 with NSGA-II [17], while [6] showed 68% corrosion reduction in carbon backfills at $> 5000 \text{ ppm Cl}^-$.

On the other hand, the field remains conceptually fragmented and empirically unanchored, particularly in tropical regions like Ghana. Soil salinity is rarely modelled as a mediating variable, LCC is typically a post-hoc metric rather than a moderating variable, and a profound simulation validation chasm exists, with zero field studies conducted in Ghana despite its unique soil challenges (10–500 $\Omega\cdot\text{m}$ resistivity, $> 5000 \text{ ppm}$ chloride, 25%–85% humidity swings) [19, 28]. This gap has tangible implications: grounding failures account for 15%–20% of substation outages in saline regions [32], threatening Ghana's National Electrification Strategy and SDG 7 objectives.

The proposed integrated research framework combining field characterisation, calibrated simulation with Sobol sensitivity analysis, and iterative pilot validation offers a pathway forward. By repositioning Ghana from a passive “test case” to an active site of methodological innovation, this approach can bridge the simulation reality divide and contribute to developing contextually grounded earthing standards that are safe, durable, cost-effective, and locally valid [19]. Future research must move beyond algorithmic replication to embrace theoretical integration and empirical grounding, ensuring that the promise of hybrid grounding materials is fully realised in the diverse and challenging soils where they are most needed.

6.1 Future research directions

Future work should priorities field validation of hybrid grounding materials in tropical soils, particularly in regions with lateritic compositions. Additional research is needed to integrate real time salinity monitoring into optimisation frameworks, explore AI driven adaptive grounding systems, and develop climate resilient grounding infrastructure for rapidly changing environmental conditions.

Conflicts of interest

The author declares no conflicts of interest.

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