Influence of the use of ground enhancement materials on the reduction of electrical resistivity in grounding systems: a review

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ABSTRACT

A grounding system (GS) is an indispensable component in an electrical system network, as it is responsible for conducting electrical discharges to the ground due to faults caused by lightning strikes or transient system failures. Globally, it is estimated that 40 lightning strikes occur per second on the planet, amounting to around 1.2 billion per year, resulting in daily losses of various electrical equipment and human fatalities ranging from 6,000 to 24,000. Additionally, soil resistivity, which impedes the flow of electricity from electrical discharges into the ground, leads to inadequate mitigation of electrical overload effects, resulting in poor GS performance. Consequently, the implementation of ground enhancement materials (GEMs) to reduce impedance to optimal levels becomes necessary. The objective of this review is to broadly examine the current status of GEMs reported in the literature for use in GS, focusing on their composition and their effectiveness in improving soil conductivity and dissipating electrical currents as well as to identify emerging trends and current challenges in the development and application of these materials, in order to provide information to guide future research in the design and implementation of efficient and safe GS.

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1. INTRODUCTION

A grounding system (GS) is an indispensable component in an electrical system network, as it is responsible for conducting electrical discharges to the ground due to faults caused by lightning strikes or transient system failures [1]. A GS refers to a deliberate link established from a circuit conductor, typically the neutral wire, to a ground electrode positioned within the soil. Conventional GS setups typically involve an array of metal rods buried underground, along with meshes and/or rails, all interlinked with electrical elements to form a pathway for channeling undesirable electrical discharges into the deeper layers of the soil [2]. The electrodes of a GS are positioned either vertically or horizontally to channel most of the overvoltage current into the soil [3].

Furthermore, when a lightning strike occurs, the GS serves as a bridge between the electrical charge and the ground; therefore, the safeguarding of electrical and electronic devices greatly relies on the properties and setup of the GS [4]. Worldwide, approximately 40 lightning strikes hit the earth every second, totaling roughly 1.2 billion annually. Consequently, there are daily incidents of damage to various electrical and electronic devices, alongside human casualties ranging from 6,000 to 24,000 [5], these outcomes stem from inadequate design and functionality of the GS [6]. Consequently, in the absence of a properly designed GS and maintenance tailored to its needs, fault currents may seek unintended pathways, potentially endangering individuals [7].

In addition, steel and copper are generally the most commonly used conventional materials for developing a rod or electrode for the GS [8]. Furthermore, the widely employed method of grounding, involving an electrode deeply implanted in the soil, remains in use for domestic purposes across many nations. Moreover, the "ufer" grounding technique, leveraging the metallic framework of structures like high-rise buildings or towers, is utilized [9].

Likewise, ensuring that the resistance value of the GS is lower or comparable to the recommended standards is crucial. This not only guarantees the effective operation of all equipment linked to the electrical system but also enhances the safety of the diverse interconnected components to the GS [10]. The Mexican standard "NOM-001-SEDE-2012" [7] stipulates that the overall resistance of the GS should not exceed 25 Ohms (Ω). Moreover, according to literature, for effective lightning protection, the resistance should ideally hover around 10 Ω [11]-[13].

Nevertheless, there is no universal agreement among regulatory bodies regarding a standardized threshold for ground resistance that is unanimously recognized. Nonetheless, the National Fire Protection Association (NFPA) [14] and the Institute of Electrical and Electronics Engineers (IEEE), two highly respected organizations globally, recommend a ground resistance value of 5 Ω or lower [15]. Likewise, there are 5 aspects believed to impact the resistance of a GS, including: the length and depth of the electrode, the diameter of the electrode, the quantity of electrodes, the GS design, and most importantly, the soil resistivity [2].

On the other hand, setting up a GS can pose challenges, especially in high-resistivity soil or constrained spaces. In such cases, utilizing diverse soil resistance-reducing agents is preferred [16]. Over recent decades, numerous researchers [16]-[26] have introduced various techniques to mitigate and sustain ground resistance at low and safe levels. These approaches often entail the implementation of ground enhancement materials (GEM), which act as supplementary materials to improve interaction between the GS and the soil [27].

A GEM is a conductive material that addresses challenges related to grounding. It is particularly effective in areas where electrical conductivity to the ground is poor, such as rocky terrain, mountain tops, and sandy soils. The GEM significantly reduces soil resistance and impedance and can reduce the size of the GS [28]. A GEM is typically placed inside the trench where the GS electrode is installed and mixed or substituted with natural soil [16]. Globally, the use of various natural and chemical substances as GEMs for GS is common and necessary because by decreasing soil electrical resistance, GEMs help maintain low impedance between the electrical system and the ground, which is essential for GS effectiveness [29].

The prevailing trend in the market is the utilization of bentonite as a GEM, given its demonstrated efficacy in reducing soil resistivity [30]-[33]. Nonetheless, the primary drawback of bentonite lies in its high cost, attributed to industrial processing, and its status as a limited natural resource, often sourced from developing countries [18]. Bentonite, a natural clay predominantly comprising the smectite mineral group, particularly montmorillonite, exhibits hygroscopic properties, absorbing water from its surroundings [33]. Commercially, two variants of bentonite are prominent: sodium bentonite and calcium bentonite [34].

Nonetheless, it's wise to investigate various materials utilized by researchers as GEMs and the properties they exhibit when employed to enhance GS. Consequently, the objective of this review is to broadly examine the current status of GEMs reported in the literature for use in GS, focusing on their composition and their effectiveness in improving soil conductivity and dissipating electrical currents as well as to identify emerging trends and current challenges in the development and application of these materials, in order to provide information to guide future research in the design and implementation of efficient and safe GS.

2. INTERACTION BETWEEN THE GROUNDING SYSTEM AND THE SOIL

2.1. Influence of soil on the electrical efficiency of grounding systems

The soil is the earth's surface layer, formed by the interaction of geological and biological materials over a considerable period of time. It consists of a mixture of minerals, organic material, water, air, and living organisms such as bacteria, fungi, insects, and plant roots. Soil plays a crucial role in terrestrial ecosystems as it provides physical support for plant growth, acts as a medium for nutrient and water cycling, and serves as a habitat for a diverse range of organisms. Additionally, it is essential for agriculture, construction, and many other human activities [35].

On another note, electrical efficiency refers to how optimally electricity is used to perform a specific task or function. Generally, it's calculated as the ratio between the desired output of an electrical system and the electrical energy consumed to achieve that output. High electrical efficiency indicates that less energy is required to achieve the same results, potentially resulting in resource savings and cost reduction. Electrical efficiency can be applied across a wide range of devices and systems, from household appliances to power plants [36].

Hence, soil properties significantly influence fault currents to ground and thereby impact the electrical efficiency within a GS. Potentials induced by electromagnetic or resistive coupling (direct ground connection) pose a risk of damaging equipment or facilities connected to the GS. Furthermore, soil non-uniformity may result in a greater potential rise, especially affecting electrical equipment in residential installations or homes [37].

Moreover, it's recognized that the physicochemical makeup of the soil plays a pivotal role in determining the optimal levels of ground resistance, given the diverse behaviors and properties exhibited by soils that influence the overall resistivity of a GS [17]. Therefore, to optimize the performance of the GS, it's crucial to acknowledge that the behavior within the GS is heavily influenced by the type of soil surrounding the electrode, given that soil acts as the interface between the ground and electrical overvoltage currents [38].

Furthermore, resistivity fluctuates according to the structure of soil materials, highlighting that both high and low resistivity values correlate with porosity. Consequently, electrical conductivity is tied to particle size and the density of electric charge on the surface of solid constituents [39]. In clayey soils, the elevated specific surface area offers additional sites for electric charges to reside on the surface of clay particles. Consequently, clay soils typically exhibit higher electrical conductivity compared to coarse-textured soils like sand, which provide fewer available surface areas for electric charges. This heightened electrical conductivity in clay soils can impact various processes, including water retention capacity, nutrient accessibility for plants, and the mobility of contaminants within the soil [40].

Electric current in soils is predominantly electrolytic, driven by the displacement of ions in the interstitial water. Consequently, soil electric current is contingent upon the water quantity and quality within the pores. Electrical resistivity diminishes as water content rises. Soil water retention capacity is contingent upon the specific soil type, as each type possesses distinct characteristics regarding water retention [41].

Furthermore, soil resistivity, impeding the flow of electricity from electrical discharges into the ground, leads to insufficient mitigation of electrical overload effects, thereby affecting the performance of GS [42]. Consequently, the efficiency of any electrical equipment is contingent upon the soil's impedance characteristics, which are influenced by factors like moisture, climate, stratigraphy, and salinity [43]. Phenomena like direct lightning strikes on the electrical grid can result in significant damage to both residential and industrial installations. Hence, soil impedance plays a crucial role, as electrical current tends to follow the path of least resistance [44]. Worldwide, topographical features impact various terrains and soil types. Certain terrains may exhibit high electrical resistivity. Consequently, it's crucial to implement measures to prevent this high resistivity from impeding the dissipation of electrical currents to the ground [45].

Hence, enhancing the functionality of a GS hinges on the soil's pivotal role, serving as the intermediary between the earth and electrical overvoltage currents [38]. Consequently, to attain effective GS, soil electrical resistance levels must be minimized, predominantly dictated by its electrical conductivity capacity [24]. Furthermore, it's essential to acknowledge that within a GS, behavior is influenced by the type of soil enveloping the electrode [25].

2.2. Design of a grounding system to improve ground impedance

Virtually all electrical and electronic equipment need to be connected to a GS [46]. An ineffective GS leads to heightened periods of unnecessary electrical downtime. Furthermore, its absence poses significant risks of failures in electrical and electronic equipment. Therefore, a proper design of the GS is paramount for ensuring the smooth operation of power systems during lightning strikes or system failures [47].

Hence, having an effective and efficient design of the GS is crucial to ensure fault currents dissipate effectively into the ground. Consequently, diverse techniques outlined in the literature [11]-[13] regarding GS investigations involve laboratory [48], [49] and field measurements [50], [51], along with analytical and computational models [52]-[54]. Moreover, numerous studies have explored intriguing aspects related to GS design, with the latest findings detailed in various scientific articles [55]-[57].

Nevertheless, basic GSs are composed of a single electrode inserted into the ground. Thus, using a single grounding element represents the most typical approach for GS design, often located in outdoor spaces of residences or workplaces. Conversely, complex grounding systems involve multiple interconnected rods, mesh or grid networks, plates, and loops as shown in Figure 1. Such systems are typically installed in power generation substations, corporate campuses, and cellular tower sites [58]. Therefore, for a GS to prove effective, it should be engineered to endure the most adverse conditions possible. Consequently, a suitable design, aligned with the requirements of interconnected equipment, can consistently impact the ultimate resistivity of the system [59].

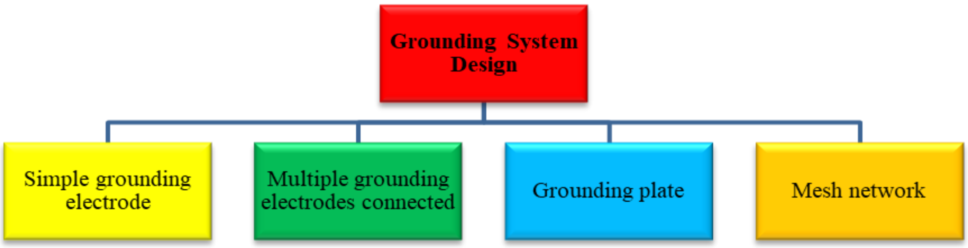

Figure 1. Various ways to design a GS [58]

3. METHODOLOGY FOR EVALUATING THE EFFECTIVENESS OF THE GROUNDING SYSTEM

3.1. Evaluation of electrical efficiency through current dissipation through the ground

The ground is responsible for dissipating fault currents that reach it. Electrically, the ground is defined by its resistivity (ρ), which is the resistance offered by a cube of the ground and is usually expressed in ohms per meter (Ωm) (1) [60].

$$\rho = \frac{\Omega m^2}{m} = \Omega m \tag{1}$$

In practice, the extreme values can vary from a few tens of Ωm for organic and moist soils to tens of thousands of ohm-meters for dry granites [60].

On the other hand, the dissipation of electrical current through the ground is the process by which unwanted currents are diverted into the soil, using the GS as the path of least resistance. This process is essential for electrical safety, as it helps protect equipment, people, and properties against electrical hazards [61], [62]. This method ensures that in case of an undesired current, like leakage or overload, the GS (grounding system) offers a low-resistance route to the ground. Through this route, current can pass from the equipment or electrical setup to the ground via the soil, ensuring safe and efficient dissipation [63]. Additionally, the dispersion of electric current through the soil is crucial for safeguarding against electrical discharges, fires, and other electrical hazards. It constitutes a fundamental element in ensuring the safety of electrical and electronic systems [64].

3.2. Methodology for evaluating the electrical resistance of a grounding system

Various techniques exist for assessing soil electrical resistivity, but the globally recognized standard is set by the IEEE, which has issued a guideline for configuring soil resistivity measurements [65], [66]. Among these techniques, the four-point or Wenner method stands out as the most prevalent approach for determining soil resistivity [15]. This method entails burying four electrodes with identical specifications and length (l) in the soil, all connected to the measurement apparatus as shown in Figure 2 [67].

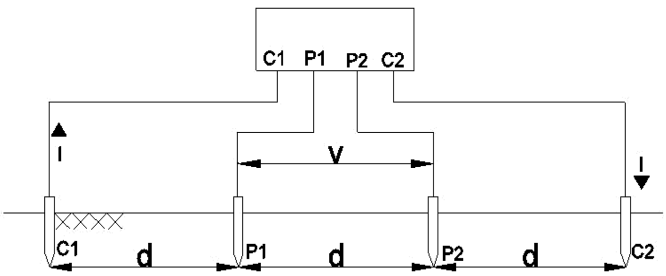

Figure 2. Measurement of earth resistance by the Wenner method [65]

The device circulates an electrical current I between the electrodes C_1 and C_2, and a potential difference V is measured between the electrodes P_1 y P_2, so that the ratio $R = \frac{V}{I}$ is obtained. The value of the measured resistivity at a given depth and with a separation between the electrodes d is obtained using (2) [65].

$$\rho = \frac{4\pi dR}{1+\frac{2d}{\sqrt{d^2+4l^2}}-\frac{d}{\sqrt{d^2+l^2}}}) \quad (2)$$

Where: ρ=apparent resistivity of the soil in Ωm, l=depth of the electrodes in meters (m), R=measured resistance in Ω, d=distance between adjacent electrodes in m.

Furthermore, Figure 3 provides a schematic representation of the methodology in comprehensive detail, allowing for the determination of electrical resistivity within a GS [65], [68]. This diagram delineates the step-by-step process for measuring electrical resistivity within a GS, encompassing site preparation, instrumentation setup, and result interpretation. Each stage holds significance in ensuring precise and dependable measurements of soil resistivity within the GS.

Similarly, a range of scholars [19], [42] have employed the Wenner methodology to assess soil characteristics when blended or replaced by a GEM. The findings from these inquiries propose that the soil's resistivity, when utilizing a GEM, displays an impedance distinct from pre-material enhancement measurements. Therefore, the Wenner approach proves apt for assessing soil resistivity pre and post GEM utilization. Consequently, electric soil resistivity measurement emerges as a benchmark for validating or refuting the GEM's efficacy in mitigating GS impedance [69]. Moreover, in instances necessitating verification of electrical equipment-GS linkage, four commonly practiced methods are available in Figure 4 [70].

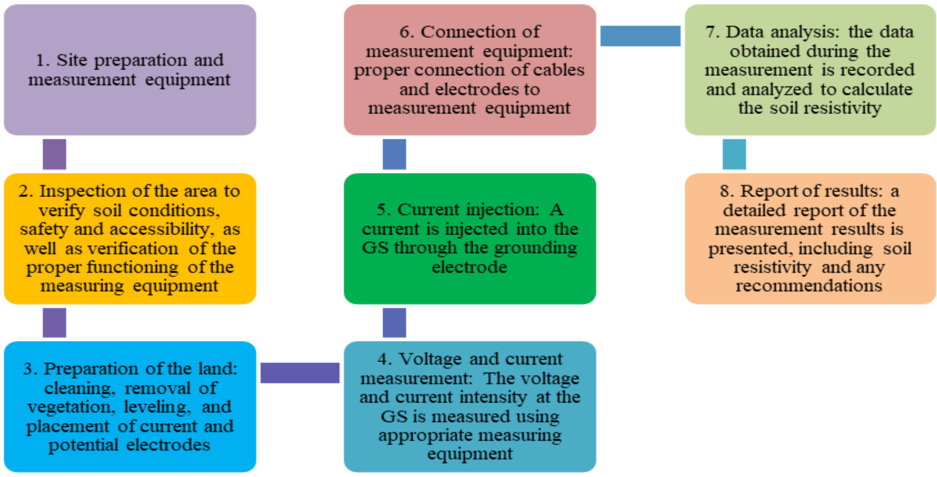

Figure 3. Detailed methodology to obtain electrical resistivity in a GS [65], [68]

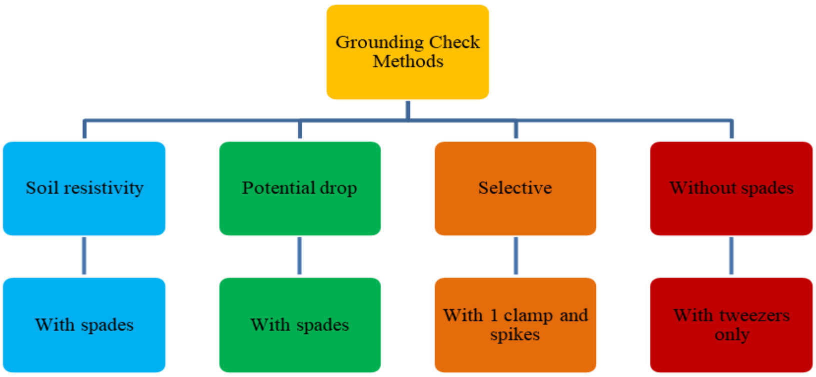

Figure 4. Weibull distribution of all filler concentrations [70]

The validation protocols for a GS, as delineated earlier in Figure 4, serve the paramount purpose of upholding electrical safety within any setup. Nevertheless, strict adherence to pertinent electrical regulations and standards within each locale is imperative for executing GS validation effectively, thereby safeguarding both electrical installations and the individuals concerned. Furthermore, in numerous jurisdictions, GS validation mandates execution by individuals possessing requisite training and certification [71].

4. GROUND ENHANCEMENT MATERIAL AS A COMPLEMENT TO IMPROVE SOIL RESISTIVITY

4.1. Ground enhancement material variants used in scientific literature

Obtaining a low impedance level in rocky and sandy soils proves highly challenging in numerous scenarios. Hence, the introduction of diverse substances, including the aforementioned GEMs, becomes imperative to mitigate and sustain ground resistance at secure and minimal levels [16]. Thus, GEMs have found widespread use as enhancers of soil impedance capacity for GSs. Nevertheless, as noted in [7], a GEM must exhibit specific characteristics to enhance GS performance; it should retain soil moisture around the GS rod and form a protective barrier to prevent corrosion. Consequently, selecting a material meeting these criteria becomes essential, taking into account the soil type, terrain, and climate of the region.

Among the attributes of GEMs, one of the most crucial, significantly impacting their efficacy as reducers of ground resistance, is their hygroscopic nature [19]. Hygroscopy denotes the ability of certain substances to absorb moisture from the surroundings. This absorption may occur via adsorption or physical uptake of water on the material's surface, or through chemical uptake where water becomes part of the material's molecular structure [72]. Hygroscopy finds relevance in various domains, spanning from food preservation, pharmaceuticals, agriculture, meteorology, to the fabrication of materials like paper, textiles, and chemicals. Hygroscopic materials may undergo alterations in their physical and chemical attributes due to water absorption, thereby potentially affecting their stability, endurance, and utility [73], [74].

Additionally, three types of GEMs, investigated as soil enhancers, are documented in the literature, comprising materials sourced from natural agents, waste, and chemicals as shown in Figure 5. Their application aims to diminish the electrical resistance of soils adjacent to the electrodes, yet each variant carries its unique inherent constraints [75]. With the preceding points in mind, we will now undertake a thorough examination of specific materials that have been employed and extensively documented in scientific literature, corresponding to the various component variants within the existing types of GEMs.

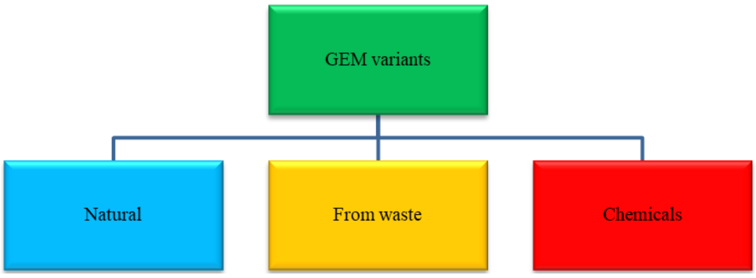

Figure 5. Variants of materials used in the development of different types of GEMs [74]

4.2. Natural materials to improve the grounding system

When it comes to natural GEMs, they can be derived from agricultural waste products, renewable sources, or materials that occur naturally on the planet; moreover, these materials are considered environmentally friendly and low-cost [76]. In agriculture, for instance, these materials are used to enhance crop growth and increase soil moisture absorption and retention capacity [77]. For electrical applications, these properties are crucial as they directly impact the reduction of soil resistivity, making the GS more efficient by providing a path of lower impedance, thus ensuring that fault currents disperse more effectively into the ground [78]. Utilizing natural materials as GEMs offers the benefit of not introducing foreign substances into the soil, thereby avoiding contamination of the surrounding environment compared to chemical methods [19]. Moreover, as highlighted by [79], the growing depletion of our natural resources emphasizes the pressing need to devise methods and designs that ensure a sustainable future.

Opara *et al.* [17] conducted a comparative study on bentonite, pig manure and a mixture of charcoal and salt as GEM reagents for GS applications. The findings indicated that pig manure produced the most favorable outcome, reducing soil resistivity from 74.94 to 8.26 Ωm, followed by bentonite at 9.25 Ωm and salt with coal at 10.87 Ωm. However, it was noted that pig manure underwent decomposition over time, resulting in a decrease in the mixture's mass and moisture content, thereby affecting soil resistance. Conversely, household salt gradually permeated the soil, and coal alone did not offer optimal resistivity around the embedded electrode. Despite its relatively high cost, bentonite emerged as the most effective agent for reducing soil electrical resistivity in this study. Soil resistivity's response to these compounds was assessed using the Wenner array method. Furthermore, soil characterization included pH measurement at a

1:2.5 ratio (soil to water), determination of soil organic carbon via the Walkley-black method, and total nitrogen (N) measurement using the Kjeldahl method. Finally, available phosphorus (P) was assessed using the Bray I extraction method.

Jasni *et al.* [19] investigated natural materials that serve as GEM to protect against electric shocks, offering an alternative to bentonite. Within this investigation, it is posited that the prevalent utilization of conventional grounding fillers like bentonite and other chemical compounds poses a substantial contemporary challenge due to economic and environmental considerations. The natural materials scrutinized as GEMs encompassed rice powder, clayey soil, and coconut fiber peat. Notably, the study identified clayey soil as the most efficacious earth filler compared to coconut fiber peat and rice powder. This determination arose from its demonstrated ability to yield the lowest ground resistance from day 25 onward (across the project's total duration of 138 days). Through the utilization of clayey soil as a GEM, the recorded GS resistivity exhibited a decline from 33 Ω on day 1 to 24 Ω on day 138. Methodologically, the research entailed the execution of resistivity measurements in accordance with the guidelines stipulated in the "IEEE guide for measuring earth resistivity, earth impedance, and earth surface potentials of a grounding system" [65]. The Frank Wenner method was deployed, employing the 62% rule. Furthermore, the potential fall technique was employed to meticulously gauge the resistance of a grounding rod, utilizing auxiliary stakes driven into the ground to form a circuit for injecting test current and measuring voltage. This methodology entailed the insertion of three rods into the ground at specified distances from each other, followed by voltage application. Despite the efficacy demonstrated by the methodology in straightforward GS setups, such as grounding rod insertion, there exists a recognized imperative for conducting a longitudinal study spanning 3 to 5 years to assess the performance of natural materials employed as grounding fillers. Such an undertaking will facilitate an equitable comparison with commercial grounding apparatuses.

Lai *et al.* [20] a review was conducted regarding the utilization of natural materials employed in agriculture like zeolite, perlite, and vermiculite, some of which showed a notable capacity for retaining moisture in the surrounding soil; hence, it is suggested that these materials could prove advantageous as GEMs for incorporation into GSs. However, certain materials examined exhibited certain constraints. For instance, perlite demonstrated a markedly low apparent density, coupled with a limited water retention capacity, rendering it unsuitable for GEM utilization. Conversely, zeolite exhibited an acceptable value in terms of its water retention capacity, showcasing satisfactory performance across various soil types and climatic conditions. Nevertheless, vermiculite, while possessing a significant moisture retention capacity comparable to bentonite, displayed a low porosity percentage, resulting in a limited number of pores facilitating external water flow into the soil. Following the study, it was determined that among the three materials evaluated, zeolite, given its observed capabilities in agricultural applications, could emerge as the optimal choice for GEM utilization within a GS

Ahmad *et al.* [21] explored the use of China clay and silica sand, combined with varying proportions of bentonite, as GEM for GS, and finally determined that bentonite serves as a clear indicator for reducing the strength of GS when used as a filler material. The samples underwent individual testing under both direct current (DC) and alternating current (AC) conditions using finite element method (FEM) software simulations for GS analysis, evaluating breakdown voltages. Subsequently, they were assessed as a composite blend in a 1:1 ratio. The amalgamation of silica sand and bentonite demonstrated a notable 30% decline in breakdown voltage compared to blends of Chinese clay and bentonite. Furthermore, FEM software analysis unveiled that the distribution of silica particles showcased a superior level of uniformity within the electric field compared to Chinese clay. Moreover, silica sand exhibited a heightened intensity within the electric field. This suggests its capability to effectively discharge electrical charges. However, future endeavors should consider conducting tests under humid environments and high-frequency conditions. Moreover, physical analyses measuring resistivity using a GS are imperative to encompass real-world scenarios, beyond mere simulation. Additionally, subjecting the proposed samples to an aging process, with tests repeated over a 6-month period, would enable the evaluation of variations in their diverse parameters

The research documented by Eduful *et al.* [22] showcases the utilization of a derivative from palm kernel oil (PKOC) as a GEM aiming to diminish the electrical resistance of soil. The amalgamation of soil, characterized by high electrical resistivity, with PKOC exhibited a noteworthy decrease in ground resistance over an extended duration. Furthermore, this blend demonstrated resistance against acidic and alkaline environments, ensuring the sustained maintenance of low soil resistance, with gradual and significant mitigation of impacts during rainy seasons. The chemical attributes of this blend underwent scrutiny at a soil mechanics research center, undergoing comparison with those of various commercial GEMs. Assessed parameters encompassed total nitrogen, carbon, phosphorus, potassium, calcium, magnesium, and pH acidity levels. The determination of organic carbon relied on the adapted Walkley and Black method [78], while total nitrogen content was determined using a modified Kjeldahl digestion and distillation approach. Soil resistivity was gauged employing the Frank Wenner technique. Key factors identified as significant contributors to PKOC's high electrical conduction included carbon concentration, moisture levels, and a low pH. It's noteworthy that PKOC exhibited a pH level of 5.13, relatively low considering the onset of copper electrode corrosion typically occurs at pH levels exceeding 7.0. Furthermore, earth resistance measurements were conducted utilizing the DET5/4R digital earth tester, implementing the potential drop method or adhering to the "62%" rule. In assessing the efficacy of earth resistance reduction techniques, a 1-meter electrode was embedded into soil with a resistivity of 300 Ωm. At this level of resistivity, an earth resistance of 236 Ω was recorded. Subsequently, soil within the critical resistance radius of the 1-meter electrode (0.4 m) was replaced with PKOC, boasting a resistivity of 5.7 Ωm. This intervention yielded a reduction in resistance to 62.54 Ω, marking a percentage decrease exceeding 73%.

However, as mentioned by Ahmad *et al.* [21], conventionally used natural GEMs such as salt, sand, lime, charcoal, and their mixtures have several disadvantages. These include dissipation into the soil, optimal performance only in moist conditions, and corrosion of the grounding electrode. Moreover, these conventional materials pose installation challenges, often necessitating deep excavation of the electrode, thereby increasing costs. In some instances, they cannot be installed in problematic environments.

4.3. Materials from waste to improve the grounding system

Residual materials encompass a broad spectrum, deriving from diverse sources like industrial remnants, urban refuse, and debris from construction and demolition. These are garnered through the treatment and processing of solid, liquid, or gaseous residues, aiming to repurpose or reintegrate them into productive cycles [80]. Chen *et al.* [16] examined the feasibility of using fly ash, derived from power plant waste, to improve the electrical conductivity of GS. Two types of mixtures were prepared: the first comprising fly ash, cement, and water, and the second including fly ash, cement, water, and salt. The outcomes from the first mixture with a ratio of 1:0.3:0.3 revealed an average soil resistivity of 103.68 Ωm, while for the second mixture with a ratio of 1:0.4:0.3:0.15, an average resistivity of 4.83 Ωm was achieved. The findings illustrated that incorporating fly ash alongside a supplementary reducing agent such as salt, subsequent to soil stabilization around the GS bars, leads to a 35% reduction in earth resistivity.

Pedroza *et al.* [18] proposed a new GEM comprising two problematic industrial wastes: coal ash derived from fossil fuel combustion (CF) and gypsum from construction and demolition waste (PW). This innovation introduces a fresh avenue for managing these residues and provides a feasible alternative to current commercial GEMs aimed at enhancing soil electrical conductivity. Initially, a mixture design methodology was utilized to estimate the required proportions of CF and PW for achieving acceptable electrical conductivity levels in the soil. Subsequently, experimental trials were conducted following the Wenner method using the optimized mixture to ascertain its technical viability. A comparative analysis of the mixture's performance, based on experimental findings, was then conducted against existing market products. The optimized blend was determined to consist of 70% CF, 15% soil, and 15% PW waste. This blend markedly elevated soil electrical conductivity from 0.065 µS/cm to 2792 µS/cm. Nevertheless, it is advisable to conduct further trials encompassing diverse mixture designs and extended durations, accounting for various climatic conditions. The comparative investigation underscored the potential for substituting prevailing commercial products with the developed solution.

Moreover, Tadza *et al.* [23] an inquiry was conducted into the effectiveness of graphite (GR) and activated carbon (AC) as alternative GEMs aimed at enhancing the performance of the GS. Aggregate electrical resistivity was gauged utilizing the soil box technique. Findings revealed that the electrical resistivity, water absorption, and crush resistance of all aggregates fluctuated over time, stabilizing at the 14-day mark. Aggregates containing GR and AC exhibited electrical resistivities of 49.20 and 185 Ωm, respectively, surpassing the 12.70 Ωm observed for aggregates utilizing commercial GEMs. This study concluded that integrating GR and AC substantially enhances electrical resistivity performance while preserving satisfactory mechanical attributes essential for GS connections. Moreover, it can be inferred that, generally, GR outperforms AC in terms of electrical resistivity.

4.4. Chemical resistivity reduction methods

Beyond the approaches utilizing materials sourced from natural origins and waste products, there are also artificial or chemical methods for reducing resistivity. Nonetheless, as discussed in [24], [81]-[84], chemical enhancement materials effectively decrease soil electrical resistance but simultaneously lead to soil contamination and corrosion of the GS electrode.

When employing chemical agents to enhance soil electrical conductivity and thereby diminish ground resistance, an electrolyte like sodium chloride, magnesium sulfate, copper sulfate, magnesium chloride, calcium chloride, ammonium chloride, or similar substances is introduced around the GS electrode. This method temporarily improves soil resistance to facilitate effective electrical current dispersion. However, it's crucial to acknowledge that these chemicals can be washed away by surface runoff and groundwater during rainy periods. As a result, the impact of chemical treatments is temporary, lasting anywhere from several months under severe conditions to a maximum of 3 years, with an average effectiveness typically around 2 years [22], [85].

According to historical analyses Camara *et al.* [28], various methods to reduce soil electrical resistivity were investigated by scientists since the 1940s, as lightning storms were quite common during that time, coupled with growing concerns for safety. Due to the increasing research on methods to decrease soil electrical resistivity, there was widespread use of sodium chloride (NaCl) as an improvement material [32].

Ahmad *et al.* [24] explored the potential use of sodium chloride, sodium thiosulfate, magnesium chloride, copper sulfate and ammonium chloride as soil improvement materials. It was demonstrated that by introducing these chemical enhancement materials near the GS electrode, the system's ground resistance gradually decreases over time. After 141 days, sodium chloride emerged as the most effective chemical enhancement material, while ammonium chloride exhibited inferior performance compared to commercial GEMs. Despite the notable improvement in GS ground impedance observed with sodium chloride, its chemical nature renders its environmental viability questionable.

Gomes *et al.* [25] conducted a study spanning 2 to 3 years to assess the effectiveness of deeply immersed galvanized iron electrodes coated with various fill materials including: metal oxide powder, limestone, sodium chloride, bentonite, iron filings, and granite powder. The most effective material was found to be the metal oxide powder, achieving a resistivity of 8 Ωm. This material was then compared against commercially available and commonly used GEMs, demonstrating satisfactory performance levels several months post-implementation. It was observed that limestone and iron filings exhibited good performance in terms of electrode corrosion, while commercially available natural bentonite performed well, yielding an average resistivity of 3 Ωm in the GS. On the contrary, sodium chloride, widely used in South Asia, resulted in a resistivity of 0.9 Ωm, albeit with significantly higher corrosion levels compared to other compounds. Additionally, granite powder displayed the highest resistivity at 24 Ωm. Notably, resistivity measurements were conducted using the Wenner Array method, with wet samples, as resistivity values tend to be higher in dry conditions.

Galvan *et al.* [26] evaluated six soil enhancement compounds under field conditions, with five based on chemical powders and one composed of concrete. Two experimental fields were established, one on volcanic rocky soil and the other on limestone rocky soil, positioned on transmission line towers to gather practical data for lightning protection strategies. While one of the compounds exhibited consistent performance across various soil resistivity levels, others showed inconsistent or diminishing effectiveness with higher resistivities. Surprisingly, the concrete-based compound demonstrated robust performance, outperforming some chemical powder counterparts. However, certain compounds exhibited steep increases over time, posing challenges for real-world applications due to potential spikes in GS resistance values. The study suggests extending the project for an additional 2 years to refine the results and understanding. Presents qualitative rather than quantitative data, focusing on the efficacy of the studied GEMs [26].

5. RESULTS AND DISCUSSION

Table 1 provides a summary of the most notable findings from the articles reviewed in this document, organized according to the three types of materials used as compounds for the development of various GEM variants. On the other hand, references [17], [19]-[22] show the natural materials that have been used by various authors to achieve soil resistivity reduction and thus improve the electrical conductivity of GSs. Among these materials, it can be observed that bentonite, combined with materials such as pig manure or China clay, offers the best results. Conversely, when working with materials from waste [16], [18], [23], some exhibit better properties that help enhance grounding systems, especially those related to carbon, such as graphite and fly ash. However, chemical materials, particularly those containing sodium as used by [24], [25], are the most effective in reducing the resistivity of the soil surrounding the grounding system's electrode.

As per the findings summarized in Table 1 from the studies conducted by the referenced authors, while acceptable results have been obtained, they often fall short of meeting the impedance standards recommended by various regulations [7], [11]-[15] for ensuring a secure connection of electrical equipment to the grounding system. Furthermore, it is commonly suggested across these studies that conducting durability tests on the samples under different climatic conditions would be advisable, as factors like rain or sunlight could impact the quality of the GEMs and consequently affect their electrical properties.

However, it can also be observed that the materials that provide the best results are those derived from chemical reduction methods. On the other hand, natural materials also offer important properties when mixed with bentonite. Additionally, materials from waste are useful not only for reducing soil resistivity but also for reusing waste, thus supporting ecology.

Table 1. Discussion of main results of reviewed articles

Author(s)	Used materials	Main results	Limitation
		Natural materials	
Opara *et al.* [17]	Bentonite, pig manure, charcoal amalgam with household salt	Pig manure produced the best result, reducing soil resistivity from 74.94 Ωm to 8.26 Ωm, followed by bentonite, 9.25 Ωm, and salt with charcoal, 10.87 Ωm	Pig manure is the most efficient natural material, but it decomposes over time, household salt leaches out, and charcoal alone does not achieve the best results
Jasni *et al.* [19]	Rice powder, clay soil, coconut fiber peat	Clay soil more efficient in ground resistance, since the resistivity of the GS varied between 33 and 24 Ω	Long-term study (3-5 years) is needed for fair comparison with commercial GEM
Lai *et al.* [20]	Zeolite, perlite, vermiculite	Zeolite stands out as the best option to improve soil moisture retention, which is why it could be studied as a GEM for GS	Perlite has low apparent density and water retention capacity. Vermiculite has a low percentage of porosity
Ahmad *et al.* [21]	China clay, silica sand and bentonite	Silica sand and bentonite show a breakdown voltage value of 30%, which means that silica sand can discharge charges easily and efficiently, since it obtained a value of 24.96 Ωm in contrast to the values of some Commercial GEMs	Use of bentonite conditions the results of the mixtures. Furthermore, only the GS simulation was done
Eduful *et al.* [22]	Palm nut oil, soil	Significant reduction in ground resistance, stability in acids and alkalis. Soil resistance reduced by 73%	Reduction of the resistivity effect in the rainy season
		Materials from waste	
Chen *et al.* [16]	Fly ash, cement and salt	Fly ash reduced soil resistivity by 35% after soil stabilization, from 22.81 Ωm to 14.83 Ωm	It is advisable to carry out more mix designs to find better results.
Pedroza *et al.* [18]	Coal ash and gypsum (industrial waste)	Optimal combination (70% coal ash, 15% sandy soil, 15% gypsum) increased soil electrical conductivity from 0.065($\mu S/cm^{-1}$) to 2792 ($\mu S/cm^{-1}$) for a time	It is recommended to carry out more tests with different mixture designs and for longer periods of time, considering different weather conditions
Tadza *et al.* [23]	Graphite and activated carbon	The resistivity of aggregates containing graphite and activated carbon was found to be 49.20 and 185 Ωm, which was higher than the 12.70 Ωm obtained for commercial GEM-based aggregates	The combination of graphite and activated carbon improved the electrical resistivity behavior but not to acceptable values
		Chemical reduction methods	
Ahmad *et al.* [24]	Sodium chloride, sodium thiosulfate, magnesium chloride, copper sulfate and ammonium chloride	Sodium chloride as the best material, ammonium chloride poor compared to commercial GEM.	As they are chemical products, their environmental use is considered unviable
Gomes *et al.* [25]	Metal oxide powder, limestone, sodium chloride, bentonite, iron filings and granite powder	Metal oxide powder the most efficient	Environmentally unfriendly, due to soil erosion and contamination
Galvan *et al.* [26]	Chemical materials in powder and concrete	The concrete-based compound showed very good performance, being even better than some of the powdered chemical type	Some compounds showed very high increases over time. The project must be carried out for 2 more years

6. CONCLUSION

Various articles have been reviewed on the use of soil-enhancing materials, better known as GEMs, and the influence their use has on GS. It has been proven that the use of these materials has a significant impact on reducing the electrical resistivity of the GS. Furthermore, it has been found that among the factors contributing to the increase in the electrical resistivity of a GS is the soil itself and, consequently, the moisture content, as well as the characteristics of the terrain. This is why, under these adverse conditions, mainly in sandy and rocky soils, the use of a GEM becomes necessary to reduce the impedance of the GS to safe values. The different types of GEMs reported by various authors have been analyzed, including those derived from natural materials, waste sources, and chemical materials. It is found that materials from chemical sources are the most effective in significantly reducing soil resistivity. However, these materials tend to corrode the GS electrode. Moreover, in some instances, they can be a source of contamination to the environment and soil ecosystem. On the other hand, natural materials, despite yielding good soil and GS resistivity values and being environmentally friendly, as well as beneficial for soil and ecosystem health, perform better only under moist conditions. Additionally, their lifespan is sometimes slightly shorter than GEMs derived from chemical sources, because climatic conditions such as rainfall tend to wash away these materials, leading to their reduction and, consequently, negatively affecting the reduction of soil resistivity and thus the GS.

Similarly, materials derived from waste sources can be identified, characterized by their residual origin, which implies an environmentally favorable approach by providing a second useful life to these materials. According to the reviewed literature, satisfactory performance of these materials has been observed when used as GEMs for the GS. Therefore, it would be considered feasible to find a balance between the use of the three types of materials available in the GEM manufacturing process, aiming to find an ideal combination among them that helps improve GS resistivity by reducing soil electrical resistance. Finally, this article also discusses some important details to consider as part of the comprehensive analysis of the GEM, including the types of GS and the significance of appropriate and efficient design of a comprehensive GS. This is aimed at improving the electrical conductivity of the system as a whole.

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