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PROTOTYPE OF A HIGH-EFFICIENCY, LOW-COST GROUNDING ELECTRODE: IMPACT ON ELECTRICAL SAFETY AND EQUITY IN THE COMMUNITY

PROTOTIPO DE ELECTRODO DE PUESTA A TIERRA DE ALTA EFICIENCIA Y BAJO COSTO: IMPACTO EN LA SEGURIDAD Y LA EQUIDAD ELÉCTRICA DE LA COMUNIDAD

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ABSTRACT:

This study presents the design, fabrication, and experimental evaluation of a prototype grounding electrode aimed at improving electrical protection and reducing the economic barrier that limits access to safe systems in vulnerable communities. The prototype, built from locally available materials with an optimized geometry, was compared to a conventional commercial rod under controlled field conditions using the same clayey soil (150 Ω·m) and backfill material. Results showed that the prototype achieved a grounding resistance of 5.00–6.09 Ω, representing a 58–62% reduction compared to the 12.29–15.80 Ω recorded for the commercial electrode, falling within the range recommended for residential settings. The steady-state leakage current was approximately double (129.50–159.20 mA vs 59.19–73.11 mA), indicating a lower-impedance path that facilitates the dissipation of fault currents and reduces hazardous touch voltages. The overall cost of the prototype system was 45% lower, due to simplified design and the elimination of commercial overhead, making it particularly suitable for social housing and rural electrification programs. These technical and economic advantages translate directly into social impact: more affordable and effective electrical protection helps prevent electrocution and fires, narrows safety inequality, and strengthens community resilience against electrical faults. Findings encourage long-term evaluations across diverse soils and climates to confirm general applicability and to facilitate integration into public policies for safe electrification.

Keywords: Grounding electrode, Community electrical safety, Low-cost, Life protection, Electrical equity.

RESUMEN:

Este estudio presenta el diseño, fabricación y evaluación experimental de un electrodo de puesta a tierra prototipo orientado a mejorar la protección eléctrica y reducir la barrera económica que limita el acceso a sistemas seguros en comunidades vulnerables. El prototipo, fabricado con materiales de disponibilidad local y geometría optimizada, se comparó con un electrodo comercial convencional en condiciones de campo controladas, con la utilización del mismo suelo arcilloso (150 Ω·m) y material

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de acondicionamiento. Los resultados mostraron que el prototipo logró una resistencia de puesta a tierra de 5.00–6.09 Ω, una reducción del 58–62 % respecto a los 12.29–15.80 Ω del electrodo comercial, ubicándose dentro del rango recomendado para entornos residenciales. La capacidad de conducción de corriente fue aproximadamente el doble (129.50-159.20 mA frente a 59.19-73.11 mA), ello indica una ruta de baja impedancia más efectiva para disipar corrientes de falla y reducir tensiones peligrosas. El costo total del sistema prototipo resultó un 45 % menor, debido al diseño simplificado y la eliminación de sobrecostos comerciales, lo que favorece su adopción en viviendas de interés social y zonas rurales. Estas ventajas técnicas y económicas se traducen en un impacto social directo: una protección eléctrica más asequible y eficaz contribuye a prevenir electrocuciones e incendios, reduce la desigualdad en seguridad y fortalece la resiliencia comunitaria. Los resultados alientan evaluaciones de larga duración en diversos suelos y climas para confirmar su aplicabilidad general y facilitar su integración en políticas públicas de electrificación segura.

Palabras clave: Electrodo de puesta a tierra, Seguridad eléctrica comunitaria, Bajo costo, Protección de la vida, Equidad eléctrica.

INTRODUCTION

Grounding systems constitute the first line of defense for the safety of people and the protection of equipment in any low-voltage electrical installation. Their fundamental purpose is to provide a controlled, low-impedance path to earth for fault currents, thereby preventing dangerous voltages from appearing on accessible metal parts and reducing the risk of electrocution or electrically ignited fires (IEEE, 2007). Despite this critical importance, a significant proportion of dwellings in rural, peri-urban, and low-income communities in Latin America lack effective grounding systems, whether due to lack of awareness, the cost of materials, or the difficulty of installation in high-resistivity soils.

The most widely used commercial electrodes are copper-clad steel rods, valued for their simplicity and durability. However, in soils with moderate or high resistivity, a common situation in many regions, a single rod rarely reaches the resistance values recommended by international standards for adequate protection, such as the 5 Ω often targeted for residential environments or even the 25 Ω that some codes allow as a maximum threshold (IEEE, 2000; Myint et al., 2020). To compensate for this limitation, configurations with multiple electrodes or chemical soil treatments are frequently employed, solutions that increase complexity, cost, and, on occasion, environmental impact. As a result, electrical safety becomes a commodity accessible only to those who can afford oversized or chemically treated systems, while families with fewer resources are left exposed to avoidable risks. Recent field surveys in Ghana revealed that over 96 % of residential buildings had earthing resistances above the nationally recommended limit, a situation attributed to both the lack of affordable electrodes and the absence of effective regulation (Nti et al., 2020).

Worldwide, the World Health Organization estimates that a significant fraction of electrical injuries occur in low-income settings where protective measures such as grounding are absent or degraded (WHO, 2018). In Latin America, studies on energy poverty have documented that deficient electrical infrastructure, including inadequate or nonexistent earthing, exposes households to disproportionate risks of electrocution and fire, reinforcing cycles of inequality (Banal-Estañol et al., 2017; González-Eguino, 2015). In sub-Saharan Africa, where over 500 million rural dwellers still lack electricity access, the absence of adequate earthing protection in existing connections amplifies the risk of electrocution and fire (Agyei-Sakyi et al., 2025). Recent epidemiological data from Brazil confirm that residential electrical accidents disproportionately affect low-income households, reinforcing the urgent need for affordable grounding solutions (de Oliveira et al., 2025).

In response to this problem, the present work proposes a prototype grounding electrode designed with two simultaneous criteria: to increase the effective contact area with the soil, thereby reducing electrical resistance and improving current dissipation, and to keep manufacturing and installation costs below those of conventional commercial electrodes. The prototype was built from widely available materials using basic machining processes, so that it can be replicated without depending on expensive industrial technologies. Its performance was experimentally evaluated under controlled field conditions, comparing it directly with a commercial copper-clad steel rod, using the same soil and the same backfill material. In addition to grounding resistance and current-carrying capacity, an economic evaluation was carried out to quantify the cost advantage and discuss its implications for adoption in communities with limited resources.

The remainder of the article is structured as follows: this introduction has set out the context, the social motivation, and the objective of the study, highlighting the financing challenges that keep safe electrical infrastructure out of reach for the hardest-to-reach communities (Pailman et al., 2025). The methodology section describes the prototype design, the installation conditions, and the measurement procedures, highlighting the simplicity and replicability of the setup. The results and discussion present comparative data on resistance, current, and cost, analyzed not only in terms of technical efficiency but also from the perspective of their potential impact on the protection of life and equity in access to electrical safety. Finally, the conclusions synthesize the findings and propose lines of future work aimed at validating the prototype under diverse conditions and exploring its integration into public policies for safe electrical infrastructure. Ultimately, this study seeks to contribute to making an effective grounding system not a privilege, but a basic and affordable component of every home.

MATERIALS AND METHODS

The study was conceived as a direct experimental comparison between a prototype grounding electrode, simultaneously designed for high electrical efficiency and low cost, and a conventional commercial copper-clad steel rod. To ensure transferability to real residential contexts, the soil and installation conditions were selected to be representative of urban and peri-urban zones in developing countries, where electrical safety remains an unresolved challenge.

Design of the prototype electrode

The prototype was built from a copper-chromium-zirconium alloy (C18150), chosen for its high conductivity, corrosion resistance, and availability on the local market. The geometry was designed to maximize the contact area with the soil within the space typical of a domestic installation, without requiring heavy machinery or complex methods.

The base of the electrode consists of a cone made up of two sections. Figure 1 shows the complete assembly and its constituent parts: part (a) presents the whole assembled cone with its components numbered for reference; part (b) shows the hollow conical body formed from a 1.50-mm-thick copper sheet; part (c) displays the solid copper tip machined to a point; and part (d) illustrates the complete cone after both parts were joined by silver brazing, resulting in a piece 9.10 cm in length that facilitates soil penetration and improves current dispersion from the lower end.

Fig 1. Cone-shaped section of the grounding electrode prototype: (a) assembled cone with numbered parts; (b) hollow copper cone; (c) solid copper tip; (d) complete cone after brazing.

The body of the device is made up of four solid copper rods, whose arrangement and final assembly are illustrated in Figure 2. Part (a) shows the three outer rods (1.27 cm in diameter, 51 cm long) arranged in a triangular configuration together with the central rod (2.54 cm in diameter, 50 cm long) that reinforces the structure and enhances contact with the surrounding soil. Parts (b) and (c) present the upper connecting pieces: a central copper connector with three arms brazed to an equilateral triangular plate of 20 cm per side and 1.50 mm thickness. Finally, part (d) depicts the fully assembled prototype electrode.

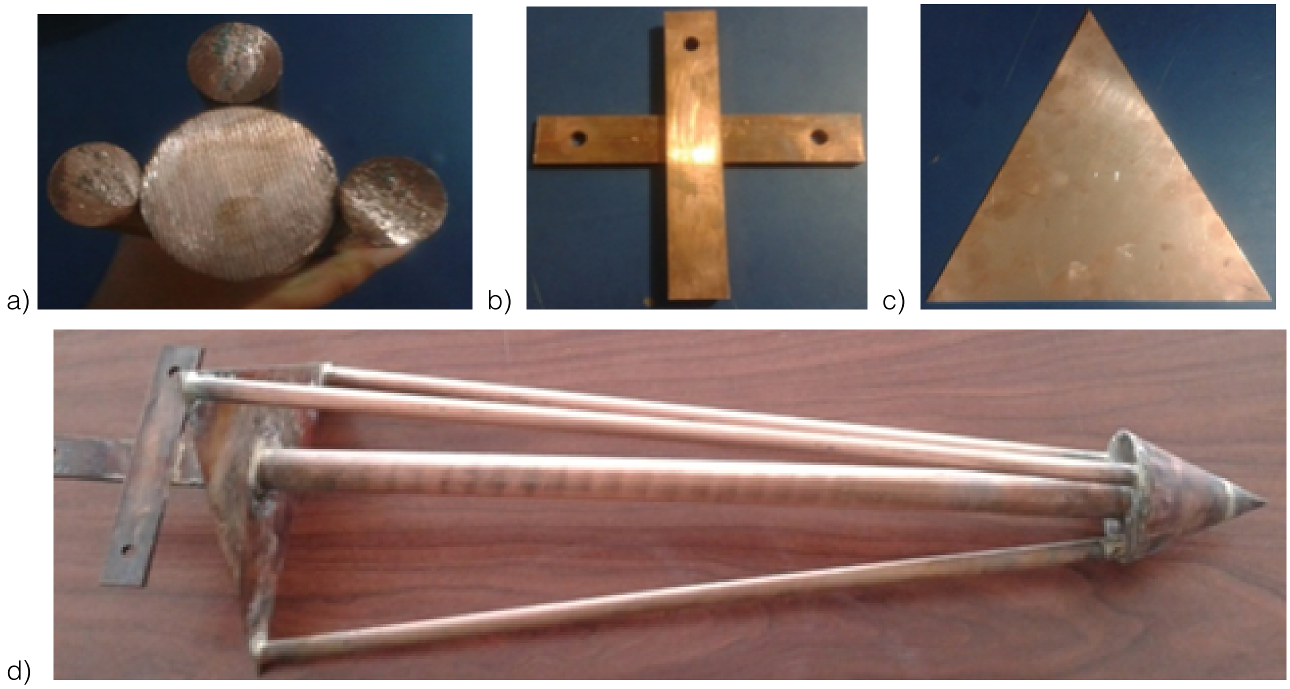

Fig 2. Body and final assembly of the prototype: (a) arrangement of the four solid copper rods; (b) perforated copper connectors and cross-shaped piece; (c) equilateral triangular copper plate; (d) fully assembled prototype electrode.

All components can be fabricated in a basic machine shop without expensive industrial processes, which is essential for eventual adoption in resource-limited settings.

Soil characterisation and resistivity measurement

The test site is an unsaturated clayey soil, a common soil type in residential areas of the region. The apparent resistivity was determined by the Wenner four-electrode method (IEEE, 2012), applying equation (1):

$$\rho = 2\pi a R \tag{1}$$

where ρρ is the soil resistivity (Ω·m), aa is the electrode spacing (m), and RR is the resistance measured between the inner electrodes (Ω). The Wenner four-electrode method is the most widely used technique in the power industry for determining soil resistivity prior to grounding system design, as it provides a reliable average value of the apparent resistivity of the soil volume that will surround the electrode (Lee et al., 2011). The average value obtained was 150 Ω·m, which falls within a range where achieving low grounding resistance typically demands a larger contact area or special backfill (IEEE, 2000, 2012).

Installation and experimental conditions

Both electrodes were installed in separate trenches measuring 0.75 m long, 0.50 m wide, and 1.00 m deep. The trenches were separated by a centre-to-centre distance of 2.20 m, sufficient to eliminate mutual interference during the measurements, as can be seen in the installation diagram of Figure 3.

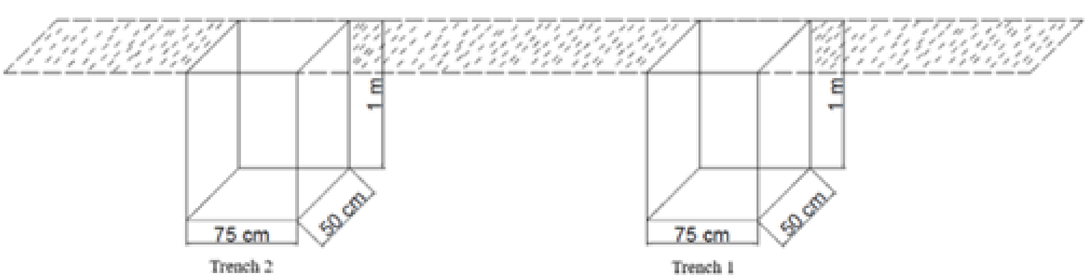

Fig 3. Dimensions of trench for the installation of grounding systems.

The test location was adjacent to a low-voltage electrical substation with a 45 kVA transformer, which allowed both electrodes to be connected to the same reference ground bus and to operate under real service conditions. The layout of the trench relative to the substation is shown in Figure 4, while the electrode installation and its wiring diagram within the trench are detailed in Figure 5.

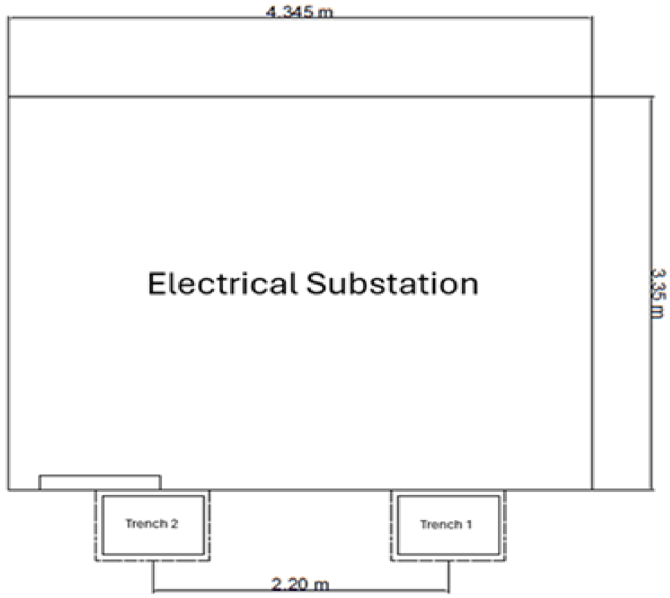

Fig 4. Diagram of installation of trench and electrical substation.

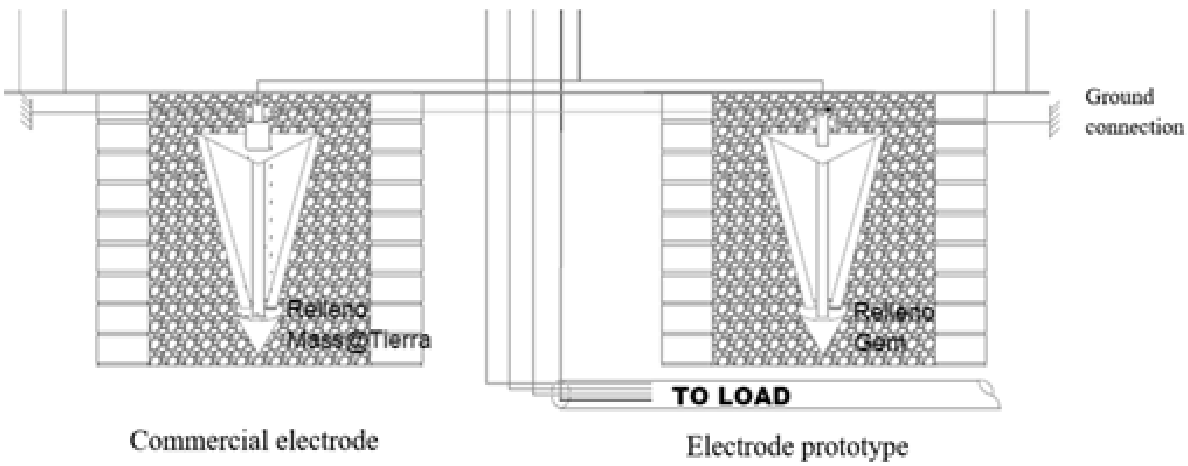

Fig 5. Electrode installation and wiring diagram in trench.

After placing the electrodes, the trenches were backfilled with the same excavated soil and compacted in layers to restore the natural density. No additional chemical compounds were added during installation, so that the comparison would exclusively reflect the design and material differences between the prototype and the commercial electrode. The same backfill material ¨a commercial ground enhancement material (GEM) composed primarily of bentonite and conductive compounds¨ was used in both cases, applied in identical quantity and manner, eliminating any bias caused by soil treatment.

The commercial electrode was connected to the system by means of a copper conductor of adequate gauge, and the prototype received an equivalent connection. The complete electrical connection diagram, including the electrodes, the substation, and the transformer, is presented in Figure 6, guaranteeing that identical electrical conditions were applied to both systems.

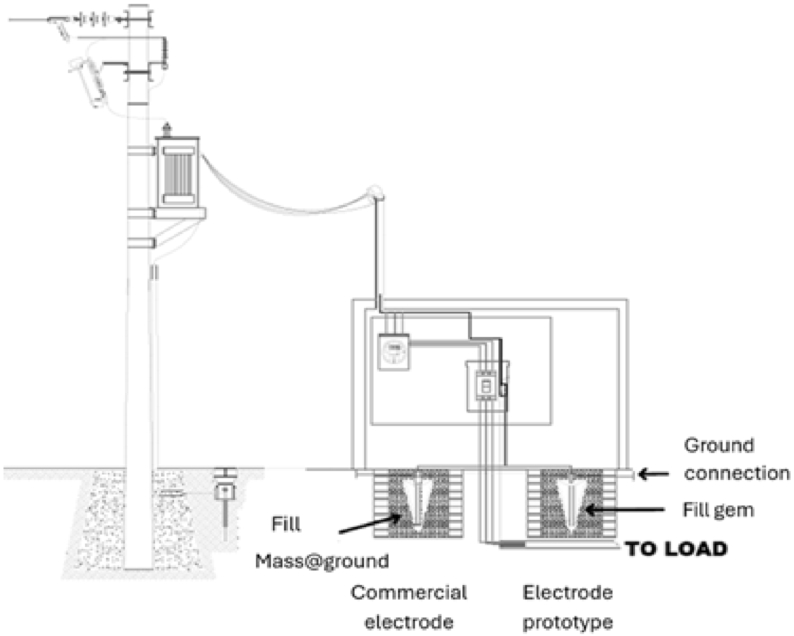

Fig 6. Installation diagram of electrodes, electrical substation and transformer.

The complete installation was carried out by two technicians using common hand tools, without the need for specialised driving equipment or complex field welding, an aspect of great importance for replication in communities with limited technical infrastructure.

Instrumentation and electrical measurements

The grounding resistance was determined by two complementary methods. First, a Fluke 1623 earth-ground tester was used, applying the standard four-point fall-of-potential method, which allows the electrode resistance to be measured without significant influence from the test leads. The measurement setup for this method is illustrated in Figure 7.

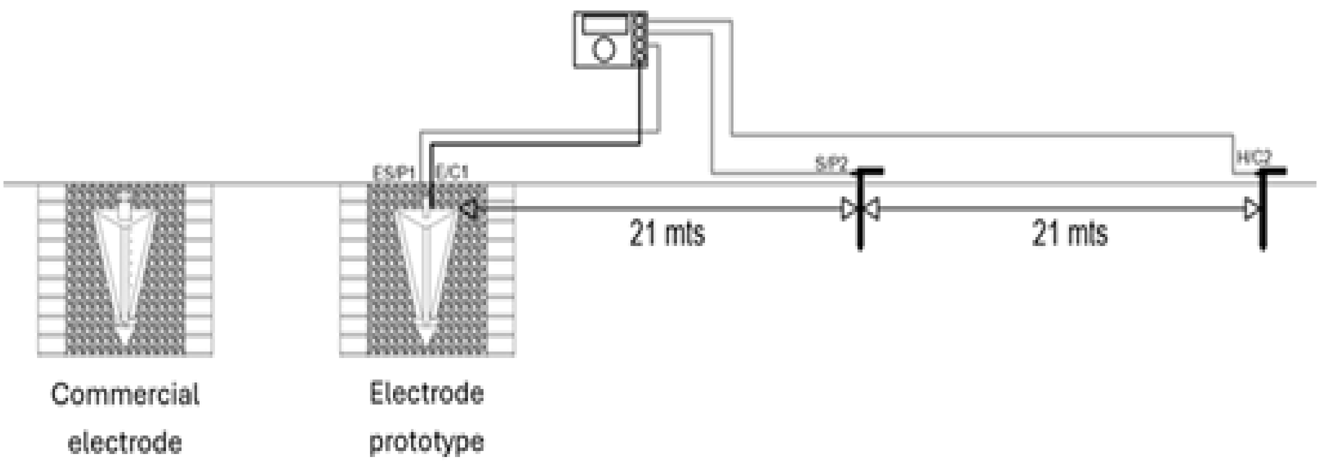

Fig 7. Diagram for measuring 4-pin resistance.

Second, a Fluke 1630 earth ground clamp meter was used in selective mode. This method measures the electrode's resistance without disconnecting it from the system, thereby reflecting operating conditions more accurately. The measurement setup is shown in Figure 8.

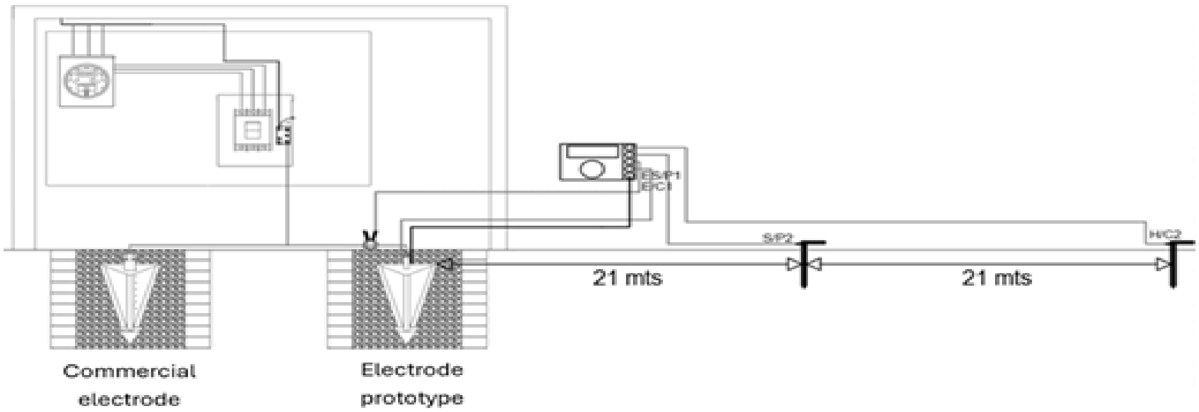

Fig 8. Selective resistance measurement using the clamp meter.

In addition, the current flowing through each electrode during normal installation operation was recorded as an indirect indicator of the earth-leakage capacity. All readings were repeated in different sessions under stable environmental conditions to guarantee repeatability and detect possible deviations. The values obtained were processed to obtain means, ranges, and measurement stability, and were compared directly between the prototype and the commercial electrode, as presented in the Results and Discussion section.

RESULTS AND DISCUSSION

The experimental measurements were carried out in a non-saturated clayey soil with an average apparent resistivity of 150 Ω·m, a value representative of common terrains found in residential and peri-urban areas of Mexico and other regions of Latin America. Both the prototype electrode and the commercial rod were installed under identical conditions and with the same backfill material (GEM), allowing a direct comparison of their electrical performance, economic cost, and social implications.

Grounding resistance and its significance for human safety

Grounding resistance determines the capacity of an earthing system to dissipate fault currents and, consequently, the magnitude of the touch and step voltages that may appear during an electrical contingency. High resistance values translate into a greater probability of dangerous electric shock or failure of protective devices to operate within the required time (IEEE, 2000; Myint et al., 2020).

Figure 9 presents the comparison of grounding resistance between both electrodes, obtained by the standard four-point fall-of-potential method. The prototype electrode recorded values in the range of 5.00–6.09 Ω, whereas the commercial electrode fluctuated between 12.29 and 15.80 Ω.

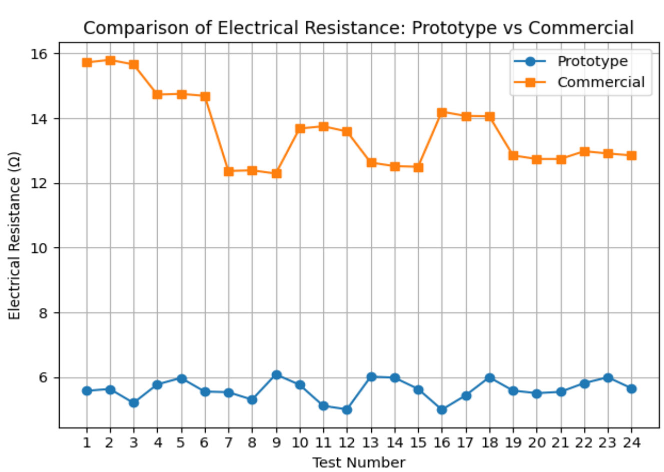

Fig 9. Comparison of electrical resistance for grounding systems using prototype and commercial.

Note: Comparison of grounding resistance obtained by the fall-of-potential method. The prototype's resistance below 6 Ω falls within the range that standards consider safe for residential protection, thereby reducing the probability of dangerous touch voltages

This represents a resistance reduction of approximately 58–62 % in favour of the prototype throughout the test period. Such a reduction has direct implications for the safety of electrical installations. First, a resistance below 10 Ω, and ideally close to 5 Ω, is the target recommended by international standards to guarantee effective protection in residential environments (IEEE, 2000). The prototype achieves this range without supplementary electrodes or aggressive chemical treatments, which the commercial electrode failed to do. Second, lower resistance implies a substantial decrease in the risk of hazardous touch voltages, a critical factor in dwellings where children, older adults, or people without technical training coexist with ageing or precarious electrical installations.

Long-term stability is also relevant for sustained protection. The selective measurements taken with the Fluke 1630 clamp meter, shown in Figure 10, reveal that the prototype maintained values between 5.57 and 5.90 Ω, with a mean of 5.74 Ω and a fluctuation of barely ±0.17 Ω.

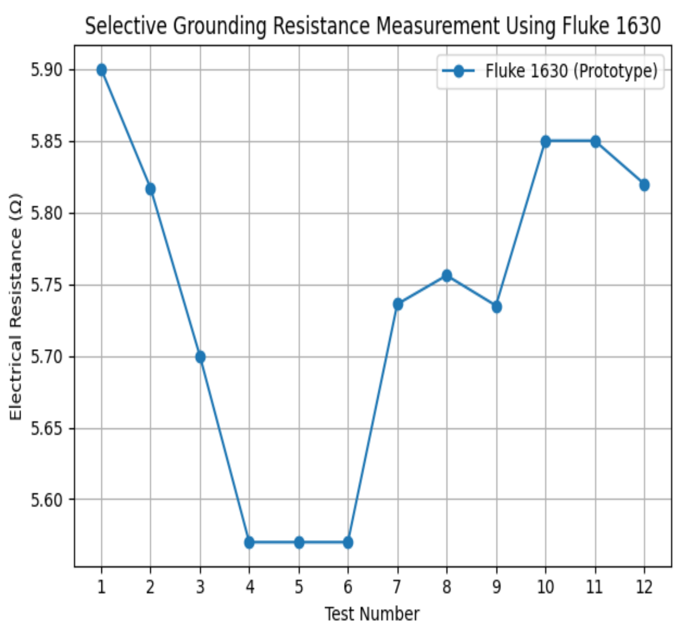

Fig 10. Selective resistance measured with the clamp meter on the prototype.

The commercial electrode, although also stable, exhibited resistances between 11.02 and 11.83 Ω, with a mean around 11.4 Ω, as can be observed in Figure 11.

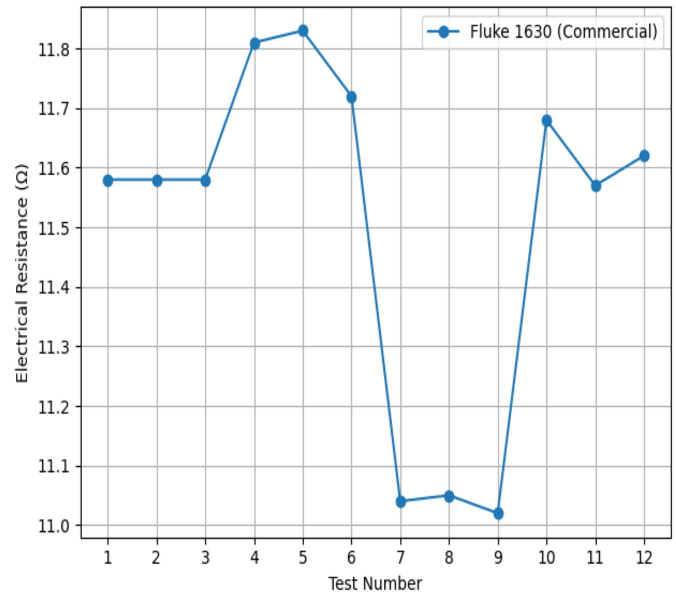

Fig 11. Selective resistance measured with the clamp meter on the commercial electrode.

The lower variability of the prototype suggests a more homogeneous contact with the surrounding soil and a reduced sensitivity to minor environmental changes, which results in more predictable protection over time.

Steady-state leakage current and its implications for fire prevention

The effectiveness of a grounding system is not measured solely by its resistance; an indirect indicator of its future fault-current performance is the steady-state leakage current under normal operation. Because both electrodes were bonded to the same substation ground bus and subjected to the same phase-to-ground voltage, the current flowing through each grounding conductor is inversely proportional to its impedance. A higher steady-state current therefore corresponds to a lower impedance and, equivalently, to a more effective dissipation path. A higher leakage current reflects a lower impedance to earth, meaning that during an actual fault the electrode can divert a larger current safely, thereby reducing the energy dissipated in unintended paths such as metal enclosures or the building wiring.

Figure 12 compares the currents measured in both electrodes. The prototype recorded levels of 129.50 to 159.20 mA, while the commercial electrode reached only 59.19 to 73.11 mA. Consistently, the prototype conducted approximately twice the current of the commercial alternative under the same test conditions.

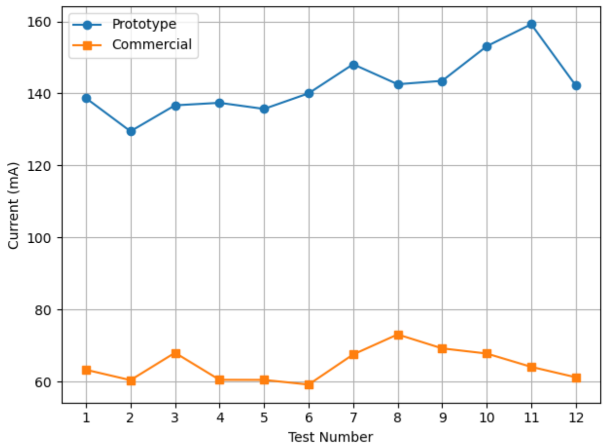

Fig 12. Comparison of electrical current of grounding systems with the prototype vs the commercial one.

Comparison of steady-state leakage current. Higher current through the prototype indicates a lower-impedance path to earth, which facilitates the rapid clearance of faults and helps prevent electrical fires in household installations

This behaviour is particularly significant for electrical fire prevention. A low-impedance path that channels fault current effectively reduces the likelihood of overheating in conductors, faulty connections, or accessible metal parts. In communities where dwellings are built with flammable materials or have unsupervised electrical installations, achieving a lower impedance under normal conditions (as indicated by the higher steady-state leakage current) translates into a greater capacity to handle fault currents safely, which can make the difference between a controlled incident and a catastrophic fire. Moreover, the higher current recorded indicates that the prototype's design makes better use of the contact area with the soil, favouring more uniform dissipation and reducing the formation of localised potential gradients that could endanger people nearby (IEEE, 2000).

Economic assessment and access to electrical safety

Electrical protection cannot be a privilege reserved for those who can afford certified commercial solutions. One of the frequent obstacles to adopting efficient grounding systems in social housing, rural areas, or informal settlements is the cost of materials and specialised installation (Myint et al., 2020). Hence, the economic evaluation of the prototype acquires an immediate social dimension.

The total implementation cost of the system using the prototype electrode was approximately USD 19.40, while the commercial electrode system reached USD 35.77, employing the same backfill technology. The prototype therefore represents 54.2 % of the commercial system's cost, a saving of about 45.8 % for the end user. The cost structure breaks down as follows: the commercial copper-clad steel electrode costs USD 29.50, the ground enhancement material accounts for USD 5.00, and the copper conductor plus connectors add USD 1.27, totalling USD 35.77. In contrast, the prototype electrode costs USD 16.87 for materials and fabrication, the backfill material USD 2.00 (a smaller volume was required due to the electrode's compact geometry), and the conductor and connectors USD 0.53, yielding a total of USD 19.40. The saving is primarily driven by the electrode itself, with the prototype's electrode representing 87.0 % of its system cost, while the commercial electrode accounts for 82.5 % of the corresponding system.

This price difference does not sacrifice performance; on the contrary, it achieves a substantial technical improvement alongside a cost reduction. For a family of medium or low income in a developing country, a saving of more than 45 % on the main component of the grounding system can be decisive in choosing to install it. Likewise, for governmental electrification or housing improvement programmes, adopting an electrode such as the prototype would make it possible to multiply the number of protected households with the same budget. The combination of low cost and high efficiency is, in essence, a factor of social inclusion in electrical safety.

Social and community safety implications

Taken together, the results obtained reveal that the prototype electrode is not merely an incremental engineering improvement but possesses attributes that can positively impact the living conditions of communities. Three dimensions merit special attention:

Protection of human life. The reduction of grounding resistance below 6 Ω, together with a current-carrying capacity approximately double that of the commercial electrode, creates a safer environment for dwelling occupants. In the event of an insulation fault, the current will preferentially flow through the electrode and not through the body of a person touching an energised appliance. The data suggest that the prototype is more effective in limiting dangerous touch voltages in soils of medium resistivity, such as those tested here. Considering that a significant proportion of domestic electrical accidents are related to deficient or non-existent grounding systems (Myint et al., 2020), the availability of a low-cost, high-performance electrode could contribute to reducing these statistics in regions where it is implemented.

Resilience of community infrastructure. Protection is not limited to dwellings; schools, health centres, and small businesses also depend on a reliable earth connection. The stability of the prototype's measurements, together with its reduced cost, makes it viable for installation at multiple points within the same community on a limited budget. In this way, local electrical resilience is strengthened and collective vulnerability to lightning storms or grid fluctuations is reduced. The concept of protective multiple earthing was already proposed decades ago as a way to improve safety in rural areas fed by overhead lines, yet its widespread implementation has been limited precisely because of the cost of effective electrodes; the prototype presented here could help overcome that historical barrier (Spagnolo et al., 2023). An effective grounding system in a school, for example, protects both the students and the computer and communication equipment, whose educational and social value is immeasurable.

Contribution to the Sustainable Development Goals (SDGs). Although larger-scale implementation is still required, the profile of the prototype electrode aligns with multiple global targets. By improving the safety of domestic electrical installations, it contributes to SDG 3 (Good Health and Well-being). By facilitating access to reliable and affordable protection, it supports the construction of resilient infrastructure (SDG 9) and promotes inclusion and the reduction of inequalities (SDG 10), particularly when targeted at rural or marginalised urban communities that currently have deficient protection (United Nations, 2015). Furthermore, its lower cost and the possibility of local manufacturing could foster responsible production and consumption (SDG 12), avoiding dependence on high-priced imported products. Furthermore, the higher leakage current and lower resistance observed in the prototype are consistent with the design principles of cost-effective earthing systems for rural electrification, where every ohm of reduction translates directly into enhanced personal safety (Sander, s.f.)

It is important to note that these results were obtained under controlled conditions and over a limited observation period. The experimental design did not include formal statistical analysis, such as confidence intervals or analysis of variance, that would strengthen the generalizability of the conclusions. Moreover, while the Wenner method employed here is standard for soil characterization (Lee et al., 2011), future work should incorporate seasonal resistivity monitoring to quantify the impact of moisture and temperature variations on the prototype's performance. Likewise, regulatory acceptance and series production are subsequent steps that exceed the scope of this study. Nevertheless, the experimental evidence presented constitutes a solid first step toward proposing a change in the way residential grounding electrodes are conceived, shifting the focus from commercial certification toward social effectiveness.

CONCLUSIONS

This work presents the design, manufacture, and experimental evaluation of a prototype grounding electrode conceived to overcome the technical and economic limitations of conventional commercial rods in low-voltage electrical installations. The results obtained allow conclusions to be drawn that transcend the purely engineering domain and enter the sphere of human safety and collective well-being.

From the standpoint of electrical performance, the prototype achieved a grounding resistance between 5.00 and 6.09 Ω, representing a reduction of 58 % to 62 % compared to the commercial electrode evaluated. This value falls within the range recommended by international standards for effective protection in residential environments and, unlike the commercial electrode, did not require aggressive chemical treatments or supplementary electrodes. In parallel, the prototype showed an approximately twofold higher steady-state leakage current, reflecting a lower-impedance path that facilitates the dissipation of fault currents. Both results translate directly into a reduction of the risk of hazardous touch voltages and, consequently, into greater protection for the people who inhabit or transit the buildings where it is installed.

From a social perspective, the most significant finding is that this substantial improvement in safety is achieved with a cost reduction of approximately 45 % compared to the commercial solution, while using the same backfill material and equivalent installation conditions. This combination of higher efficiency and lower cost makes the prototype an ideal candidate for incorporation into safe electrification programmes, social housing improvement initiatives, and community infrastructure projects in rural or marginalised urban areas. By lowering the economic barrier, access to an essential component of electrical protection, traditionally neglected because of its price or installation complexity, is democratised.

The constructive simplicity of the prototype, which can be manufactured with locally available materials and basic machining processes, favours its adoption in contexts with limited technical or industrial capacity. The installation, carried out by two technicians using common hand tools, proved comparable in complexity to that of a commercial electrode, reinforcing the feasibility of its replication without requiring specialised training or expensive equipment. This characteristic is particularly relevant for communities that depend on self-construction or local electrical maintenance brigades.

The results presented must be interpreted in light of the study's own limitations. The tests were conducted in a single type of soil and over a limited observation period. Furthermore, the experimental design did not include formal statistical analysis (such as confidence intervals or analysis of variance) that would strengthen the generalizability of the conclusions; the reported ranges and means should be taken as indicative trends rather than statistically confirmed effects. Future work should evaluate the prototype across a wider range of soils, under extreme seasonal variations, and over prolonged periods to assess performance stability and long-term corrosion resistance, and should incorporate a rigorous statistical framework to validate the observed differences. Likewise, regulatory acceptance and mass production require additional stages beyond the scope of this work. Nevertheless, the experimental evidence gathered constitutes a solid foundation for advancing in those directions.

In summary, the prototype electrode does not represent merely an incremental technical improvement but rather a commitment to more inclusive electrical safety. By simultaneously reducing grounding resistance, improving the ability to dissipate current, and lowering implementation costs, it emerges as a solution with the potential to contribute to the protection of human life, the resilience of community infrastructure, and the fulfilment of global goals related to health, inequality reduction, and sustainable development. Future work should confirm its performance under diverse real-world conditions and explore strategies for its integration into public policies on electrical safety, so that the benefits observed in the laboratory and the controlled field can materialise in the homes that need them most.

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