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13.8 To 69 kV insulators: a systematic review and applications for Honduras

13.8 to 69 kV Isolators: Systematic Review and Applications for Honduras

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ABSTRACT

In Central America, insulators on 13.8 to 69 kV lines operate under tropical climate, coastal salinity and high lightning activity. We aimed to synthesise published evidence on materials, ageing, mechanical strength, overvoltages and corrosion of these insulators and to derive technical proposals for the Honduran grid. We conducted a systematic review with descriptive synthesis; from about 330 records we screened 104, assessed 59 and included 44 studies published between 2015 and 2026, 11 of them on medium-voltage systems and 19 above 69 kV. In the published evidence, silicone rubber kept hydrophobicity transfer after 36 years of natural exposure, although 110 kV units reached HC5-7 after 26 years in service; raising NSDD from 0.11 to 0.52 mg/cm² cut flashover voltage by a factor of 1.7 to 1.83, and RTV coating raised it by 16.9 %. Separately, two engineering calculations by the author, not validated in the field, gave the minimum creepage distance per IEC TS 60815-1 and, with Rusck's formula, an estimated induced-flashover rate that, in a scenario of Ng = 10 flashes/km²·year, falls from about 41 to 6 per 100 km·year when the CFO rises from 150 to 300 kV. No Honduran studies were found. The recommendations (test-verified silicone, creepage for SPS classes c to d, a CFO of at least 300 kV, sealed hardware and leakage-current monitoring) are therefore proposals conditioned on those parameters that require local validation.

Keywords: outdoor insulators; silicone rubber; pollution flashover; lightning overvoltages; corrosion

ABSTRACT

In Central America, insulators on 13.8 to 69 kV lines work under tropical climate, coastal salinity, and high lightning activity. The objective was to synthesize the published evidence on materials, aging, mechanical resistance, overvoltages, and corrosion of these insulators and to derive technical proposals for the Honduran grid. We conducted a systematic review with descriptive synthesis; out of about 330 records, we screened 104, evaluated 59, and included 44 studies from 2015 to 2026, 11 of them at medium voltage and 19 above 69 kV. In the published evidence, silicone rubber retained hydrophobicity transfer after 36 years outdoors, although 110 kV units with 26 years of service reached HC5-7; raising the NSDD from 0.11 to 0.52 mg/cm² reduced the flame voltage between 1.7 and 1.83 times, and the RTV coating raised it by 16.9%. In addition, two engineering calculations, without field validation, gave the minimum leakage distance according to IEC TS 60815-1 and, with Rusck's formula, an estimated rate of induced flames that, in a scenario of Ng = 10 lightning strikes/km²·year, drops from about 41 to 6 per 100 km·year when the CFO passes from 150 to 300 kV. We did

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not find any Honduran studies. That is why the recommendations (test-verified silicone, leakage for classes SPS c to d, CFO of 300 kV or more, sealed fittings and leakage current monitoring) are proposals conditioned to these parameters that require local validation.

Keywords: outdoor insulators; silicone rubber; pollution flames; atmospheric overvoltages; corrosion

INTRODUCTION

In Honduras, the transmission network totaled about 1,280 km of 230 kV lines, 1,026 km at 138 kV and 694 km at 69 kV in mid-2021, and 34.5 and 13.8 kV distribution circuits come out of their substations (1). The step from 13.8 to 69 kV is the one that touches almost all users. In our search, however, most of the studies dealt with lines of 110 kV or more, and none came from Central America.

We chose the range from 13.8 to 69 kV because it brings together the primary distribution (13.8 and 34.5 kV) and the subtransmission (69 kV) that feeds the country's distribution substations. These are levels that share pole or light tower structures, whose distribution circuits usually lack a guard wire and whose insulation is low compared to lightning-induced voltages. In this band, moreover, the coordination of the insulation is governed by the voltage supported at industrial frequency and the lightning impulse, not by the maneuvering overvoltages that dominate above 245 kV (2). As the literature of this range is scarce, we incorporate studies from 110 to 500 kV only when the mechanism they analyze, be it the chemistry of the silicone, the corrosion of fittings, the mechanics of the core, the response to contamination or the performance of a diagnostic technique, does not depend on the voltage level. Their results are used as evidence of the mechanism and not as values that can simply be transferred to a 13.8 or 69 kV line.

The Honduran environment punishes isolation in three ways at the same time. The Caribbean coast deposits salt on the surfaces, the agricultural and industrial activity of the Sula Valley provides deposits that also reduce the flame tension (3), and the country is among the areas with the most lightning strikes on the planet. NASA's LIS sensor located in San Jerónimo, Honduras, a density of 99.39 discharges/km²·year, next to points in Guatemala that exceed 100 (4).

Between 2015 and 2026, the literature on insulators advanced in directions that do not always converse with each other: silicone rubber chemistry, models of fluttering due to contamination, simulations of induced stresses, corrosion of bolts, artificial vision for drones. What we are looking for here is to put these lines together and read them from a practical question: what configuration, what material, and what design and maintenance criteria have the best support for lines from 13.8 to 69 kV in a tropical, coastal country with a lot of atmospheric electrical activity.

The objective of this work is to synthesize the published evidence on configurations, materials, duration, mechanical resistance, capacity against surges, contamination and corrosion of insulators in this range, complement it with two verifiable engineering calculations and derive from both technical proposals for the Honduran network, distinguishing in each case what comes from the literature, what comes from the calculations and what still requires local validation.

LITERATURE REVIEW

Isolation configurations between 13.8 and 69 kV

At 13.8 kV, the dominant configuration in Latin America is the pin-on-crosshead insulator, with suspension insulators at finials and angles. Lefort and Martinez (5) inspected 11,482 15 and 25 kV spigot isolators in a 61,121 km Brazilian network and showed that detecting degraded units in time reduces service outages. At 34.5 kV, larger spigots, line pole type insulators and short strings coexist. At 69 kV, the practical standard is the disk chain or the long-bar composite insulator, and in compact sections the horizontal pole-type insulator.

The crosshead is part of the insulation, although it is rarely treated as such. A glass fibre reinforced polymer (GFRP) crosshead adds flame distance in series with the insulator; in impulse tests it gave critical flaming gradients of 0.706 kV/mm in positive polarity and 0.794 kV/mm in negative, dry (6). The review by Ahsan et al. reports that insulating crossheads reduced the easement width by between 3 and 5.9 m and increased the flame tolerance of single circuits by 45 % compared to steel crossheads (7).

Materials: porcelain, glass and polymer composites

Porcelain and tempered glass are still in service in much of the Central American network. Its surface is hydrophilic, so that a layer of wet salt immediately forms a conductive film. The composite insulator, on the other hand, separates functions. A GFRP core supports the load, a silicone rubber (SR) enclosure provides the creepage distance, and galvanized steel fittings transmit the stress. The advantage of silicone is that it repels water and transfers this property to the contamination deposited on it, thanks to the migration of low molecular weight chains from inside the material (8,9).

The price of this advantage is a different catalogue of failures. According to CIGRE data collected by Ogbonna et al. (10), 57% of composite insulator failures correspond to core fracture, 28% to interface rupture, 14% to envelope degradation and 1% to fittings. Zeng et al. also cite that skirt aging explains 64% of failures according to CIGRE and IEEE (11). The two figures do not contradict each other, because they describe the final mechanism and the original mechanism; a damaged envelope lets moisture into the core (12).

Table 1 summarizes the differences that the reviewed literature supports with data. We do not include catalog attributes that we do not find measured in corpus studies.

Table 1. Comparison of insulator materials according to the evidence reviewed

Criteria	Porcelain glass	Silicone Composite	Source
Surface	Hydrophilic; forms conductive film with wet salt	Hydrophobic and transfers hydrophobicity to the pollutant layer	(8,9,13)
Aging	Corrosion of hardware; perforation of zero-value units	Loss of hydrophobicity up to HC5-7 in 26 years; Entized	(14,15,16)
Dominant Failure Mode	Bolt Drilling and Corrosion	Core fracture 57%, interface 28%, envelope 14%	(10,17,18)

Criteria	Porcelain glass	Silicone Composite	Source
Lightning Boost	U50 glass up to 4% higher in positive polarity	U50 up to 6% higher in negative polarity	(19)
Mitigation Available	RTV coating: +16.9% flutter voltage	ATH and nanosilica fillers	(20,21,22)

Source: Prepared by the authors based on the studies cited.

Regulatory framework for selecting and coordinating isolation

Four sets of standards order the design. The IEC TS 60815 series classifies site contamination severity (SPS) into five classes, from very light (a) to very high (e), and assigns to each a reference specific unified creepage distance (RUSCD) of 22.0, 27.8, 34.7, 43.3 and 53.7 mm/kV, referring to the phase-to-ground voltage (23,24). IEC 60071-1 sets the standard levels of impulse withstand voltage (2). IEEE 1410 and IEEE 1243 guides address the lightning-borne behavior of distribution and transmission lines (25,26). IEC 61109 and IEC 62217 define the tests of composite and polymeric insulators, and IEC 60587 the inclined plane test for resistance to erosion and the formation of conductive paths (27,28,29).

METHOD

A systematic review of limited scope was developed, with descriptive synthesis and two engineering calculation scenarios. The guiding question was what evidence published between 2015 and 2026 describes the performance of alternating current insulators applicable to lines from 13.8 to 69 kV with respect to materials, aging, mechanical resistance, contamination, surges, corrosion and monitoring. An explicit criterion was adopted for studies of voltages above 69 kV and the published results were distinguished from the own estimates. The retrospective reconstruction of the search process is partial, so the selection flow is communicated with specific reserves.

The original review reported 36 queries made between October 1 and 5, 2026, in English and Spanish, grouped into eight axes. Table 2 shows the main formulations that were preserved. The search was carried out using a general web index used by an artificial intelligence assistant and subsequent verification was carried out on editorial pages (among others, ScienceDirect, MDPI, Springer Nature, SciELO, Redalyc and IEEE Latin America Transactions). No direct searches were performed in Scopus or Web of Science. A complete log that individually associates the 36 queries with their exact dates, engine, filters, URLs, retrieved and duplicate records is not preserved in this document; therefore, it cannot be said that the historical strategy is fully replicable. Supplementary Material A proposes 36 explicit strings for a new execution and presents a record format; These strings constitute a replication strategy, not a retrospective certification of the searches carried out.

Table 2. Main search strategies by thematic axis

Thematic axis	Main Chains (English and Spanish)	Filters applied
Materials and ageing	"silicone rubber" AND insulator AND (ageing OR aging OR hydrophobicity); "composite insulator" AND "field aged"; "aislador polimérico" AND envejecimiento	2015-2026; peer-reviewed; CA
Contamination and surface discharge	"pollution flashover" AND (ESDD OR NSDD) AND insulator; insulator AND contamination AND (coastal OR agricultural)	2015-2026; peer-reviewed; CA
Surges and lightning	"lightning induced overvoltage" AND "distribution line"; "critical flashover" AND "pin insulator"; "surge arrester" AND lightning AND line; "sobretensiones atmosféricas" AND "líneas de distribución"	2015-2026; peer-reviewed; CA
Mechanics and fracture	"composite insulator" AND ("brittle fracture" OR "core rod" OR "mechanical load" OR fatigue)	2015-2026; Peer-reviewed
Corrosion of fittings	"pin corrosion" AND insulator; "galvanized" AND bolt AND marine AND corrosion	2015-2026; peer-reviewed; CA
Monitoring and artificial intelligence	"leakage current" AND insulator AND ("machine learning" OR "deep learning"); "insulator defect detection" AND UAV; insulator AND (ultraviolet OR infrared) AND detection	2015-2026; Peer-reviewed
Coatings, Field & Design	"RTV coating" AND porcelain; "superhydrophobic coating" AND insulator; "insulated cross-arm"; "corona ring" AND "composite insulator"	2015-2026; Peer-reviewed
Regional context	isolators AND (Honduras OR Central America OR Brazil); "lightning hotspots"; "transmission network" AND Honduras	No type restriction; used as context

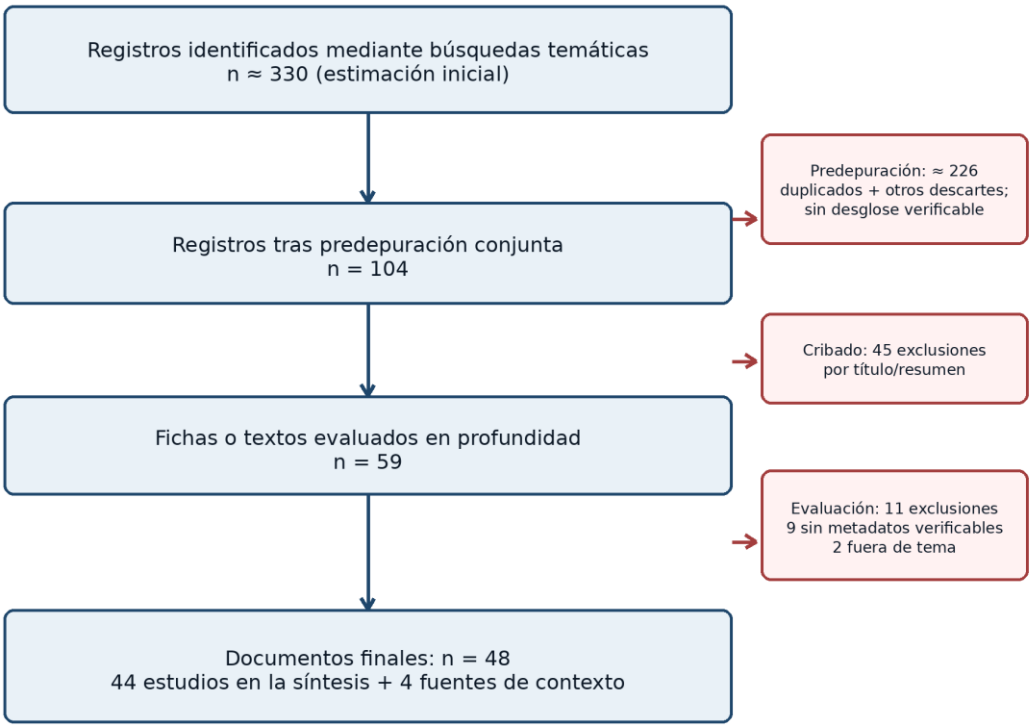
Note. AC: alternating current. The main strings in the revised version are presented. Supplementary Material A develops a replication strategy of 36 strings with log fields that must be completed when the search is run again. The full execution history of the original queries is not available. Source: Authors.

We included peer-reviewed articles, published between 2015 and 2026, with experimental, field, simulation or review data applicable to alternating current insulators and with metadata verifiable on the journal website. We excluded direct current works without transfer to the alternate case, business notes, popular articles and records whose bibliographic file we could not open. A study done above

69 kV entered only if it met two conditions: that the mechanism studied was specific to the material or component and not to the voltage level (silicone aging, bolt corrosion, core fracture, response to contamination or performance of a diagnostic technique) and that it reported the test or service conditions in sufficient detail to judge its transfer. The three studies of overvoltages above 69 kV (19,30,31) were admitted for another reason: they compare materials or protection schemes, and of them we use the relative difference, not the absolute value. Two studies prior to 2015 are cited as methodological background and are left out of the synthesis (5,9).

The historical count recorded approximately 330 records located in the queries and 104 records after a joint pre-purification of duplicates, commercial sources and dissemination materials (Figure 1). The reduction, close to 226 records, can NOT be attributed exclusively to duplicates: the preserved record does not break down the causes or establish the exact number of initial identifications. Of the 104 titles and abstracts reviewed, 45 were excluded due to lack of relevance or transferability, leaving 59 files or texts examined in depth. Another 11 were excluded: two because they were off-topic and nine because it was not possible to verify their metadata in the editorial source. The final count of the file was 48 documents: 44 studies integrated into the synthesis and four context sources. These quantities are counts reported by the original process; they do not constitute a fully auditable PRISMA flow without the original exports and exclusion records.

Figure 1. Descriptive diagram of the reported selection process (partial reconstruction; does not equate to a fully verifiable PRISMA flow).



Note. The initial figure is approximate; the pre-purge grouped duplicates and other types of exclusion without disaggregated registration. The figure adopts the PRISMA 2020 presentation structure, but does not allow a complete audit of the identification phases. Source: Authors.

Pending audit of the flow: Preserving the export by query, a deduplication key (DOI/title), the individual reason for exclusion, and the full-text record is required to convert this retrospective schema into a verifiable PRISMA 2020. Supplementary Material A provides a protocol and logsheet to execute that update without confusing it with the historical account.

Data extraction was carried out by a single reviewer, with the editorial and bibliographic support stated at the end of the article. For each reference, authors, year, journal, method, and source of the result were noted; nominal voltage or type of material; test, service, or calculation conditions; response variable; and main result. Table 3 classifies the 44 studies by their evidentiary function: MV (6.6–35 kV), HV (more than 69 kV or transmission without a specific level), M (material or component without applicable voltage), and V (various voltages). This classification is exclusive for the count and does not convert the results obtained in HV or in specimens into numerical recommendations for the levels of 13.8, 34.5, or 69 kV.

In order not to count the same evidence twice, the four corpus reviews (7,10,11,32) were used only for data that do not appear in the included primary studies, such as CIGRE and IEEE failure statistics or the coastal aging outcomes they summarize. When a finding was available in a primary corpus study, we cited the primary, and no value from the quantitative synthesis (Figure 5) comes from a review.

A critical characterization of the 44 documents was carried out using five fields scored from 0 to 2: clarity of the objective, description of the method, detail of the study conditions, transparency of the result and reasoned applicability to the 13.8–69 kV problem. For experiments, the test protocol and its repeatability were examined; for field studies, environmental conditions, duration and provenance of records; for simulations, hypotheses, inputs and sensitivity analyses; for machine learning, data partitioning, validation and metrics; and for reviews, the scope and traceability of sources. When a criterion was not directly comparable between designs, the transparency of homologous information was evaluated and rigorous equivalence between methods was not assumed. The final column of Table 3 retains the descriptive score 0–10 originally recorded, without calling it "high/medium quality" or using it as a validated risk of bias scale. There are no two independent evaluators or a psychometrically validated instrument to combine such different designs; therefore, the scores guide the reading and do not establish statistical hierarchies or replace a specialized assessment with design.

The matrix distinguishes five families of evidence: (i) laboratory, verifying material, instruments, repetitions, and conditions; (ii) field, identifying place, age, exposure, measurement, and possible selection bias; (iii) calculation/simulation, assessing definition of borders, parameters, and sensitivity checking; (iv) data-based prediction, considering training-test partition, external validation, and metrics; and (v) reviews, examining selection transparency and primary sources. A score of eight in a review is not methodologically comparable to eight in an essay; for this reason, no means are made between classes and the sum is not called a reliability scale.

Meta-analyses were not performed because the investigations combined experimental results, field studies, numerical models, machine learning, and reviews, and ranged from 6.6 to 500 kV, with non-

equivalent materials and protocols. The magnitudes of flaming, corrosion, mechanical strength, and predictive accuracy do not share a single estimate. Quantitative synthesis is limited to effects or variations reported within each investigation; their stress and test condition are made explicit and treating TA studies, materials, and MT as directly comparable populations is avoided. Secondary reviews were not counted as independent observations of primary outcomes.

Two reproducible engineering calculations were performed, separate from the published data and without validation in the Honduran grid. The first applies IEC TS 60815-1 to nominal voltages of 13.8, 34.5 and 69 kV. In Equation (1), Lmin is the reference creepage distance (mm), RUSCD is expressed in mm/kV, Um corresponds to the maximum operating voltage (14.49, 36.23 and 72.5 kV), and Ka is dimensionless (1 is assumed). The division by √3 converts the voltage between phases to phase-ground; the results are reference values subject to the contamination class and the relevant design corrections. They do not constitute a universal purchase requirement (23,33).

$$L_{\text{mín}} = \text{RUSCD} \cdot \frac{U_m}{\sqrt{3}} \cdot K_a \qquad (1)$$

The second calculation estimates the overvoltage induced by a discharge at lateral and line distance. Rusck's formulation presented in Equations (2) and (3) was used, with Z_o = 30 Ω, peak current I_o in kA, height h = 10 m, distance y in m, return velocity v = 1.2 × 10^8 m/s and c = 3.0 × 10^8 m/s (26). With this convention, Ω × kA produces kV; the dimensionless factor kV is approximately 1.295. The hypothesis simplifies the line geometry and does not consider local grounding conditions or detailed propagation.

$$V_{\text{máx}} = \frac{Z_0\, I_0\, h}{y}\, k_v \qquad (2)$$

$$k_v = 1 + \frac{1}{\sqrt{2}}\,\frac{v}{c}\,\frac{1}{\sqrt{1 - \frac{1}{2}\left(\frac{v}{c}\right)^2}} \qquad (3)$$

The survival function P(I ≥ i) of Equation (4) was adopted for the first discharge, with i and I expressed in kA, median of 31 kA and density f(I) = −dP(I ≥ i)/di (in kA^{-1}). A discharge can produce induced flutter when its point of impact is outside the radius of attraction Ra and within the critical distance yc of Equation (5); the illustrative threshold Vmax ≥ 1.5 × CFO is assumed. This threshold is a modeling decision and must be contrasted with the actual coordination of the isolation.

$$P(I \geq i) = \frac{1}{1 + \left(\frac{i}{31}\right)^{2.6}}, \quad f(I) = -\frac{dP}{dI} \qquad (4)$$

$$y_c(I) = \frac{Z_0\, I\, h\, k_v}{1.5 \cdot CFO} \qquad (5)$$

For the radius of attraction Ra (m) and the estimation of direct impacts Nd, Eriksson's expressions from Equation (6) were used, assuming b = 0 m and h = 10 m, which yields Ra ≈ 55.7 m. In Equation (7), Ng is expressed in discharges/km²·year, L = 100 km and the effective width [yc(I) − Ra] is converted from meters to kilometers before integrating it with respect to f(I). Factor 2 considers the two sides of the line. Numerical integration was evaluated between 1 and 200 kA with a pitch of 0.05 kA; the bounded domain excludes the extreme contribution outside that range. The Nind result is interpreted

as induced flamings per 100 km·year under the declared parameters, without extrapolating it to an observed rate of the network.

$$R_a = 14\,h^{0.6}, \quad N_d = N_g \frac{28\,h^{0.6} + b}{10} \quad (6)$$

$$N_{\text{ind}} = 2\,N_g\,L \int_0^{\infty} \text{máx}(0, y_c(I) - R_a)\,f(I)\,\text{d}I \quad (7)$$

Dimensional and numerical control of equations. In (1): (mm/kV) × kV × Ka = mm. In (2): Ω × kA × (m/m) = kV. In (4), f(I) is expressed in kA^{-1} and its integral is dimensionless. In (5) and (6), yc and Ra are in meters and are converted to kilometers before applying (7). As a control, v/c = 0.4 produces kv = 1.2949; with h = 10 m Ra = 55.735 m is obtained. For Ng = 1 and CFO of 150 and 300 kV, the numerical sum of (7) produces, respectively, 4.066 and 0.630 flutters per 100 km·year (rounded in the text). The verification confirms internal arithmetic consistency of the scenario, not physical validation on a network.

RESULTS

The results are presented without confusing three sources of knowledge: laboratory and field observations from the selected publications, results obtained through modeling or machine learning by their authors, and two scenarios calculated in this article. Four categories are expressly identified in the comparisons: MV, medium voltage from 6.6 to 35 kV (11 studies); HV, more than 69 kV or transmission without a declared level (19); M, materials or components without defined voltage (10); and V, various voltages (4). This segmentation conditions the transferability of any figure to 13.8, 34.5 or 69 kV.

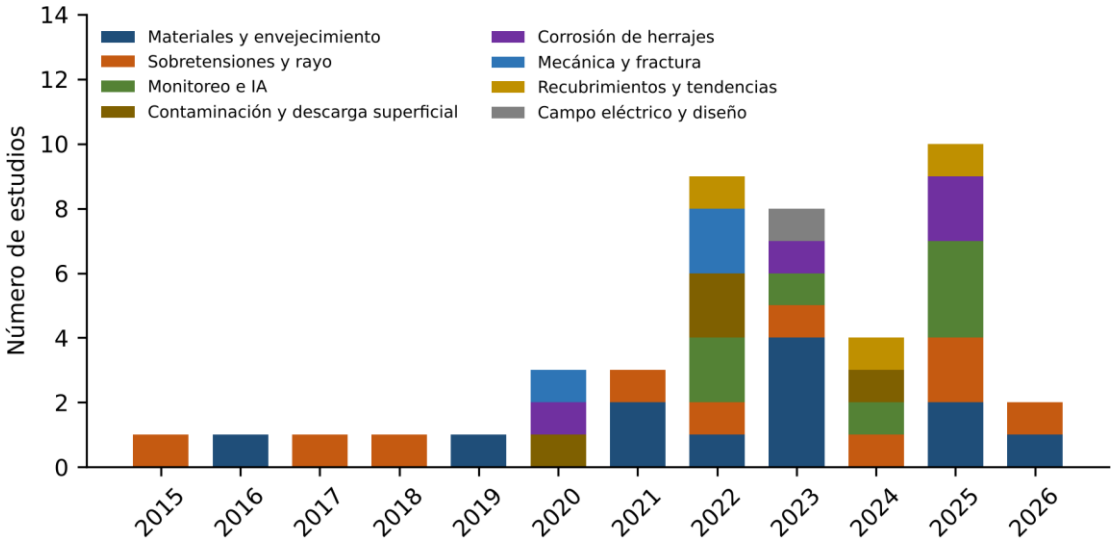
Characterization of the corpus

The 44 studies are divided into eight themes: materials and aging (12), surges and lightning (10), monitoring and artificial intelligence (7), contamination and surface discharge (4), hardware corrosion (4), mechanics and fracture (3), coatings and trends (3) and electric field (1). Production is concentrated in 2022 (9 studies), 2023 (8) and 2025 (10). By method, 15 are laboratory experimental, 9 use field data, 6 apply machine learning, 5 combine experiment and simulation, 5 are pure simulations and 4 are reviews (Figure 2).

The distribution of the 44 studies was as follows: 11 MV (6.6–35 kV), 19 HV (more than 69 kV or transmission without declared level), 10 M (materials or components), and 4 V (various voltages). No research in the corpus directly evaluated a 69 kV Honduran circuit. The MV studies report more directly on some mechanisms of contamination and overvoltage, while the HV studies mainly provide observations of aging, corrosion, and diagnosis whose transfer requires controlling geometry, electric field, creepage distance, and environment. In the original descriptive matrix, 36 publications registered between 9 and 10 points and eight registered 7–8 points. This concentration of scores is a result of the rubric used, not proof that 36 papers have "high methodological quality" or that the instrument adequately discriminates different designs.

To preserve this distinction, any subsequent numerical comparison should be read with their population of origin. MT studies have greater proximity to electrical level, but do not necessarily replicate Honduran rainfall, salinity, or topology; HV studies report material and diagnostic phenomena without automatically setting leakage lengths, CFO values, or ring dimensions at lower voltages. M and V studies support hypotheses about behavior, not closed line configurations.

Figure 2. Studies included by year of publication and topic.



Source: Prepared by the authors based on Table 3 (n = 44).

Only three studies in the synthesis use Latin American data, all from Brazil (31,34,35), to which is added the precedent of Lefort and Martinez (5). We found no published studies on insulators in networks in Honduras, Guatemala, El Salvador or Nicaragua. Table 3 lists each study with its type, voltage level, main conditions, quantitative finding and quality score.

Table 3. Studies included in the synthesis (n = 44)

Study	Theme	Type	Tension	Main conditions	Main quantitative finding	Pts.
Abd Rahman et al. (6)	Surges	Exp + sim	GFRP D-pad (M)	Lightning boost ±; dry and rainy	Rain reduces CFO 9.6-30.5%	10
Ahmad et al. (20)	Materials	Experience	Material (M)	Nano-SiO2 and micro-Al2O3 fillers; electrical, mechanical and thermal tests	4% nano-SiO2: stiffness +23.83%	10
Ahmed et al. (30)	Surges	Sim	132-275 kV (HV)	Line arrester selection protocol; dissipated energy	MCIA -74% energy vs NGLA (132 kV)	9
Ahsan et al. (7)	Coatings	Rev	Transm. (AT)	Historical review of insulating crossheads	Insulating spacers: +45% tolerance	7

Study	Theme	Type	Tension	Main conditions	Main quantitative finding	Pts.
Bielecki y Wańkowicz (36)	Mechanics	Experience	Transm. (AT)	Fatigue at 33.3-40% of 120 kN SML; 35-year unit	35 years: -30 to -40% resistance	9
Chen et al. (17)	AI Monitoring	Exp + Yes	Transm. (AT)	Porcelain IR thermography with variable humidity and contamination	More sensitive IR with moisture and contamination	8
Da et al. (37)	AI Monitoring	AA + field	15 kV (MT)	HDPE insulator leakage current; Taiwan coast	MAE -52.57%	10
Daniel et al. (38)	Corrosion	Field	Bolts (M)	Galvanized bolts 50 m from the coast of Hainan; 6 to 24 months	Zinc < 1% on surfaces exposed to 24 months	10
by Santos and Sanz-Bobi (39)	AI Monitoring	AA + field	245 kV (HV)	Coastal substation, France; pollution events	F 0.757-0.792	9
de Vasconcellos et al. (31)	Surges	Sim	138 kV (HV)	Partial protection with lightning rod; frequency-dependent grounding	Efficient partial protection	8
Dong et al. (40)	Surges	Experience	35 kV (MT)	Impulse in chains with zero-value units; mountainous area	5 mm needle: +30% margin	10
Faiza et al. (41)	Materials	Experience	Material (M)	28 cycles of acid rain, heat, humidity, UV and salt spray	5% nano-SiO2 stable after 28 cycles	9
Fofana et al. (42)	Pollution	Field	13.2 kV (MT)	7 ceramic insulators from an aluminum plant	ESDD up to 0.2125 mg/cm2	10
Ghaly et al. (43)	Pollution	Experience	Transm. (AT)	Central composite design: temperature, humidity and pressure	R2 0.996; FOV 120 at 106 kV with T	9
Khajavi et al. (44)	Electric field	Sim	230 kV (HV)	Finite elements with tower, conductor, fittings and phases	Límites 0.42/0.35/1.8 kV/mm	9
Khatoon et al. (3)	Pollution	Experience	Transm. (AT)	Agricultural and biological pollutants; RH up to more than 85%	Agricultural pollutants - 16% FOV	9
Kim et al. (14)	Corrosion	Field + exp	Transm. (AT)	Korea Industrial Zone; pH Rainfall 4.81-5.69	Life 56 years with 75 um of zinc (industrial)	9
Kong et al. (45)	Coatings	Experience	Material (M)	Superhydrophobic coating; icing test	Angle > 150°; Ice Delay x14	10

Study	Theme	Type	Tension	Main conditions	Main quantitative finding	Pts.
Liu et al. (46)	Materials	Experience	Material (M)	500 h AC crown; flaming measured in DC	FOV DC drop: SR 31%; CEP 34%; GFRP 41%	10
Mahmood et al. (47)	Surges	Exp + sim	24 kV (MT)	AC voltage plus induced overvoltage on ground with losses	High risk with resistivity > 3000 ohm-m	10
Mavrikakis et al. (13)	Materials	Field + exp	Transm. (AT)	Units with 17 years of coastal service	Useful transfer after 17 years on the coast	8
Mikropoulos y Tsouris (48)	Surges	Experience	24 kV (MT)	Negative Impulse; ANSI 56-1 & 56-2 Spikes	CFO- 187.6-232.2 kV	10
Mitrovic et al. (49)	AI Monitoring	AA	Miscellaneous (V)	Leakage current measurements; wet or dry condition	F1 > 98%; RMSE 1.16%	10
Mu et al. (15)	Materials	Field	110 kV (HV)	Units retired at 0, 10, 20 and 26 years old	26 years: HC5-7	9
Nandi & Reddy (12)	Mechanics	XP + Field	Transm. (AT)	Water ingress through the core-envelope interface; 2,000 h	Fuga 10 to 50 mA in 2000 h	9
Ogbonna et al. (10)	Mechanics	Rev	Transm. (AT)	Core failure analysis; CIGRE data	Core 57%; Interface 28%; Envelope 14%; Hardware 1%	7
Qiao et al. (32)	Materials	Rev	Miscellaneous (V)	Ageing by environment and region	Coast 5 years: HC5-7 exposed vs HC2-3 protected	8
Rao (50)	Materials	Field	11 kV (MT)	Marine environment; 2 and 3 year old units	Oxidation and loss of hydrophobicity on the coast	9
Raza et al. (21)	Materials	Experience	Material (M)	70°C and 80% RH for 120 h	15% ATH better performance	10
Rodrigues et al. (51)	AI Monitoring	AA (UV)	500 kV (HV)	Ultraviolet images in substation	Detection 85.5%	9
Salem et al. (22)	Coatings	Exp + AA	22 kV (MT)	Porcelain with RTV under different profiles and levels of contamination	Full RTV +16.9% FOV; escape -52.33%	10
Shigihara et al. (34)	Surges	Experience	15 kV (MT)	Low-amplitude non-normalized impulses	Voltage-time curves	9
Slama et al. (52)	Pollution	Experience	Distrib. (MT)	ESDD 0.12-1.0 the NSDD 0.11-0.52 mg/cm2; flameo AC	NSDD 0.11 to 0.52 mg/cm2 reduces FOV 1.7-1.83 times	10

Study	Theme	Type	Tension	Main conditions	Main quantitative finding	Pts.
Wang et al. (16)	Materials	Field	Material (M)	36 years of natural exposure	Hydrophobicity transfer at 36 years	9
Werneck et al. (35)	AI Monitoring	Field	500 kV (HV)	Optical sensor for 3 years; leakage current and climate	Leakage 10 to 70 mA; dew point	9
Yamanaka y Ishimoto (53)	Surges	Sim	6.6 kV (MT)	LEMP; lightning rod spacing and soil resistivity	Relevant LEMP with spaced arresters and low resistive soil	9
Yu et al. (54)	Surges	Sim	10 kV (MT)	Indirect lightning; U50 spigot = 170 kV	Lightning rod every 200-300 m; U50 170 kV insulator	10
S. Zeng et al. (55)	Materials	Experience	Material (M)	Multi-factor ageing with 70°C thermal cycling	Elongation - 24.1%	10
Z. Zeng et al. (11)	Materials	Rev	Miscellaneous (V)	Methods of assessing ageing	Skirt aging = 64% of composite failures (CIGRE/IEEE)	8
Zhang, Zheng, et al. (18)	Corrosion	Exp + sim	Transm. (AT)	Semiconductor coating of 2 mm or more on the base of the bolt	Semiconductor coating 500 at 5 A/m2	9
Zhang, Zhong, et al. (56)	Corrosion	Experience	Transm. (AT)	Salt spray plus leakage current (multi-stress)	Synergy salt + leakage current	8
Zhang et al. (19)	Surges	Exp + sim	110 kV (HV)	Dual-circuit tower lightning boost	Glass vs composite: 4-6%	9
Zheng et al. (57)	AI Monitoring	AA (vision)	Miscellaneous (V)	Drone Images	mAP50 91.2%; 78 FPS	10
Zhu (8)	Materials	Experience	Material (M)	Corona discharge; hydrophobicity recovery	LMW Migration Recovery	9

Note. Type: Exp, experimental; Sim, numerical modeling; AA, machine learning; Rev, review; Field, service observation. FOV: flutter voltage; HC: hydrophobicity class. Voltage: MV, medium voltage (6.6–35 kV); HV, >69 kV or transmission without declared level; M, material/component; V, various voltages. Indicator: descriptive score 0–10 according to transparency and applicability; it is not a validated methodological quality scale or a formal risk of bias assessment. Source: Authors.

Table 3 allows the voltage and design group of each publication to be audited. For conclusions directed at 13.8, 34.5 and 69 kV, values from HV, M or V are cited only to discuss mechanisms or conditioned trends; their quantitative extrapolation is subject to testing and local coordination.

Ageing and durability of materials

The data with the longest time horizon comes from Wang et al., who exposed silicone rubber to the elements for 36 years. The material maintained excellent hydrophobicity during the first decade, retained the ability to transfer it at the end of the period and its resistance to erosion remained above the regulatory requirement; the main damage was a superficial entity (16). Mu et al., with 110 kV insulators removed after 0, 10, 20 and 26 years, found another side. At 26 years of age, the skirts had gone from HC1 to HC5-7, the hardness rose continuously and the deterioration was greater at the high voltage end, where the electric field is more intense (15).

The apparent contradiction is explained by the formulation and by the electrical stress. Wang et al. note that their result applies to a silicone with a selected formula and process (16); Mu et al. evaluated commercial units subjected to real field and contamination (15). On the coast, Qiao et al. report that after five years the sun-exposed surfaces fell to HC5-7 while the protected ones remained at HC2-3 (32), and Mavrikakis et al. measured transfer of hydrophobicity still useful in units with 17 years of coastal service (13). With the exception of Rao (50), at 11 kV, the field data on aging come from lines of 110 kV or more or from specimens, so that their transfer to 13.8 kV assumes equal degradation mechanisms under a lower electrical stress.

Thermal cycling accelerates the process. Zeng et al. observed, with differences of 70 °C between extremes, a 24.1 % drop in elongation at break of HTV silicone, comparable to the 25 % loss of strength measured after seven years in the field (55). In 11 kV insulators in the marine environment, Rao (50) identified silica oxidation, oligomer formation and increased hardness as causes of failures, in units of two and three years of service, one of them with biological growth.

Filler fillers change the response. Raza et al. recommended 15% alumina trihydrate (ATH) after subjecting compounds to 70 °C and 80 % humidity for 120 h (21). Ahmad et al. measured a dielectric strength of 23.9 kV/mm with 4% nanosilica and 20% microalumina, 23.83% higher than uncharged silicone (19.3 kV/mm) (20), and Faiza et al. found that the compound with 5% nanosilica retained its dielectric properties after 28 cycles of acid rain, heat, humidity, UV, and salt spray (41). Cycloaliphatic epoxy resin (CEP) appeared as an alternative for rigid parts, since after 500 h of corona it lost 34 % of the flaming tension in continuous, compared to 31 % for silicone and 41 % for GFRP (46).

Mechanical resistance

Three studies address mechanics. Bielecki and Wańkowicz fatigue tested long-bar models with a specified mechanical load (SML) of 120 kN that broke static at 177 kN. With an average load of 33.3 % of the SML and cyclic amplitude of no more than 5 %, they estimated 45 years without failure; at 40 % of the SML the amplitude would have to be limited to 3 %. A first-generation unit retired after 35 years broke at 92 kN, between 30 % and 40 % below its original strength (36).

In-service fractures are rarely pure mechanical. Ogbonna et al. distinguish brittle fracture due to stress corrosion, initiated by nitric acid entering through the fitting, decomposition-type fracture, with chalk-like residues, and interface defects (10). Nandi and Reddy (12) reproduced in the laboratory the

inflow of water through the core-envelope interface and measured how the leakage current rose from about 10 mA to 50 mA in 2,000 h, with the same chemical pattern as the field-failed parts.

Contamination and surface discharge

Slama et al. quantified the weight of insoluble contamination. With ESDD of 0.12, 0.38, and 1.0 mg/cm², raising the NSDD from 0.11 to 0.52 mg/cm² reduced the flaming stress of silicone by 1.7 to 1.83 times, and the ratio followed the power law of Equation (8), whose coefficients α and β depend on NSDD (52).

VFO = αNSDD · ESDDβNSDD(8)

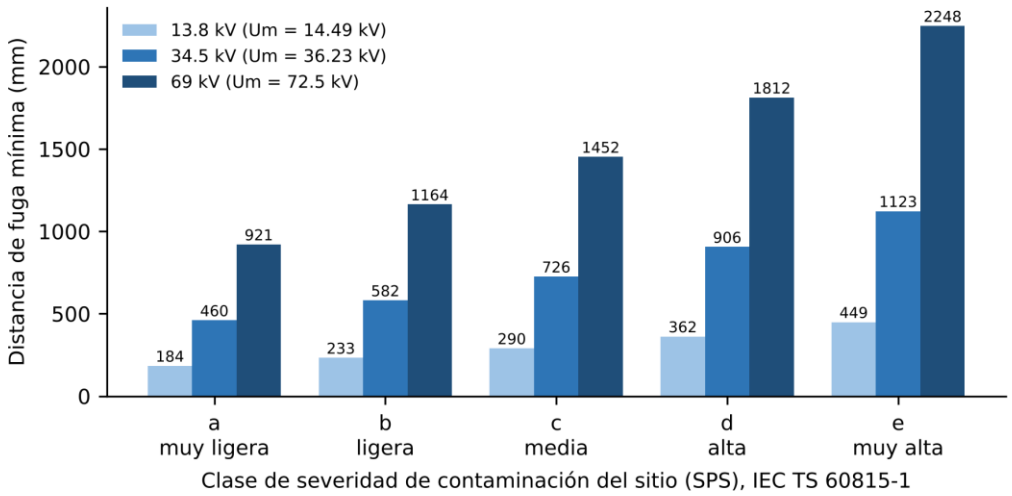
Khatoon et al. measured drops of up to 16% with agricultural pollutants and a sharp drop above 85% relative humidity; their model with ESDD, NSDD, pressure, and humidity reached $R^2 = 0.965$ (3). Ghaly et al. fitted a model with $R^2 = 0.996$ in which temperature brought the flaming voltage from 120 to 106 kV (43).

One distribution case deserves attention. Fofana et al. removed seven 13.2 kV ceramic insulators from an aluminum plant and measured ESDD between 0.0010 and 0.2125 mg/cm² and NSDD between 0.0098 and 5.02 mg/cm²; four of the seven exceeded the site design class (42). Site classification was done once, when building, and no one reviewed it afterwards.

Own calculation: minimum creepage distance (regulatory scenario)

This section applies IEC TS 60815-1 and Equation (1) to three service voltages as a pre-dimensioning exercise (Figure 3), not as a test of Honduran lines. For SPS class c, the reference creepage distance was 290 mm at 13.8 kV, 726 mm at 34.5 kV and 1,452 mm at 69 kV; for SPS e, 449, 1,123 and 2,248 mm. Table 4 distinguishes the maximum voltage used in the calculation of the normalized voltage for insulation coordination (2,33). The classification of the site should be based on representative measurements of ESDD and NSDD, rainfall, salinity and surface behavior. IEC TS 60815-3 allows the consideration of polymeric material and hydrophobicity, but no reduction is justified without checking the behavior of the formulation and its actual aging (15,24).

Figure 3. Minimum creepage distance per SPS class for 13.8, 34.5 and 69 kV.



https://doi.org/10.71068/SDIJ0005.How

Note. Illustrative pre-dimensioning with RUSCD of IEC TS 60815-1, Um of ANSI C84.1 and Ka = 1; it does not assume measured contamination class nor does it replace final selection according to site conditions.

Table 4. Insulation parameters by voltage level

Nominal voltage	ANSI C84.1 (kV)	A Standardized IEC 60071-1 (kV)	Minimum leakage class c (mm)	Minimum leakage class d (mm)
13.8 kV	14.49	17.5	290	362
34.5 kV	36.23	52	726	906
69 kV	72.5	72.5	1,452	1,812

Note. Service Um (input of the creepage distance calculation) and the IEC 60071-1 standard reference are presented separately. The selection of the withstand voltage requires the integral coordination of the insulation, operating conditions and protection level; it is not automatically deduced from this calculation. Source: Authors.

Surge Capability

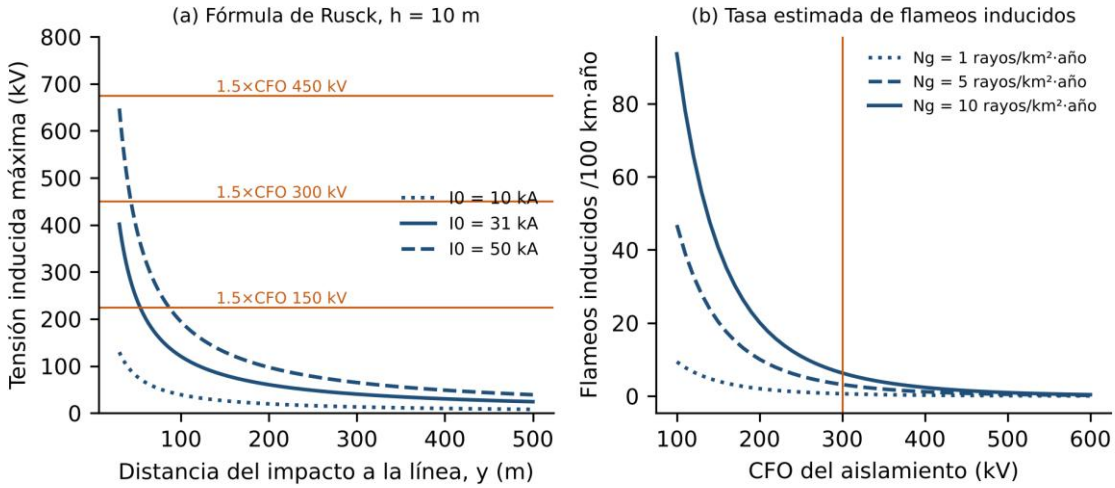
Impulse tests give the starting values. Mikropoulos and Tsouris (48) measured negative critical fluo voltages (CFOs) of 187.6 to 192.7 kV for ANSI 56-1 spigot insulators and 229.9 to 232.2 kV for ANSI 56-2, both of the 24 kV class, with a critical field of 935 kV/m. Yu et al. worked with U50 = 170 kV spigot insulators on 10 kV lines (54), and Shigihara et al. showed that the classical Darveniza-Vlastos and Hileman methods do not predict the fluttering of 15 kV insulators at low voltage levels with non-normalized waves (34). At 110 kV, Zhang et al. found no differences greater than 6 % in U50 between glass chains and composite insulators (19).

Rain and soil worsen the picture. In GFRP crossheads, the wet condition reduced the CFO between 9.6 % and 22.7 % in positive polarity and between 15.5 % and 30.5 % in negative polarity (6). Mahmood et al. demonstrated that a soil with a resistivity greater than 3,000 Ω·m markedly increases the risk of 24 kV insulator flaming, because the induced field on soil with losses is greater (47).

Own calculation: lightning-induced flaming (Ng scenarios)

The values in this section are sensitivity estimates of the Rusck model with explicit parameters and not events recorded in the field. In Figure 4a, for I_o = 31 kA and lateral distance y = 50 m, Vmax ≈ 241 kV is obtained with h = 10 m. Under the assumed criterion of 1.5 × CFO, a 150 kV CFO would only reach the flaming threshold for impacts at approximately less than 54 m, close to the assumed radius of attraction. With I_o = 50 kA, the critical distance increases to approximately 86 m for CFO = 150 kV, compared to 43 m for CFO = 300 kV. These contrasts illustrate the sensitivity to CFO and do not constitute a universal recommendation to set it at 300 kV: they also depend on direct discharge, lightning rods, line geometry, grounding and insulation coordination.

Figure 4. Lightning-induced stresses (a) and estimated rate of induced flames according to CFO (b).



Note. Ng: density of grounddischarges. The curves are scenarios calculated with Rusck/IEEE 1410, h = 10 m, v = 1.2 × 10^8 m/s, threshold 1.5 × CFO and simplified Eriksson attraction. They do not include a network characterization or Honduran validation.

Equation (7) produces, for Ng = 1 discharge/km²·year, about 4.07 induced flames per 100 km·year with 150 kV CFOs, 2.01 with 200 kV, 0.63 with 300 kV and 0.15 with 450 kV. For the illustrative scenario Ng = 10, the respective values are approximately 40.7, 20.1, 6.3 and 1.5. The change between 150 and 300 kV CFOs is equivalent to a modeled decrease of about 85% in induced flames, preserving all other hypotheses. It should not be interpreted as a total reduction in interruptions: there is a lack of direct impacts, shielding, discharges, grounding faults and protection performance. The density Ng = 10 does not come from measurements of the Honduran grid; The calculation allows sensitivities to be compared before a reliable local record is available.

Protective measures have quantitative support. Yu et al. recommend no less than one set of lightning rods every 200 to 300 m on 10 kV lines (54). Yamanaka and Ishimoto found that the electromagnetic pulse of lightning weighs more when lightning rods are widely spaced and the ground is poorly resistive (53). For 69 kV with guard wire, de Vasconcellos et al. found partial protection with lightning rods in one or two phases of a 138 kV Brazilian line to be efficient, especially when modeling grounding with frequency-dependent parameters (31); Ahmed et al. reported that a multi-chamber arrester dissipates 74 % less energy than a non-explosive lightning rod at 132 kV (30). Dong et al. added a 5 mm discharge needle to the equipotential ring of 35 kV strings with zero-value units and gained more than 30 % coordination margin (40).

Corrosion of fittings

Zhang et al. documented that steel bolts of alternating current insulators in hot and humid coastal areas fail after about 10 years, compared to 20 to 30 years for design. The leakage current on contaminated surfaces is non-sine and brings a continuous component close to 22% of the fundamental, a harmonic distortion of up to 40% and local densities that exceed the corrosion threshold of 100 A/m². A semiconductor coating of at least 2 mm at the base of the bolt lowered the maximum density from about 500 to 5 A/m² (18). In a second study, the same group identified salt

deposit as the dominant factor and a synergy between salt spray and leakage current that makes simply increasing zinc thickness insufficient (56).

Kim et al. calculated an expected life of 56 years for bolts with 75 µm of zinc in Korean industrial zone, with pH rainfall between 4.81 and 5.69 (14). The figure changes completely near the sea. In galvanized bolts exposed 50 m off the coast of Hainan, Daniel et al. saw iron oxide under zinc at six months, oxide layers of 300 µm at 24 months, and less than 1% zinc remaining on the exposed surfaces (38).

Monitoring, diagnostics and artificial intelligence

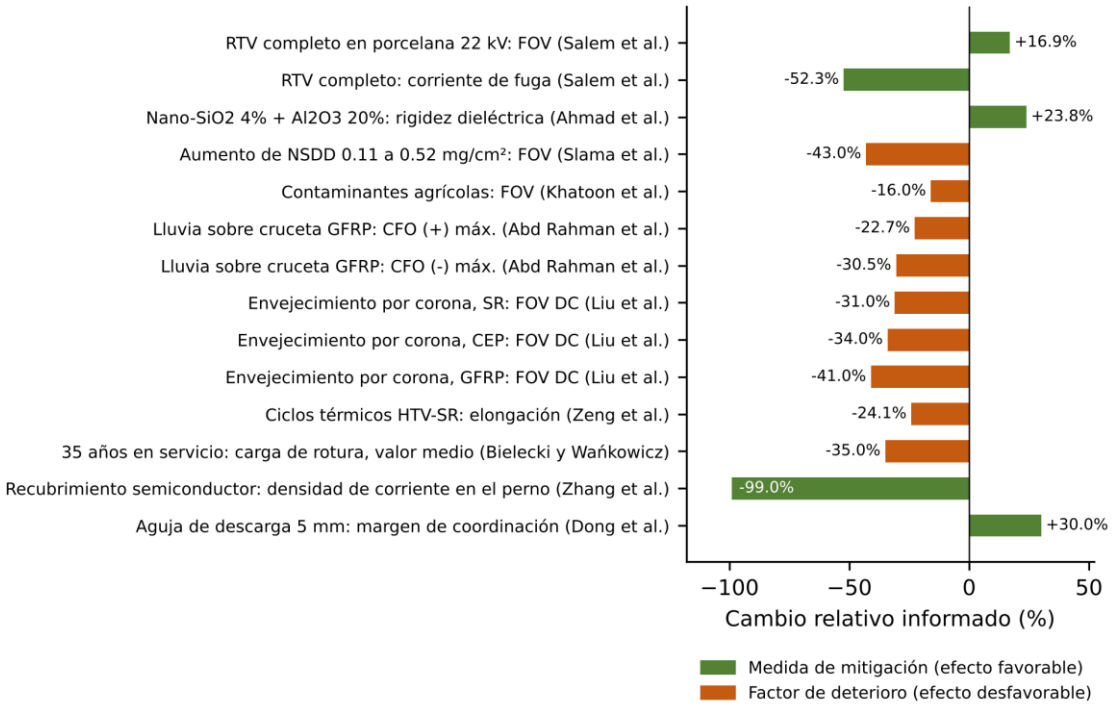
Seven studies apply machine learning or new sensors. With leakage current, Mitrovic et al. classified the wet or dry condition with F1 greater than 98 % and estimated the flame voltage with a mean square error of 1.16 % (49); de Santos and Sanz-Bobi (39) predicted contamination events in a French 245 kV coastal substation with an F-score of 0.757 to 0.792; and Da et al. classified the leakage current of 15 kV insulators on the coast of Taiwan with a mean absolute error 52.57 % lower than the base models (37). Werneck et al. measured currents of 10 to 70 mA on a 500 kV Brazilian line for three years with fiber optics and found that partial discharges spike when the local temperature reaches the dew point, not only with high humidity (35).

In imaging, Zheng et al. increased the mean accuracy (mAP@0.5) of defect detection in drone photos from 88.7 % to 91.2 % at 78 frames per second (57), and Rodrigues et al. detected insulation in ultraviolet images with 85.5 % accuracy and found that 72.7 % of the discharge sources in a 500 kV substation originated far from the insulation (51). Chen et al. showed that thermography better detects zero-value porcelain insulators with high humidity and contamination, just when there is more risk (17). In distribution, the precedent of Lefort and Martinez (5) continues to be useful, since a low-cost ultrasonic antenna identified 85 % of degraded insulators and reduced outputs due to insulator failure by about 50 %.

Quantitative synthesis

Figure 5 summarizes the percentage changes that the studies report against their own reference. The deterioration factors (insoluble contamination, rainfall, corona, thermal cycles, years of service) produce losses of 16 % to 43 % in flutter voltage or resistance. The mitigation measures with the greatest relative effect act on the current. The RTV coating reduced the leakage current by 52.3 % (22) and the semiconductor coating lowered the current density in the bolt by 99 % (18). The NSDD data is expressed as a reduction of 43 %, which is equivalent to the mean factor of 1.77 reported by Slama et al. (52). All the values in Figure 5 come from primary studies; none were taken from the reviews.

Figure 5. Relative changes reported by the included studies.



Note: Each bar is a point value reported by the cited study; it is not a combined effect. Source: Authors.

DISCUSSION

Reading the evidence for the Honduran network

Three results clash with the usual practice of catalog purchases. The first is that the hydrophobicity of silicone is not a fixed fact. It can last 36 years in a careful formulation (16) or be lost in 26 years of electric field and contamination (15). That is why asking for "silicone" in a specification alone is not enough; inclined plane tests according to IEC 60587, accelerated aging tests according to IEC 62217 and, if possible, decommissioned samples for comparison (27,29).

The second result has to do with site classification. A single ESDD measurement when building does not protect the line. Fofana et al. found four out of seven insulators above the design class (42), and NSDD, which many companies do not measure, can reduce the flame stress by almost half (52). On the Honduran north coast and in the San Pedro Sula industrial corridor this makes it advisable to measure ESDD and NSDD on a regular basis. According to our calculation in Figure 3, the jump from class c to d at 69 kV costs an additional 360 mm of leakage.

The third result is related to atmospheric discharges. Rusck's scenario suggests that increasing the CFO can decrease induced flaming under fixed parameters, but does not demonstrate that 300 kV is the optimal or enforceable threshold for a 13.8 kV Honduran line. In addition, an increase in the CFO does not replace the analysis of direct impacts, location of lightning rods, grounding and operation of protections (26). The final selection should be derived from insulation coordination and an economic evaluation by circuit, with data on real discharges and outputs.

Bolt corrosion is also not resolved by more zinc. Daniel et al.'s data on nearly zinc-free galvanized bolts at two years in Costa Tropical (38) and the salt-current synergy described by Zhang et al. (56) point to sealing the current entry point and using semiconductor coatings on the bolt base (18). Kim et al. further suggest exploring alternatives to zinc or additional waterproof coatings (14).

What the evidence supports and what requires local validation

Not all the proposals in this paper are based on the same type of evidence. Some are based on the coincident results of several international studies, although obtained in other climates or at higher voltages; others depend on their own calculations and, therefore, on the assumed parameters; and none have been verified in the Honduran network. Table 5 separates, for each proposal, the evidence that supports it, the nature of this support and what would need to be measured or tested in the country before turning it into a design criterion. The behavior of the materials and the corrosion of fittings have the most solid support, because their mechanisms do not depend on the level of tension; the figures for lightning strikes are the most conditioned, because they depend on a density of ground discharges that has not been measured in Honduras.

Table 5. Support for the proposals for Honduras and pending local validation

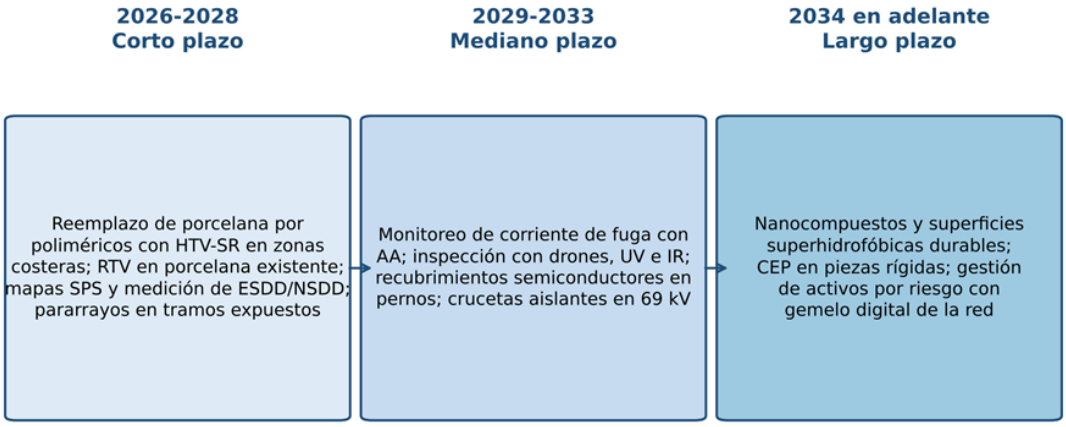
Proposal	Evidence that supports it	Nature of the Endorsement	Local validation pending
Coastal Silicone Composite Isolators, with Assay Verified Formulation (IEC 60587, IEC 62217)	Wang et al. (16); Mu et al. (15); Qiao et al. (32); Mavrikakis et al. (13)	International field and laboratory evidence; 110 kV data or specimens	Natural aging in stations in the Honduran Caribbean; samples withdrawn from service
Measure ESDD/NSDD and determine the SPS class per site; C–D classes are pre-sizing scenarios, not verified classifications.	Fofana et al. (42); Slama et al. (52); Khatoon et al. (3); self-calculation (Equation 1)	Medium-voltage and laboratory evidence; calculated regulatory minimums	Seasonal contamination studies and leakage validation and isolator design by real geometry/environment.
Study CFO increases to mitigate induced flames; 300 kV is used only as a comparative calculation scenario.	IEEE (26); Ahsan et al. (7); own calculation (Equations 2 to 7)	Rusck's technical guide and parametric scenario; no confirmation in Honduras.	Study of coordination of insulation, direct discharges, soil, lightning rods, protections, costs and real failure rates.
Direct impact lightning rod; partial protection at 69 kV	Yu et al. (54); Yamanaka e Ishimoto (53); de Vasconcellos et al. (31)	Simulation at 6.6, 10 and 138 kV	Soil resistivity and grounding of Honduran lines
Sealing bolts or semiconductor coating on coastal hardware	Zhang, Zheng, et al. (18); Zhang, Zhong, et al. (56); Daniel et al. (38)	Laboratory and exposure in Costa Tropical; transmission isolators	Pilot test on 13.8 and 34.5 kV lines with real leakage current
Leakage Current Monitoring with Machine Learning and Risk-Based Maintenance	Da et al. (37); Mitrovic et al. (49); de Santos y Sanz-Bobi (39); Werneck et al. (35)	Field and machine learning, from 15 to 500 kV	Model training with local climate and leakage current
Evaluate field control rings at 69 kV according to circuit geometry; do not transfer 230 kV thresholds.	Khajavi et al. (44)	Simulation at 230 kV	Simulation of local assembly, coordination of insulation and electrical tests appropriate to 69 kV.

Note: None of the proposals have been validated in the Honduran network. Source: Authors.

Projection into the future

Figure 6 orders in time what the evidence suggests for the 13.8 to 69 kV network. In the short term, the replacement of porcelain with composite insulators with HTV silicone in coastal areas, the RTV coating of porcelain that remains (22) and the systematic measurement of ESDD and NSDD. In the medium term, leakage current monitoring with machine learning models (37,39,49), inspection with drones and UV and infrared cameras (17,51,57) and the incorporation of insulating crossheads in 69 kV (7). In the long term, nanocomposites (20,41), superhydrophobic surfaces, which already exceed contact angles of 150° but have yet to prove their durability in the field (32,45), and CEP for rigid parts (46).

Figure 6. Proposed technological roadmap for 13.8 to 69 kV isolators in Honduras.



Source: Authors' elaboration based on the synthesis of the included studies.

The most far-reaching change may not be a material. It is a shift from calendar maintenance to risk-based maintenance, in which the washing, replacement or installation of lightning rods is decided with data on leakage current, climate and pollution. De Santos and Sanz-Bobi propose it this way to schedule washes (39), and Mitrovic et al. to instruct asset managers (49).

Limitations

The review has limitations that condition its conclusions. First, the search was carried out with a general web index and editorial verification, without direct queries to Scopus or Web of Science; nor is a complete historical record of the 36 queries, filters, and results preserved, which prevents the full reproduction of the identification. Second, the initial count of approximately 330 records and their passage to 104 groups duplicates and non-bibliographic exclusions without a breakdown; Figure 1 is a partial reconstruction, not a fully auditable PRISMA flow. Third, a single reviewer performed the selection, extraction, and characterization; descriptive scores are not a validated measure of risk of bias and may favor certain designs. Fourth, only 11 of the 44 studies were classified as TM; 19 come from AT/transmission, 10 from materials, and four from various stresses, with limited transferability. Fifth, no primary studies carried out in the Honduran network were located. Sixth, the calculations of leakage distance and induced flutters are scenarios with assumed parameters, without field validation

or complete probabilistic analysis of uncertainty. These limitations prevent converting the results into definitive specifications for specific circuits.

Registration and supplementary material. Included separately is "Supplementary Material A: Search Replication Protocol and Methodological Rubric by Design". The 36 strings formulated there allow a new documentable search to be performed. They are not labeled as "36 queries executed" because the historical search outputs are not fully recorded in the available documents.

Recommendations

Proposals addressed to Honduran operators are presented as design hypotheses and verification lines, not as approved specifications. First, characterize by site the severity of contamination through representative series of ESDD, NSDD, salinity, rain washout, and leakage current in the north coast, the Sula Valley, and industrial corridors; define the sampling frequency based on seasonal variability and circuit risk. Second, provisionally use SPS class d only as a PRE-DIMENSIONING CONSERVATIVE ASSUMPTION in coastal scenarios without data (362 mm at 13.8 kV and 906 mm at 34.5 kV, with the calculation hypotheses), not as a proven environmental classification or final purchase criterion. Final adoption requires site characterization, geometric corrections, and pertinent tests according to IEC 60587 and IEC 62217. Third, evaluate at 69 kV the convenience of field control rings by modeling the actual geometry; the field limits published for 230 kV by Khajavi et al. (44) are not automatically approved thresholds at 69 kV. Fourth, to study lightning protection in a comprehensive way (direct and induced discharges, CFO, grounding, lightning arresters, and protection coordination), considering a CFO of 300 kV as a comparative scenario, not as a universal value. Fifth, to contrast the installation of insulating crossheads and the protection against corrosion of bolts in coastal environments by means of pilots, recording failures, costs, and operating conditions before extending measures. Sixth, to analyze leakage current monitoring and diagnostic systems using algorithms trained and evaluated with representative data from the local network.

Lines of future research

First of all, a database of insulator failures in the Honduran network is needed, with date, location, type of insulator and cause. With it, the aging and flame models reviewed here could be validated locally. Other pending lines are the measurement of the density of ground discharges with regional detection networks to move from Ng scenarios to measured values; natural aging tests of silicone and CEP in coastal stations in the Honduran Caribbean; the evaluation of bolt corrosion under real leakage current in 13.8 and 34.5 kV lines; and the development of machine learning models trained with local climate and leakage current data.

CONCLUSIONS

Evidence published between 2015 and 2026 supports the use of silicone-enveloped composite insulators in tropical and coastal environments, with two conditions: that the formulation is verified with tests and that the creepage distance is dimensioned with real ESDD and NSDD measurements. That advantage is not absolute. Silicone maintained hydrophobicity transfer for 36 years in a selected formulation, but commercial 110 kV units reached HC5-7 at 26 years under intense electric field and

contamination, and porcelain with RTV coating remains a valid option where it is already installed. In corrosion, studies agree that bolt deterioration on shoreline responds to salt and deformed leakage current rather than a lack of zinc, and in laboratory semiconductor coatings reduced current density by two orders of magnitude.

The two calculated exercises, which were not validated in the field, yield reference values of creepage distance for an assumed SPS class—for example, from 290 mm at 13.8 kV to 1,452 mm at 69 kV in class c—and a modeled decrease of about 85% in induced flames when comparing 150 and 300 kV CFOs with identical parameters. For Ng = 10 discharges/km²·year, this corresponds to approximately 40.7 and 6.3 flames per 100 km·year, respectively. Neither the SPS nor Ng class were determined by Honduran measurements; moreover, the figures do not include all failure mechanisms. Their end use requires characterizing the site, coordinating isolation, and testing solutions with pilot tests.

For Honduras, the recommendations of this work are conditional technical proposals. Those related to materials and fittings have the broadest support; those related to lightning coordination depend on parameters that the country has not yet measured. Leakage current monitoring with machine learning and drone inspection can sustain risk-based maintenance, as long as their models are trained with local data. No proposal has been validated in the Honduran network, and the most needed step is to record and publish their failure data, measure the density of ground discharges and the severity of contamination per site, and test the proposed solutions in the field.

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ETHICAL CONSIDERATIONS

The study was developed through a literature review based exclusively on previously published documentary sources. It did not involve the direct participation of human or animal beings, the performance of interventions, the use of biological samples, or access to personally identifiable data. Consequently, it did not require approval from an ethics committee or the obtaining of informed consent. During the research process, the principles of scientific integrity, adequate attribution of authorship, rigorous citation, and responsible use of the sources consulted were observed.

ARTIFICIAL INTELLIGENCE (AI) USAGE STATEMENT

The authors state that the AI tool was used exclusively to support the organization of the article and the translation of the text. Its use did not determine the scientific content, study design, selection of sources, data analysis, interpretation of results, or conclusions. Full responsibility for the content remains with the authors.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest related to this study and that all the procedures followed comply with the ethical standards established by the journal. They also confirm that this work is unpublished and has not been published, either partially or totally, in any other publication.

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