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Fungi and algae behaviour on high-voltage insulators under environmental conditions

Biological contamination of high-voltage insulators by fungi and algae threatens power system reliability, especially in humid tropical and subtropical environments. Field and laboratory data show that algal and fungal biofilms persistently reduce hydrophobicity and flashover strength under wet conditions. Dielectric analyses reveal that hydrated biofilms behave as lossy dielectrics with elevated permittivity and loss tangents, distorting local electric fields and accelerating surface degradation. The synergistic coexistence of algae and fungi intensifies the chemical, mechanical and dielectric deterioration of insulation materials. Microbial growth and persistence are strongly regulated by environmental factors such as humidity, rainfall, surface roughness and shading. By integrating microbiological behaviour with insulation engineering, this study establishes a unified framework for understanding biologically driven insulation degradation and informs predictive maintenance, material selection and mitigation strategies for high-voltage infrastructure operating in biologically aggressive environments.

Significance:

Biological contamination of high-voltage insulators poses an under-recognised reliability risk in climates characterised by high humidity and rainfall, such as those found across much of South Africa. This study demonstrates how algal and fungal growth alter surface dielectric behaviour, accelerate electrical ageing, and increase maintenance demand. By clarifying the environmental–biological–electrical coupling underlying these effects, the findings support more informed inspection, material selection and mitigation strategies for resilient power transmission infrastructure.

Introduction

Biological contamination of high-voltage (HV) insulators by fungi and algae poses a growing threat to power system reliability, particularly in humid tropical and subtropical environments. Field and laboratory evidence shows that algae and fungal biofilms act as persistent surface contaminants that reduce hydrophobicity, increase leakage currents and lower flashover strength under wet conditions. Dielectric characterisation shows that hydrated biofilms behave like lossy dielectrics, exhibiting elevated relative permittivity and loss tangents, which distort local electric fields and accelerate surface degradation. The synergistic coexistence of algae and fungi further intensifies chemical, mechanical and dielectric deterioration of insulating materials. Microbial growth and persistence are strongly regulated by environmental factors, including humidity, rainfall, surface roughness and shading. By integrating microbiological behaviour with insulation engineering, this study provides a unified framework for understanding biologically driven insulation degradation and informs predictive maintenance (PdM), material selection and mitigation strategies for HV infrastructure operating in biologically aggressive environments.

The study holds particular significance for South Africa, where diverse climatic conditions – from humid coastal belts to polluted urban zones and high-rainfall inland regions – create an ideal environment for fungal and algal contamination of HV insulators. Biological growth accelerates surface degradation, reduces flashover voltage and increases maintenance costs, directly threatening transmission reliability. Given South Africa's heavy reliance on long-distance HV transmission to link coal, renewable and urban load centres, understanding biologically driven degradation is critical for grid resilience. By providing predictive insights and mitigation pathways, this research supports more reliable and cost-effective operation of the national transmission network.

The presence of fungi and algae on insulator surfaces adversely affects their electrical performance. A primary concern is the reduction in hydrophobicity, which is critical for preventing the formation of conductive water films that lead to surface leakage currents and flashovers. Research has shown that algal contamination can significantly decrease silicone rubber insulators' hydrophobicity, lowering their flashover voltage.[1,2]

Previous experimental studies demonstrate that surface condition strongly influences breakdown voltage, discharge development and surface degradation mechanisms.[3-5]

Fungal growth, particularly by species such as *Curvularia* and *Aspergillus*, has been linked to the degradation of composite insulators. These fungi can produce metabolic byproducts that deteriorate polymeric materials, compromising the mechanical integrity and longevity of the insulators.[6]

Different insulating materials exhibit varying degrees of susceptibility to biological contamination. Polymeric insulators, especially those made from silicone rubber, are particularly prone to biofilm formation due to their surface properties.[7] Biofilms, comprising microbial cells embedded in a matrix of extracellular polymeric substances, can persist on insulator surfaces and lead to sustained degradation of hydrophobicity and increased surface conductivity.[8-10]

Biofilm persistence is strongly influenced by surface chemistry and roughness, which regulate microbial adhesion and long-term colonisation.[11,12]

HV/medium-voltage insulators exposed to different environmental stressors exhibit distinct patterns of surface contamination that affect both their aesthetic appearance and electrical performance.

Biological, urban and coastal pollution produce distinct surface contamination patterns that modify wetting behaviour and promote conductive surface films under humid conditions. These pollutants create conductive pathways when wetted, significantly reducing insulating strength. Figure 1 and Table 1 summarise the characteristic appearances, environmental settings and electrical risks associated with these contamination types.

Addressing biological contamination on HV insulators requires a multifaceted approach. Regular cleaning and maintenance are essential to remove biofilms and prevent microbial accumulation. However, the effectiveness of cleaning methods varies depending on the type and extent of contamination, as well as the insulator material.[13] Preventive strategies include the application of hydrophobic coatings and the selection of materials less prone to microbial colonisation. For instance, certain room temperature vulcanised (RTV) silicone coatings have demonstrated resistance to biological growth, although their long-term efficacy under varying environmental conditions requires further investigation.[2,14]

Despite extensive prior work, biological contamination and electrical degradation of HV insulators are often treated as separate phenomena. This study highlights the importance of understanding fungal and algal behaviour on HV insulators. By investigating the environmental factors that affect microbial growth and the resulting impacts on insulator performance, engineers and researchers can create more effective materials and maintenance strategies to reduce the risks associated with biological contamination.

Methodology

The methodological framework adopts a systems-based approach in which environmental, biological, material and electrical processes are treated as interacting components rather than isolated variables (Figure 2). Climatic drivers such as humidity, rainfall intensity, temperature and atmospheric pollution govern the initiation and persistence of algal and fungal biofilms on exposed surfaces. These biological layers modify surface properties, including roughness, hydrophobicity and effective dielectric parameters, thereby altering local electric field distributions under wet and polluted conditions.

These surface modifications directly influence leakage current initiation, surface discharge activity and electric field enhancement, thereby accelerating ageing mechanisms such as hydrophobicity loss, tracking and erosion.

Environmental variables (humidity, rainfall, temperature, solar exposure and shading) regulate the formation, hydration state and persistence of algal and fungal biofilms, which in turn modify surface hydrophobicity, roughness, chemical stability and dielectric behaviour.

Under operating voltage, hydrated biofilms act as lossy dielectric layers with elevated permittivity and conductivity, distorting local electric fields and promoting leakage currents and surface ageing.

Methodologically, the study combines (i) field observations of biologically contaminated insulators across representative climatic regions, (ii) laboratory-based electrical and dielectric characterisation under controlled wet and dry conditions and (iii) comparative analyses across insulator materials.

This integrated approach enables direct linkage between environmental exposure, biological growth, surface modification and electrical response.

Types of HV insulators

HV insulators mechanically support and electrically isolate conductors in overhead transmission and substation environments. Their selection is governed by voltage level, environmental stressors (e.g. pollution, humidity and biological activity), mechanical loading and regional practices.[15,16]

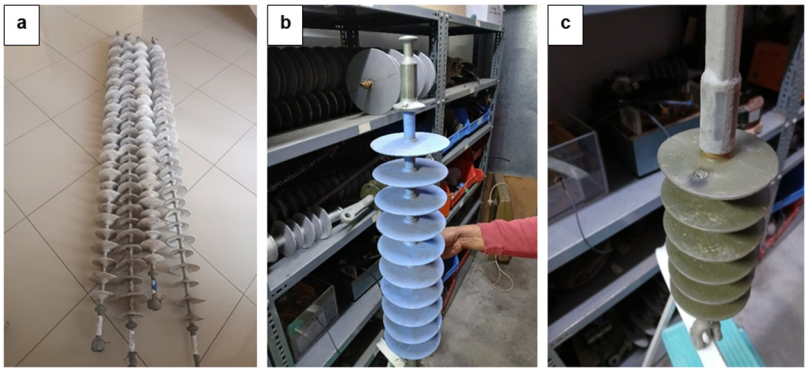


Figure 1: (a) 275 kV insulators from Arnot (Mpumalanga Province) with significant fungal contamination. (b) 132 kV insulators from near Johannesburg, contaminated by urban and industrial pollution. (c) 75 kV insulators from Durban are heavily exposed to sea breeze. All regions are in South Africa. Photo of the 275 kV insulator is courtesy of Dr Philip Tshubwana.

Table 1: Comparative characteristics of high-voltage insulator pollution from biological, urban and coastal sources

Pollution type	Visual appearance	Typical field locations	Flashover risk characteristics
Biological growth	Greenish, brownish or black slimy patches due to algae, fungi, lichens or mosses. May form irregular crusts or films, especially in humid zones.	Tropical/subtropical regions, shaded rural areas, forest edges, damp river valleys.	High flashover risk when wetted; uneven surface films create localised leakage currents and dry-band arcing.
Urban pollution	Grey to black soot, dust, or industrial particulates form a dull, opaque coating. Often streaked by water run-off.	Industrial zones, metropolitan areas and power substations near traffic corridors.	High flashover risk due to conductive carbonaceous layers; risk increases during fog or light rain.
Coastal breeze pollution	Whitish or light-grey crystalline deposits of sea salts, often granular and encrusted, are denser on windward sides.	Coastal transmission lines, offshore substations, islands, ports.	Very high flashover risk during high humidity, fog or mist; saline deposits dissolve readily, forming conductive films.

Although insulation principles are universal, material choice varies by region due to climate, utility practices and availability. Polymeric insulators dominate in the Americas, China and India, while porcelain and glass remain common in parts of Europe and Africa. A detailed illustration of regional insulator preferences is presented in Table 2.[15,17-20]



Figure 2: Conceptual system diagram showing interactions between environmental forcing, biological growth, electrical response and material ageing, including feedback mechanisms relevant to lightning-related degradation.

Traditionally, Europe favours porcelain and glass insulators due to legacy infrastructure and conservative replacement practices. In the Asia–Pacific region, rapid electrification and newer infrastructure encourage the use of polymeric insulators, especially in highly polluted and coastal areas. In most African countries, porcelain remains common due to availability and robustness, but polymeric insulators are gaining ground in high-contamination zones and remote installations. Both North and South American countries, such as the USA, Brazil, and Mexico, have adopted polymeric insulators widely due to their ease of installation and reduced maintenance.

The biological performance of these materials also varies. Porcelain and glass readily support biofilm adhesion once their surfaces become roughened, while polymeric insulators initially resist biological growth due to hydrophobic properties, but they become susceptible as ageing increases surface roughness and promotes chemical degradation.[21-23]

This classification provides engineers and system planners with a foundational understanding of how insulator material selection relates to both environmental conditions and biological fouling risks. For further optimisation, hybrid insulators or nanocomposite coatings are being explored as future alternatives that offer enhanced resistance to microbial growth, pollution and weathering.

Types of algae and fungi

Algal colonisation of HV insulators is predominantly observed in humid and subtropical climates, where moisture and moderate temperatures facilitate growth. The presence of algae can significantly degrade the hydrophobic properties of insulator surfaces, leading to increased leakage currents and a reduction in flashover voltage.[1,21,24]

Several algal genera, including *Chlorella, Scenedesmus*, and *Nostoc*, have been identified on HV insulator surfaces, where their biofilms retain moisture, reduce surface resistivity and promote conductive pathways under wet conditions.[7,24-26]

Fungi are ubiquitous organisms that can colonise a wide variety of surfaces, including those of HV insulators. Their spores can adhere to insulator materials, germinate and form hyphal networks that penetrate surface layers.[8]

Fungal genera frequently isolated from contaminated insulators include *Aspergillus, Penicillium* and *Cladosporium*, which form persistent hyphal

Table 2: Preferences for insulators by region

Material type	Common regions of use	Advantages	Disadvantages	Remarks
Porcelain (ceramic)	Europe, Africa, the Middle East, South Asia	-High mechanical strength -Long lifespan (≥50 years) -Resistant to UV and weathering	-Brittle; prone to breakage during transportation -Heavier -Susceptible to surface contamination	Preferred for high mechanical loads and desert/arid climates
Toughened glass	Europe, Latin America, Central Asia	-High dielectric strength -Transparent (facilitates visual inspection) -Self-cleaning during rain	-Breaks into small shards when damaged -Slightly heavier than polymeric -Limited shapes	Often used where visual monitoring is crucial
Polymeric (composite)	USA, China, India, Southeast Asia	-Lightweight -Excellent hydrophobicity -Better resistance to biological growth in early life -Flexible under impact	-Shorter life (20–30 years) -Prone to ageing under UV and corona -Susceptible to vandalism and rodent damage	Ideal for polluted, coastal, and high-humidity zones; requires advanced quality control

networks that retain moisture, particulates and salts, thereby enhancing surface conductivity and accelerating material degradation.[7,8,14]

Fungal metabolic activity, including organic acid production and enzymatic degradation, can compromise both the mechanical integrity and electrical insulation performance of polymeric materials.[7,27]

Algal and fungal biofilms frequently coexist on insulator surfaces, producing synergistic biological, chemical and dielectric degradation effects that are regulated by environmental exposure.[2]

The key physical, dielectric and thermal properties of algal and fungal biofilms relevant to HV insulation are summarised in Table 3.[28-41]

Electrical behaviour of algae and fungi

Both algae and fungi, when present as hydrated biofilms on HV insulators, act as lossy dielectric layers that alter surface electrical behaviour. These biological films exhibit high relative permittivity ($\varepsilon_r = 20–80$) and loss tangent values ($\tan \delta = 0.1–0.7$) in the wet state, comparable to those of biological tissues.[42-44] Such dielectric properties enhance local field distortion, reduce flashover voltage and promote partial discharge initiation, particularly under humid or polluted conditions.[7,45,46]

Their high water content and ionic mobility increase surface conductivity (10^{-8}–10^{-4} S/m), thereby promoting leakage currents and surface discharges during mist or dew events.

Fungal hyphae further enhance conduction by binding dust, salts and moisture, thereby forming conductive bridges that facilitate corona discharge and surface erosion.[45]

Across diverse engineered systems, biofilm formation is strongly governed by surface material properties, environmental conditions and nutrient availability (Tables 4 and 5). Smooth, hydrophilic or nutrient-rich surfaces generally support higher microbial loads, while antimicrobial materials such as copper inhibit colonisation. These trends are consistent across HVAC (high-voltage alternating current) systems, wastewater treatment facilities and outdoor infrastructure systems, underscoring the transferability of biofilm–surface interaction principles to HV insulators.

Empirical evidence across aquatic, terrestrial and atmospheric systems demonstrates that precipitation is a dominant driver of algal and fungal proliferation (Table 6). Increased rainfall enhances nutrient availability, microbial abundance and species richness, often by orders of magnitude, with direct implications for biofilm formation and persistence on outdoor HV insulation surfaces.[47-52]

Discussion

Environmental drivers and biological colonisation

The results confirm that environmental exposure plays a dominant role in governing the extent and persistence of biological contamination on HV insulator surfaces. High humidity, frequent rainfall, moderate temperatures and limited solar exposure collectively promote algal and fungal growth, particularly on polymeric insulators deployed in subtropical and coastal regions.

These findings are consistent with broader ecological evidence indicating that precipitation and humidity are primary regulators of microbial proliferation across both engineered and natural systems. Accordingly, HV infrastructure in high-rainfall and coastal regions is inherently more vulnerable to persistent biological contamination.

Electrical and material aspects of biofilm formation

Biological colonisation alters the electrical behaviour of HV insulators primarily by modifying surface hydrophobicity, roughness and dielectric properties. Hydrated biofilms behave as lossy dielectric layers with elevated permittivity and conductivity, leading to electric field distortion, leakage current initiation and accelerated surface ageing.

This behaviour provides a mechanistic explanation for the observed reduction in flashover voltage and increased surface discharge activity under humid conditions.

Table 3: Comparative physical, dielectric and thermal properties of algal and fungal biofilms on high-voltage (HV) insulator surfaces

Property	Algal biofilms	Fungal biofilms	Relevance to HV insulators
Water content	95%–99%	60%–85%	Increases conductivity; supports leakage current initiation
Electrical conductivity (σ)	$\sim 10^{-4}$ S/m (wet)	10^{-8}–10^{-5} S/m (moist)	Facilitates surface discharges under humidity
Relative permittivity (ε_r)	30–80 (wet), 3–5 (dry)	20–70 (wet), 4–6 (dry)	Alters electric field distribution; lowers flashover voltage
Loss tangent (tan δ)	0.1–0.6 (wet)	0.2–0.7 (wet)	Causes dielectric losses; enhances corona and partial discharges
Thermal response	Absorbs solar radiation; local heating	Insulates, modifies thermal ageing	Affects material ageing under cyclic stress
Optical properties	Pigmented (green/brown); photosensitive	Opaque, UV-resistant	Alters albedo and surface charge distribution
Effect on electromagnetic propagation	Alters dielectric constant and field uniformity	Absorbs low-MHz energy	Affects wireless sensor signals and electromagnetic interference patterns

Table 4: Comparison of the growth response of algae and fungi to environmental parameters

Organism type	Optimal temperature (°C)	Relative humidity (%)	Optimal pH	Salinity tolerance (‰)	Surface/atmospheric acidity	Surface smoothness
Algae	20–30	Not specified	6.0–8.5	25–30	Sensitive to acidic conditions	Prefer smooth surfaces for attachment
Fungi	20–30	>80%	5.0–6.0	Varies; some tolerate up to 30	Generally prefer neutral to slightly acidic environments	Can colonise both smooth and rough surfaces

Table 5: Biofilm formation and surface preferences of selected microorganisms

Organism/functional group	Preferred material surfaces	Colonisation rate/biofilm biomass	Environmental context
Skeletonema costatum (diatom)	Glass, polycarbonate, polyethylene, polyvinyl chloride (PVC)	High colonisation on smooth, hydrophilic surfaces; specific rates vary with conditions	Marine environments
Nodularia spumigena (cyanobacteria)	Polyethylene, concrete, organic-rich sediments	Rapid colonisation in nutrient-rich waters; specific rates not quantified	Eutrophic aquatic systems
Hypnea cervicornis (red alga)	Coral skeletons, limestone rocks, PVC mesh	Effective attachment on calcareous surfaces; growth rates influenced by light and nutrients	Coral reef ecosystems
Rhizopus oligosporus (fungus)	Cooked soybeans, stainless steel, glass, ceramic	Optimal growth at 42 °C and high humidity; biomass accumulation significant in fermentation setups	Food fermentation environments
Penicillium expansum (fungus)	Apples, wood, cardboard, paper, polystyrene	Rapid colonisation on porous, organic substrates; contributes to post-harvest losses	Agricultural storage facilities
Talaromyces albobiverticillius (fungus)	Paperboard, woven cotton, nutrient-rich polyethylene	Growth favoured on nutrient-rich, moist surfaces; specific rates not quantified	Textile and paper industries
Xerophilic fungi (*Eurotium, Wallemia*)	Wood, drywall, dust-coated plastics, painted concrete	Thrive in low humidity; colonisation rates increase with surface roughness and dust presence	Indoor environments
Flavobacterium spp.	PVC, steel	Biofilm thickness up to 100 μm on PVC after 22 days; dominant in cooling tower systems	Cooling tower environments
Pseudomonas aeruginosa	PVC, steel	Low adherence; washed out within 4 days in cooling towers	Cooling tower environments
Klebsiella pneumoniae	PVC, steel	Low adherence; washed out within 2 days in cooling towers	Cooling tower environments
Legionella pneumophila	Various HVAC materials	Persistent biofilms; resistant to disinfectants; recolonisation occurs rapidly post-treatment	HVAC systems
Mixed bacterial communities	Aluminium heat exchangers	Average bacterial concentration: 11 411 CFU/cm^2; up to 163 081 CFU/cm^2; fungal average: 378 CFU/cm^2	HVAC systems
Mixed bacterial communities	Copper heat exchangers	Average bacterial concentration: 3 CFU/cm^2; fungal average: <1 CFU/cm^2	HVAC systems
Algal-bacterial consortia (*Chlorella vulgaris, Scenedesmus obliquus*)	Canvas, pine sawdust, bamboo	Biomass productivity: 5.53–52 g/m^2/day; effective in nutrient removal from wastewater	Wastewater treatment systems
Mixed microbial communities	K5 carriers in MBBR systems	Active biomass: 0.71–1.68 g COD/m^2 (aerobic), 0.39–1.44 g COD/m^2 (anoxic); species richness peaked on day 63	Municipal wastewater treatment

Fungal hyphal networks intensify degradation by binding particulates and moisture, forming conductive bridges that promote corona discharge and erosion.

Feedback mechanisms and long-term degradation

A critical insight emerging from this study is the presence of a self-reinforcing degradation loop linking biological colonisation and electrical ageing. Initial microbial growth degrades surface hydrophobicity and dielectric integrity, which in turn enhances moisture retention and electrical stress concentration, further promoting biological attachment and persistence.

This coupled behaviour explains the accelerated ageing often observed in biologically contaminated insulators exposed to repeated wetting and electrical stressing.

Over long service periods, these feedback mechanisms substantially reduce insulation lifespan in wet and humid climates.

Collectively, these results demonstrate that biological contamination represents a coupled environmental–biological–electrical degradation process rather than a superficial soiling phenomenon.

The integrated analysis clarifies how environmental exposure propagates through biological colonisation to influence material degradation and electrical performance.

This systems-level perspective supports improved risk assessment, inspection strategies and material selection for HV networks operating in biologically active environments.

Comparison with previous research in terms of efficiency and cost

This study advances earlier research on biological contamination of HV insulators by integrating environmental, biological and electrical variables into a unified diagnostic framework. Previous investigations[1,2,14] primarily evaluated hydrophobicity loss or dielectric performance under controlled laboratory conditions, without explicitly coupling microbial activity and climatic variability. In contrast, the current framework improves analytical efficiency by enabling causal interpretation across multiple stressors within a single model. This multidimensional approach reduces the number of laboratory trials required for performance prediction, thereby lowering experimental and monitoring costs.

From a mitigation perspective, conventional surface-cleaning or RTV re-coating methods remain costly and time-consuming, with maintenance intervals typically under 1 year in humid tropical climates.[13] Conventional mitigation strategies such as live-line washing or RTV re-coating typically require annual or biannual interventions in humid climates, with recurring labour, outage and material costs.[13,14] In contrast, the predictive framework proposed here allows utilities to target only high-risk zones, potentially

Table 6: Influence of precipitation on algal and fungal growth

Organism/group	Environment	Precipitation influence	Quantitative data
Phytoplankton (e.g. *Skeletonema costatum*)	Hyper-eutrophic lagoon (Taiwan)	Increased rainfall intensity correlates with higher phytoplankton bloom magnitude	Chlorophyll-a concentrations increased by an order of magnitude during heavy rainfall
Airborne fungi (e.g. *Cladosporium, Penicillium*)	Urban atmosphere (Tianjin, China)	Rainfall events alter fungal community composition; certain genera become more abundant on rainy days	*Schizophyllum* increased to 8.2% abundance on rainy days compared to non-rainy days
Fungal bioaerosols	Various outdoor and indoor environments during monsoon season	Rain events significantly increase fungal bioaerosol concentrations	Fungal concentrations increased by 3 to 7 times during rain compared to non-rainy conditions
Root-associated fungal endophytes (e.g. *Paraphaeosphaeria* spp.)	Semiarid grassland (New Mexico, USA)	Increased precipitation enhances the abundance of certain root-associated fungi	Not specified quantitatively; observed increase in fungal load with added moisture
Fungal communities (*Ascomycota*, *Basidiomycota*)	Intermountain West (USA)	Fungal abundance and richness positively correlated with moisture availability; negatively with extended dry periods	Up to 72% of variation in fungal richness explained by duration of unfavourable humidity conditions
Fungal plant pathogens	Eucalyptus phyllosphere (Australia)	Precipitation is a significant predictor of fungal pathogen abundance	Abundance exhibited a positive linear relationship with precipitation; potential for up to 100-fold increase under future climate scenarios

Table 7: Illustrative maintenance efficiency and cost comparisons (per kilometre of transmission line)

Metric	Reactive/preventive approach	Predictive/framework-based approach (as proposed)	Notes
Estimated maintenance cost (% of capital cost per year)	0.5–1% (planned) + high unplanned costs	0.3–0.7% (lower with predictive maintenance)	Planning and research literature (general)
Downtime/unplanned failures	High; unpredictable	Reduced by ~30–45%	Typical predictive maintenance studies (varies by asset)
Inspection/labour share	High	Lower (automated monitoring)	Industry-accepted trends
Insulator maintenance share (relative)	Up to ~50% of line maintenance	Lower due to targeted scheduling	Industry reports on pollution impact

extending cleaning intervals by 30–50% and reducing associated operational costs by approximately 20–30%, consistent with trends reported for condition-based maintenance systems in power assets.[14,17]

To contextualise the practical advantages of the proposed diagnostic framework, it is useful to consider illustrative maintenance cost and efficiency comparisons between traditional reactive or preventive maintenance practices and a PdM-orientated approach. Traditional maintenance of overhead transmission lines typically encompasses both scheduled preventative actions and frequent corrective interventions, with insulators often contributing disproportionately to outage-related repair costs due to flashovers and environmental fouling.[1-3] Although insulator hardware itself may account for only 5–10% of total line capital cost, performance failures can contribute up to roughly 50% of line maintenance costs and unplanned outage impacts in harsh environments.[8]

By contrast, studies of PdM across industrial sectors suggest that condition-based strategies can reduce overall maintenance costs by 10–40% and decrease unplanned downtime by 30–45% compared with reactive or purely schedule-based approaches, despite requiring moderate upfront investment in sensing and analytics infrastructure. For example, predictive models can shift inspection resources from calendar-based schedules to condition-based thresholds, reducing unnecessary labour and extending component service life, which in power systems could translate into reduced frequency of live-line insulator cleaning or replacement and lower outage risk.

Although precise financial quantification for HV insulators in African transmission systems is beyond the scope of this study, these generalised efficiency trends, combined with evidence that poor environmental and biological fouling can dominate maintenance efforts, illustrate that integrating predictive diagnostic indicators (e.g. biofilm-driven dielectric change) aligns with broader industry benefits of predictive over reactive maintenance strategies (Table 7).[53,54] This supports the practical and cost-efficient value of the framework proposed here, especially for utilities operating in tropical and subtropical climates where environmental stressors accelerate degradation.

Practical applicability, scalability and limitations

The systems-based framework developed in this study offers tangible applications for HV asset management. By integrating field diagnostics with laboratory dielectric characterisation, utilities can predict contamination-prone zones and schedule preventive maintenance more effectively. Environmental variables, such as humidity, rainfall, temperature and pollution indices, can be incorporated into geographic information systems for scalable risk mapping across diverse voltage levels and climatic regions. Dielectric parameters obtained in this study may also be integrated into online monitoring systems for real-time condition assessment.

Nevertheless, certain limitations should be acknowledged. The current model is primarily validated under South African climatic conditions and may require recalibration for other geographical contexts. Laboratory tests

capture short-term biofilm behaviour and may not fully represent long-term environmental ageing. Additionally, the scalability of the biofilm–dielectric coupling model depends on advances in sensor technologies capable of detecting microscale conductivity variations. Despite these constraints, the methodological framework presented here establishes a transferable foundation for PdM, material selection and the design of biologically resilient insulation systems under varying environmental stresses.

Mitigation strategies and future research directions

The findings of this study indicate that biological contamination is not merely a surface fouling phenomenon but a coupled biological–dielectric degradation process. Accordingly, effective mitigation requires strategies that simultaneously address environmental exposure, material susceptibility and surface electrical behaviour.

Future work should focus on the development of bio-resistant insulating surfaces through nanocomposite silicone rubbers, fluorinated RTV coatings and antimicrobial fillers (e.g. copper- or zinc-based additives) that inhibit microbial adhesion while preserving hydrophobicity. Micro- and nanoscale surface texturing to reduce biofilm anchorage, combined with self-cleaning or photocatalytic coatings, represents a promising direction for long-term contamination control.

The systems-based framework proposed here can be extended into a decision-support tool by integrating climatic data (humidity, rainfall, shading and pollution) into geographic information systems–based risk maps. Utilities could then shift from time-based to condition-based maintenance, targeting only biologically high-risk corridors and substations. This approach would reduce unnecessary washing or re-coating and improve cost efficiency.

Future research should explore low-cost dielectric or surface conductivity sensors for detecting early-stage biofilm formation. Coupled with leakage current monitoring and infrared/optical imaging, such systems could provide real-time warnings before flashover risk becomes critical.

Long-term comparative field trials across different climatic regions are required to quantify the durability and cost-effectiveness of bio-resistant coatings and materials. Life-cycle cost and environmental impact analyses should be incorporated to support utility-scale adoption.

Finally, coupling microbial growth kinetics with dielectric ageing and electric field simulations would enable more accurate prediction of insulation lifespan under biological stress, guiding both design standards and maintenance policies.

Collectively, these strategies translate the present findings into a practical roadmap for improving the resilience and sustainability of HV insulation systems operating in biologically aggressive environments.

Conclusions

This study examined the role of biological contamination, particularly algal and fungal growth, in the degradation of HV insulator performance under diverse environmental conditions. By integrating field observations, laboratory-based electrical and dielectric characterisation and synthesis of ecological evidence, the work demonstrates that biological growth is a critical yet often underappreciated driver of insulation ageing.

Environmental drivers such as humidity and rainfall promote microbial colonisation, which degrades surface hydrophobicity and dielectric behaviour, increases leakage currents and accelerates ageing through tracking and erosion.

A central outcome is the identification of a self-reinforcing feedback loop linking biological growth and electrical degradation.

These insights support biologically informed inspection, material selection and mitigation strategies, particularly for HV networks operating in humid and high-rainfall environments.

Future work should prioritise long-term field validation, bio-resistant surface treatments and predictive models integrating climatic, biological and electrical ageing processes.

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Data availability

All the data supporting the results of this study are included in the article itself.

Declarations

I have no competing interests to declare. I have no AI or LLM use in the text to declare. Figure 2 in this paper was initially developed manually using graphic design software (Photoshop) and subsequently refined with the assistance of generative AI tools (ChatGPT) to improve visual clarity and presentation quality. No AI tools were used to generate the conceptual content of the figures or the scholarly arguments of the paper. I reviewed and approved the final figure and assume full responsibility for its accuracy and integrity.

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