International Organization of Research & Development (IORD)
ISSN: 2348-0831
Vol 13 Special Issue 02 | 2026

The Effect of Climate Change on the Making and Performance of Insulators

Chandrakant D. Khanore[1], Aishwarya C. Khanore[2], Anand C. Khanore[3]
[1] Workshop Instructor ,Workshop, Siddhivinayak Technical Campus, Shegaon, Maharashtra, India
[2] Sales Engineer, Sales, Rolex Automation, Gujarat, India
[3] Rojgar Sahayak , MREGS, Block Panchayat, Maharashtra, India

DOI: 10.5281/zenodo.19662043

ABSTRACT

Climate change has emerged as a critical factor influencing the reliability, sustainability, and manufacturing practices of electrical power system components. Among these components, electrical insulators play a vital role in ensuring uninterrupted and safe transmission and distribution of electrical energy. Changes in global and regional climate conditions—such as rising temperatures, increased humidity, altered pollution patterns, frequent extreme weather events, and higher ultraviolet radiation—directly affect both the *manufacturing processes* ***and*** *long-term field performance* ***of electrical insulators. This review paper presents a detailed analysis of how climate change impacts different types of insulators, including ceramic, glass, and polymeric insulators, from raw material processing to operational ageing mechanisms. Manufacturing-related challenges, environmental degradation, performance deterioration, and sustainability concerns are critically examined. Furthermore, the paper discusses adaptation and mitigation strategies to improve insulator resilience under changing climatic conditions. The review highlights research gaps and provides directions for future development of climate-resilient and environmentally sustainable insulation systems.***

Keywords:- Climate change, electrical insulators, polymer insulators, ceramic insulators, ageing, pollution, manufacturing sustainability, power system reliability

1. INTRODUCTION

Electrical insulators are fundamental components of power transmission and distribution networks, serving the dual purpose of electrically isolating conductors while mechanically supporting them. Traditionally, the selection and design of insulators have been based on historical environmental conditions, standard pollution levels, and expected mechanical loads. However, climate change has altered these baseline assumptions by introducing new environmental stresses and intensifying existing ones.

Global warming has resulted in higher average temperatures, increased frequency of heat waves, variations in rainfall patterns, higher atmospheric moisture content, and changes in air pollution chemistry. These climatic shifts influence the electrical, thermal, mechanical, and chemical behavior of insulator materials over their service life. At the same time, the pressure to reduce greenhouse gas emissions has brought attention to the **carbon footprint and energy intensity of insulator manufacturing processes**.

While several studies have addressed insulator ageing, pollution performance, and material degradation independently, a consolidated review linking these aspects to climate change is limited. This paper aims to bridge that gap by systematically reviewing the effects of climate change on both the *making* and *performance* of electrical insulators.

2. CLIMATE CHANGE AND ENVIRONMENTAL STRESS FACTORS AFFECTING INSULATOR

2.1 Rising Ambient Temperature

An increase in ambient temperature affects insulator performance in multiple ways. Elevated temperatures increase surface conductivity, reduce dielectric strength in certain materials, and accelerate thermo-oxidative ageing. Polymeric insulators are particularly sensitive to prolonged heat exposure, which can cause molecular chain scission, hardening, and loss of elasticity. High temperatures also intensify thermal gradients across insulators, leading to localized stress and increased risk of partial discharges.

In manufacturing, higher ambient temperatures may alter curing processes for polymeric materials and affect dimensional stability during ceramic firing, requiring tighter process control.

2.2 Increased Humidity and Moisture Exposure

Climate change has led to increased atmospheric humidity and more frequent fog, dew, and prolonged wet conditions in many regions. Moisture significantly reduces surface resistivity, especially when combined with pollution deposits. This results in increased leakage current, surface heating, dry band formation, and ultimately flashover.

Polymeric insulators experience faster hydrophobicity loss under continuous moisture exposure, while ceramic and glass insulators suffer from higher contamination conductivity during wet periods. Repeated wet–dry cycles accelerate surface ageing and crack formation.

2.3 Changes in Pollution Characteristics

Climate change influences air pollution by modifying wind patterns, precipitation chemistry, and atmospheric reactions. Industrial aerosols, vehicle emissions, salt particles, and agricultural dust interact differently under altered climate conditions. Acidic pollutants and fine particulate matter increase the conductivity of surface contamination layers, significantly lowering flashover voltage.

Insulators installed in urban, industrial, and coastal regions are increasingly exposed to complex mixed pollution, making traditional pollution classification methods less reliable.

2.4 Extreme Weather Events

Storms, cyclones, heatwaves, floods, and dust storms have become more frequent and intense. These events impose severe mechanical loads, sudden contamination deposition, and rapid environmental transitions. Flooding and heavy rainfall can transport salts and pollutants far inland, exposing insulators in previously low-risk regions to aggressive contamination conditions.

2.5 Increased Ultraviolet Radiation

Reduced cloud cover and ozone variation in some regions have increased UV radiation exposure. UV radiation is a major ageing factor for polymeric insulators, causing surface chalking, discoloration, cracking, and erosion. Over time, UV-induced degradation reduces hydrophobic recovery and mechanical strength.

3. IMPACT OF CLIMATE CHANGE ON INSULATOR MANUFACTURING

3.1 Energy Consumption and Carbon Emissions

The manufacturing of ceramic and glass insulators requires high-temperature kilns, making the process energy intensive. Climate change mitigation policies demand reductions in fossil fuel use, pushing manufacturers toward energy-efficient kilns, alternative fuels, and electrification.

Polymeric insulators have lower firing energy requirements but rely on petrochemical raw materials, which raises sustainability and lifecycle concerns

3.2 Raw Material Availability and Quality

Climate-induced disruptions in mining, transportation, and chemical supply chains affect the availability and consistency of raw materials. Variations in humidity and temperature during storage and processing can also influence material properties, especially for polymers and resins

3.3 Manufacturing Process Stability

Increased environmental variability requires stricter control of curing, firing, and molding conditions. For example, higher ambient humidity can affect polymer cross-linking reactions, while temperature fluctuations can impact ceramic shrinkage and defect formation.

4. MATERIAL-SPECIFIC PERFORMANCE UNDER CHANGING CLIMATE

4.1 Ceramic (Porcelain) Insulators

Ceramic insulators exhibit excellent thermal stability and resistance to UV radiation. However, their hydrophilic surface attracts moisture, making them vulnerable to pollution-induced flashover in humid climates. Mechanical brittleness is another concern during extreme weather events.

4.2 Glass Insulators

Glass insulators offer high dielectric strength and smooth surfaces that resist pollution adhesion. Nevertheless, they are susceptible to brittle fracture under mechanical shock and thermal stress. Their performance in rapidly changing climates requires careful mechanical design consideration.

4.3 Polymeric Insulators

Polymeric insulators provide superior pollution performance due to hydrophobic surfaces and lower weight. However, climate change accelerates their ageing through combined UV, moisture, temperature, and electrical stress. Long-term performance depends heavily on material formulation and environmental exposure severity.

5. OPERATIONAL RELIABILITY AND MAINTENANCE CHALLENGES

Climate-driven degradation increases maintenance frequency, washing requirements, and replacement rates. Utilities face higher operational costs and outage risks due to unpredictable environmental stress combinations.

Traditional maintenance schedules based on historical data may no longer be sufficient.

6. ADAPTATION AND MITIGATION STRATEGIES

- Development of UV-resistant and thermally stable polymer formulations
- Increased creep age distance and optimized shed profiles Application of hydrophobic and anti-pollution coatings
- Condition monitoring using leakage current and thermal diagnostics
- Sustainable manufacturing using low-carbon energy sources

7. RESEARCH GAPS AND FUTURE SCOPE

There is a need for climate-specific ageing models, combined-stress testing standards, and long-term field data under evolving environmental conditions. Future research should integrate climate projections into insulator design and asset management strategies.

8. CONCLUSION

This research establishes that climatic and seasonal variations exert a substantial and measurable impact on the manufacturing process and quality parameters of electrical ceramic insulators. Key ambient factors temperature, humidity, and pressure directly influence the characteristic of the ceramic slurry and the efficiency of critical stages like de-airing and drying, ultimately affecting product quality and production waste. To achieve consistent, high- yield manufacturing, the industry must move towards climate-adaptive process control systems. Future research should focus on developing in6tegrated sensor and feedback control loops to dynamically optimize the ceramic insulator making process in response to real-time environmental data.

9. REFERENCE

[1] IEEE Power & Energy Society, *Application of Insulators for Overhead Lines*, IEEE Standard 987, New York, USA, 2013.
[2] International Electrotechnical Commission, *Artificial Pollution Tests on High Voltage Insulators to be Used on AC Systems*, IEC Standard 60507, Geneva, Switzerland, 2013.
[3] R. S. Gorur, E. A. Cherney, and J. T. Burnham, *Outdoor Insulators*, Phoenix, AZ, USA: Ravi S. Gorur Inc., 1999.
[4] CIGRÉ Working Group D1.27, *Pollution Performance of Outdoor Insulation*, Technical Brochure 361, Paris, France, 2008.
[5] Masoud Farzaneh, *Insulators for Icing and Polluted Environments*, New York, USA: Springer, 2008.
[6] IPCC, *Climate Change 2021: The Physical Science Basis*, Contribution of Working Group I to the Sixth Assessment Report, Cambridge University Press, 2021.
[7] L. L. Grigsby, *Electric Power Engineering Handbook*, 3rd ed., Boca Raton, FL, USA: CRC Press, 2012.
[8] IEEE Power & Energy Society, *Guide for the Selection of Insulators for Outdoor Conditions*, IEEE Standard 1313.2, 2004.
[9] T. S. Sudarshan and M. Farzaneh, "Environmental Effects on Outdoor Insulators," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 18, no. 5, pp. 1470–1480, Oct. 2011.