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Review of Electrical Insulator Materials: Performance, Innovation, and Environmental Factors

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Abstract -- Electrical insulators are vital components in power transmission and distribution systems. The performance of insulators is greatly affected by environmental conditions such as humidity, pollution, and temperature, as well as by their material composition. This study reviews several recent scientific publications related to the performance of ceramic, polymer, and composite insulators under various environmental conditions. The analysis results show that environmental contamination significantly reduces the performance of insulators, while industrial and agricultural waste-based materials such as rice husk ash (RHA) and fly ash offer great potential as innovative and environmentally friendly solutions. Experimental and simulation methods play an important role in understanding the electrical characteristics of insulators thoroughly.

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I. INTRODUCTION

A. Background

The Electrical insulators are important components in power transmission and distribution systems because they separate conductive parts from supporting structures and prevent leakage current [1]. In tropical regions such as Indonesia, environmental challenges such as high humidity, air pollution, and moss growth can accelerate insulator degradation [2]. Research shows that contaminants such as sea salt, dust, and biological particles can form conductive layers that increase leakage current and trigger flashovers [3]. Even when insulators appear clean, humid environmental conditions can significantly reduce insulation performance [4]. One of the key parameters for measuring contamination levels is the value of ESDD (Electric Surface Deposit Density) and NSDD (Non-Soluble Deposit Density) [5]. Research by Saputra et al. demonstrated that moss contamination can cause leakage current THD (Total Harmonic Distortion) values to reach 36%, far above the IEEE STD 519-2014 standard limit of 15% [6].

To address these issues, various alternative materials such as rice husk ash (RHA) and fly ash are being studied because of their high silica content and good hydrophobic properties [7]. In addition, silicone rubber insulators have shown more stable performance against temperature and humidity compared to ceramic insulators [8]. Sensor-based monitoring technology and FEM (Finite Element Method) simulation are now used to detect critical points in insulator design more accurately [9]. Therefore, studies that combine experimental, simulation, and field observation approaches are needed to design reliable insulator systems in tropical environments [10].

This paper was developed because there are still limited studies that compare different types of insulators in detail and comprehensively. Most previous studies only focused on a single type of insulating material or highlighted only one performance aspect, such as leakage current [1][2], without relating it to mechanical properties [4][13], resistance to temperature and humidity [11][12][14], or responses to pollution and contamination [3][5][8]. In fact, in tropical environments such as Indonesia, insulators must be able to simultaneously withstand complex challenges such as high humidity [19], salt particles, extreme temperatures, and moss growth [2][5][6]. Therefore, this review aims to compare the performance of insulators made of ceramic, polymer, and composite materials comprehensively, both mechanically and electrically, including their influence on leakage current and flashover risk [1][7][9][10]. The goal is to provide a complete and practical overview to support the selection of reliable insulators for tropical environments [6][12][14].

II. METHOD

This study uses a systematic literature review approach combined with descriptive-comparative analysis [1][2][3]. The objective is to provide a comprehensive understanding of research developments related to the performance of electrical insulators in various environmental conditions, material types, and testing techniques [4][5]. This method allows for the collection, critical evaluation, and synthesis of information from relevant and verified scientific sources [6][7]. Data sources were drawn from scientific articles published between 2020 and 2025, with a main focus on medium to high-voltage insulator systems [8][9]. The selected articles present clear testing methodologies and provide technical data such as leakage current, breakdown voltage, contact angle, and THD [10][11]. The analysis process involved identifying key variables, classifying results by material type and evaluation method, and comparing performance across studies [12][13][14].

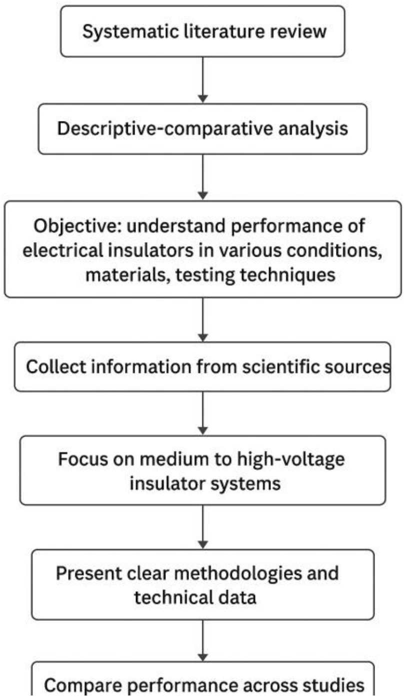

Figure 1. Flowchart for method

III. RESULT AND DISCUSSION

This study demonstrates that the performance of electrical insulators is significantly influenced by the type of insulating material, operating environment, and evaluation methods employed. Factors such as high humidity, air pollution, and biological contamination (e.g., moss) critically determine leakage current stability, insulation capability, and long-term durability of a material.

Ceramic is known for its high mechanical strength, heat resistance, and long service life under dry conditions [1][4]. However, its weakness lies in sensitivity to surface contamination, particularly in humid and dusty tropical environments. Research indicates that under moss-covered conditions, leakage current in ceramic insulators can reach 36% THD, exceeding the safe limit according to IEEE Std 519-2014 [1]. Even on seemingly clean surfaces, leakage current values remain significant when environmental humidity is high [2][5]. Fog-type ceramics offer better pollution resistance but have drawbacks in terms of weight and production costs [4].

Polymers such as silicone rubber and epoxy resin offer advantages including natural hydrophobic properties, light weight, and ease of installation. Polymers also exhibit improved resistance to tracking and erosion in newer formulations [20]. In tropical environments, these materials demonstrate more stable performance as they can repel water and prevent the formation of conductive pathways on surfaces [5][12][14]. However, epoxy-based insulators have weaknesses in resistance to high humidity and UV-induced aging. UV exposure causes polymer surfaces to become brittle and develop micro-cracks, thereby reducing insulation effectiveness [10][11][15][16].

Waste-based alternative materials, such as RHA and fly ash, are increasingly being researched as environmentally friendly insulator solutions. RHA features high silica content and a water contact angle >109°, indicating excellent hydrophobicity [3]. Meanwhile, fly ash can enhance the breakdown voltage value in epoxy resin composite materials [9][10]. However, performance may decline if concentration is too high, due to uneven particle distribution [7]. Test results from various journals show that leakage current values in ceramic insulators are substantially higher compared to polymers and composites. For instance, leakage current in ceramics under humid conditions can reach 188 µA, while silicone rubber records only about 22 µA [12][13]. This reinforces the argument that polymers and composite materials are superior in withstanding extreme tropical climates.

A. Comparison of Material Characteristics

Ceramic insulators possess high mechanical strength and heat resistance, but their performance drastically declines when contaminated with moss or salt, which increases leakage current and flashover risk [1][2][4]. In contrast, polymers such as silicone rubber and epoxy resin exhibit good hydrophobic properties and greater stability in tropical environments, although they are susceptible to UV aging [5][12][14].

Meanwhile, waste-based composite materials like Rice Husk Ash (RHA) and fly ash offer environmentally friendly alternatives with competitive insulation performance. RHA contains high silica content that enhances water contact angle and durability against moisture [3][9]. However, their long-term stability and application under extreme conditions still require further validation [7][10].

Considering tropical environments and contamination potential, polymers and waste-based composites demonstrate superiority for modern insulator applications compared to ceramics or glass [13].

A review of the collected journals was conducted to identify key findings, along with publication years and total citations, as explained in Table 1. The table provides an overview of journals analyzed from 2019 to 2024 using the keywords bioenergy, technology, and conversion. The collected articles were reviewed based on their main topics and abstracts to identify key research points, along with publication years and citation counts [4,9,19].

TABLE I.
Comparison of Insulator Materials

Material	Advantages	Disadvantages	References
Ceramic	Heat resistant, mechanically strong	Prone to contamination, high THD	[1][2][4][6]
Polymer	Hydrophobic, lightweight, stable in humidity	UV sensitive, rapid aging	[5][11][12][14]
RHA/Fly Ash	High silica content, eco-friendly	Requires long-term validation	[3][7][9][10]
Glass	High breakdown voltage	Less moisture resistant	[13]
Fog-type Ceramic	Contamination and flashover resistant	Heavy and expensive	[10]

B. Review Results of Each Insulator Material

Ceramics are heat-resistant and strong but vulnerable to contamination. Leakage current and THD increase sharply when exposed to moss or high humidity, even if the surface appears clean [1][2][4][5][8]. Polymers like silicone rubber and epoxy are more stable in tropical environments due to their hydrophobic properties. Fog-type ceramics resist contamination and flashover but are physically heavy and more expensive. However, epoxy resin is sensitive to high humidity and less resistant to UV aging [10][11][12][14].

RHA and fly ash show high potential as alternative insulators. RHA is silica-rich and highly hydrophobic, while fly ash enhances breakdown voltage, though performance declines with excessive content [3][7][9][10].

TABLE II.
Percentage of Material Types on Leakage Current

Material Type	Leakage Current Percentage	Leakage Current	Method	References
Ceramic	21.84%, 18.27%, 36%	-	Fast Fourier Transform (FFT)	[1]
Clean 150 kV Insulator	-	0.9444 mA, 0.67 mA	Hileman Method	[2]
Disc Porcelain & Glass	-	188.672 µA, 194.831 µA	Outdoor Test	[13]
Porcelain	-	66.191 µA	Direct Measurement	[14]
Silicone Rubber	-	22.397 µA	Field Method	[12]

C. Evaluation of Testing Methods

Laboratory experimental methods are widely used to measure leakage current, THD, breakdown voltage, and contact angle on insulator surfaces [1][2][3][4]. Their advantage lies in accurate and controlled results, though they are limited to small scales and artificial conditions. These tests often reference international standards describing artificial pollution tests [17], serving as references in statistical analysis of electrical insulation failures [18].

FEM simulations are effective in mapping electric field distribution and identifying critical points in insulator design [6][9]. This method is highly useful for design optimization before prototype manufacturing, though it requires experimental validation. Field observations provide realistic insights into insulator performance under tropical environmental conditions such as rain, pollution, and high humidity [5][8][13]. Although the data varies and is difficult to control, this approach is crucial for understanding actual degradation.

IV. CONCLUSION AND RECOMMENDATIONS

This study demonstrates that electrical insulator performance is significantly influenced by material type and environmental conditions. Ceramic insulators are vulnerable to contamination in tropical environments, while polymers show more stable performance due to their hydrophobic properties. Alternative materials like RHA and fly ash have potential as efficient and environmentally friendly insulator solutions. The most effective insulator evaluation combines experimentation, simulation, and field observation.

Further testing of composite materials is necessary to ensure their long-term stability. Polymer and industrial waste-based insulators require additional development, particularly for tropical regions. Moreover, the utilization of leakage current sensor-based monitoring technology and numerical modeling like FEM, is highly recommended to enhance insulation system reliability.

Further development and testing of alternative insulator materials (RHA and fly ash) are crucial. Research focus should be directed toward optimizing material mixtures, enhancing long-term stability, and understanding mechanical and electrical behavior under various extreme environmental conditions for broad and reliable application. Polymer insulators are recommended for tropical regions to reduce failure risks due to contamination and humidity. However, special attention must also be given to UV degradation and oxidation issues through the development of durable polymer formulas.

Combined evaluation methods (laboratory, simulation, and field observation) should be routinely adopted in insulator material research and testing. This ensures valid, realistic results applicable to real-world scenarios and identifies potential material failures before widespread implementation. Further research is needed in formulating and manufacturing environmentally friendly insulator technologies that meet electrical performance standards and mechanical durability. The use of industrial and agricultural waste materials must be accompanied by processing technologies capable of producing high-quality, long-lasting insulators.

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