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Performance of Used and Aged Glass Insulators Against Basic Insulation Level (BIL)

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ABSTRACT — High-voltage insulators are crucial for ensuring the reliability and safety of electrical systems operating under high voltage. Their primary function is to electrically separate phase conductors from each other and the ground. In designing electrical power systems, the basic insulation level (BIL) is a key parameter that must not be neglected, representing the maximum voltage the system can endure before a flashover occurs on the insulator. Besides voltage endurance, insulators are required to withstand environmental factors like temperature, humidity, and pollution, which can considerably affect their performance. This research examined the performance of glass insulators used at the Adipala power plant under diverse environmental conditions, comparing the outcomes against the BIL standard. Four testing scenarios were employed: optimal conditions, wet conditions, polluted conditions, and polluted insulators in humid environments. Findings indicate that wet conditions and the combined presence of pollution and humidity exert the most substantial impact on insulator performance. Under clean conditions with exposure to rain, insulator performance degraded by 19% to 25%. In contrast, when subjected to pollutants with an equivalent salt deposit density (ESDD) of 0.113816 mg/cm² and a non-soluble deposit density (NSDD) of 1.309962 mg/cm² at 90% humidity, performance diminished by 41% to 53%, falling significantly below the BIL threshold.

KEYWORDS — Insulator, BIL, Humidity, ESDD, NSDD.

I. INTRODUCTION

Insulators are a fundamental component in high-voltage equipment, serving as the medium separating phase conductors from other phase conductors and from the ground [1]. The materials comprising the insulator must exhibit properties such as thermal resistance, high mechanical strength, robust insulation capacity, and effective sealing against liquids or gases that could diminish the insulator's dielectric strength [2]. Insulating materials may be composed of solids, liquids, or gases, each with distinct dielectric strength values. Dielectric strength is defined as the ability of a material to withstand voltage per unit length (kV/m). Solid insulators can be further categorized based on both their constituent materials and shapes. According to [3] several insulator profiles exist, including standard profiles, aerodynamic profiles, anti-fog profiles, and alternating shed profiles.

Mechanically, the insulator functions to withstand the load of the overhead line wire. Electrically, the insulator functions to isolate the voltage line so that there is no current leakage [4]. Insulators utilize the inherent properties of constituent dielectric materials to inhibit the movement of electric charges, ensuring that no current flows [5]. Insulators utilize the inherent properties of dielectric materials to inhibit the movement of electric charges, ensuring that no current flows [5]. Dielectric materials are typically classified into three types: solid, liquid, and gaseous, with further subdivisions within each type based on specific properties. The selection of dielectric material depends on the insulator's performance requirements. This paper focuses on solid insulators, as they are commonly used in electrical power systems. Common solid insulator materials include glass, ceramics, and composite materials, with glass becoming increasingly popular. Glass has a dielectric strength of 140 kV/cm, significantly higher than that of ceramics, which stands at 60 kV/cm [5]. This research specifically examines glass solid insulators due to their superior dielectric strength compared to ceramics. The insulator type under study features an anti-fog profile, which is increasingly implemented in the field to minimize dew formation on the insulator surface.

In addition to the dielectric strength of the material, another critical factor in insulator selection is the creepage distance. Creepage distance is defined as the minimum distance along the insulator surface between two conductive parts at opposite ends of the insulator [6]. An increase in creepage distance, for a given dielectric strength, enhances the insulation capacity of the insulator. When calculating creepage distance, non-insulating materials such as cement are excluded. Generally, a greater creepage distance corresponds to higher insulation strength, thereby reducing the likelihood of surface discharge.

The basic insulation level (BIL) represents the maximum voltage threshold before an insulator experiences a flashover. Each nominal voltage has an associated BIL, such as 110 kV for a 15 kV nominal voltage, 150 kV for a 25 kV nominal voltage, and 200 kV for a 34.5 kV nominal voltage [7]. BILs are classified into conventional and statistical types. The conventional BIL denotes the peak level of standard lightning impulse voltage that does not result in damage, whereas the statistical BIL indicates the peak standard lightning impulse voltage at which the insulator has a 90% probability of withstanding the impulse and a 10% probability of failure [8]. BIL is essential in power system design, as it informs the maximum operating voltage and contributes to the safety of both equipment and personnel.

In high-voltage electrical systems, creepage distance and BIL are interdependent parameters that must be jointly considered to ensure effective and reliable insulation performance. The creepage distance must be sufficient to achieve the required insulation strength, while the BIL must be adequate to withstand the system's maximum operating voltage. Designing high-voltage insulation systems requires accounting for environmental factors—such as temperature, humidity, and pollution—that can influence both creepage distance and BIL.

The insulating strength of an insulator is influenced by both internal and external factors. Internal factors, such as the material's dielectric strength, significantly impact the insulator's ability to withstand voltage: a higher dielectric strength corresponds to a stronger resistance to voltage stress. Additionally, production imperfections, such as micro voids within the insulator's structure, can substantially affect performance. External factors also play a crucial role in determining insulation strength. Environmental conditions—temperature, humidity, pollutant deposition, sunlight, and water droplets on the insulator surface—can degrade the insulator and reduce its surface insulation strength [9]. A continuous decrease in insulation strength can result in increased surface leakage current, also known as surface discharge [10]. If the surface discharge continues unchecked, it can initiate a flashover. Repeated flashovers may ultimately cause the insulator's surface glaze to peel, further diminishing its insulating properties.

A decrease in insulation strength compromises the insulator's capacity to withstand voltage surges originating from internal network phenomena, such as switching surges, or external sources, such as lightning strikes. Such voltage increases can adversely impact and potentially damage the electrical system [3], [11].

In practical applications, glass insulators are predominantly used in outdoor environments, where they are inevitably exposed to pollutants and variations in ambient humidity. Persistent pollutant exposure forms a contaminant layer on the insulator surface. Under dry conditions, this layer has a minimal effect on the insulating strength. However, in humid conditions, the electrolyte within the contaminants can dissolve, increasing the surface conductivity of the insulator. This rise in conductivity directly reduces insulation strength and raises the risk of flashover, significantly impacting the stability and safety of the power system [12]–[14].

The pollution severity of an insulator site can be assessed by measuring the equivalent salt deposit density (ESDD) and non-soluble deposit density (NSDD) values [15], [16], as shown in Figure 1. ESDD measurement quantifies the conductivity of contaminants in mg/cm^2. ESDD can be defined as the amount of sodium chloride (NaCl) dissolved in demineralized water contained within the contaminants. ESDD measurement begins with the removal of contaminants attached to the insulator surface into 100–300 ml of distilled water. The conductivity of this solution, containing all dissolved pollutants from the insulator, is then measured using a conductivity meter.

In addition to the ESDD, the NSDD of pollutants must also be taken into account. NSDD refers to the concentration of pollutants that are insoluble in distilled water and is measured in mg/cm^2. The NSDD measurement process begins by filtering distilled water containing pollutants through filter paper after conductivity has been measured. The difference in the filter paper's weight before and after filtration provides the NSDD value.

Since insulators are predominantly installed outdoors, environmental factors such as pollutant deposition and humidity are critical in assessing their performance. This study

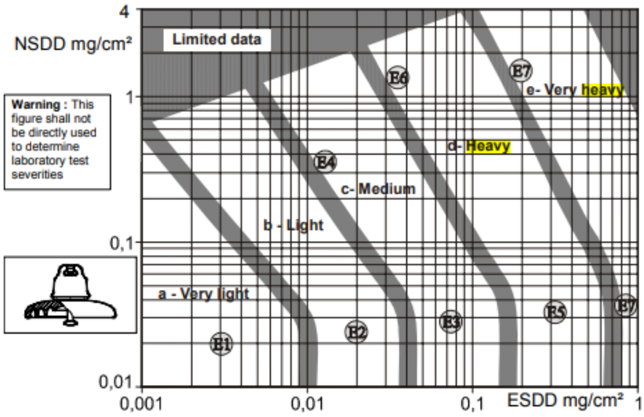

Figure 1. Site pollution severity (SPS) [16].

aims to evaluate the performance of decommissioned glass insulators from the Adipala power plant (*pembangkit Listrik tenaga uap*, PLTU Adipala) under various environmental conditions, with a comparison to their BIL rating.

II. MATERIALS AND METHODOLOGY

A. MATERIALS AND EQUIPMENT

1) GLASS INSULATORS

The test objects consist of three previously utilized glass insulators that exhibit surface degradation, including treeing and cracks. These insulators were originally part of the 500 kV transmission network, as illustrated in Figure 2.

2) FLY ASH AND SALT

A pollutant mixture comprising 300 g of fly ash and 50 g of sea salt was prepared. Both components were dissolved in 300 ml of distilled water to produce a liquid pollutant, which was then uniformly sprayed onto the insulator surfaces. This fly ash and salt mixture simulates type A pollutants, representative of sand-based contamination.

3) DISTILLED WATER

Distilled water served as a cleaning agent for the insulator, as a component in humidity control mist, and as a solvent for fly ash and sea salt contaminants. Its low conductivity was selected to prevent interference with test results.

4) POLLUTANT SPRAYER

The pollutant sprayer was utilized to uniformly apply contaminants to the insulator surface. This device consists of a spray gun for pollutant dispersion, a motor, and a frequency-controlled speed regulator to maintain the stable rotation of the insulator. The combination of these components ensures consistent pollutant application across the insulator surface. Figure 3 illustrates the pollutant application device.

5) CONDUCTIVITY METER

A conductivity meter was used to determine the conductivity of pollutants adhered to the insulator surface. The measured conductivity value of the pollutants was then utilized to calculate the ESDD of the contaminants.

6) PRESSURE-REDUCING PUMP

The pressure-reducing pump accelerated the filtration process of pollutants using filter paper in order to measure the pollutant mass attached to the insulator.

7) FILTER PAPER

The filter paper used has a diameter of 47 mm, thickness of 0.26 mm, and pore size of 1.6 µm [16]. It served as a medium

Figure 2. Test insulators.

Figure 3. Pollutant sprayer device.

to separate water-soluble pollutants from water-insoluble pollutants. Water-insoluble pollutants are retained on the filter paper, which is subsequently used in NSDD measurement.

8) A SCALE

A scale was used to measure the mass of water-insoluble pollutants retained on the filter paper. This mass measurement provides data necessary for determining the NSDD value.

9) CHAMBER

Testing insulators in humid environmental conditions is not possible outdoors, as the humidity on the insulator decreases sharply after a flashover event. This was mitigated by using an acrylic chamber, which isolated the internal humidity from external conditions. The chamber dimensions were 250 cm × 250 cm × 270 cm. Figure 4 illustrates the chamber used in this testing setup.

10) HUMIDIFIER

The humidifier was placed within the chamber as a mist generator using distilled water. The generated mist served to elevate the chamber's humidity levels.

11) TEMPERATURE AND HUMIDITY SENSOR

The temperature and humidity sensors were installed inside the chamber and integrated with the humidifier. This sensor provided real-time temperature and humidity data and controlled the humidifier's operation based on the pre-set humidity threshold.

12) AIR PRESSURE SENSOR

The air pressure sensor provided measurement values of air pressure within the testing environment.

13) SPONGES

Sponges were used to clean insulators and to remove any artificial pollutants adhered to insulators.

14) BEAKER GLASS

The beaker held distilled water, liquid contaminants, and the liquid used for cleaning the insulators.

B. INSULATOR DURABILITY TESTING METHOD

The surrounding environmental conditions significantly impact the insulation strength of glass insulators. Humidity and pollution levels are the most influential and controllable factors in durability testing. To assess the impact of these factors, a comparative test combining both is necessary. In this study, a used anti-fog glass insulator, previously employed on 500 kV transmission lines, served as the test object. Typically, 26–30 insulator discs are used in such 500 kV networks. According to [8], the BIL of the insulator must withstand 3,500 kV, meaning each insulator disc should endure a voltage range of 117 kV to 134 kV. Four testing schemes are outlined below to evaluate the insulator's performance under voltage stress.

Figure 4. Chamber for humidity control.

1) STRENGTH TESTING OF INSULATORS UNDER CLEAN AND DRY CONDITIONS

The first test scheme involved setting the insulator in a clean, pollutant-free state and conducting the test under dry conditions. This setup aimed to obtain data on the insulator's maximum performance when subjected to voltage.

2) STRENGTH TESTING OF INSULATORS UNDER CLEAN AND WET CONDITIONS

In the second test scheme, the insulator was maintained in a clean state but tested under wet conditions, where humidity was a primary factor observed. Moisture, such as that from rain, influences the insulator's ability to withstand voltage.

3) STRENGTH TESTING OF INSULATORS UNDER POLLUTED AND DRY CONDITIONS

The third test scheme involved applying a homogeneous layer of pollutants to the surface of the glass insulator, followed by testing under dry conditions. This setup examined the effect of dry pollutants on the insulator's voltage withstand capability.

4) STRENGTH TESTING OF INSULATORS UNDER POLLUTED AND HUMID CONDITIONS

The fourth testing scheme involved using an insulator treated with uniform contaminants and subjected to humid conditions. Humidity levels were controlled in a chamber set to 90%, simulating conditions akin to rainy environments. This setup allowed for observing the impact of wet pollutants on the insulator's performance in withstanding voltage.

C. METHOD FOR MEASURING POLLUTANT LEVELS

The performance of an insulator, indicated by its breakdown voltage (BDV) value, is affected by various factors, including pollutant severity, quantified by ESDD and NSDD values. As these pollutant values increase, the insulator's resistance decreases, leading to a reduction in its BDV [17]. To assess pollutant severity on the insulator surface, testing of ESDD and NSDD values is required [18], [19]. The procedure for this assessment is outlined as follows [16].

1) ESDD TESTING

The ESDD testing procedure began by removing pollutants from the insulator surface using 100–300 ml of distilled water and a sponge. The sponge, moistened with distilled water,

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allowed pollutants on the insulator surface to adhere more effectively. The insulator surface was gently wiped with the sponge, which was then squeezed into a measuring cup containing distilled water to transfer the collected pollutants. This cleaning process was conducted slowly to minimize any uncollected pollutants, and the wiping was repeated until the insulator was free from contaminants. The distilled water containing pollutants was then tested for conductivity using a conductivity meter. Based on this conductivity measurement, ESDD was calculated using (1) and (2).

$$Sa = (5{,}7\sigma_{20})^{1.03} \tag{1}$$

$$ESDD = Sa\frac{V}{A} \tag{2}$$

where Sa is the salinity (kg/m^3), σ_{20} represents the conductivity at 20 °C (S/m), ESDD is the equivalent salt deposit density (mg/cm^2), V is the volume of distilled water (cm^3), and A is the pollutant pick-up area on the insulator (cm^2).

2) NSDD TESTING

While ESDD testing focuses on water-soluble pollutants, NSDD testing targets water-insoluble pollutants. The NSDD measurement process utilized the test solution from the ESDD procedure. The primary objective of the NSDD test was to determine the weight of water-insoluble pollutants. This was achieved by filtering the distilled water containing pollutants from the ESDD testing process through filter paper. The weight of the pollutants was determined from the difference between the two measured values. To expedite the filtration, a pressure-reducing pump was employed, increasing the pressure differential across the filter paper. Following filtration, the filter paper was placed in an oven to accelerate the drying process. The weight of the filter paper was then compared between its pre-filtering and post-filtering conditions.

$$NSDD = 1000\frac{Wf-Wi}{A} = 1000\frac{Wp}{A} \tag{3}$$

$$Wp = Wf - Wi \tag{4}$$

where NSDD is the non-soluble deposit density (mg/ cm^2), Wp is the weight of pollutants (grams), Wf is the weight of the filter paper containing pollutants in a dry state (grams), Wi is the weight of the clean and dry filter paper (grams) and is the pollutant pick-up area on the insulator (cm^3).

III. RESULTS AND DISCUSSION

A. STRENGTH TESTING OF INSULATORS UNDER CLEAN AND DRY CONDITIONS

The initial test measured the strength of glass insulators under clean and dry conditions, free from pollutants. This test aimed to establish the maximum voltage withstand capability of the insulator. Insulators cleaned with distilled water were tested ten times. As illustrated in Figure 5, the BDV values of insulators A and B were relatively stable, while insulator C displayed greater fluctuations. The average BDV values obtained were 94 kV for insulator A, 97 kV for insulator B, and 100 kV for insulator C. These values serve as reference points for the maximum capability of each insulator under clean and dry conditions.

B. STRENGTH TESTING OF INSULATORS UNDER CLEAN AND WET CONDITIONS

The subsequent test evaluated insulator performance with clean surfaces under wet conditions. Each insulator was tested ten times. This test was conducted during rainfall, with humidity levels recorded at 87.3% for insulator A, 88.5% for insulator B, and 93% for insulator C. Figure 6 shows a reduction in BDV values for each insulator compared to the clean and dry test results. The average BDV values were 74.46 kV for insulator A, 79.48 kV for insulator B, and 75.13 kV for insulator C.

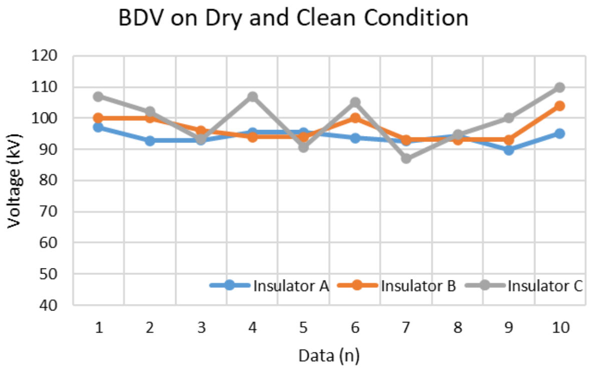

Figure 5. Breakdown voltage under clean and dry conditions.

The average values obtained under rainy conditions were lower than those recorded under dry conditions. Notably, insulator C exhibited the greatest decrease in performance, attributed to its highest humidity levels during testing. This outcome suggests that increased humidity and wet conditions significantly reduce insulator performance.

C. ESDD AND NSDD TESTING RESULTS

The ESDD and NSDD measurements provided data on the pollutant quantities present on the insulator surface. The ESDD value was determined by conductivity data, the volume of distilled water, and the surface area of the insulator, while the NSDD value was based on pollutant weight data and the insulator surface area. The parameters required for ESDD and NSDD measurements are summarized in Table I.

Upon obtaining all necessary data, ESDD and NSDD values were calculated using (1) through (3). The calculated results are presented in Table II.

Based on pollution severity classifications shown in Figure 1, the three insulators were categorized under the heavy severity level, a level typically observed in coastal areas, deserts, arid regions, and industrial zones with significant pollution.

D. STRENGTH TESTING OF INSULATORS UNDER POLLUTED AND DRY CONDITIONS

Following testing under clean conditions, the insulator was evaluated with the presence of pollutants. In this test, pollutants consisting of a mixture of fly ash and salt were applied to the insulator, which was then tested ten times under dry conditions. As shown in Figure 7, Insulator A demonstrated the most stable BDV value across the ten measurements compared to the other two insulators. The average BDV values recorded under polluted and dry conditions were 92.85 kV for insulator A, 94.75 kV for insulator B, and 96.49 kV for insulator C.

These values show minimal deviation from the BDV values obtained under clean, dry conditions, indicating that the presence of pollutants does not significantly impact insulator performance when humidity is low. This finding aligns with previous research, which suggests that pollutants alone, without high humidity, do not substantially affect BDV values [20].

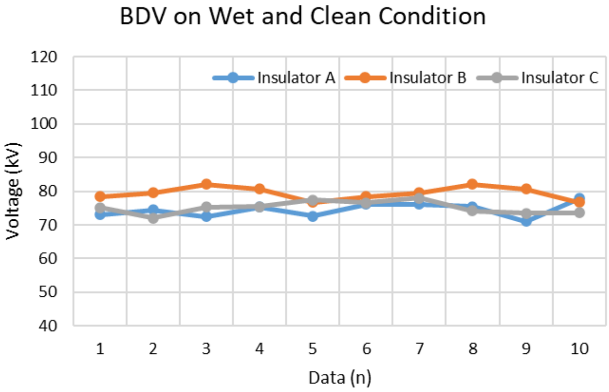

Figure 6. Breakdown voltage under clean and rainy conditions.

TABLE I
ESDD AND NSDD MEASUREMENT PARAMETERS

Parameters	Insulator A	Insulator B	Insulator C
Conductivity (S/m)	0.3	0.284	0.12
Volume of distilled water (cm^3)	400	400	400
Surface area (cm^2)	5,772	5,772	5,772
Pollutant mass (g)	9.9167	7.5611	6.4568

TABLE II
ESDD AND NSDD CALCULATION RESULTS

Measurement Results	Insulator A	Insulator B	Insulator C
ESDD (mg/cm^2)	0.120426	0.113816	0.046864
NSDD (mg/cm^2)	1.718070	1.309962	1.118642

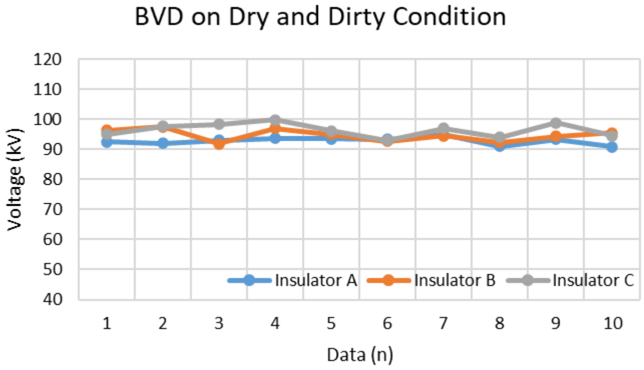

Figure 7. Breakdown voltage under polluted and dry conditions.

E. STRENGTH TESTING OF INSULATORS UNDER POLLUTED AND HUMID CONDITIONS

The subsequent insulator test involved evaluating insulator performance in a high-humidity environment with pollutant exposure. This test differed from the clean insulator testing under simulated rainy conditions, as rain could potentially wash away pollutants. To mitigate this, testing was conducted in a chamber equipped with a humidifier, maintaining air humidity at 90%.

As shown in Figure 8, all three insulators exhibited a marked performance decline compared to the initial test. In this test, the average BDV values recorded were 56.07 kV for insulator A, 45.48 kV for insulator B, and 52.21 kV for insulator C.

These values represent the lowest BDV measurements across all four tests conducted. Compared to the initial test, performance decreased by 41% for insulator A, 53% for insulator B, and 48% for insulator C. The substantial reduction in BDV under the combined influence of pollutants and high humidity aligns with previous studies [21], [22].

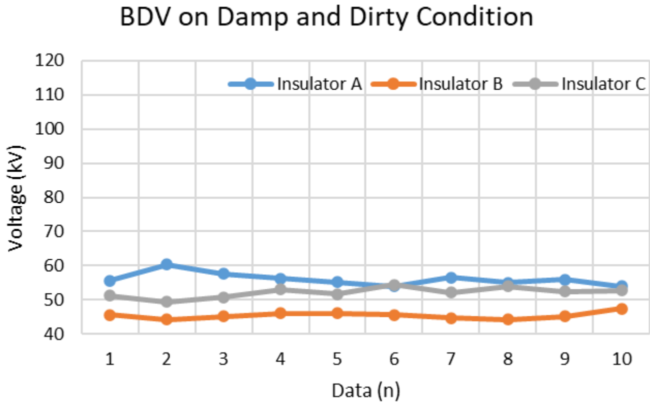

Figure 8. Breakdown voltage under polluted and humid conditions.

IV. CONCLUSION

Based on test results for three anti-fog insulators previously used in a 50 kV transmission network, it was observed that under optimal conditions, all insulators exhibited breakdown voltages below the BIL standard of 117–134 kV. Ideally, these insulators should withstand BIL voltage even under adverse conditions (dirty and humid). Additionally, pollutants under dry conditions were found to have minimal impact on insulator performance in terms of voltage withstand capability. However, when pollutants were present in wet or humid conditions, insulator performance declined significantly. In this experiment, insulator performance decreased by up to 53% when exposed to pollutants with an ESDD of 0.113816 mg/cm^2 and an NSDD of 1.309962 mg/cm^2 under 90% humidity.

CONFLICTS OF INTEREST

The authors declare that this research was conducted and reported without any conflict of interest.

AUTHORS' CONTRIBUTIONS

Conceptualization, Naufal Hilmi Fauzan; methodology, Naufal Hilmi Fauzan; formal analysis, Naufal Hilmi Fauzan and Adhimas Daffa Kurnia; investigation, Naufal Hilmi Fauzan; data curation, Adhimas Daffa Kurnia, Prayudi Efendi, Daryadi, Prasetyohadi; writing—original draft preparation, Naufal Hilmi Fauzan, Adhimas Daffa Kurnia, and Prayudi Efendi; writing—reviewing and editing, Naufal Hilmi Fauzan; visualization, Adhimas Daffa Kurnia and Prayudi Efendi; supervision, Naufal Hilmi Fauzan; project administration, Naufal Hilmi Fauzan; funding acquisition, Naufal Hilmi Fauzan.

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