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Experimental comparison of air, oil, and liquid nitrogen cooling media on the efficiency of a single-phase transformer

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ABSTRACT

Transformers are critical component in electric power system, where minimizing energy losses is essential for efficiency and reliability. While ideal transformers operate with zero losses, practical transformers dissipate energy through winding and core losses caused by resistive heating. This study investigates the impact of three cooling media with ambient air, mineral oil, and liquid nitrogen on the efficiency and thermal performance of a 1 kVA single phase copper wound transformer. The experiment applied a resistive load under each cooling condition, recording input and output parameters using a HIOKI power meter model PW3360. Thermal behavior was monitored using infrared thermography and thermocouples. Copper winding resistivity was evaluated using a four-point probe within a cryogenic magnet system. The results show that liquid nitrogen cooling significantly reduced copper resistivity due to low-temperature conditions, achieving a transformer efficiency of 89.9%. Oil cooling improved efficiency to 86.0%, compared to 80.7% with air cooling. Although liquid nitrogen provided the greatest efficiency enhancement, its practical use is limited due to handling complexity and cost. In contrast, oil cooling offers a more feasible and effective solution for improving transformer performance in real world applications. These finding provide valuable insight for optimizing transformer thermal management strategies in power systems.

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1. INTRODUCTION

In order to ensure grid dependability and provide steady power delivery, power transformers are a vital part of contemporary power systems [1]. However, design, material characteristics, and operating conditions have a big impact on their effectiveness and performance. Overall system efficiency is directly impacted by transformer losses, which are mostly composed of copper, iron, dielectric, and stray losses [2] [3]–[5]. Conductor resistance rises as a result of current flow-induced resistive heating of windings, raising operating temperatures and hastening insulation ageing [6], [7]. Therefore, to increase transformer performance, prolong service life, and guarantee a dependable power supply, efficient heat management techniques are essential.

Extensive research has been conducted to investigate transformer cooling methods and their impact on performance. Conventional techniques such as air natural (AN), air forced (AF), and oil natural air forced (ONAF) cooling rely on heat exchanger, natural convection, or forced circulation to dissipate thermal energy [8]. However, advancements in thermal design have introduced innovative solutions, including adsorption based cooling [9] forced oil circulation system, and cryogenic cooling using liquid nitrogen [10], [11]. These studies demonstrate that liquid nitrogen significantly reduces winding resistivity and improves efficiency by lowering operational temperatures, while oil cooling remains the most practical choice for conventional power systems. Despite these advancements, a direct experimental comparison of air, oil, and liquid nitrogen cooling under identical load and measurement conditions remain scarce.

Recent works have focused on computational simulation and diagnostic assessments to analyze transformer performance and optimize cooling strategies. Studies based on finite element methods (FEM) have evaluated magnetic flux distribution, current density, and hotspot formation under unbalanced loading conditions, providing valuable insight into heat transfer and thermal behavior [12]–[14]. Optimization techniques targeting transformer core design, material selection, and geometry further enhance energy efficiency and minimize losses [15], [16]. Further demonstrated that core geometry and material selection directly influence power losses and thermal stability. However, simulation-based approaches often lack experimental validation, particularly under diverse cooling environments, highlighting the need for comparative measurements using an actual transformer system. At the same time, condition monitoring techniques based on electrical diagnostics and partial discharge detection offer tools for predictive maintenance and early fault detection. Despite these contributions, experimental studies integrating diagnostic, thermal management, and efficiency measurements are still limited.

Furthermore, intelligent monitoring systems are becoming a crucial component of improving transformer performance. Real-time temperature monitoring, neural network-based defect prediction, and adaptive control techniques are made possible by internet of things (IoT) based systems [17]–[20]. These advancements complement experimental studies by integrating sensor-based advanced data acquisition and a control framework [21]. Cryogenic high-temperature superconducting (HTS) systems for power transformers have also been investigated further [22]–[24], demonstrating significant improvements in efficiency and compactness, as well as the use of thermopower-based measurements to improve monitoring accuracy under extreme temperature environments [25]–[27]. Furthermore, transformer life-cycle performance assessments show that effective cooling techniques can lower maintenance costs and increase overall dependability, directly promoting grid sustainability and stability [28].

Effects of temperature changes on the winding resistance. The resistance on transformer winding can be calculated using the formula,

$$R = \rho \frac{l}{A} \tag{1}$$

Where R is the resistance (Ω), ρ is the resistivity of the conductor (Ω.m), l is the length of the conductor (m), and A represents the cross-sectional area of the conductor (m²). The resistivity of a given conductor varies with its temperature. The four-point probe approach was used to measure the resistivity of the conductor in a cryogenic system. It is common practice to measure electrical resistance using four terminal potentiometric DC techniques [24]. Consequently, by immersing the transformers in liquid nitrogen (77 K or -196 °C), the winding's resistivities drop significantly. In [2], the operating resistivity at temperature T °C is given as (2),

$$\rho_t = \rho_0[1 + \alpha(T - T_0) \tag{2}$$

where ρ_t is the resistance at temperature "T", and ρ_0 is a conductor resistance at a reference temperature, α is the temperature coefficient of resistivity, T is conductor temperature in degrees Celsius, and T_0 is the reference temperature that α is specified at for the conductor material. The increase in the transformer temperature will affect the output power produced. Electrical power in a transformer with a resistive load can be calculated by (3),

$$P = I^2.R \tag{3}$$

where P is the real power (watt), I is current (A), and R is the resistance (Ω). To calculate the electrical energy consumed use (4),

$$E = I^2.R.t \tag{4}$$

where E is the electrical energy (watt-hour) and t is the time. The heat generated when the transformer operates can cause considerable power losses so that sufficient cooling medium is needed.

In order to meet the increasing need for high-efficiency power transformers, this study experimentally compares three distinct cooling techniques using air, oil, and liquid nitrogen. The results have implications for increasing transformer efficiency, decreasing losses, and improving thermal control. Future developments in transformer design and thermal management techniques may benefit from the comparative experimental data and useful insights it offers for energy-efficient power systems.

2. MATERIALS AND METHOD

The objective of this study is to experimentally investigate the effect of three cooling media ambient air, mineral oil, and liquid nitrogen on the thermal and electrical performance of a 1 kVA single phase transformer. The experimental framework integrates resistive load testing, infrared thermography, thermocouple-based temperature sensing, and copper resistivity measurements using a four-point probe within a cryogenic magnet system. This approach enables precise quantification of temperature distribution, resistivity variations, and their impact on transformer efficiency.

A 1 kVA transformer with a 230-volt input-output rating was tested under controlled resistive load conditions. A variable transformer supplied adjustable input voltages from 0–220 volt, while a HIOKI power energy meter PW3360 and HIOKI Clamp-on power meters measured current, voltage, power factor, frequency, and energy consumption in real time. Three cooling configurations were applied: natural air cooling, oil immersion cooling, and liquid nitrogen cooling using a specially designed dual-layer stainless steel cryogenic container with epoxy and fiber insulation to minimize heat transfer and maintain stable LN_2 temperatures.

The winding resistivity was measured using the four-point probe approach in the cryogenic magnet system for high accuracy under low-temperature LN_2 conditions; while winding and core temperatures were tracked during testing using infrared thermography and thermocouples positioned at strategic points. Figure 1 illustrates the direct comparison of transformer performance under each cooling media through the continuous collection of data at various load levels, from no-load to full load operation, utilizing a resistive load of 1000 watt. This approach makes it possible to thoroughly assess thermal management techniques and how well they work to increase transformer dependability and energy efficiency.

Table 1 presents the transformer specifications, including a 1 kVA capacity, 230-volt operating voltage, and 50 Hz frequency, with copper windings of 2 mm diameter. The temperature distribution of the transformer under different cooling conditions was measured using a NEC TH9100 infrared thermography system combined with thermocouples for precise monitoring. Additionally, the variation in copper wire resistivity with decreasing temperature was analyzed using the four-point probe method within a cryogenic magnet system, enabling accurate characterization of electrical properties at low temperatures in the laboratory.

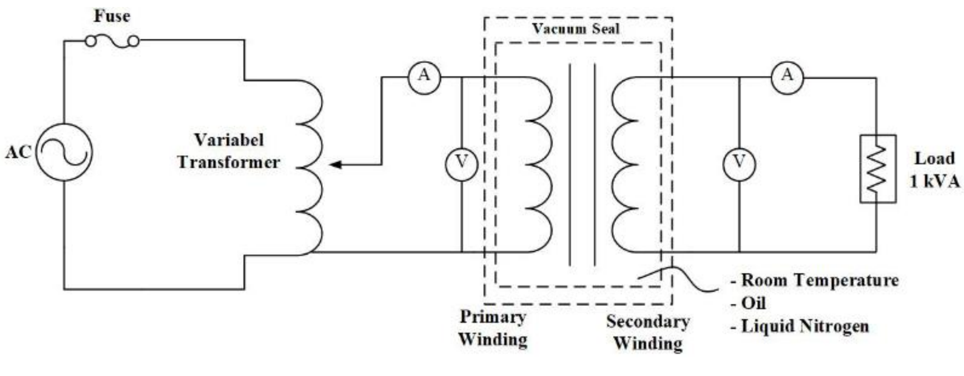


Figure 1. Transformer experimental setup with different cooling media

Table 1. Specifications of the transformer

Parameter	Specification
Primary/Secondary voltage	230/230 volt
Frequency	50 Hz
Apparent power	1 kVA
Winding	Copper Material 2 mm
Core	NGO silicon steel 0.5 mm

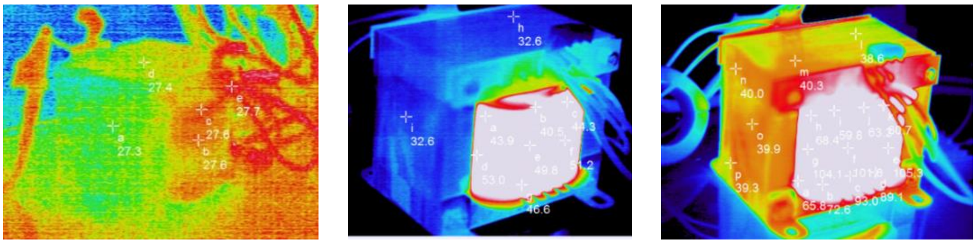
3. RESULTS AND DISCUSSION

This study advances current knowledge by experimentally validating how different cooling media affect transformer performance, bridging the gap between conventional thermal management (air and oil) and emerging cryogenic techniques. The test results showed that the real power and efficiency increased when the transformer temperature was low. At room temperature, the real power and efficiency were 0.807 kW and 80.70%, in oil, 0.86 kW and 86%, and liquid nitrogen (77 K), 0.899 kW and 89.9% as shown in Table 2. In other words, it is the transformer real electrical resistance power consumption. Efficiency or power factor is the measure of how close the real power is to the apparent power or the total power of the system. The apparent power of the transformer in this experiment was 0.807 kW/80.70% or 0.86 kW/86% or 0.899 kW/89.9% equaling 1 kVA as stated in Table 2.

Thermal infrared testing of the transformer at room temperature revealed a significant rise in core and winding temperatures across different voltage level, as shown in Figure 2. At a 10 Volt load, the initial core and winding temperatures averaged 32 °C. When the voltage increased to 110 Volt, the temperatures rose to an average of 51 °C in both the winding and core regions. At full load (220 volt), the winding temperature reached an average of 85 °C, with certain winding points recording peak temperatures of up to 100 °C.

Table 2. Real power and efficiency (%) of transformer

Cooling medium	Real power P (kW)	Efficiency (%)
Room temperature	0.807	80.70
Oil	0.86	86
Liquid Nitrogen (77K)	0.899	89.9



10 V 110 V 220 V

Figure 2. Thermal infrared of transformer cooled by air medium

Figure 3 shows the schematic of thermocouple placement on the transformer body to compare temperature readings from thermal infrared measurements and thermocouple sensors. Four thermocouples were positioned at key points: T1 on the primary winding, T2 on the secondary winding, T3 on the transformer core, and T4 on the bottom secondary winding. As shown in Figure 4(a), the thermocouple measurements recorded a winding temperature of approximately 85 °C on both the input and output sides at full load, while the core temperature remained around 37 °C. According to IEC 60076-7 standards, the hotspot temperature limit for large transformers under normal loading is 120 °C, indicating that the observed temperatures remain within the safe operational range.

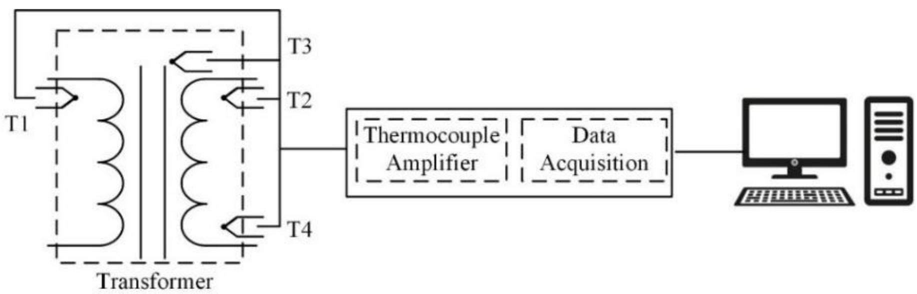
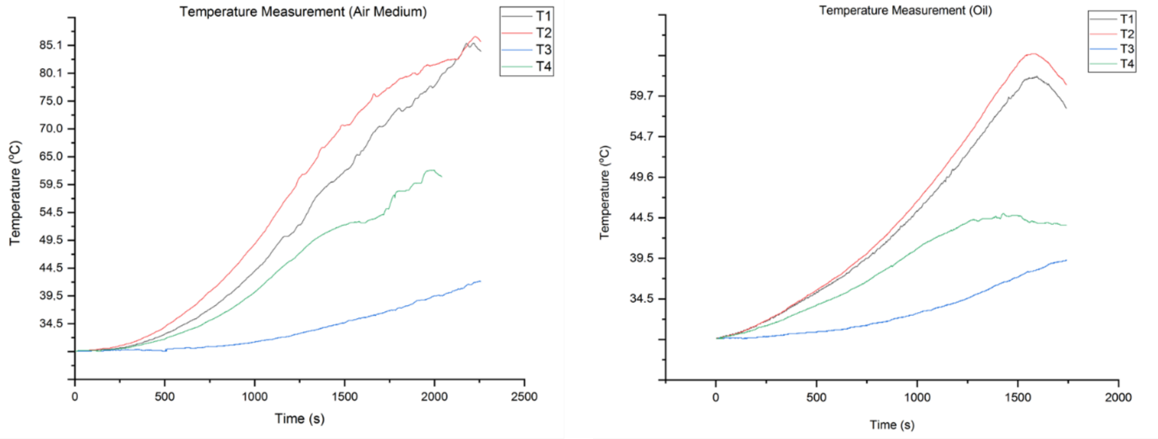


Figure 3. Schematic temperature measurement for transformer using thermocouples

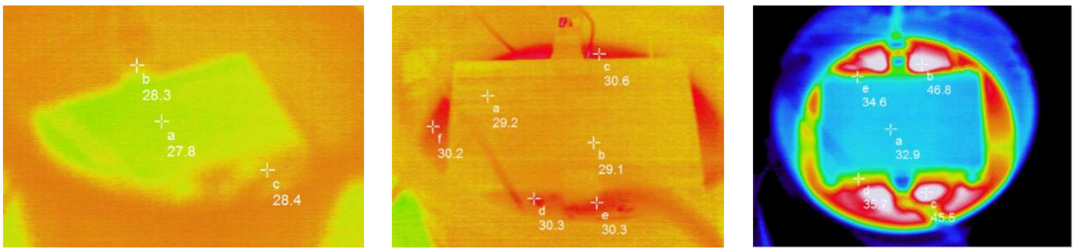
Figure 4(b) illustrate the heat distribution within the transformer under oil cooling across voltage variations from 10-220 volt. Since the winding were fully submerged in the oil bath, their temperatures could not be observed directly, but the core temperature was clearly visible, averaging around 35 °C. Additionally, the winding temperatures at measurement points T1 and T2 increased progressively from 26 °C at no load to 64 °C at full load, indicating the effect of increasing current on heat generation.



(a) (b)

Figure 4. Transformer temperature measured by thermocouple sensors cooled by (a) ambient air and (b) oil

Heat measurement was measured using a thermocouple sensor as shown in Figure 4(b). The temperature on the winding exhibited an average of 62 °C, lower than the transformer that was cooled by ambient air. The third medium for cooling the transformer was liquid nitrogen with a boiling temperature of 77K. Thermal infrared testing of the transformer cooled by oil medium revealed a significant cooling in core and winding temperatures across different voltage level, as shown in Figure 5. At a 10 volt load, the initial core and winding temperatures averaged 28 °C. When the voltage increased to 110 volt, the temperatures rose to an average of 30 °C in both the winding and core regions. At full load, the winding temperature reached of 45 °C.



10 V 110 V 220 V

Figure 5. Thermal infrared of transformer cooled by oil

Figure 6 shows the temperature distribution of the transformer was cooled by liquid nitrogen. It could reach a temperature of -185 °C. In these conditions, the copper wire temperature became very low and electrons could flow well so that the current ran smoothly and the efficiency increased. Figure 7 present a comparison of transformer output power and efficiency across three different cooling media with ambient air, mineral oil, and liquid nitrogen. At full load conditions of 220 volt, the transformer achieved its lowest efficiency of 80.7% under ambient air cooling due to higher heat accumulation and resistive losses. When cooled with mineral oil, efficiency improved to 86%, showing better heat dissipation and reduced winding resistance. The highest efficiency of 89.98% was obtained under liquid nitrogen cooling, indicating that cryogenic temperatures significantly minimize copper resistivity and improve overall transformer performance.

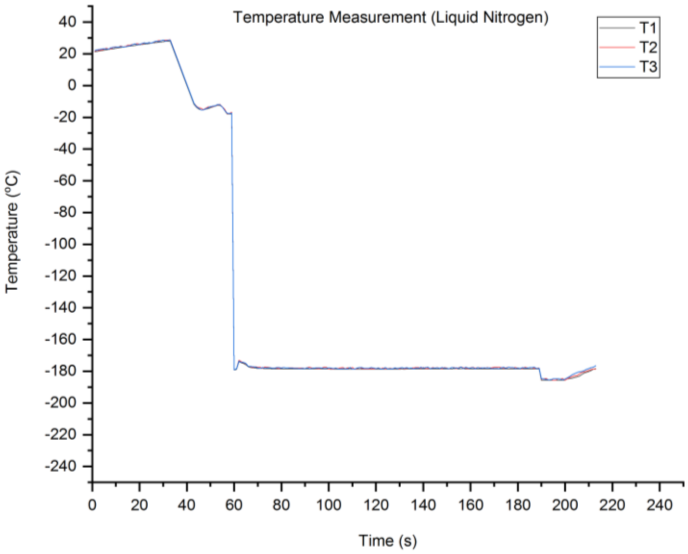


Figure 6. Transformer temperature measured by thermocouple sensor and cooled by liquid nitrogen

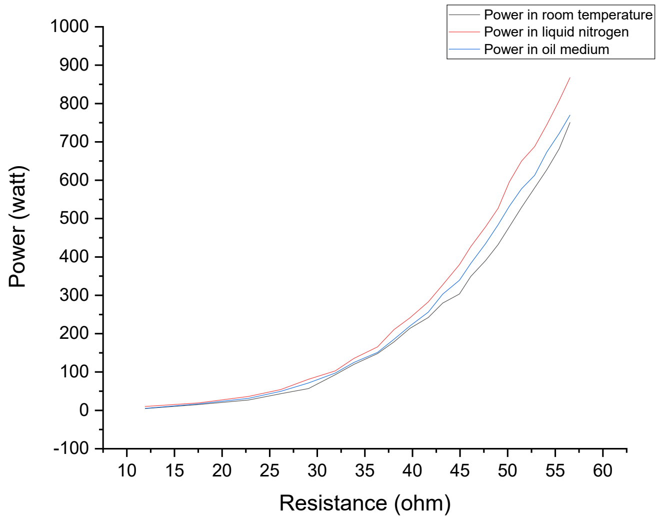


Figure 7. Resistance dependence power output

To precisely record resistivity values in this experiment, the copper wire sample was placed on a specialized sample holder that was furnished with voltage and current measuring cables, as illustrated in Figure 8(a). Measurements at temperatures as low as 10K were made possible by the system being housed inside a cryogenic container with accurate temperature control. The findings show that copper resistivity reduces linearly with temperature, suggesting that cryogenic temperatures improve electrical conductivity. By lowering resistive losses and increasing its capacity to support larger loads without experiencing thermal deterioration, copper greatly increases transformer efficiency at very low temperatures by facilitating the free passage of electric current. The transformer winding's resistivity was measured using the four-point probe method in a cryogenic magnet system as shown in Figure 8(b), which offers a controlled low-temperature environment between 10K and 300K, as shown in Figure 8(c). With this configuration, copper winding resistivity may be precisely characterized over a broad temperature range, guaranteeing precision data collection in cryogenic settings. Thermal effects and electrical conductivity are directly related, as seen by the winding material's considerable decrease in resistance as the temperature drops. To comprehend how liquid nitrogen cooling helps reduce power losses and increase transformer efficiency, these measurements are crucial.

Furthermore, copper's ability to reach quasi-superconductive behavior under realistic engineering constraints is highlighted by the significant decrease in resistivity at 10K. Copper's significantly reduced resistivity reduces Joule heating and permits higher current density, resulting in more compact and effective transformer designs, even though copper does not become completely superconducting state. Longer insulation life and less maintenance are further benefits of less heat stress on the windings. Liquid nitrogen-based cryogenic cooling has intriguing uses in scientific equipment, aircraft, defense, and superconducting power devices, where high performance, dependability, and thermal stability are crucial, even though it is not yet practical for large-scale power grids [26], [27].

(a) (b) (c)

Figure 8. Resistivity measurement (a) cryogenic magnet system and (b) resistivity measurement result of the transformer copper wire (at 5K – 300K) and (c) curve of resistivity measurement

Our findings confirm that transformer efficiency strongly correlates with the operating temperature of the copper windings, consistent with model of temperature-dependent resistivity [2] as shown in Figure 8(c). The improvement in efficiency from 80.7% (air) to 89.9% (LN_2) demonstrates the theoretical boundary achievable with cryogenic cooling. However, this aligns with previous work [10] that noted the challenges of cryogenic systems for standard power grid use. In contrast, our results show that mineral oil cooling, improving efficiency to 86.0%, supports previous evidence [8] that oil immersed transformers offer reliable, practical performance gains. This work adds to the knowledge base by providing side by side experimental data across these cooling regimes, which had not been systematically compared in prior studies.

The resistivity of the transformer would benefit greatly from cryogenic closed loop cooling using subcooled liquid nitrogen natural convection in terms of compactness, efficiency, and dependability [10], [24], [28]. The results demonstrate a significant reduction in copper resistivity and improved transformer efficiency under liquid nitrogen cooling, achieving an efficiency of 89.9%, compared to 86.0% with oil and 80.7% with air. Unlike previous studies that investigated these cooling methods separately, this work provides a direct, side by side experimental comparison under identical load and measurement conditions, enabling a unique understanding of cooling-media performance trade off.

4. CONCLUSION

The impact of three cooling media liquid nitrogen, mineral oil, and ambient air on the thermal performance and efficiency of a 1 kVA single-phase transformer was experimentally assessed in this study. Because copper winding resistance is significantly reduced at cryogenic temperatures, the results demonstrate that liquid nitrogen cooling offers the greatest efficiency improvement when compared to oil and air cooling. A linear drop in resistivity with decreasing temperature was validated by measurements made using the cryogenic magnet system, which enhanced electrical conductivity and transformer performance in general. Although liquid nitrogen offers significant efficiency increases, cost, complexity, and safety concerns limit its practical use in large-scale power systems. In contrast, mineral oil provides a more practical and dependable alternative for traditional transformer cooling.

Future studies should concentrate on creating hybrid cooling plans and high capacity of the transformer, looking at affordable cryogenic methods using superconducting wire for transformer, and Internet of Things based real-time monitoring systems to improve transformer dependability and performance. Scalability evaluation also requires long-term research on material stability, insulation deterioration, and transformer longevity under harsh cooling conditions. This paper concludes by showing that transformer efficiency may be greatly increased by lowering copper resistivity through efficient thermal management. The comparative analysis of air, oil, and liquid nitrogen cooling provides a foundation for future advancements in designing energy-efficient transformers and developing innovative thermal management solutions for next-generation power systems.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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C : **C**onceptualization	I : **I**nvestigation	Vi : **Vi**sualization
M : **M**ethodology	R : **R**esources	Su : **Su**pervision
So : **So**ftware	D : **D**ata Curation	P : **P**roject administration
Va : **Va**lidation	O : Writing - **O**riginal Draft	Fu : **Fu**nding acquisition
Fo : **Fo**rmal analysis	E : Writing - Review & **E**diting	

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

INFORMED CONSENT

We have obtained informed consent from all individuals included in this study.

DATA AVAILABILITY

Derived data supporting the findings of this study are available from the corresponding author HN on request.

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