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# THE INTERNATIONAL COMPETITION ON SUSTAINABLE EDUCATION

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TRANSFORMING EDUCATION, DRIVING INNOVATION AND ADVANCING LIFELONG LEARNING FOR EMPOWERED WORLD

# INTEGRATING GREEN NANOTECHNOLOGY RESEARCH INTO ENGINEERING EDUCATION USING PALM-OIL-BASED TRANSFORMER NANOFLUIDS

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## ABSTRACT

*This paper outlines an educational innovation that involves incorporating sustainable engineering research by developing graphene and hematite (Fe2O3) doped palm oil based transformer nanofluids as a green substitute for traditional mineral oil. The work addresses environmental and learning objectives by allowing real world problem solving in research. In this research nanofluids were synthesized with 6 grams of hematite and 2%, 4%, and 6% concentration of graphene in refined, bleached, and deodorized palm olein (RBDPO). Structural characterization was performed through X-ray diffraction (XRD), while electrical performance was tested through AC breakdown voltage testing in accordance with ASTM D1816. The results showed that the 6g hematite nanofluid with 4–6% graphene had the highest improvement in AC breakdown voltage, with a recording of up to 37% enhancement over unmodified RBDPO. These improvements show the potential of nanotechnology to significantly enhance the insulating capacities of biodegradable transformer oils. The project captures the integration of outcome-based education (OBE) and engineering education for sustainable development (EESD) since it captures SUSED2025's vision of facilitating potential educators with innovative and sustainability-oriented research. The technical and pedagogical implications of the project enhance the building of green solutions in electrical insulation while enhancing student competence through experiential learning.*

***Keywords:*** *Graphene (Gr), Iron (III) Oxide (α-$Fe_2O_3$), Transformer Oil (TO), Nano Fluids (NF), Nanocomposites, X-ray Diffraction (XRD), AC Breakdown Voltage (AC-BDV), Nanoparticles (NP)*

## INTRODUCTION

The international drive towards sustainable and environment-friendly technologies has spurred the quest for alternatives to traditional mineral-based transformer oils. Although widely utilized, mineral oils are non-biodegradable by nature and present significant environmental hazards from their toxicity and environmental persistence. These issues have fueled growing interest in bio-based insulating fluids, with refined, bleached, and deodorized palm olein (RBDPO) being biodegradable, locally available, and demonstrating good electrical and thermal characteristics.

Although RBDPO offers a sustainable base fluid, its dielectric and thermal performance needs to be improved to qualify for the high-voltage application with stringent requirements. For this purpose, the use of nanomaterials in base oils has proven to be an effective solution. Here, nanocomposites of graphene and iron(III) oxide ($Fe_2O_3$, hematite) were introduced into RBDPO to enhance its insulating properties. Graphene provides high thermal conductivity and structural stability, whereas hematite offers dielectric strength and moisture resistance. These materials, when synergistically coupled, are likely to provide a nanofluid with excellent electrical and thermal performance characteristics.

The current study seeks to optimize the composition of graphene-hematite nanocomposites in RBDPO and systematically assess the impacts on critical properties like AC breakdown voltage. The ultimate objective is to create a high-performance, biodegradable insulating fluid that can be applied in contemporary transformer systems, and hence support the overall objective of sustainable and high-efficiency power infrastructure.

The increasing need for eco-friendly insulating materials in power systems has established a strong interest in the substitution of traditional mineral-based transformer oils with sustainable alternatives. Mineral oil, although common in use due to its dielectric qualities, is an environmental concern due to its non-biodegradability and possible ecological risks during leakage incidents. Refined, bleached, and deodorized palm olein (RBDPO), however, is an excellent bio-based alternative, especially in countries like Malaysia where palm oil is abundant.

Even so, the inherent dielectric strength of RBDPO needs to be enhanced to achieve the demanding specifications of high-voltage insulation applications. Contemporary studies have established that the incorporation of nanomaterials can be used to enhance the dielectric properties of insulating oils. For instance, the addition of MgO nanoparticles to natural esters has been shown to enhance AC breakdown voltage by as much as 22% when utilized at optimal concentrations [1]. Likewise, graphene-modified palm oil methyl esters have recorded breakdown voltages of over 30 kV, which is far better than the performance of unmodified oils [2]. Research on hybrid nanofluids, such as preparations containing $TiO_2$ and CNTs, also corroborates this trend, with reports of AC breakdown voltage enhancement up to 9% [3], while $TiO_2$-dispersed fluids have demonstrated a performance enhancement of approximately 50% under humid conditions [4].

Inspired by these results, the present work investigates the development of RBDPO-based nanofluids with graphene and iron(III) oxide ($Fe_2O_3$, hematite) nanoparticles with the prospect of enhancing AC breakdown behavior. These nanomaterials have been promoted for having high electrical conductivity and dielectric strengthening ability, respectively, and are predicted to work synergistically to enhance the electrical strength of palm-oil-based insulating fluids as technologically is an acceptable and environmentally friendly alternative for transformer use.

## METHODS

This study employed an experimental approach to evaluate the dielectric and thermal performance of refined, bleached, and deodorized palm olein (RBDPO) enhanced with graphene and iron(III) oxide ($Fe_2O_3$, hematite) nanoparticles. The methodology consisted of three primary phases: material preparation, nanofluid formulation, and performance characterization.

In the first phase, hematite nanoparticles were synthesized via a solution-based method using iron(III) chloride hexahydrate ($FeCl_3 \cdot 6H_2O$) and urea as precursors. The solution was ultrasonicated, heated in a water bath, filtered, dried, and annealed at 500°C to obtain phase-pure $\alpha$-$Fe_2O_3$. Commercial high-purity graphene nanopowder was used without further modification. Structural confirmation of the synthesized nanoparticles was conducted through X-ray diffraction (XRD).

For nanofluid formulation, 600 mL of RBDPO was used as the base fluid. A fixed mass of 6 grams of hematite was dispersed in the oil, while graphene concentrations varied at 2%, 4%, and 6% by weight. Each nanofluid sample underwent ultrasonication for 60 minutes to ensure uniform nanoparticle dispersion and stability. The results were analyzed to identify the optimal graphene concentration and assess the nanofluids' suitability for high-voltage insulation applications

## RESULTS AND DISCUSSION

The incorporation of graphene and hematite nanoparticles into RBDPO resulted in notable improvements in the electrical and thermal performance of the base fluid. Among the three formulations tested 2%, 4%, and 6% graphene combined with a fixed 6g of hematite the sample with 4% graphene demonstrated the most balanced and optimized results.

The AC breakdown voltage (AC-BDV) of the base RBDPO was recorded at 9.03 kV. With the addition of nanocomposites, the dielectric strength increased significantly, reaching 12.4 kV for the 4% graphene formulation representing a 37.4% improvement. This enhancement is attributed to the synergistic interaction between graphene's high surface area and thermal conductivity, and hematite's ability to suppress electrical discharges and moisture sensitivity.

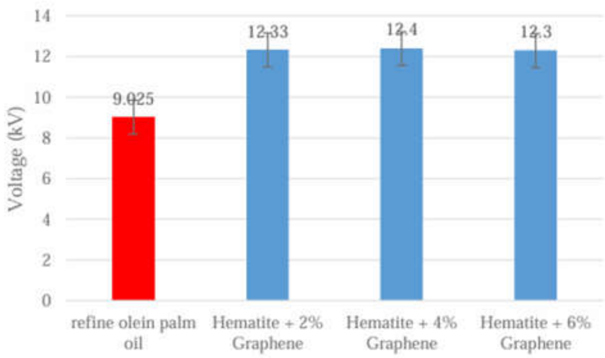
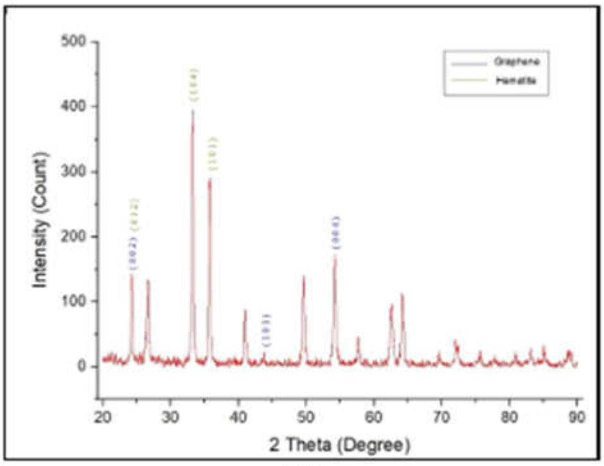
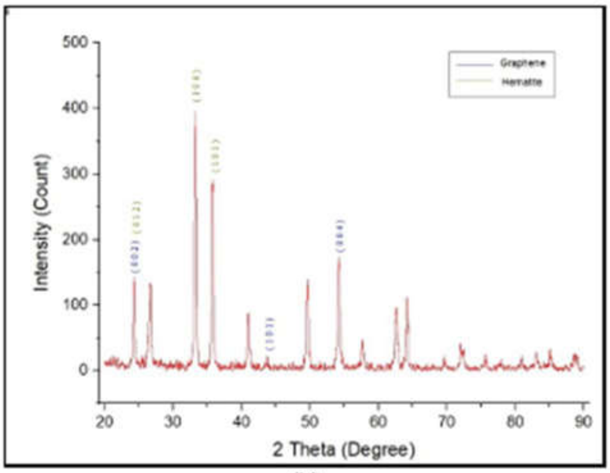



**Figure 1.**: Breakdown voltage of nanoparticle-doped-palm olein's

X-ray diffraction (XRD) confirmed the successful synthesis of highly crystalline, phase pure $\alpha$-$Fe_2O_3$ and graphene, which contributed to the nanofluid's stable dispersion and functional performance. Overall, the study demonstrated that a 6g hematite and 4–6% graphene formulation in RBDPO yields a high-performance, biodegradable insulating fluid suitable for use in sustainable power transformer applications.




(a)

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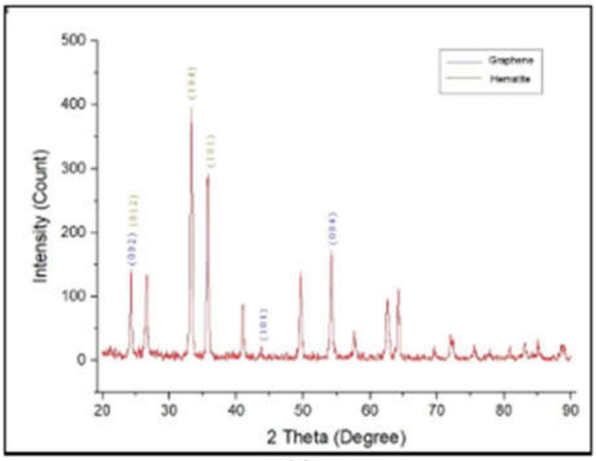


(c)

**Figure 2.**: XRD results annealed at 500°C for synthesized Hematite with (a) 2% Graphene, (b) 4% Graphene, (c) 6% Graphene.

## CONCLUSION

This study successfully demonstrated the potential of palm-oil-based nanofluids enhanced with graphene and hematite nanoparticles as a sustainable alternative to conventional mineral-based transformer oils. Among the tested formulations, the nanofluid containing 6 grams of hematite and 4–6% graphene exhibited the most favorable performance, with significant improvements in AC breakdown voltage, moisture resistance, and thermal stability. These enhancements are primarily attributed to the synergistic effects of graphene's high thermal conductivity and hematite's dielectric reinforcement capabilities.

The experimental results validate that nanocomposite-modified RBDPO can meet the functional requirements for high-voltage insulation, while offering environmental advantages such as biodegradability and reduced ecological risk. The findings contribute meaningfully to the advancement of green nanofluids for power system applications, supporting broader global efforts toward sustainable energy infrastructure.

Furthermore, this research provides a replicable formulation and testing methodology that can guide future investigations into bio-based insulating materials. By optimizing nanoparticle concentration and characterizing their effects using standardized testing protocols, this work establishes a foundational reference for the development of next-generation transformer oils.

In summary, the integration of graphene and hematite nanocomposites into RBDPO offers a technically viable and environmentally responsible solution for transformer insulation. This innovation not only supports Malaysia's palm oil valorization efforts but also aligns with international sustainability goals in the electrical power sector.

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