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Full Length Research

Evaluation of the impact of green antioxidants on the functionality of power transformer bio-coolants

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ABSTRACT: This research was conducted based on the necessity of substituting mineral (conventional) transformer oil with safer and ecologically friendly bio-based oils, due to public health challenges associated with mineral oils. Palm oil (PO) was blended with varying concentrations of turmeric extract (TE), and African nutmeg extract (AME). The physical and electrical properties of the blended and unfortified PO specimens were evaluated in harmony with ASTM procedures. Outcomes of the experimental investigated depicted that the TE initiated an 64, 130, 38 and 46% improvement of the oil's breakdown voltage, pour point, flash point and viscosity levels, respectively; likewise, the AME caused 41, 90, 32 and 39% enhancement on the oil's breakdown voltage, pour point, flash point and viscosity levels, respectively. The results further revealed that the green additives successfully increased the likelihood of utilising PO as a suitable bio-based oil and coolant in a power transformer. Remarkably, this study's findings have emphasised the possibility of using bio-antioxidants in enhancing green oils and bio-coolants' performance and sustainability.

Keywords: Bio-based oil, green energy, mineral oil, power transmission, public health.

INTRODUCTION

Electrical power generation, transmission and distribution involves the integration of various software, hardware and other related materials, working together to achieve a specific goal. A transformer is one of the critical parts of electric power transmission and distribution; it has the potential to regulate (stepping up and stepping down) the voltage to the level required by the consumers (Jain *et al*., 2021). Specifically, transformers come in different types, which operate based on different principles. Power, distribution, instrument, isolation and multi-winding transformers are some of the common types of transformers used in electrical installations. The mode of operation of transformers is guided by factors, which include: voltage and current levels, power rating, efficiency requirements and specific application. Specifically, the utilisation of coolant (transformer oil) as a cooling agent in a power transformer is dependent on the type and the transformer's design (Karthik and Narmadhai, 2024; Koca *et al*., 2024). Coolants are necessary in modern power transformers to enhance their integrity, performance, and durability (Sorte *et al.,* 2025).

Mineral oils (fossil-based oils) are widely utilised in electric power transformers as a coolant and insulating material, primarily due to their excellent insulating and thermal properties (Li *et al.,* 2023). However, their production and utilisation of these oils have some environmental consequences, resulting in the emission of harmful substances into surrounding ecosystems. Apart from the poisonous discharge associated with the extraction and refining of mineral oils, their spills into the environment had an adverse effect on the soil and water qualities. Ecological contamination associated with fossil

oil pollution poses serious health hazards to the environment, leading to public health issues (Akpokodje and Uguru, 2019; Tiwari *et al*., 2024). This has led to comprehensive research into the production of more environmentally friendly oils for industrial purposes, which will align with the United Nations' goals of reducing global lethal gases and compounds footprints.

Bio-coolants (green coolants) are ecologically friendly insulating fluids/oils obtained from plant/animal-based oils. They are increasingly being utilised as a prospective replacement for traditional oils (fossil oils) in power transformers, while improving the power system's sustainability (Karthik and Narmadhai, 2024). These oils have numerous ecological advantages, such as: lower toxic gas emissions, biodegradability, availability ease, and non-toxicity to humans, which are linked to most traditional transformer oils (Li *et al*., 2023; Osuji *et al*., 2025). Currently, bio-coolants have issues correlated with oxidative degradation, which can be rectified through the utilisation of appropriate green additives to improve their functionality and performance characteristics. Additives are formulated to improve the oils' oxidation stability, thermal conductivity and dielectric properties. These materials can be in the form of antioxidants, metal deactivators, and pour/boiling point tranquillisers. Green antioxidants are basically natural bioactive compounds extracted from plant materials, which have the potential of inhibiting oxidation and degradation processes in oils and other fluids (Uguru *et al.,* 2023; Mustangin *et al.,* 2025). These bio antioxidants are rich in flavonoids, vitamins (A, B and E), as well as other essential phytochemical compounds, which help to stabilise the reactive species. Therefore, they are highly effective in retarding fluids' rancidity process, thereby increasing their preference over synthetic antioxidants in various industrial applications (Ghoneim *et al.,* 2021; Pruteanu *et al*., 2023). The major goal of this research is to identify a suitable green additive which will enhance the transformer's bio-oils (coolants) consistency and performance. Interestingly, findings obtained from this research will highlight the significance of green antioxidants in augmenting the functionality and sustainability of bio-coolants.

MATERIAL AND METHODS

Samples collection

The oil palm fruits, turmeric rhizomes, and African nutmeg were purchased from a local market in the Isoko region of Delta State, Nigeria.

Samples preparation

The palm oil (PO) was extracted from oil palm fruit through the solvent extraction approach, using the n-hexane solvent, as explained by Abushal *et al.* (2024). Additionally, the turmeric extract (TE), and the African nutmeg (*Monodora myristica*) extract (AME), were prepared by using ethanol as the extraction solvent, by following standard procedures as explained by Igwe *et al*. (2005).

Research design

The palm oil (PO) was blended with various concentrations of TE and AME. These quantities - 0, 0.5, 1.0, 1.5, 2.0 and 2.5% (v/w) of TE and AME, were thoroughly mixed with the PO samples at room temperature (30±5°C). The research was done under uncontrolled environmental conditions.

Physical and Electrical testing of the specimens

The breakdown voltage (BV), pour point (PT), flash point (PT) and viscosity levels of the PO samples were tested in accordance with American Society for Testing and Materials (ASTM) guidelines, as explained by Osuji *et al*. (2025).

Data analysis

The research outcomes were statistically analysed to evaluate the impact of the green antioxidants and their concentrations on the bio-oil performance. All the tests were conducted in triplicate.

RESULTS AND DISCUSSION

The results of the impact of the additives on the bio-oil electrical and thermal properties are presented in Figures 1, 2, 3 and 4. It can be seen that the additives have a substantial influence on the bio-coolant's breakdown voltage values, regardless of the additive type, though TE tends to have a higher impact on the oil's BV value. The BV value of the oil blended with TE increased from 22 to 36 KV, while the AME improved the oil's BV value from 22 to 31 KV. Also, the TE and AME were able to reduce the PO's pour point level from 10 to -3°C and 10 to 1°C, respectively; while the flash point value varied from 275 to 171°C and 175 to 187°C, for the PO samples fortified with TE and AME, respectively. Additionally, it was noted that the PO viscosity value at 100°C ranged from 7 - 13 mm^2/s for the specimens blended with TE, and the samples fortified with AME viscosity (at 100°C) varied from 8 to 13 mm^2/s for the samples fortified with AME (Figure 4).

Remarkably, it was observed that the incorporation of TE (at a level greater ≥2.0%) and AME (≥2.5%) were able to increase the oil's BV level to meet the recommended value (≥30), approved by ASTM D1816 for new transformer oil.

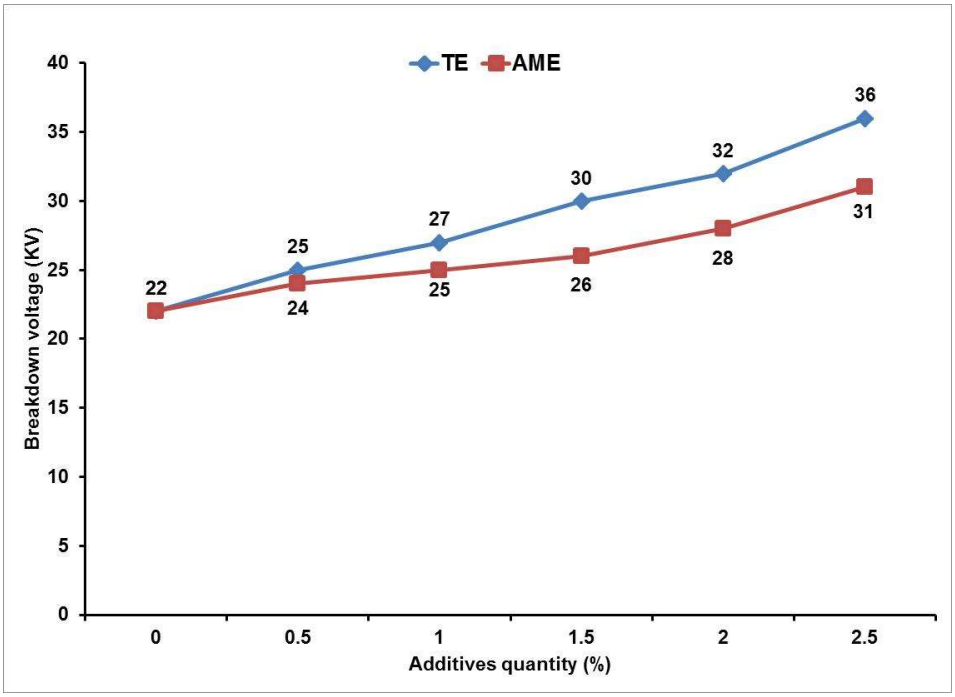

Figure 1. The influence of the green additives on the PO BV level.

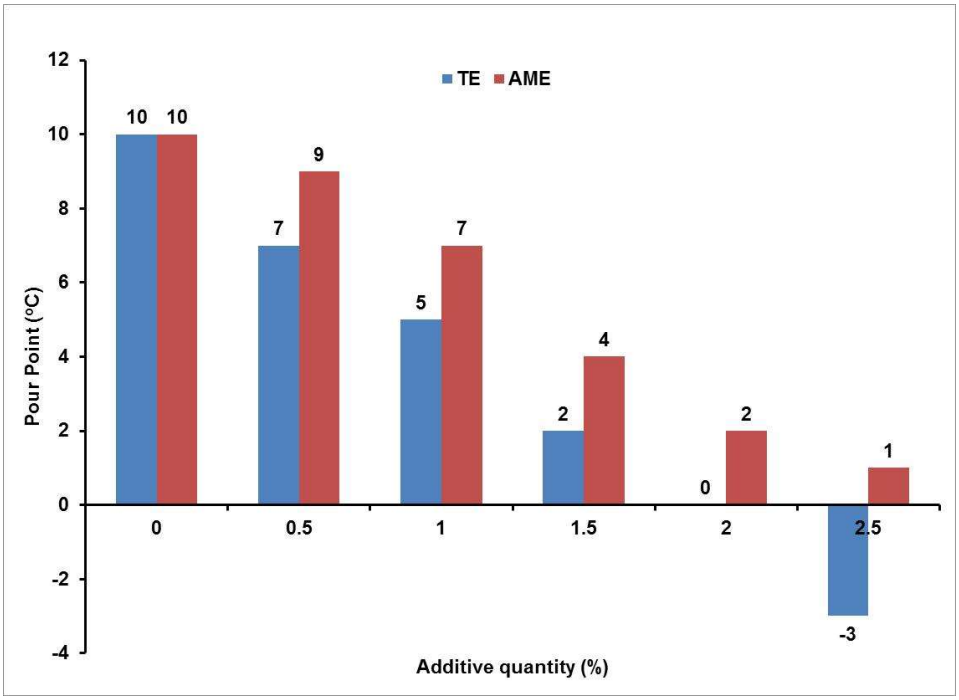

Figure 2. The PO pour point is influenced by the additives.

The BV level obtained in this study was less than the result (81 KV) recorded by Oparanti *et al.* (2024a, b), for refined PO. The differences noted between these results could be attributed to palm fruit variety, processing approach, storage method, and treatments applied. Breakdown voltage is a vital parameter of transformer oil, which shows the

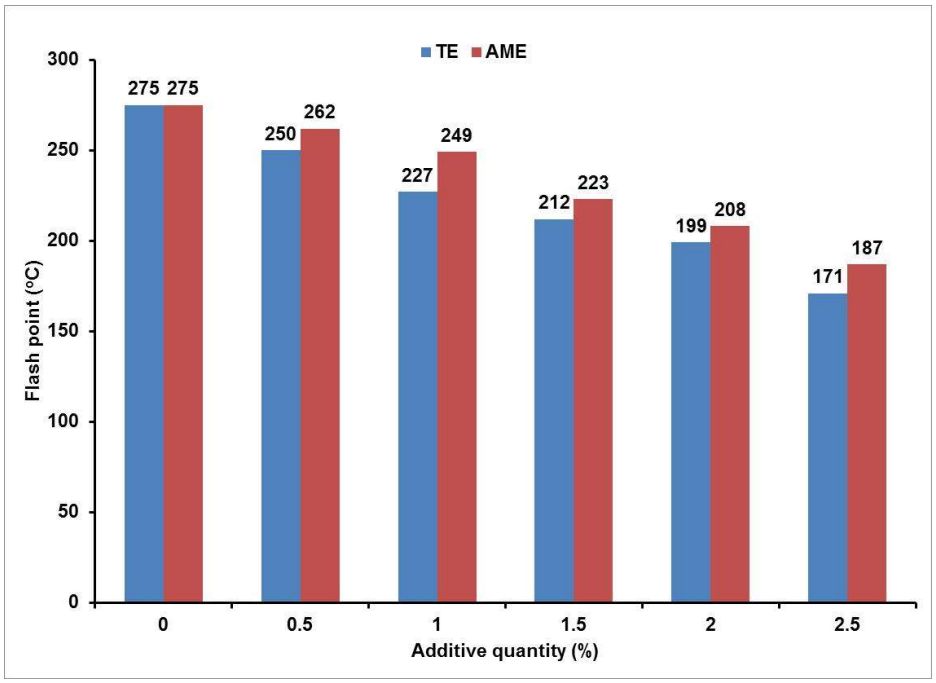

Figure 3. The FT of the PO samples.

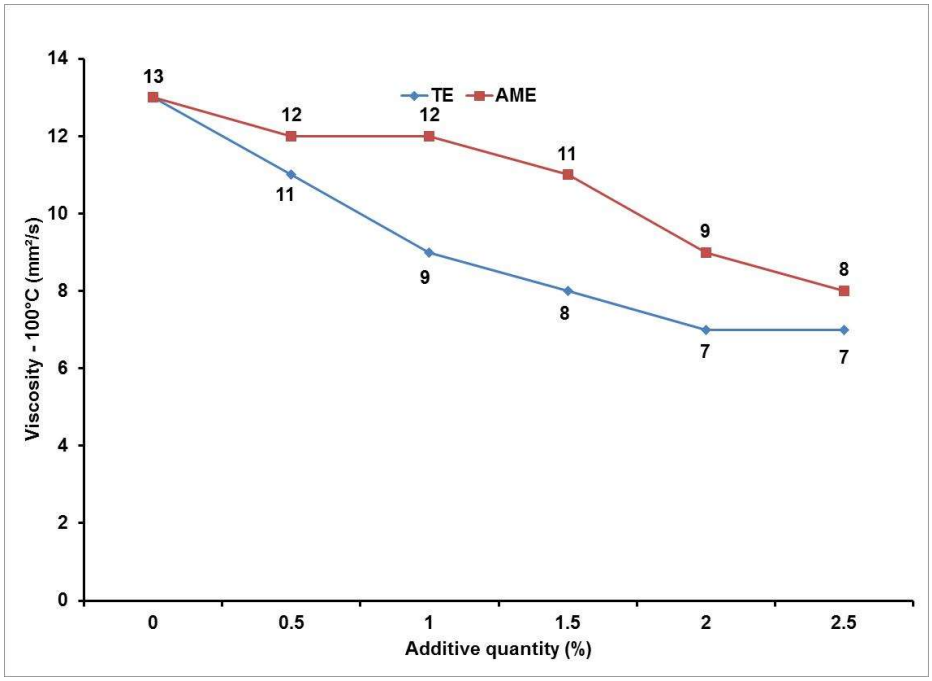

Figure 4. The viscosity of the blended PO specimens.

fluid's (oil and coolant) insulating properties; hence, oils with greater BV values tend to have higher insulation power and lower conductivity (Ghoneim *et al.,* 2021). According to Oparanti *et al*. (2024a), oils with greater BV values have the capability of absorbing larger voltages before their subsequent degradation. These oils (having higher breakdown voltage values) are preferable in power transformer installations, primarily due to their elevated

transformer safety efficacy, operational reliability, and reduced electrical failures.

Furthermore, it was observed that the additives positively influenced the pour point of the bio-based oil. This parameter (pour point) is a crucial oil factor, as a lower value is beneficial for transformer's performance and stability, mostly in cooler working environments (Oparanti *et al*., 2024a). Siddique *et al*. (2024) stated that pour point has a significant effect on oil transmission, cooling effectiveness, thermal properties, and insulation stability. This study's findings with respect to the PO's pour point behaviour, aligned with previous observations made by Mustangin *et al.* (2025) during their experimental investigation into palm oil's engineering properties. Interestingly, the results highlighted that the green antioxidants reduced the viscosity of the oil. Viscosity is another vital property of transformer oil, influencing its cooling and insulating abilities; hence, its high level (oil with elevated viscosity level) tends to hinder transformer performance (Rafiq *et al.,* 2021). Sorte *et al.* (2025) reported that high viscosity leads to a decline in heat dissipation ability of the oil (reduced cooling effect), thereby resulting in poorer functionality of the transformer, speeding up dilapidation of oil properties, and stimulating sludge production.

Interestingly, this research's outcomes have depicted that the green additives substantially improved the PO engineering properties. This aligned with previous observations that natural antioxidants have the potential to improve bio-based oil properties; hence, increasing their substitution for mineral oils in power transformers (Oparanti *et al*., 2024a,b). Discrepancies observed in the BV, PT, FT and viscosity values of the two fortified palm oil samples could be attributed to the difference in the antioxidant concentrations in the two extracts - TE and AME (Uguru *et al*., 2023).

Conclusion

This research was conducted to evaluate natural antioxidants (additives) efficacy, in enhancing the natural oils' properties, as well as the utilisation of fortified natural oil as a mineral oil substitute in power transformer operation. The oil samples (fortified and unfortified) were prepared and tested in accordance with standard procedures. Notably, the results reflected that the turmeric extract and African nutmeg extract have positive impacts on the PO's engineering properties - breakdown voltage, pour point, flash point and viscosity levels. Fascinatingly, the results highlighted that the higher concentrations (≥ 2.0%) of turmeric extract increased the PO's breakdown voltage value to meet the approved International (ASTM) rating. Merits recorded in this study portrayed that bio-additive fortified PO is a good alternative for transformer oil; hence, minimising the hazards associated with fossil oils.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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