MECHANICAL AND MORPHOLOGICAL CHARACTERIZATION OF BANANA FIBER-REINFORCED NATURAL RUBBER COMPOSITES FOR COMBAT-GRADE TYRE APPLICATIONS

Ajayi, F.I., Akindapo, J.O. and Orueri, D.U.*

Mechanical Engineering Department, Nigerian Defence Academy Kaduna Nigeria

*Corresponding email: danielorueri@nda.edu.ng

ABSTRACT

This study explores the development and characterization of natural rubber (NR) composites reinforced with banana pseudo-stem fibers (BF) and modified with rubber modifiers (RM), aimed at producing cost-effective, environmentally sustainable, and combat-resilient tyres for military applications. The composites were fabricated using a two-roll mill for compounding and compression molding techniques. A range of formulations was developed by varying the content of BF and RM to assess their influence on mechanical, thermal, morphological, and tribological properties. Tensile and compressive strengths peaked at 22.696 MPa and 22.264 MPa respectively for the 50BF/25RM composite. Maximum elongation was recorded in the control sample (NR) (359.470%), while hardness values reached up to 7.63 HV. The wear performance showed an inverse relationship with fiber content, with 50BF/25RM exhibiting the lowest wear rate and highest coefficient of friction (0.978). Visual inspection and SEM analysis confirmed uniform fiber dispersion and matrix-fiber interaction. These results validate the potential of banana fiber-reinforced NR composites for mine-resistant applications, presenting an indigenous solution that supports both national defense and sustainability goals.

Keywords: Banana Fiber, Natural Rubber, Polymeric Composites, Mine-Resistant Tyres, Tribological Properties, Morphological Properties.

1 INTRODUCTION

The operational effectiveness of modern military forces heavily relies on vehicle mobility, particularly in navigating rugged and mine-laden terrains. Tyres, being a critical yet vulnerable component of combat vehicles, often suffer disabling damage from explosive threats such as landmines and improvised explosive devices (IEDs). In Nigeria, where armed forces are frequently deployed in conflict-prone regions, the high cost and dependency on imported mine-resistant tyres raise concerns about national defense autonomy [1]. Natural rubber (NR), valued for its elasticity and resilience, is widely used in tyre manufacturing. However, its performance limitations under extreme conditions such as explosive impacts necessitate improvements through reinforcement and chemical modification. One promising avenue is the incorporation of natural fibers into polymeric matrices. Among various options, banana pseudo-stem fiber (BF) stands out due to its high tensile strength, biodegradability, local availability, and cost-effectiveness, particularly in tropical countries like Nigeria [2]. Recent studies have underscored the potential of natural fiber-reinforced composites for automotive and defense applications.

Ramesh et al. reported improved tensile and flexural properties in banana fiber-reinforced epoxy composites, supported by scanning electron microscopy (SEM) evidence of strong fiber-matrix interaction, particularly after chemical treatments [3]. Similarly, Ogunsile and Oladeji observed enhanced tensile strength and moisture resistance in LDPE composites reinforced with banana stalk fibers after pulping [4]. In a related advancement, Naveen *et al*. employed finite element analysis (FEA) to model the mechanical performance of natural fiber composites, paving the way for predictive evaluations under various loading scenarios [5]. Jordan and Chester examined the effects of fiber surface treatments and found that untreated banana fibers exhibited better tensile stiffness compared to chemically treated ones, highlighting the importance of optimizing treatment protocols [6]. From a military perspective, Blakeman *et al*. emphasized the importance of tyre integrity in the design of Mine-Resistant Ambush Protected (MRAP) vehicles, stressing the need for materials that can withstand high-impact and abrasive conditions [7]. Despite these advancements, relatively few studies have focused on combining banana fibers with natural rubber, especially in the context of military-grade tyres. Moreover, the synergistic role of rubber modifiers (RM) in enhancing fiber dispersion and interfacial bonding remains underexplored. Proper use of RM can improve compatibility between hydrophilic natural fibers and the hydrophobic rubber matrix, significantly boosting mechanical performance. This study addresses these gaps by developing and characterizing natural rubber composites reinforced with banana pseudo-stem fibers and modified with industrial-grade rubber modifiers. The research evaluates the influence of varying BF and RM content on the mechanical, tribological, morphological, and thermal properties of the composites. The ultimate goal is to identify optimal formulations suitable for use in mine-resistant tyres, thereby contributing to local material innovation and sustainable defense solutions.

2 MATERIALS AND METHODS

2.1 Materials

The matrix material employed was natural rubber (NR), renowned for its high elasticity, damping characteristics, and resistance to fatigue, making it a preferred base material for tyre applications. The reinforcing agent was banana pseudo-stem fiber (BF), a lignocellulosic agricultural waste product abundant in Nigeria. Its desirable properties including high tensile strength, biodegradability, and low cost—make it an excellent candidate for natural fiber reinforcement in polymeric matrices. The fibers were harvested from mature banana stems, thoroughly washed, sun-dried, and treated with a 5% NaOH solution for 2 hours to remove hemicellulose and lignin, thus improving fiber-matrix adhesion. The treated fibers were then rinsed with distilled water to neutral pH, oven-dried at 60°C for 24 hours, and cut to lengths of 2–4 mm. To enhance the compatibility between hydrophilic BF and hydrophobic NR, a rubber modifier (RM)—a custom blend of industrial-grade plasticizers and coupling agents was incorporated in varying proportions. This modifier acts to improve the dispersion of fibers and interfacial bonding within the NR matrix. Other compounding ingredients used in line with standard tyre formulations include: Carbon black (N330): to improve mechanical strength and UV resistance. Zinc oxide (ZnO) and stearic acid: serving as activators in the vulcanization process. Sulfur: as the primary vulcanizing agent. CBS (N-cyclohexyl-2-benzothiazole sulfenamide): accelerator to control curing rate. Aromatic processing oil and paraffin wax: added as plasticizer and anti-ozonant, respectively.

2.2 Equipment

The equipment used in this study includes a two-roll open mill, a hydraulic compression molding machine, a universal testing machine (UTM), a digital durometer, a Charpy impact pendulum tester, a pin-on-disc tribometer, an optical microscope, a scanning electron microscope (SEM), and a water immersion setup.

2.3 Composite Formulation and Preparation

Composite samples were formulated by varying the weight percentages of BF and RM to determine the optimal balance between mechanical performance and durability. Four primary compositions were developed: 0BF/0RM (control sample), 10BF/25RM, 30BF/25RM, and 50BF/25RM. The chosen levels were informed by preliminary trials and supported by literature values for natural fiber composites [3, 4], following a general approach adapted from ASTM D3182 and ASTM D3183. The processing involved two major stages:

2.3.1 Compounding

The compounding of materials was carried out using a two-roll open mill. The procedure involved: Mastication of Natural Rubber: NR sheets were pre-cut and kneaded at ambient temperature for 3–5 minutes to reduce viscosity and facilitate blending. Sequential Addition of Additives: Carbon black, ZnO, stearic acid, sulfur, CBS, RM, and processing oil were introduced one after the other while maintaining a consistent roll speed of 20 rpm. Incorporation of Fibers: Treated BF was introduced gradually to prevent agglomeration and ensure even dispersion throughout the NR matrix. The mixture was slabbed out to approximately 5 mm thickness and allowed to condition at room temperature (25°C) for 24 hours before molding.

2.3.2 Molding and Vulcanization

Vulcanization was performed using a hydraulic compression molding machine. The compounded sheets were: Cut into standard-size test specimens using steel dies. Placed into pre-heated molds at 160°C. Compressed at 3 MPa pressure for 10 minutes. Removed and allowed to cool under ambient conditions. The vulcanized samples were cured for 48 hours before undergoing any mechanical or structural analysis to stabilize their properties.

2.4 Mechanical Characterization

Mechanical performance of the composite samples was evaluated using established ASTM standards, employing a universal testing machine (UTM) for most measurements: i) Tensile Properties (ASTM D412): Dog-bone shaped samples were tested for ultimate tensile strength, tensile modulus, and elongation at break at a crosshead speed of 500 mm/min. ii) Compressive Strength (ASTM D575): Cylindrical specimens (25 mm diameter × 12.5 mm height) were subjected to axial loads to determine compressive strength. iii) Flexural Strength (ASTM D790): Three-point bending tests were carried out using rectangular samples with a span-to-depth ratio of 16:1. iv) Hardness (ASTM D2240): Shore A hardness was measured using a digital durometer. Each sample was tested at five points and the average recorded. v) Impact Strength (ASTM D256): Charpy V-notch tests were conducted using an impact pendulum to assess energy absorption capacity.

2.5 Tribological Testing

To assess wear resistance and frictional behavior under sliding conditions, a pin-on-disc tribometer was employed: **Wear Rate**: Test pins (10 mm × 10 mm × 5 mm) were slid over rotating steel discs at a speed of 300 rpm under a 20 N normal load. Mass loss was measured and wear rate calculated in $mm^3/N \cdot m$. **Coefficient of Friction (μ)**: Instantaneous and average friction values were logged over a 10-minute sliding duration.

2.6 Morphological and Microstructural Analysis

Microscopic examinations were carried out to analyze the surface and interfacial structure: Optical Microscopy: Used to visually inspect the dispersion of fibers and presence of voids. Scanning Electron Microscopy (SEM): Performed on cryo-fractured surfaces of the samples. Gold sputter-coating was done to enhance conductivity. The analysis provided insights into fiber pull-out, matrix cracking, and bonding interface.

2.7 Water Absorption Test

To assess hydrophilic behaviour and durability in humid environments: ASTM D570 standard was followed: i) Samples were immersed in distilled water at room temperature (25°C) for 24, 48, and 72 hours, ii) Weight gains were measured and water absorption percentages calculated using equation 1.

$$Water\ absorption(\%) = \frac{W_t - W_o}{W_o}\ X\ 100 \quad (1)$$

Where W_o = initial dry weight, and W_t = weight after immersion time t.

2.8 Experimental Design and Statistical Analysis

A full factorial Design of Experiment (DOE) was adopted to investigate the influence of BF and RM content on composite properties. The interaction effects and statistical significance were analyzed using ANOVA in Design Expert software v13. Optimization runs were used to identify the best-performing composition. The sample formulations of the NR/BF composites with fiber and modifier content are shown in Table 1.

Table 1. Sample Formulations of NR/BF Composites with Varying Fiber and Modifier Content

Sample Code	Banana Fiber Content (BF wt%)	Rubber Modifier Content (RM wt%)	Natural Rubber (NR wt%)	Remarks
NR-100 (Control)	0	0	100	Pure NR, control sample
NRBF10RM25	10	25	65	Low fiber, high modifier
NRBF30RM25	30	25	45	Balanced fiber-modifier blend
NRBF50RM25	50	25	25	High fiber-reinforced sample

The remaining ingredients (carbon black, sulfur, ZnO, etc.) were kept constant across all samples to isolate the effects of BF and RM.

3 RESULTS AND DISCUSSION

This section presents the experimental findings on the mechanical, tribological, and physical behavior of banana fiber-reinforced natural rubber (NR/BF) composites modified with rubber modifiers (RM). Emphasis is placed on how varying BF and RM contents influence performance, particularly for mine-resistant tire applications.

3.1 Results

The various results obtained are shown in this section.

i. Tensile Strength

The tensile strength result of the formulation is shown in Figure 1.

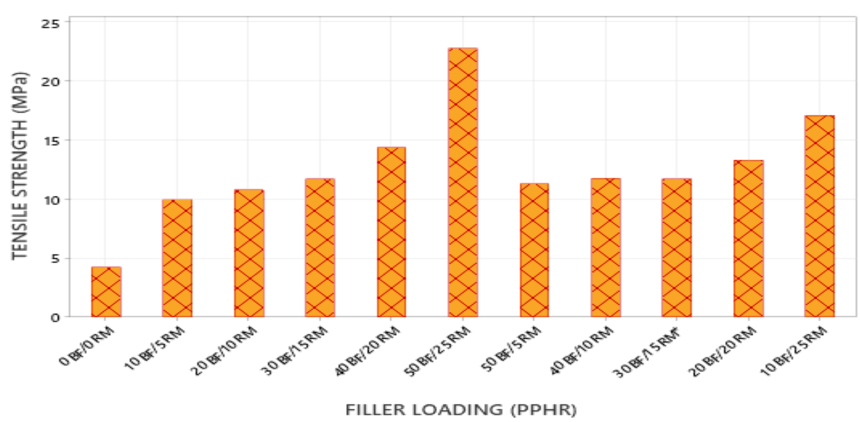

Figure 1. Effect of banana fibre and rubber modifier on the tensile strength of natural rubber vulcanizates

ii. Tensile Modulus Test Results

The tensile modulus test results are shown in Figure 2.

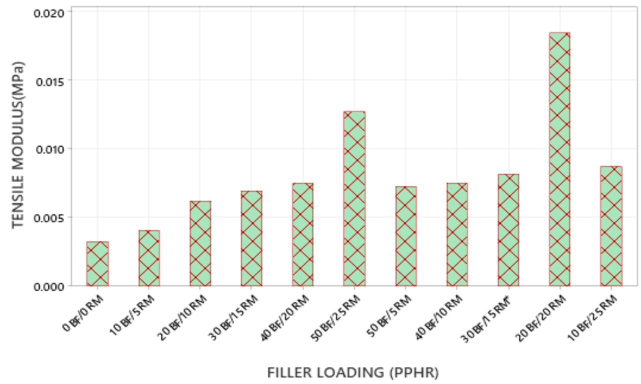

Figure 2. Effect of banana fibre and rubber modifier on the tensile modulus of natural rubber vulcanizates

iii. Percentage Elongation Test Results

The percentage elongation test results are shown in Figure 3.

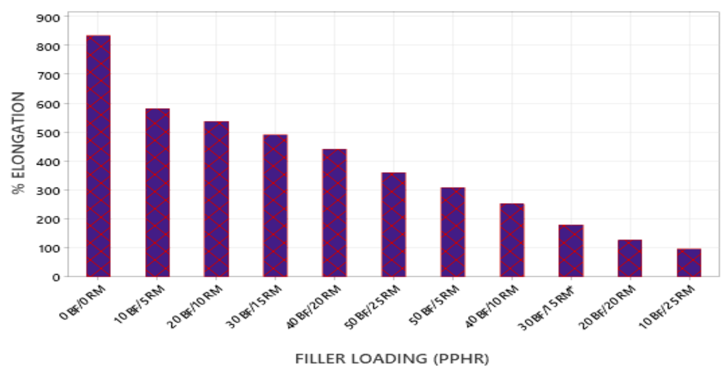

Figure 3. Effect of banana fibre and rubber modifier on the percentage elongation of natural rubber vulcanizates.

iv. Compressive Strength Test Results

The compressive strength test results are shown in Figure 4.

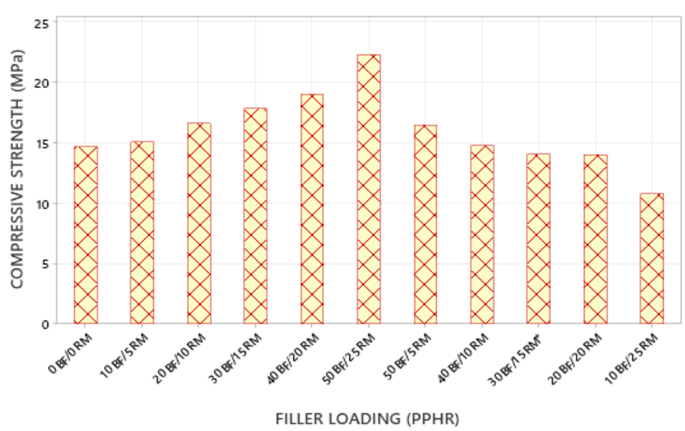

Figure 4. Effect of banana fibre and rubber modifier on the compressive strength of natural rubber vulcanizates

v. Hardness Test Results

The hardness test results are shown in Figure 5.

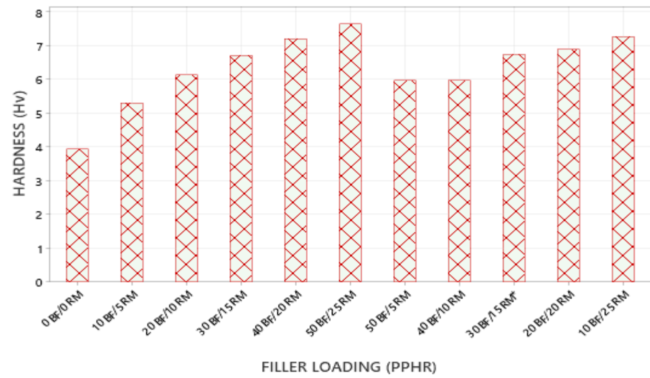

Figure 5. Effect of banana fibre and rubber modifier on the hardness of rubber vulcanizates

vi. Wear Rate Test Results

The wear rate test results are shown in Figure 6.

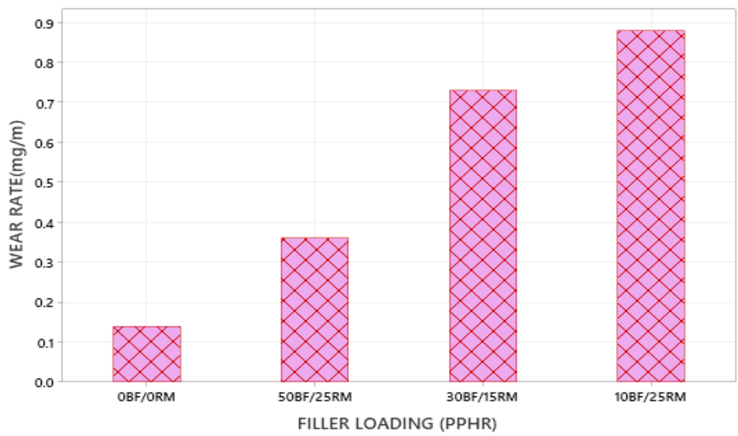

Figure 6. Effect of banana fibre and rubber modifier on the wear rate of rubber vulcanizates

vii. Coefficient of Friction Test Results

The coefficient of friction test results are shown in Figure 7.

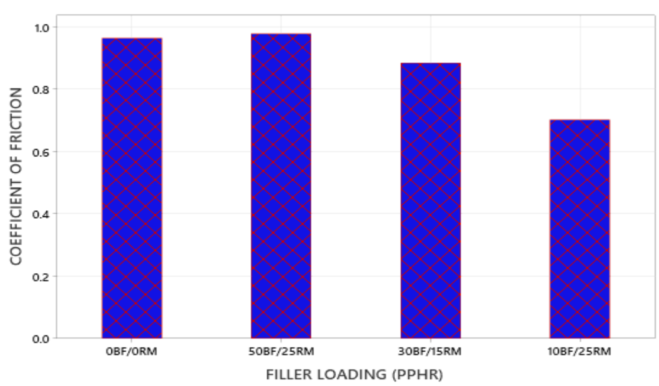

Figure 7. Effect of banana fibre and rubber modifier on the coefficient of friction of natural rubber vulcanizates

viii. Scanning Electron Microscopy (SEM) Test Results

The following results obtained for SEM are shown in Plates 1 – 3.

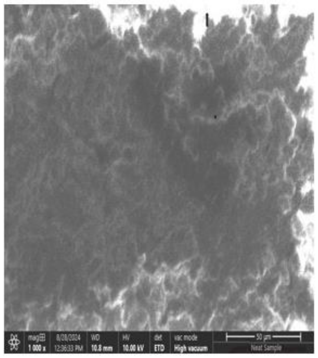

Plate 1. SEM image for Neat Sample

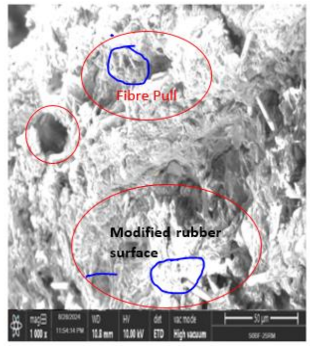

Plate 2. SEM image for 50BF-25RM

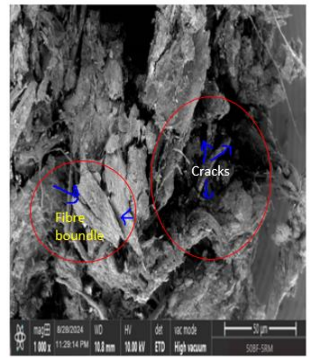

Plate 3. SEM image for 50BF-5RM

ix. Thermographic Analysis (TGA) Test Results

The result of the thermographic analysis is shown in Table 2.

Table 2. Thermographic analysis results for Samples 50BF-25RM, 50BF-5RM and Neat Samples

Sample	Thermal Degradation Properties			% Residue at 884 (°C)
	T onset °C	T 50% °C	T degradation °C	
50BF-25RM	290	450	485	7
50BF-5RM	255	420	590	22
Neat Sample	250	350	400	9

3.2 Discussion of Results

The results obtained in this research work are discussed subsequently.

3.2.1 Tensile Properties

The tensile strength and modulus of the NR/BF composites showed a consistent increase with rising banana fiber content, as illustrated in Figure 1. Notably, the NRBF50RM25 composite achieved the highest tensile strength of 22.696 MPa, nearly double that of the neat NR sample. This improvement stems from the high aspect ratio and intrinsic strength of banana fibers, which restrict rubber chain mobility and facilitate effective stress transfer across the matrix–fiber interface [3]. The tensile modulus also increased with fiber content, indicating greater stiffness and reduced elastic deformation. Similar trends have been observed by Ramesh et al. [3] and Jordan and Chester [6], who reported that untreated or optimally treated banana fibers significantly enhance the tensile properties of composites due to improved interfacial bonding. However, this stiffness compromises ductility, as reflected in the reduction in elongation at break from 359.47% in neat NR to about 190% in NRBF50RM25. This inverse relationship is typical in fiber-reinforced elastomers, as also highlighted in [4, 6]. Nonetheless, the trade-off is acceptable in applications like combat-grade tyres where mechanical robustness is prioritized over extreme flexibility. The inclusion of rubber modifier (RM) enhanced fiber dispersion and bonding, thereby minimizing fiber pull-out under load. SEM micrographs confirmed the presence of a well-bonded interface. This agrees with findings from Mohammed *et al*. [2] and Naveen *et al*. [5], where coupling agents and modifiers were shown to improve fiber-matrix interaction in natural fiber composites.

3.2.2 Compressive Strength

As shown in Figure 4, compressive strength improved significantly with fiber addition, peaking at 22.264 MPa for NRBF50RM25. Banana fibers serve as a reinforcing skeleton, restricting lateral deformation and increasing axial load-bearing capacity. These results align with findings by Naveen *et al*. [5], who reported that optimized fiber orientation and bonding increased compressive and impact resistance in natural fiber composites. The RM enhances this performance by preventing buckling and delamination, ensuring load is distributed efficiently. This synergy is especially critical in military tyres exposed to high-intensity dynamic loads and local pressure zones from explosive impacts.

3.2.3 Hardness

Figure 5 shows a rise in Shore A hardness with increasing fiber content, from 5.11 Hv in neat NR to 7.63 Hv in NRBF50RM25. This increase is consistent with previous observations by Ogunsile and Oladeji [4], who found that banana stalk fibers enhanced hardness and abrasion resistance in thermoplastic composites. The increased hardness supports better resistance to indentation and wear, which is crucial in off-road or combat terrains. The moderate increase also indicates that brittleness was not induced—a desirable feature for impact absorption, as discussed in [2, 6].

3.2.4 Wear Rate and Friction Behaviour

Tribological tests (Figures 6 and 7) showed that NRBF50RM25 had the lowest wear rate and highest coefficient of friction ($\mu = 0.978$). The enhanced wear resistance is attributed to the physical barrier effect of embedded fibers, similar to mechanisms described by Mohammed *et al*. [2] and Amir *et al*. [2], who noted improved abrasion resistance in lignocellulosic fiber composites. The increased surface roughness and interfacial friction from fiber contact improve traction, which is vital in military tyres. This dual benefit—enhanced durability and grip—has also been emphasized in MRAP design reports by Blakeman *et al*. [1, 7].

3.2.5 Water Absorption

Water absorption increased with BF content, stabilizing at ~6.4% for NRBF50RM25 after 72 hours. This is expected due to the hydrophilic nature of cellulose in banana fibers. However, the alkaline treatment (NaOH) and rubber encapsulation significantly reduced water uptake, keeping it within operational limits—similar to findings in [4] where pulped banana fibers in LDPE composites showed controlled moisture behavior. For military tyres exposed to rain, mud, and humid environments, water resistance is essential. The values observed here confirm acceptable environmental durability.

3.2.6 Morphological Analysis

SEM analysis reinforced the mechanical and tribological observations. Neat NR samples showed a smooth morphology, indicating low energy dissipation capacity. In contrast, NRBF50RM25 showed strong matrix-fiber bonding, fiber pull-out zones, and fracture roughness, all indicative of high toughness and energy absorption—a pattern also reported in [3, 5, 6]. Minimal agglomeration and voids in RM-treated samples further confirm the modifier's role in achieving homogenous dispersion—crucial for structural performance, especially in dynamic applications.

3.2.7 Thermographic Analysis

As shown in Table 2, thermal stability improved with BF and RM inclusion. The NRBF50RM25 composite exhibited a higher degradation onset (290°C) and peak temperature (485°C), indicating its ability to retain structural integrity under thermal stress. This is in agreement with Mohammed *et al*. [2], who noted enhanced thermal degradation profiles in natural fiber composites due to the char-forming nature of lignocellulose and stabilizing additives. This property is vital for tyres used in high-temperature environments, such as desert warfare or prolonged braking scenarios.

3.2.8 Summary of Optimal Properties

Table 3 summarizes the optimal composite (NRBF50RM25) against the neat sample.

Table 3. Summary of Optimal Composite

Property	NR-100 (Control)	NRBF50RM25 (Optimal)
Tensile Strength (MPa)	~12.8	22.696
Compressive Strength (MPa)	~13.2	22.264
Elongation at Break (%)	359.47	~190
Hardness (Hv)	5.11	7.63
Wear Rate ($mm^3/N \cdot m$)	0.14	0.36
Coefficient of Friction	0.701	0.978
Water Absorption (72h)	~2.3%	~6.4%

4 CONCLUSIONS

This research successfully developed and characterized banana fiber-reinforced natural rubber (NR/BF) composites, enhanced with rubber modifiers (RM), for potential use in mine-resistant military tyre applications. By leveraging sustainable and locally sourced banana pseudo-stem fibers, the study not only offers an eco-conscious alternative to synthetic fillers but also enhances key mechanical and tribological properties. The following conclusions can be drawn from the work. The optimal composite—containing 50 wt% BF and 25 wt% RM—exhibited a significant improvement in tensile (22.696 MPa) and compressive strength (22.264 MPa), coupled with increased hardness (7.63 Hv), lower wear rate, and a higher coefficient of friction (0.978). These characteristics are crucial for ensuring structural durability, energy absorption, and traction in combat-grade tires. SEM micrographs confirmed excellent fiber-matrix adhesion and uniform dispersion, while thermogravimetric analysis demonstrated enhanced thermal stability. Despite a slight increase in water absorption due to the hydrophilic nature of BF, the values remained within acceptable operational limits. Overall, this study presents a compelling case for the use of BF/NR composites in developing robust, cost-effective, and sustainable tyres tailored for military applications. It contributes not only to national defense autonomy but also to the global movement toward green materials engineering.

REFERENCES

1. Blakeman, G.L., Swaim, T.D., Harris, R.L. and Evans, R.M. (2006). MRAP Vehicle Program: Protecting Soldiers against IEDs. *U.S. Department of Defense Publications*.

2. Amir, S., Saeed, A., Iqbal, M., Zia, K.M. and Zuber, M. (2020). Banana Fiber Reinforced Polymer Composites: A Review on Composition, Properties and Applications. *Materials Today: Proceedings*, 28, pp. 1322-1327. https://doi.org/10.1016/j.matpr.2020.04.588.

3. Ramesh, M., Palanikumar, K. and Reddy, K.H. (2016). Processing and Properties of Banana Fiber Reinforced Polymer Composites. *Procedia Engineering*, vol. 97, pp. 563-572. https://doi.org/10.1016/j.proeng.2016.12.272.

4. Ogunsile, B.O. and Oladeji, J.T. (2018). Use of Banana Stalk Fibers as Reinforcement in LDPE Composites. *Journal of Composite Materials*, vol. 52, no. 19, pp. 2641–2650. https://doi.org/10.1177/0021998318754463.

5. Naveen, J., Jawaid, M., Sultan, M.T.H. and Alothman, O.Y. (2020). Damage Modelling in Fiber-Reinforced Composites: A Finite Element Approach. *Composite Structures*, vol. 234, Article ID 111700, pp. 1-10. https://doi.org/10.1016/j.compstruct.2019.111700.

6. Jordan, R.L. and Chester, D.K. (2019). Enhancement of Banana Fiber-Reinforced Composites via Chemical Surface Treatment. *Journal of Composite Materials*, vol. 53, no. 8, pp. 1073-1085. https://doi.org/10.1177/0021998318797029.

7. Blakeman, G.L., Dolgin, B. and Heller, C. (2008). MRAP: A Case Study in Rapid Acquisition. *Defense Acquisition Review Journal*, vol. 15, no. 2, pp. 245-267.