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RESEARCH

Comparison and Simulation of Agro-Waste Materials as Brake Pad Frictional Components

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A B S T R A C T

The automotive industry moving to use eco-friendly materials as some of the applications make harm to environment. Day by day, the climatic proportions and weather conditions are not similar to its usual behaviour. So it is compelled to adapt to natural environment back. This study investigates the structural deformation performance of eco-friendly brake pad composites reinforced with a agro waste product of coconut oil residu (COR). For comparison, coconut coir fibers and asbestos materials Finite element simulations are performed in ANSYS to assess pad deformation, stress distribution, and contact behavior under nominal braking conditions. The maximum deformation observed in the composites was 0.415mm for coconut coir, 0.313mm for COR and 0.311 mm for asbestos indicating that coconut coir composites exhibits highly compliance with maintaining structural integrity. These results were complemented by material characterization SEM. The study demonstrates that coconut coir based brake pads can achieve comparable performance to conventional materials offering a sustainable alternative with potential environmental and economic benefits. The findings also highlight critical processing considerations for optimizing composite behavior guiding future experimental validation and industrial application.

1. INTRODUCTION

Vehicles have become essential in daily life worldwide, with recent studies reporting over 1.64 billion vehicles in operation as of 2025. This rapid growth intensifies the demand for environmentally conscious automotive components. In response, the integration of natural, sustainable materials in vehicle parts, including brake pads, is gaining momentum, which must perform reliably under diverse climatic challenges. Researchers are actively seeking safe, effective alternatives to asbestos-based brake pads due to the environmental and health hazards associated with asbestos use in the first generation of traditional composite materials. Waste-based hybrid composites, especially those using banana peel and carbon, show strong potential as sustainable, high-performance alternatives to asbestos brake pads. Their mechanical and wear properties are competitive, and numerical simulations confirm their suitability for automotive use. The field continues to evolve, with ongoing research into optimizing compositions and integrating multiple waste materials for improved performance and sustainability [1-7]. This research focuses on the braking assembly, aiming to enhance brake pad frictional materials with natural composites. While semi-metallic and ceramic brake pads dominate the commercial market, the development and implementation of organic and non-asbestos brake pads remain a growing area of research and industrial interest, motivated by increasing environmental regulations and the demand for low-toxicity, eco-friendly friction materials [8-10]. A number of reviews and recent studies have documented successful use of agricultural by-products such as coconut shell, palm kernel shell, sugarcane bagasse, banana peel, wood powder, and other natural fibres as fillers and reinforcements in non-asbestos friction composites, reporting broadly comparable ranges of hardness, density, and friction coefficient under laboratory testing conditions. These studies emphasize that composite function formulation with fillers and binders critically controls tribological performance and mechanical integrity [11,12].

Palm kernel fiber, cane wood, banana peel ash, palm slag, sisal, jute, and pineapple leaf fiber exhibit promising friction–wear behavior as reinforcements in composite brake materials [13-17]. These materials offer adequate mechanical strength, high lingo-cellulosic content, and stable friction performance, making them suitable for sustainable friction material development. Agro-waste fibers contribute to favorable friction stability through the formation of primary and secondary plateaus, regulating wear and debris generation during braking [18]. Material selection, pressure, temperature, and sliding velocity significantly influence particle emissions from brake systems, highlighting the importance of natural fiber-based formulations [19,20].

Coconut fibre and shell powder are employed as brake pad reinforcement and fillers, exhibiting encouraging tribological properties. Maintaining precise fibre content and particle size is crucial to prevent excessive porosity and subsequent wear degradation. Microstructural analyses of coconut fibre-reinforced materials reveal fibre breakage, pits, and micro-cracks on worn surfaces, while small additions of natural fibres can yield stable friction coefficients and wear resistance. Coconut oil residues are also being explored as inexpensive friction composite fillers. Oil residue incorporation in polymer matrix brake linings influences particle dispersion, porosity, and interfacial bonding, ultimately controlling deformation and wear. However, research on polymer matrix composites with oil residues remains limited due to a lack of detailed characterization and simulation linking morphology to performance [20-24].

Experimental studies on agro-waste friction materials commonly provided in pin-on-disc tribometry wear tests and basic mechanical characteristics, SEM images of worn surfaces are included to show recurring features such as pits, broken fibers, interfacial bonding, or high local stresses. But there are common limitations that are not explored as follows:

- Studies that are purely experimental with limited or no numerical modelling to predict stress concentration and deformation
- Despite the significant influence of test conditions and specimen preparation on COF and wear rates, the literature often lacks a thorough rationale for the specific parameters employed.
- A few more studies conduct a combined microstructure with simulation and tribology workflow that links SEM observed defects to stress and deformation fields to measure tribological outcomes.

Finite Element Modelling (FEM) is used to study contact pressures, Von-Mises stresses, and deformation of brake pads but many modelling studies either model standard commercial materials rather than agro-waste composites or simplify microstructural features without linking the model inputs to measured microstructure. Consequently, simulation results are rarely validated against detailed microstructure evidence or paired with SEM to explain where cracks initiate with stress concentration being higher for certain compositions. Such limitations prevent modeling data from informing material design or predicting failure in natural fiber and oil residue-based composites.

There are limited cross-linking of microstructure and mechanical response showing SEM of worn surfaces with wear rates, but they do not quantify how specific microstructural features map to local stress fields or total deformation predicted by FEM [25]. This makes interpretation mechanistic and incomplete. Several studies selected contact pressure friction coefficients and load conditions without providing their justification tied to real braking scenarios that reduces comparative values from traditional materials. While coconut coir and shell powders are well represented in some of the research, the body of work on coconut oil residue (COR) as a friction material filler is spare and for conventional material, it lacks detailed SEM comparisons for paired FEM analysis [26].

Coconut coir is widely available and low cost, and its fibrous morphology provides potential reinforcement benefits [21-23]. From research, coir-based brake composites can reach acceptable mechanical and tribological ranges when formulation and processing are optimized. COR (Coconut Oil Residue) represents a high-potential agro-waste filler that is both widely available and cost-effective. Furthermore, its fine morphology offers the technical advantage of enhanced particle packing and reduced porosity within the composite matrix. Individually, studying coir and COR enables evaluation of both fibrous and powdery agro-waste forms and their combined effect on pad microstructure, deformation, and stress response. This comparison is directly relevant for designing sustainable brake linings with balanced stiffness, strength, and frictional properties.

Despite numerous experimental reports on agro-waste fillers for brake friction materials, key knowledge gaps remain:

- The mechanistic link between microstructural defects and local stress and deformation fields predicted by FEM is under-explored [27].
- Coconut oil residue (COR) has received limited systematic evaluation and comparison with both coconut coir and conventional asbestos-based materials.
- Performs SEM microstructural characterization,
- Measured/justified material properties and test parameters in finite-element simulations, and
- Interprets simulation outputs in direct relation to observed wear/failure modes.

The present study addresses these gaps by combining SEM characterization with ANSYS finite-element simulations to compare deformation and Von-Mises stress for coconut coir, COR, and asbestos materials under justified braking conditions, thereby linking morphology to predicted mechanical response and informing material optimization [28,29].

2. METHODOLOGY AND MATERIALS

The overall methodology followed in this study is illustrated in Fig. 1 and summarized as follows. The process began with the collection of raw materials, where epoxy resin was used as the binder, while coconut coir fibers and coconut oil residue (COR) powders were sourced locally. The preparation involved sieving and oven-drying the COR powder to ensure a dry, fine consistency. Concurrently, the epoxy matrix was prepared by mixing the resin and hardener at a 10% ratio to achieve the desired cure profile. The composite fabrication was carried out using a compression moulding technique with a die of dimensions 300 × 300 mm and a plate thickness of 3 mm. The moulding was performed under a maximum temperature of 400 °C and a pressure of 400 bar to ensure uniform bonding and adequate mechanical strength.

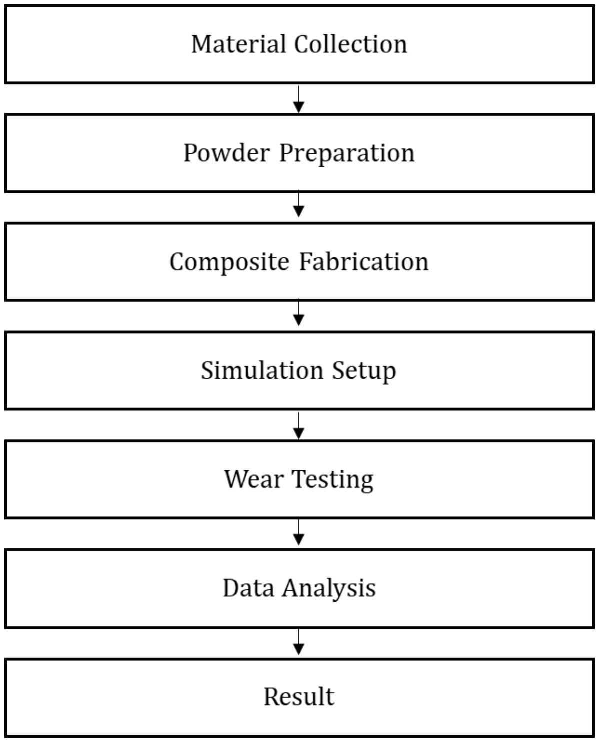


Fig. 1. Schematic methodology.

Finite element simulations were conducted via ANSYS Workbench to assess the brake pads' performance. The process involved importing CAD models, generating the mesh, and applying boundary conditions to analyze the resulting stress and deformation patterns. Following ASTM G99 standards, wear and friction characteristics were evaluated using a pin-on-disc setup. Tests were performed for a 20-minute duration at loads ranging from 20 to 40 N and speeds between 150 and 250 rpm. The study synthesized simulation data, experimental wear rates, and SEM morphology to validate the model and interpret the underlying mechanisms governing material behavior during operation. The workflow concludes with data interpretation and formulation of conclusions concerning the suitability of COR- and coir-based composites as sustainable alternatives to asbestos in brake pad applications [30-32].

This research tackles key gaps in existing studies by enhancing structural and numerical evaluation of natural fiber-based brake pads through finite element analysis, deepening the understanding of deformation and stress behaviour in coconut-derived materials under braking, and linking SEM morphology with FEA predictions and assumptions for coconut composites [33]. Through the development of coconut-based composites, this research compares bio-based friction materials with asbestos pads. The integration of SEM observations and mechanical simulations highlights a promising, eco-friendly solution for industrial brake applications.

2.1 Materials and ingredients

A comprehensive review of coconut oil extraction techniques highlighted the influence of processing methods on the physical and chemical properties of coconut-derived residues. It also outlined the growing industrial applications of coconut by-products, supporting their suitability as sustainable fillers in composite materials [34,35]. The basic raw materials selected for the development of the frictional composite are epoxy resin as the binder and coconut oil residue (COR) powders as the primary reinforcement material. The COR powders were collected from Rehoboth Oil Mill and Epoxy resins from Leo Enterprises, located in Tamil Nadu, India. The oil residue was obtained after mechanical extraction of coconut oil, sun-dried, and ground to a fine powder using a milling process. The physical properties and chemical composition of the residue were determined to evaluate its suitability for frictional applications. The material exhibits low density and moderate hardness, making it a lightweight and sustainable filler option [36]. The high carbon and oxygen content indicate the presence of organic compounds such as lignin and cellulose, which contribute to energy absorption and wear resistance under braking conditions. Table 1 presents the measured physical and chemical characteristics of the coconut oil residue powder.

Table 1. Physical properties of COR.

Property	Value
Density	1.18 g/cm^3
Particle size	50-150µm
Moisture content	4.2%
Hardness	32 shore D
Ash content	2.6%
Elemental Composition	C and O; Si, Ca, K, Fe traces
Thermal behaviour	Ligno-cellulosic decomposition 200–300 °C

2.2 Specimen preparation

Coconut flour's flowability is highly sensitive to moisture content, with higher moisture reducing flow and increasing cohesiveness. For optimal processing and storage, maintaining low moisture levels is crucial to prevent agglomeration and ensure efficient handling.

The brake pad composite specimens were prepared using coconut oil residue (COR) powder as the reinforcement material and epoxy resin as the matrix. The formulation consisted of 60 g of COR powder blended with 45 g of epoxy resin, to which 10% hardener was added to initiate cross-linking. The constituents were thoroughly mixed until a uniform consistency was achieved and then processed using the compression moulding technique. A steel mould of 300 mm × 300 mm dimension and a plate thickness of 3 mm was employed to produce test specimens of consistent geometry. The moulding process was carried out under controlled conditions, with the system capable of sustaining a maximum pressure of 400 bar and a temperature up to 400 °C, ensuring adequate consolidation and curing of the composite [37].

(a) Powder form (b) Solid form

Fig. 2. Specimen of COR.

The resulting specimens exhibited good surface finish and dimensional accuracy, making them suitable for subsequent mechanical and tribological characterization. The prepared specimen in solidified form is illustrated in fig.2

2.3 Wear test

Pin-on-disc testing of individual brake pad ingredients demonstrated how each component contributes differently to friction behaviour, wear mechanisms, and transfer-layer formation. The importance of ingredient-level characterisation for understanding single composite brake pad performance and optimising friction material formulations [38].

The friction and wear behaviour of the composite samples was evaluated under dry sliding conditions using pin-on-disc tribometer, following the guidelines of ASTM G99. The tests were performed at normal loads of 10N, 20N, 30N and 40N. During testing, both the coefficient of friction and wear loss were continuously monitored and recorded for each composite specimen. The wear loss was quantified by measuring the mass of each specimen before and after testing using a high-precision electronic balance. The weight differential was then used to calculate the specific wear rate according to the following relation,

$$W = \frac{W_1 - W_2}{\rho \, X \, A}$$

W_1 and W_2 are the initial and final weights of the specimen (g), ρ is the density (g/cm^3), and A is the contact area (cm^2).

The pin-on-disc setup used in this investigation is illustrated in fig. 3. The observed weight loss corresponds to the material removal resulting from frictional interaction between the pin specimen and the rotating disc surface. This measurement clarifies the wear resistance and tribological performance of the developed brake pad composites.

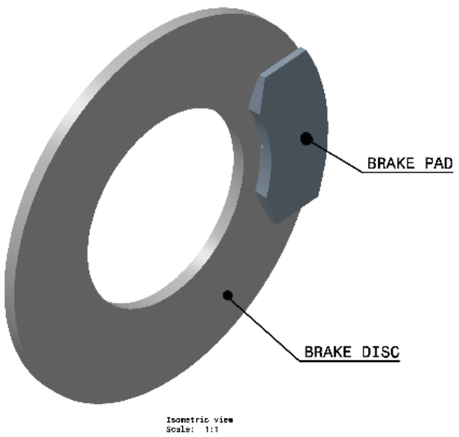
Fig. 3. Pin-on-disc setup.

3. SEM ANALYSIS

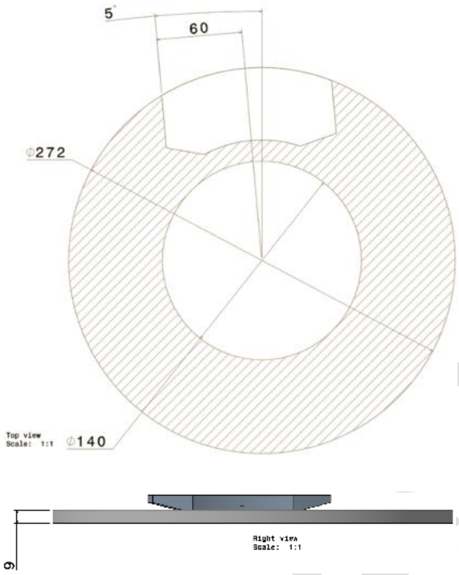
Scanning electron microscopy (SEM) analysis is widely used for detailed examination of composite materials, primarily to understand their surface morphology, microstructural features, and elemental composition. It is conducted by scanning the sample surface with a focused electron beam, which interacts with the atoms in the material and produces signals used to generate detailed images and micro chemical maps. SEM examination of coconut-fiber-reinforced polyester composites revealed characteristic fracture features such as fiber pull-out, matrix cracking, and interfacial debonding. These microstructural observations highlight how fiber matrix interaction governs failure behaviour and influences the mechanical performance of natural fiber composites. These insights help establish the relationship between microstructural defects such as cracks and macroscopic properties like strength, toughness, and failure modes, driving advancements in composite material design and optimization.

4. CAD MODELLING

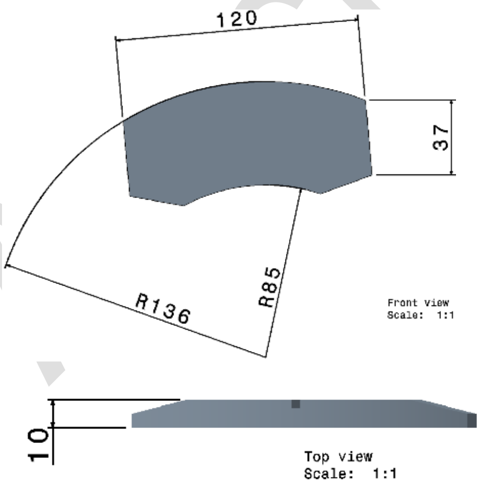
Computer-Aided Design (CAD) modeling is an essential technique for visualizing, designing, and optimizing composite materials and their structural components. Utilizing CAD allows researchers and engineers to represent complex geometries, heterogeneous material distributions, and fiber architectures in three-dimensional models, which is critical for capturing the intricate features of advanced composites.



(a) Brake pad assembly



(b) Assembly dimensions



(c) Dimensions of brake pad

Fig. 4. Schematic drawing of brake pad with rotor disc [MODEL].

The geometric model of the brake disc and brake pad is created in CATIA software. The dimensions of the brake pad are generated with a rotor brake disc diameter of 136 mm, 9mm thick and a brake pad thickness of 10 mm and other dimemsions are mentioned in Fig. 4. The internal portion of the disc is removed for computational ease for lowering the number of discretization of elements. The static load of the brake pad is mainly for the pressure developed by the piston through the caliper assembly, but it is not in contact with the rotor disc. Brake systems in vehicles can be divided into two main categories: disc brakes and drum brakes. In disc brakes, a friction system is used to slow down the vehicle using brake pads that are mechanically forced against a rotor disc with a set of calipers. Similarly, in drum brakes, a set of pads is pressed against the brake drum to slow down the vehicle.

The current study employs an integrated design-manufacturing-environment framework to optimize the brake pad, utilizing eco-friendly composites to reduce component volume while strictly preserving mechanical integrity. The study aims to optimize different parameters of the brake pad, including mass, strain, and stress parameters. The approach involves drawing a brake pad using CATIA software and applying static analysis in ANSYS with various materials, including natural fibers, used during the manufacturing of brake pads. Finally, different deformations, strains, and stresses of each material are compared to select the optimal fiber.

5. CAE ANALYSIS

Finite element analysis (FEA) is a powerful tool for analyzing the behaviour of brake pads. FEA facilitates the analysis of critical performance metrics, including interfacial contact pressure and wear, alongside the thermal gradients and dynamic vibrations occurring within the pads. Additionally, FEA can be used to study the effects of braking forces on the brake pads, as well as the effects of friction coefficient, material properties, and other parameters. It also facilitates design optimization, ensuring the brake pads achieve superior performance and long-term structural integrity.

When analyzing brake pads, several assumptions are generally made. Key variables include the friction coefficient and wear rate, along with the pad's material properties, temperature distribution, and vibrational levels. Other assumptions may also be necessary depending on the specific application. Additionally, when calculating the strength of the pads, it is assumed that the pads are properly positioned and that the disc is rotating at a constant speed. During the analysis of the brake disc, the material is assumed to be homogeneous and isotropic. Additionally, the analysis is considered to be axially symmetric. Finally, it is assumed that inertial forces can be ignored during the analysis, and it is assumed that the pressure applied by the brake pad to the disc is uniform. This assumption can simplify the analysis process and make it easier to model and analyze the behaviour of the brake disc.

The frictional contact between the brake pad and brake disc is determined by factors such as load, speed, temperature, surface texture, vibration, and lubricants. The filler materials can play a role in the performance character in automotive brakes. The disc material is considered as grey cast iron. The static analysis focuses on the normal force transmitted from the brake pedal to the pad-disc contact interface. The brake disc with the brake pad model is considered for the proper assumptions for analyzing the material behaviour in terms of durability and stress conditions. The assumptions for importing CAD to ANSYS for the data interface are listed below.

- Simplifying the small corners and chamfer and by ignoring grooves and holes.
- The physical properties of the parts are considered as isotropic and homogeneous.
- Negligible of all forces including inertia force during braking.
- The total frictional force applied on the rubbing surface is equal to the force distributed on one brake disc.
- Neglecting small holes in caliper injector and back plate holders and the riveted joints.

The brake pad model was set to flexible, and the disc rotor model was set to rigid, with a switch from bonded to frictional contact. The contact surface has defined as the front surface of the brake pad model and the targeted surface is defined as the surface of the disc rotor model. The coefficient of friction has been applied based on the material used for the brake pad model. The disc rotor model has been assumed to rotate freely, without any obstructions, in a large external domain to prevent any boundary effects.

5.1 Brake pad model mesh grid

The tetrahedral element is used for this finite element model of a brake pad in fig. 5. The main advantage of this kind of automatically generated mesh with isometric characteristics would be the increase in the number of grids. The size of the grid cell formation is 5 mm and the number of grid nodes and grid elements are found as 7004 and 3221 respectively. Static load conditions of the brake pad are not subject to change in the external force and pad itself. In most FE-based brake models, the disc is constrained as static, while the pad is defined as the active component since the pad undergoes more significant deformation during braking, whereas the disc primarily serves as a rigid support with minimal elastic deflection. Several researchers adopted the same modelling assumption, fixing the disc and applying normal load or equivalent braking pressure on the pad to examine structural behaviour. So that the conditions of the brake pad do not change with time, which means the brake disc is not considered for acceleration.

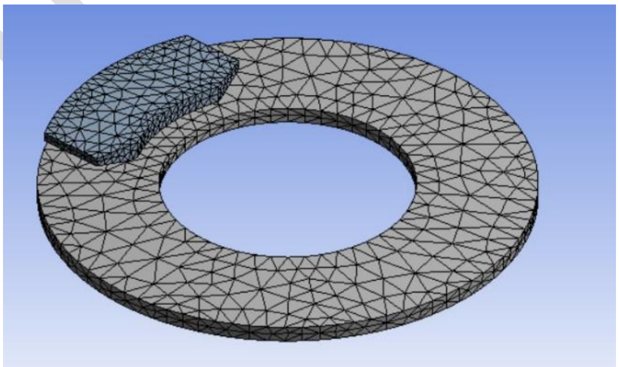


Fig. 5. Mesh grid.

5.2 Loads and constraints

The boundary conditions of the brake pad are complex; therefore, simplified constraints are applied based on static load stress conditions. The disc material is considered as mild steel to support the pad, with a braking force of 45 KN acting on the pad under the rotational velocity of the disc at cylindrical support. A 3D model of the pad is created in ANSYS, where loads and constraints are defined to simulate real operating conditions. The software generates results such as stress and deformation, which help identify potential failure zones and guide improvements in brake pad strength and durability. Table 2 summarizes the applied boundary conditions, while Fig. 6 illustrates their representation in the simulation.

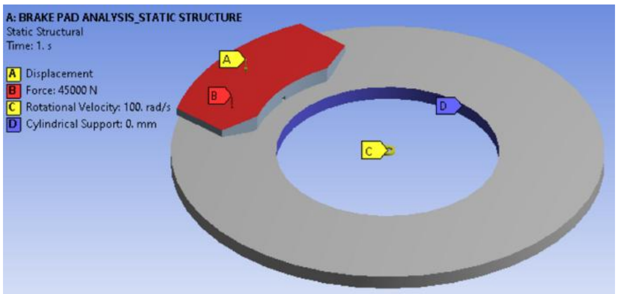


Fig. 6. Boundary conditions for brake pad.

Table 2. Boundary conditions with vehicle data.

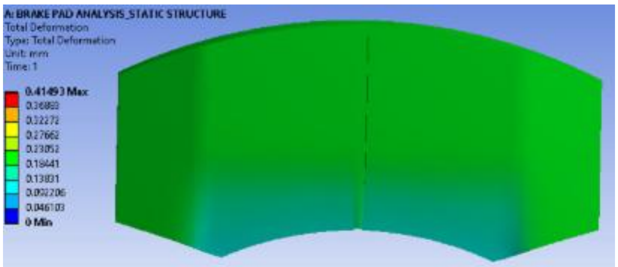
Parameters	Values applied
Displacement	Applied on brake pad
Force	45KN
Rotational velocity	100 rad/s
Cylindrical support	Fixed for axial and free for radial
Initial velocity	60 m/s
Duration of braking application	1 sec
Radius of disc	137.6mm
Radius of the wheel	380mm
Coefficient of friction	0.32
Pad surface	56025.52mm^2

Consistent with literature for natural fiber composites, the COR specimen achieved a COF of 0.28–0.39, staying within the expected 0.25–0.45 range across varying loads and speeds. Coconut-fiber–based friction composites similarly show stable friction characteristics within this range, confirming good adaptability to braking applications. In comparison, conventional asbestos and semi-metallic pads generally present COF values around 0.30–0.40, which aligns as 0.32 for the boundary condition that closely with the values recorded.

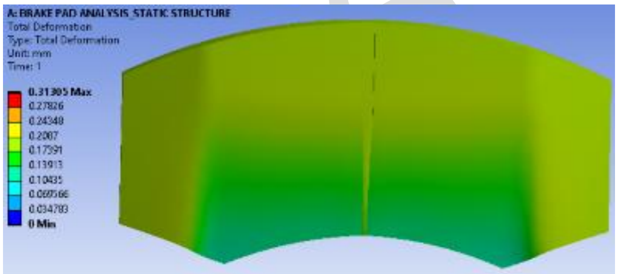
6. RESULTS AND DISCUSSION

6.1 Deformation analysis

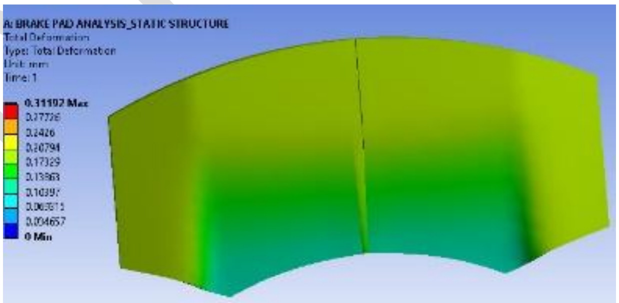
Numerical approaches such as finite element analysis (FEA) and molecular dynamics simulations are widely employed to predict material deformation under varying loads and environmental conditions. These computational methods incorporate parameters such as stress, strain rate, temperature, and boundary constraints to identify regions susceptible to deformation or fracture, thereby supporting design optimization and improved understanding of material behaviour.



(a) Coconut Coir Fiber



(b) Coconut Oil Residue



(c) Asbestos fiber

Fig. 7. Deformation results.

Table 3. Deformation result.

Material	Maximum Value
Coconut coir	0.415
COR	0.313
Asbestos	0.311

In this study, the deformation characteristics of coconut oil residue (COR), coconut coir, and asbestos brake pad materials were evaluated using structural FEA. The results, illustrated in Fig. 7 and summarized in Table 3, show that maximum deformation occurs near the braking caliper, where compressive stresses are concentrated. Coconut coir exhibited the highest deformation (0.415 mm), while COR (0.313 mm) and asbestos (0.311 mm) displayed comparatively lower values. This behaviour reflects the intrinsic stiffness of the materials and their ability to maintain geometric stability under braking loads. Fig. 8 highlights that coconut coir's greater deformation is linked to its lower stiffness and fiber porosity, whereas COR and asbestos demonstrate nearly identical rigidity and structural stability. The similarity between COR and asbestos suggests that COR can provide comparable load-bearing capability while offering the advantage of being an eco-friendly alternative.

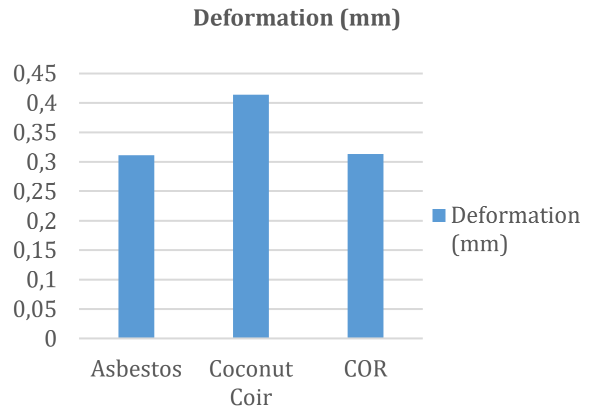


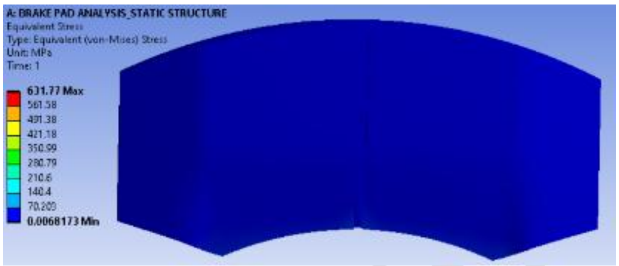
Fig. 8. Deformation vs Materials.

6.2 Stress analysis

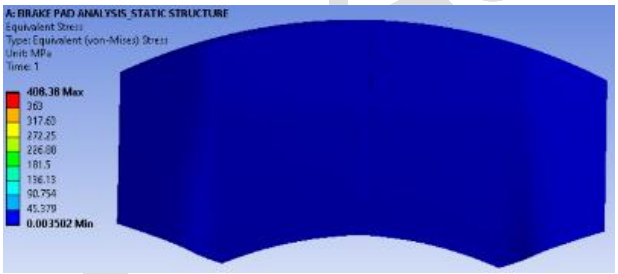
Static stress analysis is a widely applied numerical method used to determine the stresses and strains generated within a material when subjected to external loads under steady-state conditions. In this approach, the CAD model of the component is subjected to applied loads and boundary conditions, and the resulting stress distribution is computed using FEA. This analysis allows the identification of high-stress regions critical for assessing the structural integrity, durability, and performance of friction materials.

For brake pad applications, understanding the stress distribution is essential because high localised stresses may lead to cracking, delamination, or accelerated wear, all of which negatively affect braking performance and safety. Predicting and reducing these stress concentrations supports the development of more reliable friction materials with improved load distribution and dimensional stability.

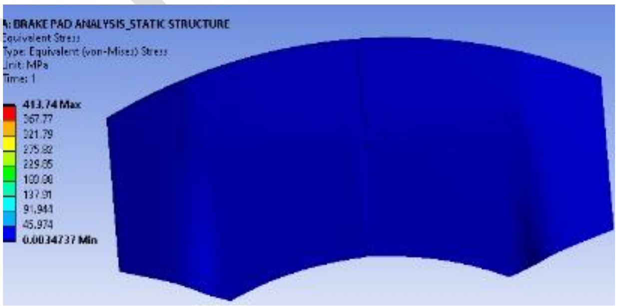
The von Mises stress (Fig. 9) values obtained from the static analysis for each material are presented in Table 4. Coconut coir exhibited the highest stress value (631.77 MPa), indicating greater stress sensitivity under loading, while COR (408.38 MPa) and asbestos (413.74 MPa) exhibited lower values, suggesting better mechanical stability.



(a) Coconut Coir Fiber



(b) Coconut Oil Residue



(c) Asbestos fiber

Fig. 9. Stress Analysis results.

Table 4. Stress analysis result.

Material	Maximum Value, MPa
Coconut coir	631.77
COR	408.38
Asbestos	413.74

Fig. 10 presents a comparative analysis of the maximum von Mises stress observed in the three materials. Coconut coir shows the highest stress value, indicating limited stress-bearing capacity due to its fibrous, less-dense microstructure. COR and asbestos exhibit significantly lower stress values, demonstrating their ability to distribute braking loads more evenly. The close agreement between COR and asbestos highlights COR's potential as a structurally stable and sustainable replacement for traditional asbestos-based friction materials.

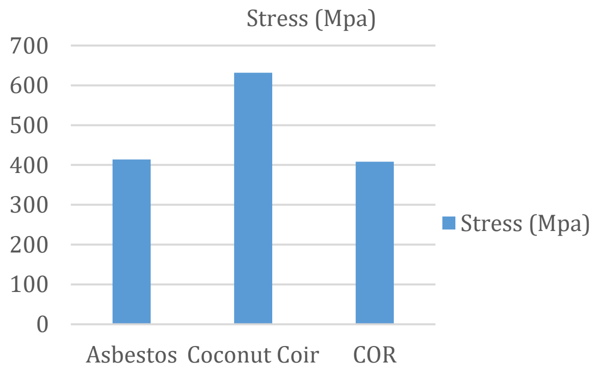


Fig. 10. Stress vs materials.

6.3 Morphological defect analysis

The SEM image of the coconut oil residue (COR) worn surface reveals visible micro-cracks, fissures, and irregular surface morphology (Fig. 11). The observation of fiber pull-out, matrix cracking and delamination with wear grooves and pits in coconut coir-polyester composites under static loads of 10 N, 20 N and 30 N.

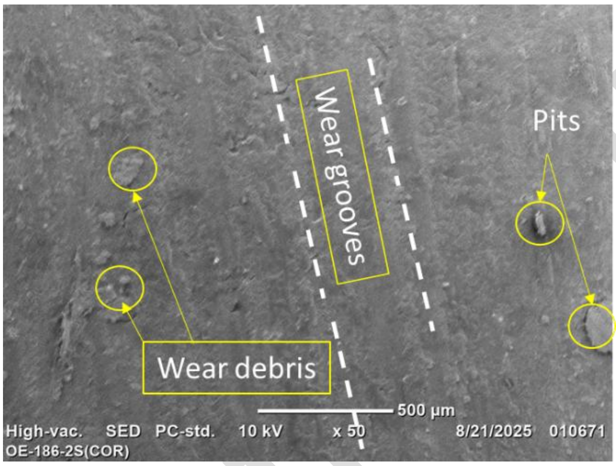


Fig. 11. SEM image of COR composite.

Simultaneously, in hybrid brake friction materials reinforced with plant fibers, micro cracks, pits, and broken fibers were a key feature of worn surfaces for high fiber content specimens [38]. These defects are understood to act as stress concentrators, accelerating deformation and increasing maximum Von-Mises stresses, consistent with our simulation results, which show higher deformation and stress in the coconut coir material. Therefore, even without direct SEM of coir/asbestos in our current work, it is reasonable to infer that the observed deformation & stress differences partly stem from microstructural defects like those seen in the COR SEM image and those reported in the cited studies.

6.4 Wear test results

Table 5 details the wear and friction performance of the COR composite at different loads and speeds. The results indicate that both wear loss and coefficient of friction increase with increasing applied load and sliding velocity. This behaviour is typical in dry sliding conditions, where higher loads promote greater interaction and material removal due to intensified contact pressure and frictional heating.

Table 5. Wear loss and COF of COR Specimen.

Normal load (N)	Sliding Velocity (rpm)	Wear Loss (g)	Frictional Coefficient (µ)
10	150	0.002	0.284
20	150	0.0022	0.282
30	150	0.0025	0.277
10	300	0.0051	0.311
20	300	0.0053	0.334
30	300	0.006	0.363
10	500	0.0066	0.379
20	500	0.0071	0.381
30	500	0.011	0.387

At lower loads and speeds, the composite showed minimal wear (0.002–0.0022 g) and stable friction below 0.29, indicating smooth surface adaptation and reduced micro-ploughing. As the operating conditions intensified (30 N, 500 rpm), the wear loss increased to 0.011 g and the friction coefficient reached 0.387, indicating a mild-to-severe wear transition driven by localized temperature rise and softening of the resin matrix.

The overall increase in friction coefficient with load is associated with the formation and periodic removal of transfer films on the counter surface. These moderate friction values (0.28–0.39) mean the COR composite performs predictably. It provides a stable brake response, striking a healthy balance where the pad doesn't stick too aggressively to the disc or lose its grip. The simulations predicted the material would stay strong under stress, and the microscope images backed this up, revealing a solid, compact microstructure that resisted wear and kept cracks from forming. The fact that the material lost so little weight under all those different conditions tells us it has great wear resistance. It proves that the COR composite is tough enough to stay intact, even during long-term use. Thus, the COR composite demonstrates consistent wear resistance and frictional stability, making it a promising material for eco-friendly brake pad applications.

The contour plot in Fig. 12 illustrates the combined influence of normal load (10–30 N) and sliding velocity (150–500 rpm) on the wear loss of the COR brake pad specimen. The color gradients represent different wear-loss ranges, with lighter shades indicating lower wear and darker shades representing higher material removal.

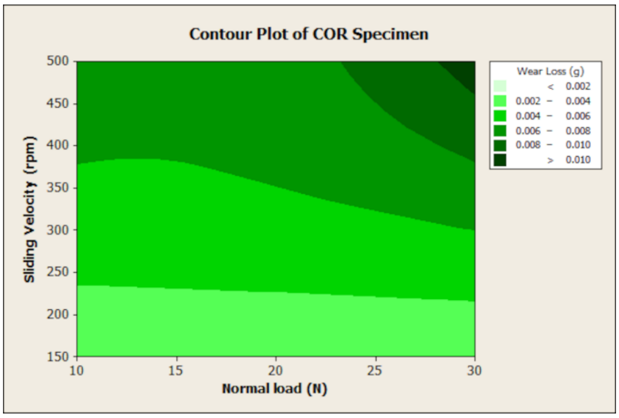


Fig. 12. Contour plot of COR specimen.

At lower loads (10–15 N) and lower speeds (150–200 rpm), the contour remains in the light-green region, indicating minimal wear (<0.004 g). This suggests stable frictional contact and adequate structural integrity of the COR composite under mild operating conditions. As the sliding velocity increases beyond 300 rpm, the wear loss gradually increases, shown by the transition to medium-green zones (0.004–0.008 g), reflecting the rise in frictional heat and abrasion rate.

At higher loads (25–30 N) combined with elevated sliding velocities (400–500 rpm), the contours shift to darker regions (>0.010 g), indicating significant wear. As expected, the material wears down faster at higher loads and speeds. This happens because the surfaces rub together more intensely, creating heat that softens the material and makes it easier to pull apart.

7. CONCLUSION

Eco-friendly brake pads made from coconut fibers and residue were compared to asbestos-based materials using simulations and microstructural analysis.

The key findings are summarized below:

- Both coconut-based composites held their shape well under pressure, with the COR version performing almost identically to traditional asbestos..
- Stress analysis shows that maximum von Mises stresses of 631.77 MPa (coir), 408.38 MPa (COR), and 413.74 MPa (asbestos), confirming that COR-based composites exhibit heavy load capability.
- SEM morphology showed COR composites had fewer surface cracks and stronger bonding, which explains their better stress handling and wear resistance.
- Composites containing coconut oil residue worked effectively because the carbonaceous matter improved bonding and lowered stress concentrations.
- Coconut coir fibers, rich in lignin and cellulose, contributed to mechanical stability and moderate flexibility during simulated braking conditions [34].

These findings indicate that COR-based composites are promising substitutes for asbestos in friction materials, providing both mechanical reliability and environmental benefits.

Although several natural fibres have been explored for brake pad applications, limited studies investigate coconut oil residue (COR) as a friction material, particularly combining experimental wear behaviour with numerical structural analysis. Furthermore, the deformation and stress characteristics of COR-based pads under braking loads remain insufficiently reported. This study addresses this gap by integrating material fabrication, tribological testing, SEM evaluation, and finite element simulation with single ingredients [38].

Further work involving experimental wear and thermal testing as in vehicular condition is suggested to validate and optimize the performance of these natural fiber–based brake pads.

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REFERENCES

[1] M. Yigrem, O. Fatoba, and S. Tensay, "Tensile strength, wear characteristics and numerical simulation of automotive brake pad from waste-based hybrid composite," *Materials Today: Proceedings*, vol. 62, pp. 2954–2964, Mar. 2022, doi: 10.1016/j.matpr.2022.02.557.

[2] M. Eriksson and S. Jacobson, "Tribological surfaces of organic brake pads," *Tribology International,* vol. 33, no. 12, pp. 817–827, Nov. 2000, doi: 10.1016/S0301-679X(00)00127-4.

[3] E. Obika, C. Achebe, J. Chukwuneke, and O. Ezenwa, "Effect of cane wood and palm kernel fibre filler on the compressive strength and density of automobile brake pad," *Advances in Mechanical Engineering*, vol. 12, no. 7, Jul. 2014, doi: 10.1177/1687814020947611.

[4] C. O. Mgbemena, R. U. Esigie, C. E. Mgbemena, and C. M. Ata, "Production of low wear friction lining material from agro-industrial wastes," *Journal of Engineering and Applied Science*, vol. 69, no. 1, Aug. 2022, doi: 10.1186/s44147-022-00130-3.

[5] Irawan AP, Fitriyana DF, Tezara C, Siregar JP, Laksmidewi D, Baskara GD, Abdullah MZ, Junid R, Hadi AE, Hamdan MHM, Najid N., "Overview of the important factors influencing the performance of eco-friendly brake pads," *Polymers*, vol. 14, no. 6, p. 1180, Mar. 2022, doi: 10.3390/polym14061180.

[6] C. M. R. Ghazali, H. Kamarudin, J. B. Shamsul, M. M. A. B. Abdullah, and A. Rafiza, "Mechanical properties and wear behavior of brake pads produced from palm slag," *Advanced Materials Research*, vols. 341–342, pp. 26–30, Sep. 2011, doi: 10.4028/www.scientific.net/AMR.341-342.26.

[7] A. J. Kumar, N. A. Ramaseshan, and T. Lakshmanan, "Tribological analysis on basalt/aramid hybrid fiber reinforced polyimide composites: an alternate brake pad material," *Tribology in Industry*, vol. 43, no. 2, pp. 334–347, Nov. 2021, doi: 10.24874/ti.912.06.20.12.

[8] S. Vasiljevic, J. Glišović, B. Stojanovic, N. Stojanovic, and I. Grujic, "The analysis of the influential parameters that cause particles formation during the braking process: A review," *Proceedings of the Institution of Mechanical Engineers Part J Journal of Engineering Tribology*, vol. 236, no. 1, pp. 31–48, Mar. 2021, doi: 10.1177/13506501211004798.

[9] A. Maithani, V. Mall, and S. G. Roy, "Structural and thermal analysis of magnesium based brake friction material," *International Journal for Research in Applied Science and Engineering Technology*, vol. 10, no. 5, pp. 398–408, May 2022, doi: 10.22214/ijraset.2022.41899.

[10] C. Pinca-Bretotean, A. L. Craciun, C. Preda, and A. K. Sharma, "Physico-mechanical and tribological characteristics of composites used for brake pads," *Journal of Physics Conference Series*, vol. 1781, no. 1, p. 012032, Feb. 2021, doi: 10.1088/1742-6596/1781/1/012032.

[11] T. K. Mulenga, A. U. Ude, and C. Vivekanandhan, "Techniques for Modelling and Optimizing the mechanical properties of natural fiber composites: A review," *Fibers*, vol. 9, no. 1, p. 6, Jan. 2021, doi: 10.3390/fib9010006.

[12] G. S. Krishnan, L. G. Babu, R. Pradhan, and S. Kumar, "Study on tribological properties of palm kernel fiber for brake pad applications," *Materials Research Express*, vol. 7, no. 1, p. 015102, Nov. 2019, doi: 10.1088/2053-1591/ab5af5.

[13] C. Pinca-Bretotean, R. Bhandari, C. Sharma, S. K. Dhakad, P. Cosmin, and A. K. Sharma, "An investigation of thermal behaviour of brake disk pad assembly with Ansys," *Materials Today Proceedings*, vol. 47, pp. 2322–2328, Jan. 2021, doi: 10.1016/j.matpr.2021.04.296.

[14] S. S. Karthikeyan, E. Balakrishnan, S. Meganathan, M. Balachander, and A. Ponshanmugakumar, "Elemental analysis of brake pad using natural fibres," *Materials Today Proceedings*, vol. 16, pp. 1067–1074, Jan. 2019, doi: 10.1016/j.matpr.2019.05.197.

[15] F. Z. Elhilali and H. Fihri-Fassi, "Towards the development of mechanical systems entirely based on natural materials," *Fluid Dynamics & Materials Processing*, vol. 18, no. 5, pp. 1285–1292, Jan. 2022, doi: 10.32604/fdmp.2022.021803.

[16] S. S. Raj, T. Chellapandian, and B. Nanjappan, "Effect of glycerol on the properties of coconut oil cake reinforced poly(lactic acid)," *Polimery*, vol. 67, no. 2, pp. 61–66, Feb. 2022, doi: 10.14314/polimery.2022.2.2.

[17] S. S. Todkar and S. A. Patil, "Review on mechanical properties evaluation of pineapple leaf fibre (PALF) reinforced polymer composites," *Composites Part B Engineering*, vol. 174, p. 106927, May 2019, doi: 10.1016/j.compositesb.2019.106927.

[18] X. Xiao, Y. Yin, J. Bao, L. Lu, and X. Feng, "Review on the friction and wear of brake materials," *Advances in Mechanical Engineering*, vol. 8, no. 5, May 2016, doi: 10.1177/1687814016647300.

[19] M. Sunil Kumar Hemanth and J. Edwin Raja Dhas, "Characteristics of brake pad materials and their selection criteria: A quantitative survey," in *Advances in Materials Science Research*, vol. 55, pp. 153–182, 2022.

[20] M. R. Manikantan, R. P. K. Ambrose, and S. Alavi, "Flow-specific physical properties of coconut flours," *International Agrophysics*, vol. 29, no. 4, pp. 459–465, Oct. 2015, doi: 10.1515/intag-2015-0051.

[21] T. N. B. Narendiranath, B. Shivasai, M. Vattikuti, and P. Reddy, "Design and analysis of coconut fiber reinforced polyester composite leaf spring," *International Journal of Mechanical Engineering and Technology*, vol. 8, no. 6, pp. 544–552, Jun. 2017.

[22] N. Athanassiou, U. Olofsson, J. Wahlström, and S. Dizdar, "Simulation of thermal and mechanical performance of laser cladded disc brake rotors," *Proceedings of the Institution of Mechanical Engineers Part J Journal of Engineering Tribology*, vol. 236, no. 1, pp. 3–14, Apr. 2021, doi: 10.1177/13506501211009102.

[23] S. A. M. Da Silva and D. V. V. Kallon, "FEA on different disc brake rotors," *Procedia Manufacturing*, vol. 35, pp. 181–186, Jan. 2019, doi: 10.1016/j.promfg.2019.05.025.

[24] A. Raju and M. Shanmugaraja, "Recent researches in fiber reinforced composite materials: A review," *Materials Today Proceedings*, vol. 46, pp. 9291–9296, Apr. 2020, doi: 10.1016/j.matpr.2020.02.141.

[25] S. M. S. Idid, M. R. Isa, O. S. Zaroog, M. F. A. Jalal, S. N. Sulaiman, and N. M. Zahari, "A simulation study of thermal and mechanical properties of brake pads using different type of materials," *AIP Conference Proceedings*, vol. 2339, p. 020044, Jan. 2021, doi: 10.1063/5.0044222.

[26] A. Belhocine and A. Afzal, "Computational finite element analysis of brake disc rotors employing different materials," *Australian Journal of Mechanical Engineering*, vol. 20, no. 3, pp. 637–650, Feb. 2020, doi: 10.1080/14484846.2020.1733175.

[27] Y. S. Chouhan and S. Tiwari, "Static structural and thermal analysis of disc brake pad model," *IOP Conference Series Materials Science and Engineering*, vol. 810, no. 1, p. 012073, Mar. 2020, doi: 10.1088/1757-899x/810/1/012073.

[28] A. Belhocine and O. I. Abdullah, "Thermomechanical model for the analysis of disc brake using the finite element method in frictional contact," *Multiscale Science and Engineering*, vol. 2, no. 1, pp. 27–41, Mar. 2020, doi: 10.1007/s42493-020-00033-6.

[29] B. Zheng, J. Zhang, and W. Liu, "Finite Element Analysis of Brake Shoe Based on ANSYS Workbench," *Advances in Intelligent Systems Research,* Jan. 2018, doi: 10.2991/icaita-18.2018.23.

[30] M. Badri, S. Sugiman, A. Aguswandi, and J. Jayadi, "SEM observation on fracture surface of coconut fibers reinforced polyester composite," *Journal of Ocean Mechanical and Aerospace -science and Engineering- (JOMAse)*, vol. 40, no. 1, pp. 22–27, Feb. 2017, doi: 10.36842/jomase.v40i1.389.

[31] C. Wang, R. Li, H. Lin, S. Yuan, L. Wang, and Y. Ma, "Preparation and Properties of Brake Friction Materials Reinforced with Coconut Fiber and Dypsis Lutescens Fiber," *Materials*, vol. 17, no. 16, p. 3926, Aug. 2024, doi: 10.3390/ma17163926.

[32] A. B. D. Nandiyanto, M. Fiandini, D. N. A. Husaeni, R. Ragadhita, and S. N. Hofifah, "Production of Brake Pad from Epoxy Resin: From Polymerization Concept to the Experiment with Analysis of Mechanical Properties," *Jurnal Penelitian Enjiniring*, vol. 25, no. 2, pp. 110–115, Jul. 2022, doi: 10.25042/jpe.112021.05.

[33] K. Mausam, A. Sharma, and P. K. Singh, "Calculating stress, temperature in brake pad using ANSYS composite materials," *Materials Today Proceedings*, vol. 45, pp. 3547–3550, Jan. 2021, doi: 10.1016/j.matpr.2020.12.991.

[34] M. S. K. Hemanth and J. E. R. Dhas, "Eco-friendly materials for brake pad- ANSYS overview," *Materials Today Proceedings*, May 2023, doi: 10.1016/j.matpr.2023.05.194.

[35] Y. J. Ng, P. E. Tham, K. S. Khoo, C. K. Cheng, K. W. Chew, and P. L. Show, "A comprehensive review on the techniques for coconut oil extraction and its application," *Bioprocess and Biosystems Engineering*, vol. 44, no. 9, pp. 1807–1818, May 2021, doi: 10.1007/s00449-021-02577-9.

[36] G. S. Andrés, S. Aguilar-Sierra, and N. B. Graziella, "Morphological, physical, and chemical characterization of coconut residues in Ecuador," *Heliyon*, vol. 9, no. 9, p. e19267, Aug. 2023, doi: 10.1016/j.heliyon.2023.e19267.

[37] M. Naidu, A. Bhosale, Y. Munde, S. Salunkhe, and H. M. A. Hussein, "Wear and friction analysis of brake pad material using natural hemp fibers," *Polymers*, vol. 15, no. 1, p. 188, Dec. 2022, doi: 10.3390/polym15010188.

[38] D. Carlevaris, F. Varriale, J. Wahlström, and C. Menapace, "Pin-on-disc tribological characterization of single ingredients used in a brake pad friction material," *Friction*, vol. 12, no. 11, pp. 2576–2593, Aug. 2024, doi: 10.1007/s40544-024-0922-3.