

A Review on Banana Fiber Reinforced Composite Brake Pads for Sustainable Automotive Applications

Dipak D. Bari¹, Samadhan M. Khaire², Mayuri R. Patil³, Vaishnavi Chaudhari⁴
^{1,2,3,4} Assistant Professor, Mechanical Engineering Department, KCES's CoEM Jalgaon, Maharashtra, India

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ABSTRACT

Banana fibers composites are good alternative for conventional asbestos materials used for brake pads of an automotive application. Natural banana fibers are cheaper in cost, environmental friendly and biodegradable. Conventional asbestos brake pads and other hazardous materials are avoided because of its carcinogenic nature that may cause health and environmental risks. In recent years, banana fiber, derived from banana pseudostems and peels, has emerged as a promising eco-friendly reinforcement material. This review paper analyses banana fiber-based composite brake pads, its material composition, fabrication techniques, tribological behavior, mechanical and thermal properties, and environmental benefits. The performance of banana fiber reinforced composite is compared with other natural fiber-reinforced brake pad materials. Also, the processing methods and challenges associated with their use are discussed. Despite these challenges, the review highlights the potential for these composites and exhibits competitive friction and wear characteristics which play an important role in sustainable and eco-friendly brake pad applications.

Keywords: - Asbestos, Banana Fiber, Composites, Mechanical Properties, Sustainable Application.

1. NTRODUCTION

The use of composite materials has been increasing in many applications. Over the past several years due to composite material possesses unique properties and ability to shape up them to specific requirements. Among the various types of composite materials, natural fiber-reinforced composites have been getting considerable attention due to their environmental and economic benefits over traditional glass fiber composites [15]. The expeditious growth of the automotive industry has led to an increased demand for high-performance and reliable braking systems which ensures vehicle safety. Brake pads are most important components of disc and drum braking systems. They are responsible for converting the vehicle's kinetic energy into thermal energy which generated through friction. The performance of brake pads directly influences braking efficiency, stopping distance, wear characteristics, noise generation, and overall vehicle safety. Brake pads generally consist of asbestos-based and synthetic fiber-reinforced with polymeric matrix along with several other ingredients due to their excellent frictional and thermal properties.[4,6,14] Traditionally used asbestos fiber have been avoided due to its carcinogenic nature. However, the severe health hazards and environmental risks associated with asbestos fibers have resulted in strict regulations and bans in many countries.

In the late1960's most car used drum brakes. The pads for these drum brakes were organic and often consisted of resins and asbestos as well as a variety of other materials to help improved braking and wear. In the late1960's and early 1970's, automobile manufacturers started use of disc brakes, especially for larger motor vehicles, because such brakes had better braking performance.[1] In response to these concerns, non-asbestos organic (NAO) brake pads have gained significant attention, incorporating synthetic fibers such as aramid, glass, and carbon as reinforcement materials. Though these materials exhibit acceptable mechanical and tribological performance, they are expensive, non-biodegradable, and energy consuming to produce.[19] Furthermore, the increasing emphasis on sustainability and environmental responsibility has encouraged researchers and manufacturers to explore alternative materials derived from renewable and biodegradable sources. As a result, natural fiber-reinforced composites have emerged as promising candidates for eco-friendly brake pad applications.[1,14,20]

Natural fibers such as jute, sisal, coconut, kenaf, bamboo, and flax have been extensively investigated as reinforcement materials in brake pad composites. All these natural fibers offer many advantages, including low density, cost effectiveness, renewability, biodegradability, and reduced environmental impact. Among the various natural fibers, banana fiber has attracted considerable research interest due to its desirable mechanical properties and plentiful availability as agricultural waste. Banana fiber is primarily extracted from the pseudo stem and peel of banana plants, which are typically discarded after harvesting of fruit. The utilization of banana

fiber adds value to agricultural waste and contributes to waste reduction and sustainable material development.[5,7,11]

Banana fiber consists mainly of lignin, cellulose, and hemicellulose that contribute to its strength, flexibility, and thermal behavior. Relatively high tensile strength and low density nature of banana fiber make it a suitable reinforcement material for composite applications. In brake pad formulations, banana fiber can function as a reinforcing and friction-modifying agent, influencing key performance parameters such as coefficient of friction, wear resistance, thermal stability, and noise generation.[8,15,16] Several experimental studies have reported that banana fiber-reinforced brake pad composites exhibit stable friction characteristics and acceptable wear behavior under varying load and speed conditions.

Despite these promising results, the performance of banana fiber composite brake pads is strongly influenced by factors such as fiber content, fiber length, surface treatment, binder material, and fabrication technique. Other challenges like moisture absorption, fiber-matrix interfacial bonding, and degradation at elevated temperatures remain significant obstacles to their widespread industrial adoption.[1] Therefore, a comprehensive evaluation of existing research is essential to understand the current state of development, identify limitations, and propose future research directions.

This review paper aims to present a systematic and critical analysis of banana fiber-reinforced composite brake pads reported in the literature. The review focuses on the material characteristics of banana fiber, fabrication methods, tribological, mechanical, and thermal properties of the composites, as well as their environmental and economic benefits. Additionally, the performance of banana fiber composites is compared with other natural fiber-based brake pad materials. The challenges associated with their practical implementation and potential future research opportunities are also discussed, with the objective of assessing the feasibility of banana fiber composites as sustainable alternatives to conventional brake pad materials.

2. MATERIALS AND FABRICATION METHODS FOR BANANA FIBER COMPOSITE BRAKE PADS

Selection of constituent material and fabrication technique play important role in performance of banana fiber-reinforced composite brake pads. Brake pads are complex multi-component systems typically composed of reinforcement materials, binders, fillers, and friction modifiers.

2.1 Methods for extracting and preparing banana fibers

The extraction and preparation of banana fibers are essential steps in processing banana fiber composites. The fibers are extracted from the banana pseudo-stem, the stem-like structure supporting the banana fruit. The fibers are separated from the rest of the pseudo-stem by a process known as decortication. This can be done manually by peeling the fibers away from the stem or using machine-assisted methods. The fiber consists mainly of cellulose, hemicellulose, and lignin, which impart strength and flexibility. Once the fibers have been extracted, they are usually washed to remove any impurities, such as dirt, sap, or pith. The fibers are then dried to reduce their moisture content, which is important for preventing mold growth and ensuring the stability of the composites. The dried fibers are cut into small pieces, and their length and diameter are measured. Short, chopped fibers are most frequently used in brake pad formulations to ensure uniform dispersion and isotropic properties.[1,4,16]

2.2 Fabrication Techniques

Several techniques for fabricating banana fiber composites include hand layup, compression molding, injection molding, and filament winding. Compression molding and hot pressing are the most commonly used fabrication techniques for banana fiber composite brake pads. Compression molding is another popular technique for fabricating banana fiber composites. In this process, the fibers and resin are placed into a preheated mold, and the mold is then compressed to produce the final composite. Processing parameters such as molding pressure, curing temperature, and curing time play a critical role in determining the density, porosity, and mechanical integrity of the brake pad composite.[13,16,19] Proper optimization of these parameters results in uniform fiber distribution, reduced void content, and enhanced mechanical and tribological properties. Post-curing treatments are sometimes applied to further improve thermal stability and wear resistance.[8,16,18]

Interfacial bonding with hydrophobic polymer matrices is weak. So, to overcome this limitation, surface treatment of banana fibers is widely adopted to enhance fiber-matrix adhesion. Alkali treatment using sodium hydroxide (NaOH) is the most commonly employed method.[1,17] It removes surface impurities, waxes, and hemicellulose, resulting in increased surface roughness and improved mechanical interlocking between the fiber and matrix. Several studies have reported that alkali-treated banana fiber composites exhibit improved mechanical strength, reduced porosity, and enhanced wear resistance compared to untreated fiber composites. To improve moisture resistance and interfacial bonding silane treatment and acetylation, have also been

explored. The selection of treatment method and treatment parameters significantly influences the tribological and mechanical performance of the resulting brake pad composites.[14,15]

Phenolic resin is the most widely used binder in banana fiber composite brake pads which plays a crucial role in holding the composite constituents together and maintaining structural integrity under braking conditions. Also, it has good thermal stability, mechanical strength, and compatibility with natural fibers.

Epoxy resin has also been used as a binder for laboratory-scale investigations in some studies. It offers good mechanical properties and ease of processing, but its thermal stability is generally lower than that of phenolic resins, limiting their applicability in high-temperature braking environments. Common fillers include graphite, barite, calcium carbonate, and fly ash, which contribute to improved wear resistance, thermal stability, and noise reduction. So that fillers and friction modifiers are incorporated into brake pad formulations that improve performance characteristics.

3. MECHANICAL PROPERTIES OF BANANA FIBER COMPOSITE

Mechanical properties determine the structural integrity, durability, and reliability of brake pad materials under service conditions. During braking brake pads are subjected to repeated compressive loads, shear stresses, and impact forces. Therefore, adequate mechanical strength and hardness are essential to ensure consistent performance and resistance to deformation. Several studies have evaluated the mechanical behavior of banana fiber-reinforced composite brake pads to assess their suitability for braking applications. Compressive strength is a critical mechanical property for brake pad materials, as they experience high compressive forces during braking. Banana fiber composite brake pads have demonstrated adequate compressive strength to withstand braking loads without significant deformation. Studies have reported that alkali-treated banana fiber composites exhibit higher compressive strength compared to untreated fiber composites.

Idris et al. [1] developed a non-asbestos brake pad using banana peel waste (Figure 1) as a filler with phenolic resin (phenol formaldehyde) as a binder. The work varied the resin content from 5 wt% to 30 wt% with an interval of 5 wt%. This work investigated and tested for mechanical, physical, wear, and morphological properties of the new brake pad. The samples containing non-carbonized banana peels (BUNCp) with 25 wt% and carbonized (BCp) sample with 30 wt% gave the best properties in all the samples. Also, showed the compressive strengths of the produced samples. The results have a similar trend with that of hardness values. The compressive strength increases with increased in the wt% of resin addition.



Fig -1: Banana Peel

3.1. Flexural properties

Flexural strength provides an indication of the composite's resistance to bending and cracking under load. Banana fiber composite brake pads have shown satisfactory flexural strength, which is essential for maintaining structural stability during braking. An increase in fiber content generally leads to improved flexural strength due to the reinforcing effect of banana fibers. Narra Ravi Kumar et al developed glass reinforced hybrid polypropylene composites (BGPP) were then tested for their mechanical properties. For flexural properties they performed three point bend tests in accordance with ASTM D790M standard to measure the flexural properties.[4,15] The samples were 98mm long by 10mm wide by 4mm thick. In three point Bending test, the outer rollers are 64mm apart and the samples were tested at a strain rate of 1mm/min. The flexural strength and flexural modulus of the composites are determined. He found that flexural strength of BGPP composites at different percentages of fiber loading. The flexural strength increased with fiber loading up to 10% weight fraction of the fiber, and decreases after 10% fiber loaded composites.[1,22]

3.2 Impact Strength

Impact strength is particularly important in brake pad applications, as brake pads may be subjected to sudden loads and vibrations during braking. Izod impact test specimens were prepared by Narra Ravi Kuma et al in accordance with ASTM D256-97, to measure the impact strength. The dimensions of specimens are 64 x 12 x 9 mm width. A V-notch is provided having an included angle of 45° at the centre of the specimen, and at 90° to

the sample axis. The depth of the specimen under the notch is 10.16 ± 0.05 mm. Five identical specimens were tested for each composition. The fibers play a very important role in the impact resistance of the composite as they interact with the crack formation in the matrix and act as stress transferring medium. [4,22] The samples were fractured in a plastic impact testing machine and the impact toughness was calculated from the energy absorbed and the width of the sample.



Fig -2: Analog Izod/ Charpy impact tester [4]

3.3. Tribological Behavior

When natural fibers are used as reinforcement elements, the tribological properties can be improved by controlling the fiber content at certain levels. The natural fiber content affects the tribological properties, mainly due to the change in the binder(matrix) to the natural fiber ratio. Therefore researchers have focused their efforts on measuring different mechanical and tribological properties of natural fiber composite materials that are prepared by using various binders and natural fiber types and contents. ZeinaAmmar et al and Idris et al tested tribological properties of brake pad sample. They also measured the porosity, density, hardness, thermal conductivity, compressibility, wear rate and coefficient of friction (COF) of the prepared composites.[1,8]

A pin-on-disc test apparatus with disc made of white cast iron of hardness value 62HRC, 120mm track diameter and 8mm thick was used to investigate the dry sliding wear rate of the samples accordance with ASTM:G99-05 standard. The initial weight of the samples (pin) was measured using a single pan electronic weighing machine with an accuracy of 0.0001g.

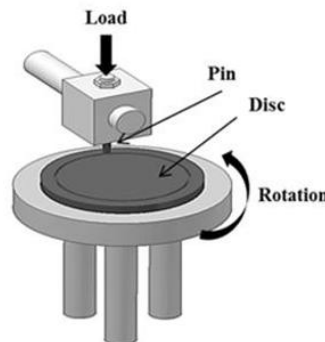


Fig -3: The schematic of the pin-on-disc machine [8]

The co-efficient of friction of the samples increases as the wt% of resin increased in the formulation shown in figure 3, Again the effect of uncarbonized banana peels particles shows a marked effect as higher friction was recorded for brake pad composites as the wt% of resin increased. Increases in friction coefficient does not tend to have higher wear rate because it is not a mechanical property but it is a response of a machine. [1,8]

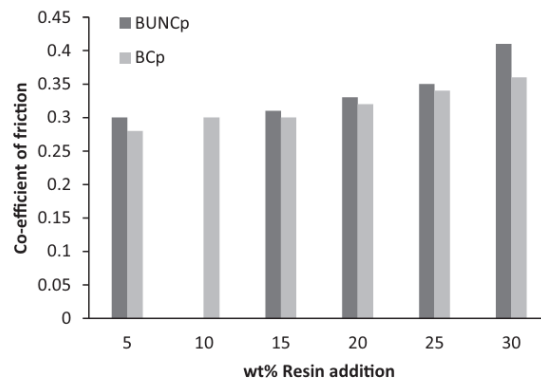


Chart -1: Variation of co-efficient of friction with wt% of resin addition

Wear rate of the found by samples shown figure (4) Decrease in wear rate as the weight fraction of resin increased in the banana peels particles. This may be attributed to higher/ closer packing of the microstructure which has affected stronger bonding of banana peels with resin. The decreased in wear rate of the brake pad formulation be attributed to higher load bearing capacity of formulation and better interfacial bond between the particle and the resin reducing the possibility of particle pull out which may result in higher wear.[1]

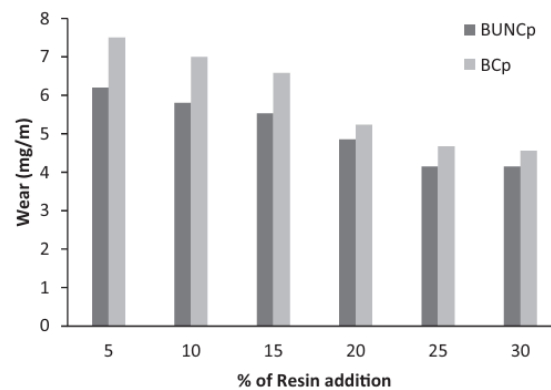


Chart -2: Variation of wear rate with wt% of resin addition

3.4. Thermal Properties

It is main crucial factor in the evaluation of brake pad materials, as braking generates significant heat due to friction between the brake pad and the rotating disc or drum. Excessive heat can lead to thermal degradation of the brake pad material, resulting in reduced friction performance, increased wear, and brake fade. Therefore, brake pad materials must possess adequate thermal stability and heat resistance to ensure reliable operation. Several studies have investigated the thermal behavior of banana fiber–reinforced composite brake pads to assess their suitability for braking applications.

Thermal stability refers to the ability of a material to retain its structural and functional properties at elevated temperatures. Banana fiber composite brake pads exhibit moderate thermal stability, which is comparable to other natural fiber–based non-asbestos organic brake pad materials.

Lamis et al explores utilizing starch based composites reinforced with pseudostem banana fibers in fabricating biodegradable maxillofacial bone plates. Also they investigates thermal properties and showed that the best results are achieved at the 50 wt.% banana fibers. Thermogravimetric analysis (TGA) studies reveal that the thermal degradation of banana fiber composites occurs in multiple stages that shows the onset degradation temperature of starch increased with increasing the BF's wt.%.[16,23]

4. COMPARISON WITH OTHER NATURAL FIBER BRAKE PADS

When compared with other natural fiber–reinforced brake pads, banana fiber composites exhibit thermal performance comparable to jute, coconut, and sisal fiber composites. While all natural fiber composites face challenges related to thermal degradation at high temperatures, banana fiber's relatively high cellulose content contributes to stable thermal behavior under moderate braking conditions. The properties of some of the natural fibers are compared in Table 1.0 Property [4,9]

Table -1: Properties of Select Natural Fibers [4,9]

Property	Jute	Banana	Sisal	Pineapple	Coir
Width or Diameter(mm)	-	80-250	50-200	20-80	100-450
(Density gms./cc)	1.3	1.35	1.45	1.44	1.15
Tenacity MN/m ²	440-533	529-753	568-640	413-1627	131-175
Elastic Modulus GN/m ²	-	8-20	9-16	34-82	4-6

Oluwafemi et al developed substitute brake pad materials from sustainable sources. Biomass-based composites from agricultural waste such as natural fibers waste are reviewed. Brake pad production from biomass materials to substitute asbestos brake pad materials has become the center of research in laboratories, and many studies and investigations are ongoing.[9] The mechanical, physical and tribological properties of these brake pads developed from agro-waste biomass materials had certain advantages compared to commercial brake pads., the wear resistance improved with the addition of natural fibers as a filler to the friction formulation. Normal load and speed have a significant effect on the wear rate of the brake pad composite. The finer the size of the sieve, the better its properties. The small particle size of natural fibers had a positive result on the composite wear rate. These findings suggest that banana fiber composites are suitable for applications where extreme thermal loads are not encountered.

Table -2: Properties of Asbestos based brake pad, banana natural composite and agricultural waste

Property	Asbestos Based	banana peels uncarbonized at 25% resin	banana peels carbonized at 30% resin	Palm Kernel Shell	Maize husks-based
Wear Rate (mg/mm)	3.80	4.15	4.67	9.67E-7	2.16
Tensile Strength (MPa)	7.00	-	-	23	20.22
Hardness	101	98.8	71.6	55.7	127.8
Friction Coefficient	0.3-0.4	0.40	0.35	0.735	0.37-0.40
Specific Gravity (gm/cm ³)	1.89	1.26	1.26	1.2	0.853

5. ENVIRONMENTAL BENEFITS

Banana fiber is a biodegradable material obtained from agricultural waste, primarily from banana pseudostems and peels discarded and further extracted after fruit harvesting for getting its fibers. The utilization of banana fiber in brake pad composites contributes to effective waste management and reduces environmental pollution associated with agricultural residues. By using banana fiber composites help minimize health hazards and environmental risks. So replacing conventionally used synthetic fibers and asbestos-based materials is beneficial.

The production of banana fiber requires significantly lower energy compared to the manufacturing of synthetic fibers such as aramid or glass fibers. This reduction in energy consumption leads to a lower carbon footprint and supports sustainable material development. Furthermore, the biodegradability of banana fiber reduces long-term environmental impact at the end of the brake pad's service life, unlike conventional brake pads that contribute to persistent waste.[14,20]

Banana fiber composite brake pads also contribute to reduced airborne particulate emissions during braking. Natural fibers tend to generate less toxic wear debris compared to asbestos and synthetic fibers, improving air quality and reducing health risks associated with brake wear particles. These environmental advantages align with global regulations and standards aimed at reducing automotive emissions and promoting eco-friendly materials.

6. CHALLENGES IN BANANA FIBER COMPOSITE BRAKE PADS

Main challenges associated with banana fiber composites is moisture absorption. Because of the hydrophilic nature of natural fibers, banana fiber tends to absorb moisture from the surrounding environment, which can lead to swelling, reduced interfacial bonding. This in turn can lead to degradation of mechanical and tribological properties. This issue becomes particularly critical under humid operating conditions and prolonged service life. Thermal stability at elevated temperatures is another significant disadvantage. Although banana fiber composites exhibit acceptable thermal stability for braking applications, their performance deteriorates under high-temperature conditions. Decomposition of organic constituents and thermal softening of the polymer matrix can result in brake fade, increased wear, and reduced friction stability.

Variability in banana fiber properties may also be an additional challenge. The mechanical and physical characteristics of banana fiber can vary depending on factors such as plant variety, growing conditions, extraction method, and fiber treatment. This inconsistency can lead to variations in composite performance.

Manufacturing challenges also exist, particularly in achieving homogeneous isotropic property, uniform fiber dispersion and consistent composite density. Poor processing conditions may cause porosity, fiber agglomeration, and weak fiber–matrix bonding, which adversely affecting performance. Additionally, noise, vibration, and harshness (NVH) characteristics of banana fiber composite brake pads remain insufficiently explored in existing literature.

7. RESEARCH GAPS AND FUTURE SCOPE

Several research gaps remain, although numerous laboratory-scale studies have demonstrated the feasibility of banana fiber composite brake pads. With limited data and aging behavior Most of existing studies focus on short-term tribological and mechanical testing. There is a lack of comprehensive studies evaluating the performance of banana fiber brake pads under real-world braking conditions.

Hybrid composite systems combining banana fiber with other natural or synthetic fibers have not been extensively explored. Such hybridization may enhance thermal stability, wear resistance, and moisture resistance. Additionally, limited research has been conducted on the optimization of fiber surface treatments and their long-term effectiveness. Also the use of bio-based or biodegradable binders has received limited attention, despite their potential to further improve environmental performance.

To reduce moisture absorption and enhance thermal resistance researcher should focus on developing advanced fiber treatment techniques in future aspects. Optimization of composite formulation and processing parameters is also necessary to achieve consistent and reliable performance.

Long-term performance evaluation, including wear durability, thermal cycling, and environmental aging studies, are essential to assess the practical feasibility of banana fiber composite brake pads. Noise and vibration analysis should be incorporated into future studies to ensure compliance with automotive standards.

Additionally, industrial-scale fabrication and field testing are required to bridge the gap between laboratory research and commercial application. Long-term creep tests are needed to estimate the prediction performance of modeling techniques and testing. Long-term weathering or accelerated weathering treatment is needed to simulate the circumstances in real applications. Comprehensive life cycle assessment and cost–benefit analysis will help establish banana fiber composites as viable and sustainable alternatives to conventional brake pad materials.

8. CONCLUSION

This work reviews a comprehensive analysis of banana fiber–reinforced composite brake pads as sustainable alternatives to conventional brake pad materials. The increasing demand for eco-friendly automotive components have driven extensive research into natural fiber–based friction materials due to which the growing concerns related to environmental pollution, health hazards of asbestos-based brake pads. Among the various natural fibers investigated, banana fiber has emerged as a promising reinforcement due to its favorable mechanical properties, low density, abundant availability, and biodegradability.

The use of banana fibers as reinforcements in various matrices has shown promising results, particularly regarding the composite's mechanical and thermal properties. Also, it offers significant environmental and economic advantages, including reduced reliance on synthetic fibers, lower material and processing costs, and effective utilization of agricultural waste. However, challenges such as moisture absorption, thermal degradation, fiber property variability, and limited long-term performance data remain obstacles to large-scale industrial adoption.

The review also highlights important research gaps, including the need for hybrid composite systems, advanced fiber treatments, fiber extraction method and length of banana fibers, bio-based binders and long-term durability studies.

Overall, banana fiber–reinforced composite brake pads demonstrate strong potential as sustainable and cost-effective friction materials for automotive applications. With continued research focused on overcoming existing limitations and validating performance under real-world conditions, banana fiber composites could play a significant role in the development of environmentally friendly braking systems in the future.

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