Type of contribution:
Editorial
Research Paper
Case Study
▶ Review Paper
Scientific Data
Report of Tech. Application

e-issn. 2798-5245

Mechanical Engineering for Society and Industry
Vol. 4, No. 3 (2024) pp 337-367
Special Issue on Technology Update 2024
https://doi.org/10.31603/mesi.12271

Opportunities and challenges in the sustainable integration of natural fibers and particles in friction materials for eco-friendly brake pads

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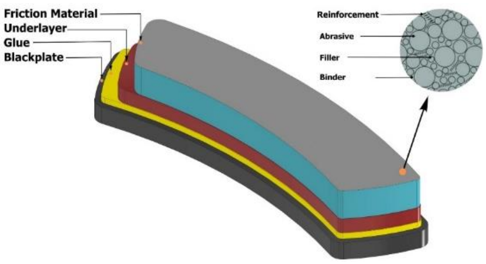
This article contributes to:

9 INDUSTRY, INNOVATION AND INFRASTRUCTURE
SUSTAINABLE DEVELOPMENT GOALS



Highlights:

- Eco-friendly materials like natural fibers are used to replace metal in brake pads for sustainability.
- Natural fibers face challenges like low heat resistance and degradation in extreme conditions.
- Eco-friendly brake pads cut emissions and support a greener automotive industry.

Abstract

The high concentration of metallic components in the pad composite improves breaking ability at elevated temperatures and frequencies, bolstering the automobile's braking system. The brake pad operates through friction mechanisms, generating PM 10 and PM 2.5 particulate matter that is emitted into the atmosphere, adversely affecting the well-being of humans and animals. Therefore, eco-friendly materials like natural fiber and organic particles are being used as substitutes for the metal in brake pads. However, natural fibers and particles exhibit unique characteristics when interacting with other materials, presenting significant challenges in brake pad composites such as variations in physical properties, limited thermal resistance, and potential degradation at high temperatures and humid environments. These aspects play a crucial role and can affect the structural strength, wear resistance, and overall performance of composite brake pads, especially when operating under extreme braking conditions. This paper review critically discusses automotive braking systems, the benefits of non-natural fiber brake pads, the process of particle emission formation, the components and manufacturing factors of composite brake pads, and the environmentally friendly qualities of brake pads. This study provides an exciting opportunity to advance our knowledge of the presence of natural fibers and organic particles in composite brake pads, which greatly improves the performance of automotive brake systems because they have super physical and mechanical properties, as well as great tribological and thermal endurance. Moreover, eco-friendly brake pads are typically biodegradable, which helps reduce ecological damage, minimize health concerns for humans and animals, and promote a sustainable automobile sector. Furthermore, eco-friendly brake pads show great potential for further advancement in reducing pollutant emissions and enhancing performance.

Keywords: Eco-friendly brake pad; Natural fiber; Filler; Friction materials; Tribology

Article info

Submitted: 2024-09-11
Revised: 2024-11-11
Accepted: 2024-11-21

Publisher
Universitas Muhammadiyah Magelang

1. Introduction

The vehicle manufacturing sector has rapidly evolved in response to the growing number of human actions. The demand for transportation is increasing due to the expansion of facilities, expanding populations, and economic improvements [1]–[3]. According to **Figure 1**, it is evident that global motorized vehicle production will reach 85.4 million in 2022, reflecting a 5.7% increase from 2021. **Figure 1** displays the production share for motorbikes in 2021 and 2022, categorized by area and measured in thousand units. The rising production of vehicles leads to the implementation of automotive standards of excellence, which include ecologically friendly transportation, superior security measures, and advanced technological innovations to enhance passenger convenience and security [4].

To meet stricter safety standards and meet the need for better performance, innovation in the transportation industry is becoming increasingly important. The braking system is one of the most critical components in ensuring vehicle safety [5], [6]. Safety aspects, including the braking system, are a fundamental issue for all types of vehicles, such as motorcycles, cars, trains, and planes. The brake pad, part of the braking system, can be made from metal-based cast iron or composite-based non-magnetic and magnetic types [7]–[9]. Each material has different characteristics but has the same function to support superior braking performance and is adapted to the needs and specifications of the vehicle used [10]. Hence, the choice of material for brake pads needs to consider the production process from a technological aspect, economics, and ecology [11]–[13].

Composite brake pads consist of a polymer binder, reinforcement made of fibers, filler, friction modifier, additive, and abrasive material [14]–[16]. Each of these elements works together to enhance the brake pad's performance under particular conditions in the environment, consisting of slipping, acceleration, temperature, pressure, and humidity [17]. The material known as asbestos, a natural fiber mineral, has become a prominent material in brake pad manufacturing due to its benefits such as heat resistance, high coefficient of friction durability, wear resistance, and corrosion resistance. Asbestos enhances the effectiveness of brake pads, but usage has been limited or prohibited in some countries because of the health hazards linked to human exposure to asbestos fibers released as particles [18]–[20]. Synthetic fibers like carbon, glass, rock wool, aramid, lapinus, steel, brass, copper, and zinc sulfide fiber are viable options for creating brake pad materials due to their ability to enhance braking performance, withstand high temperatures, and increase durability. prolonged utilization [21]–[25].

The brake pad system operates based on friction between the disc pad and the brake pad [26], [27], resulting in elevated temperatures, vibrations, noises, and wear that impact the brake pad's performance [28]–[30]. Wear happens because of friction, which happens when the brake pad and disc pad don't touch evenly during operation. This makes noise and is bad for people's health [31], [32]. The braking system design also contributes to dust emissions [33]. The main substance content of metal brake pad materials significantly influences the generation of PM 2.5 wear particles commonly seen on urban, highway, and rural roadways. The particles possess significant potential as environmental toxicants, adversely affecting air quality and human health [34]. Composite brake pads must possess excellent mechanical, physical, thermal, and tribological qualities, as well as address health and ecological issues in their fabrication. Intelligent decision-making regarding materials plays an essential part in establishing an industry that promotes the achievement of sustainable development goals (SDGs). Natural fibers, including banana, coconut, and rice husk, are increasingly favored in research

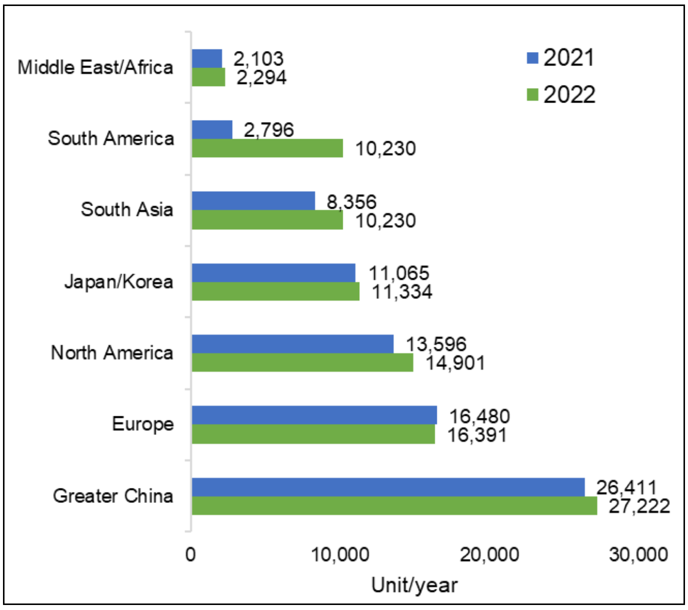


Figure 1. World motor vehicle production in 2021 and 2022

and industry due to their ecological affection, biodegradable properties, ease of access, lowered weight, superior mechanical characteristics, and the potential to reduce the use of metal materials [35]–[37].

Previous investigators have extensively documented explorations of using natural fibers and organic particles in Brake Pad Composites (BPC). However, there is a current lack of high-quality examined and discussed focusing specifically on the braking system in vehicles, the advantages of non-fiber composite brake pads, the process of particulate emissions formation, substantial evidence type, composition, manufacturing technique, physical and mechanical features, tribological attributes, and thermal characteristics. This comprehensive review outlines the potential advantages and limitations of utilizing natural fibers and organic particles to enhance the performance of composite brake pads within vehicles. Furthermore, it develops an understanding of the contribution of eco-friendly BPC to reducing pollutant particles in the atmosphere and minimizing negative impacts on human and animal well-being.

2. Automotive Braking System

The braking system plays a vital role in ensuring the safety and convenience of modes of transportation. The system's operation is divided into three fundamental assignments: initially, bring the car to an abrupt stop, indicating the maximum braking force on the wheels. To manage the velocity when the vehicle's natural retardation is caused by inadequate mechanical contact and impediments to motion. A modest braking force is provided to the wheel for an extended duration. To keep the vehicle stationary on an inclined surface, Braking must counteract the effect of gravity pulling the car downhill in this scenario [38]. The braking system's effectiveness on each vehicle is affected by the kind of vehicle and operating conditions. In addition, the brake pad's function is influenced by pressure, deflecting, wear, temperature, and tire attention, requiring the driver to manage the brake system effectively. Hamada and Orhan [39] classify the primary elements affecting braking system performance into three subclasses: vehicle, route characteristics, and traffic conditions, as depicted in **Figure 2** [40]. High-speed and high-pressure circumstances in vehicles accelerate wear, leading to more particulate matter and decreased brake efficiency [41].

The brake pad design typically includes drum and disc-style brakes, with disc brakes being a common option in modern automobiles. The disc braking system uses mechanical action to slow down and bring the vehicle to a halt by pressing the disc pad against the brake pad. Disc pads may consist of gray-cast iron, aluminum alloy, silicon carbide (A357/SiC) hybrid, and carbon fiber-reinforced polymer. Various disc pad designs, including holes, slit forms, straight slots, vanes, and edge cuts, have a role in enhancing heat concentration, thermal distribution, and structural stability [42], [43]. The ANSYS program is capable of modeling thermal distortion, von Mises stress distribution, contact pressure distribution, and on Mises stress at the inner pad. The analytical results offer valuable insights for designing and selecting materials for the brake system that exhibit excellent braking performance, cost-effectiveness, ease of manufacture, environmental friendliness, and prolonged durability [44], [45].

In 2023, Ilie and Cristescu [46] evaluated the correlation between wear and braking system efficiency. This study compared the brake system with new discs and pads involving variable vehicle mass/distance driven (1566 kg/115,477 km; 1462 kg/134,141 km; 1480 kg/134,141 km; 1526 kg/134,141 km), travel speed (25; 40; 50) km/h, braking distance (1.31; 1.38; 3.92; 4.26; 5.14; 5.44) m, and braking time (1.17s; 1.21s; 1.74s; 1.89s; 2.20s; 2.46s). The research results show that a vehicle mass of 1526 kg/134,141 km produces the lowest brake service efficiency of 59%, which indicates that the vehicle travel distance and vehicle load accelerate the rate of wear and reduce braking

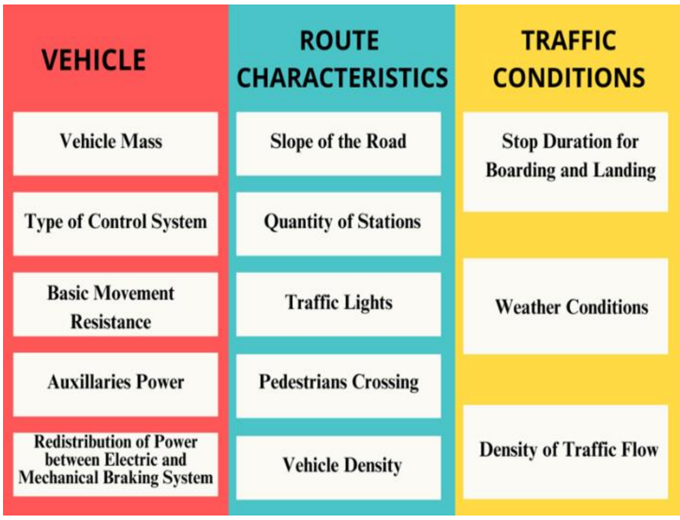


Figure 2. The variables influencing the effectiveness of the braking system [40]

efficiency. Apart from that, a brake system with new discs and pads produces braking system efficiency of 72%, higher than worn discs and pads of 59%. This value is still above the 43.5% minimum limit permitted by the United States of America (U.S.A.) federal regulations, the North American Standard, and the European Community. However, values that are so close indicate that the brake discs and pads need to be replaced to maintain the functionality of the brake system. The vehicle's speed of movement and axial load cause different wheel diameters, which affect the brake pad's heat level. Braking force that is less than optimal causes an uneven distribution of load and thermal stress, triggering wear and reducing braking efficiency [47].

Employing the multiple piston caliper style can enhance durability from wear, prevent corrosion, and minimize stress on the brake pad. This setting ensures a uniform transfer of the force generated on the brake disc, optimizing the performance and longevity of the brake pad [48]. Additionally, the shape of the disc pad is crucial to enhancing the brake pad's functionality. Naveed and Whitford [49] classify several versions of disc brake pads, such as angled spokes, waved edges, drilled holes, additional material, no airflow, and multiple drilled holes. Utilizing vented brake discs with different ventilation gaps while taking into account the pad, rim, tire, and dust shield can serve as an effective cooling mechanism to manage heat absorption and minimize the impact of heat on the brake pad [50], [51].

3. Brake Pads Composed of Non-Natural Fiber

Metallic substances provide essential benefits for enhancing brake pad effectiveness, including consistent and effective stopping ability under varying working situations. This brake pad variety is mostly composed of metal subject matter, providing durability against elevated temperatures, a consistent moderate coefficient of friction, and a long-lasting service life. Several researchers utilize copper (Cu) as a structural material with varying compositions: 58% [52], 60% [53], and 15% [54]. Copper significantly impacts friction surfaces by adjusting them and enhancing the integrity of the tribolayer because of the high thermal conductivity of copper fibers. This enhances heat dissipation from the pad's friction surface, preventing the breakdown of organic compounds and therefore improving the fade and recovery ratio at elevated temperatures [55]. The material type and content significantly impact brake pad performance. Using slag with aluminum oxide (Al_2O_3), iron oxide (Fe_2O_3), and silicon dioxide (SiO_2) can enhance friction, decrease wear, and bring down operating temperatures. Excessive use of slag was discovered to result in an inconsistent friction coefficient during operation. The increased amount of slag, which raises the hardness of the brake pads, is likely responsible for the situation. Slag was shown to be unsuitable as a lubricant in brake linings, despite its effectiveness as an abrasive and filler [54].

Wear begins with the creation of a heat-affected zone on the brake pad's surface caused by periodic friction between the disc pad and brake pad. The heat causes the interactions created between the binder, fibers, and other elements to break down, leading to easy separation of the materials and faster wear. An outer layer that peels with fractures, the development of profound grooves, and the appearance of chipped skin can all be indicators of wear [56]. Carbon fiber orientation, specifically at 0°, 45°, and 90°, considerably influences tribological characteristics. When compared to other brake pads, those with short carbon fibers in a carbon-silicon carbide (C/C-SiC) matrix that are oriented at 45° have better tribological properties between 0.54-0.61. C/C-SiC composites with randomly distributed short carbon fibers exhibit notable tribological characteristics ranging from 0.54 to 0.57. When the braking duration increases, the high friction level is attributed to minimal fluctuations and reliable brake stability, making it a suitable option for manufacturing outstanding durability friction compounds [23].

It was 2022 when Yanar et al. looked at composite brake pads made of phenolic resin, rockwool, steel, and aramid fibers, as well as barite, graphite, hexagonal boron nitride (h-BN), and magnetic materials. Optimal levels of h-BN significantly enhance wear and friction resistance, along with thermal stability. The inclusion of graphite and a tiny quantity of h-BN in brake pads serves as a lubricant, ensuring reliability under excessive friction and temperature variations [57]. Graphite keeps being steady at temperatures up to 500 °C, establishing an important contribution towards preserving friction resistance [58]. Weak chemical adhesion between fluorite and phenolic resin enhances bonding potential. Fluorite can prevent the breakdown of phenolic resin, enhance the heat resistance of friction materials, and significantly decrease the rate of wear [24].

In 2022, Borawski [59] developed and assessed a metal-based composite brake pad consisting of a friction material screen, binder layer, and support plate (black plate). Non-natural steel fiber (3.3–4.17%), glass (6.09–7.99%), cast iron fiber (2.40–3.64%), and other things like silicon carbide

(0.82-1.5%), zeolites (3.80–5.68%), zinc oxide (1.41-2.33%), graphite (2.18–2.86%), copper (6.03-8.23%), barite (15.63-18.58%), silicates (8.36–9.46%), magnesium oxides (15.52-17.05%), and rubber particles (6.22%–6.68%) make up the friction substance. Modifications in phenolic resin, lubricant substance, and fiber content led to fluctuating Coefficient of Friction (CoF) values ranging from 0.357 to 0.477. Intense temperature fluctuations when stopped lead to significant temperature accumulation, causing periodic stress and deformation. It also changes the consistency and stickiness of the solid part when mixed with phenolic resin, which in turn changes the hardness to 52–55 (HRC) and the amount of material released into the air to 0.559–0.657 g. Zinc oxide acts as a lubricant material, while graphite provides structural support to the brake pad under high braking frequency and temperature conditions [60]. The uneven distribution of a few big graphite particles has been shown to decrease mechanical and tribological properties [61]. Tribological oxide films consist of metal oxides such as FeO, Fe_3O_4, Fe_2O_3 (iron oxide), and CuO_2 (copper oxide) [62]. Iron (Fe) was chosen as the brake pad's matrix material because it can keep its coefficient of friction (CoF) stable and its wear rate low. This is because it has a tribo-oxide coating on the outside that stays in place at high temperatures [63].

4. Brake Particulate Matter Emission and Regulation

Particle emissions have been identified as a significant issue in industry, the environment, and human well-being [65]. Non-exhaust pollutants are classified as sources of emission that originate from brake wear, tire wear, road wear, and resuspended road dust particulate matter (PM) emissions. Mechanical interaction between the brake pad and disc pad generates brake wear particles, which disperse into the environment through atmospheric deposition and affect aquatic and soil ecosystems [66]. $BaSO_4$ (barium sulfate) generates more potent PM than $CaOH_2$ (calcium hydroxide) and $CaCO_3$ (calcium carbonate) [67]. Particle emissions can be separated by size into coarse, fine, and ultrafine particles. The creation process is influenced by elements such as the brake pad type, road type, and braking intensity [68]. Correspondingly, Alemani et al. [69] found that friction plays a crucial role and that variations in temperature are the primary contributors to the creation of particles and pollution. Humans are exposed to air pollution, leading to medical problems such as lung irritation, chronic respiratory disease, and a higher risk of cardiovascular disease [70].

The data in **Figure 3** depicts various spatial factors that affect the number of particles emitted into the atmosphere. Both escaping of substances from the brake pad composite towards the surrounding atmosphere can be affected by both internal and external influences [64]. Sheikh et al. [71] conducted a study in 2022 to measure and evaluate air pollution particulates that adhere to leaves growing near roads with heavy vehicle traffic. Fe nanomaterials originating from the brake pad material were found to be plentiful. Nanometal particles, including Fe (iron), Cu (copper), Cr (chromium), Ni (nickel), Sb (antimony), and Zn (zinc), are too small for the human eye to see. However, they are spread around by air circulation and can cause health problems like Alzheimer's disease, inflammatory responses, and ambient PM [71], [72]. In 2020, Idris et al. [73] found that the metal content was highest in the order Fe (iron) > Mn (manganese) > Cr (chromium) > Pb (lead) > Zn (zinc) > Cu (copper) > Co (cobalt) > Cd (cadmium). Fe and Mn tend to bond to dust particles in the air. Vehicle variables like excessive beginning braking speed, wider acceleration, braking frequency range, and braking duration are closely linked to the creation of PM10 emissions throughout stopping at elevated speeds and extreme friction on surfaces [74]. Studies have shown that when braking temperatures exceed 200 °C, PM10 emissions increase [75].

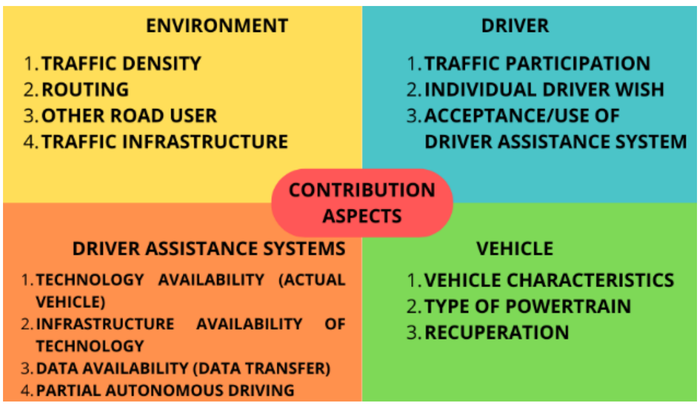


Figure 3. The elements that affect the circulation of traffic and the brake emissions of particles [64]

In 2021, Straffelini and Gialanella [76] categorized brake airborne particles into three distinct categories: coarse (2–3 µm), fine (0.3–0.5 µm), and ultrafine (<0.1 µm). Emission particles contain PM10 and PM2.5 with iron (Fe), copper (Cu), carbon (C), graphite, and barite inclusions. Sethupathy et. al. [77] found that particles containing copper originated from worn brake pads and were dispersed into the air, eventually reaching lakes and rivers. This results in aquatic species, including seafood, becoming infected, which adversely affects the well-being of both the fish and people who consume them. The distribution of particle matter (PM) among particles varies periodically due to the substance, microstructure, and heat distribution of the disc [78]. Initially, the braking wear process generates bigger particles, which later decrease in size when a stable contact plateau forms on the pad surface. Particle dimensions rise at the conclusion of stopping as a result of the disintegration of the plateau at high temperatures [79].

The United States of America developed guidelines regulating the automotive industry's choice of components in order to safeguard human beings and their surroundings against the heavy metal impact created by composite brake pads. Heavy metals are categorized based on their composition, and the years 2014, 2021, and 2025 have set a maximum limit of 0.1% weight for hexavalent chromium (Cr VI), lead (Pb), and mercury (Hg), and 0.01% weight for cadmium (Cd). Conversely, the heavy metal copper (Cu) underwent fluctuations in quantity. In the year lacking amount constraints, it declined by 5.0% wt in 2021 and by 0.5% wt in 2025 [80].

5. Composition of Eco-Friendly Brake Pad

Composite brake pads are made up of a variety of components that improve the brake pad's effectiveness and provide vehicle comfort and security. **Figure 4** displays the composition of the eco-friendly brake pad composite, which necessitates a structure that offers benefits like uniform heat delivery, responsiveness to fluctuating environmental issues, high dependability, high effectiveness, quiet operation, and cost-effectiveness. The proportion of quantity to that of quality is demonstrated to be outstanding [81]. The brake pad's integrity is enhanced by its physical, mechanical, thermal, and tribological features, which greatly contribute to the stopping system's operation. Composite brake pads' higher performance is determined by the substance category, arrangement, and manufacture technique [82].

5.1. Binder

The binder is a polymer resin essential in brake pads that is responsible for bringing together multiple substances such as fiber, reinforcement, modifier, and abrasive material. It aids in conveying stress in all directions, as well as encouraging the brake pad's structure and strength during braking. Polymer binders must take into account wear resistance, temperature resistance, chemical resistance, cost, ease of production, resistance to corrosion and solvents, lightweightness, and impact resistance [83]. A large volume of publications describes the binder of BPC, with the majority creating formulations ranging from 10% to 35%, as depicted in **Figure 5** [22]–[25], [37], [54]–[57], [59]–[61], [67], [84]–[141].

A considerable amount of literature has been published on the brake pad composite. Phenolic resin is a common binder employed in composite brake pads. This is due to the benefits provided, such as being strongly compatible with a wide range of materials, including metal, natural fiber, synthetic fiber, particles, and organic materials [57]. Additionally, binders can reduce thermal stress during braking [14] while also managing noise and vibration [84]. In 2022, Irawan et. al. [142] found that the high disintegration temperature of phenolic resin contributes to improved wear resistance and damping in brake pads, ultimately increasing their service life. Moreover, brake

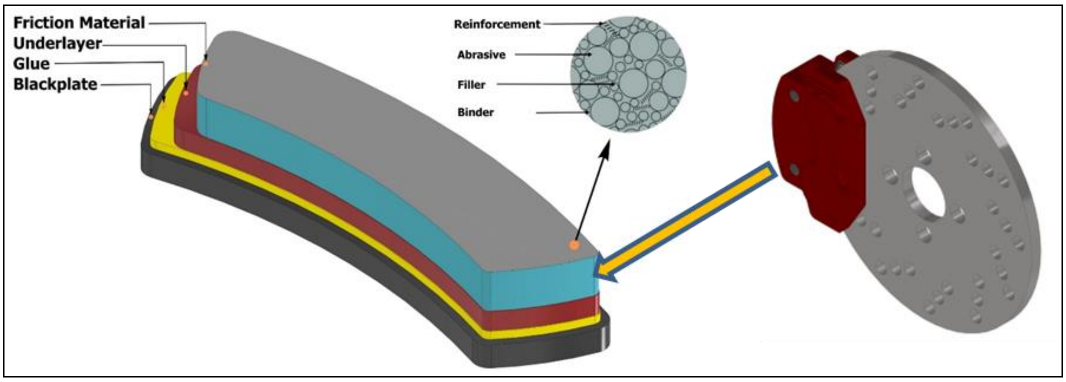


Figure 4. Structure of the materials that make up the eco-friendly composite brake pad

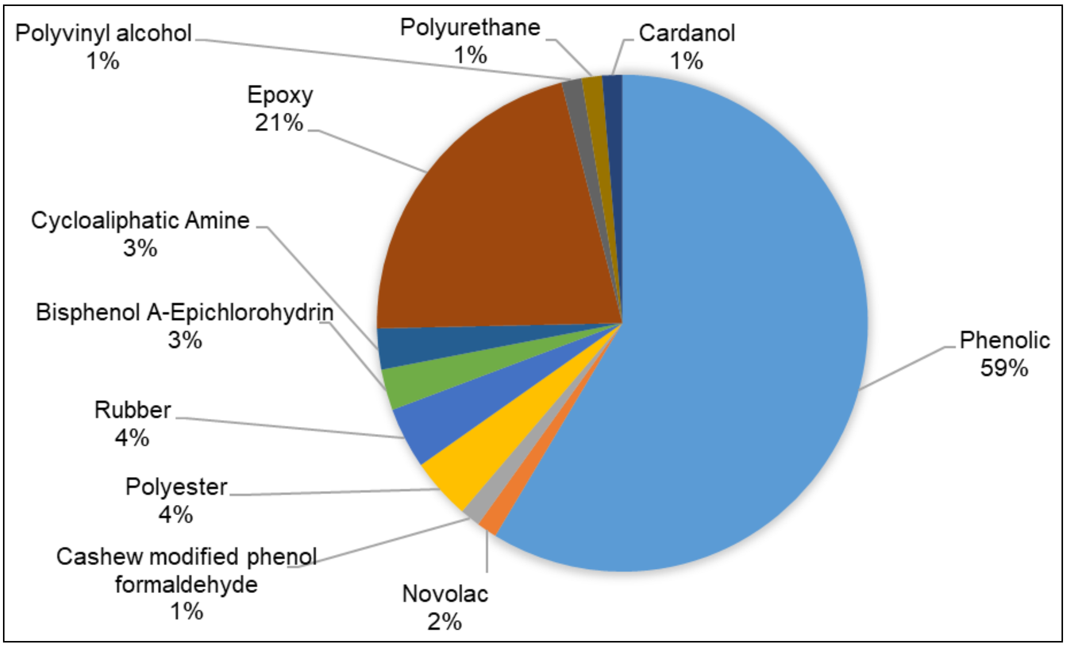


Figure 5. Types of binder in brake pad composites

linings with altered phenolic resin will yield superior outcomes. The resin's heat resistance was enhanced through a modification procedure, including the addition of additives to the phenol resin. This technique raises the decomposition temperature and results in a higher and more consistent friction coefficient. Phenolic resin is mixed with various rubbers, such as styrene butadiene rubber and nitrile butadiene rubber, to enhance the material's energy absorption capabilities [143].

Resin-based brake linings are prepared by connecting and compressing the reinforcing elements using resin polymerization, such as epoxy, at room temperature. Epoxy resin is recognized for its exceptional chemical and wear resistance. It has the advantage of being lightweight and resistant to most alkalis and acids. Epoxy resin exhibits excellent pressure resistance, retains stiffness and flexibility, and is ideal for applications demanding outstanding mechanical properties and minimum curing shrinkage [120]. Epoxy resin can undergo a cross-linking reaction with co-reagents to generate polyepoxy. Phenoxy resin, a type of bisphenol A-epichlorohydrin phenolic resin, is utilized as a material for brake lining matrices [51].

The epoxy resin synthesis method begins with a chemical reaction involving bisphenol A and epichlorohydrin to create bisepoxide. When bisepoxide combines with sodium hydroxide, it produces diglycidyl bisphenol ether A (DGEBA), water, and sodium chloride. Bisphenol A enhances the strength, elongation, and rigidity of the epoxy matrix. DGEBA undergoes an oligomerization process with another bisphenol A to produce a high-molecular-weight epoxy polymer. Hardening is achieved by utilizing a cross-linking agent, cycloaliphatic amine, to create a rigid, three-dimensional framework that is tough and resistant to dissolving. The procedure entails cleaving the oxirane chain in the hardening agent molecule, resulting in an elongated C-O bond. This hardening process creates a robust structure that benefits resin-based brake linings by enhancing their electrical, mechanical, and thermal capabilities, as well as promoting a strong bond [108].

5.2. Reinforcement

Natural fiber serves as an ecologically appropriate replacement for asbestos and synthetic fiber in reinforcement materials owing to its regenerative nature, eco-friendliness, and enthusiasm for sustainable businesses. Various natural fibers have been investigated, assessed, and utilized as component fibers in composite brake pads, as detailed in **Table 1**, with fiber sizes ranging from 0.5 to 5 mm. Natural fiber enhances the physical and mechanical characteristics of the brake pad. Additionally, it can decrease the occurrence of stress and mechanical failure in the brake pad caused by the forces applied while slowing down, therefore preserving the brake pad's effectiveness [14]. It is important to note that each natural fiber reacts uniquely when coming into contact with binders and other components. Kumar et al. (2021) found that adding more than 6% flax fiber to phenolic resin causes agglomeration, which can have a detrimental effect on brake pad performance [109].

Table 1. Types of natural fiber in composite brake pads

Nataural Fiber	Composition (wt%)	References
Allium sativum	8	[87]
Abaca	5-20	[88]
Mulberry	1.5-6	[89]
Fleece	NA	[92]
Eichhornia crassipes	NA	[93]
Banana	30-40	[94]
Leucas aspera	NA	[96]
Banana	4-16	[103]
Coir	NA	[107]
Flax	2-8	[109]
Pineapple leaf	NA	[113]
Palm kernel	2-12	[114]
Palm kernel	20-40	[117]
Coir	10-30	[119]
Areva javanica	6	[121]
Bamboo	40-60	[122]
Kenaf	NA	[126]
Jute	NA	[126]
Aloe vera	NA	[126]
Palm kernel	25-35	[127]
Palm kernel	10-50	[128]
Nile roses	2-15	[128]
Sisal	25-35	[129]
Coir	10	[130]
Palm	8	[131]
Cyperus pangore	13	[135]
Banana	0-21	[136]
Areca	5-10	[137]
Banana peel	5-10	[138]
Bagasse	5-10	[138]
Palm kernel	0-10	[141]
Prosopis juliflora	NA	[144]
Jute	NA	[145]
Sabai grass	5-20	[146]
Coir	2-8	[147]
Pineapple leaf	NA	[148]
Coir	NA	[148]
Areca	NA	[148]
Coir	5-20	[149]
Durina peels	NA	[150]
Banana midribs	NA	[150]
Demostachya Bipinnata	NA	[151]
Snake grass	NA	[152]
Palm fruit	NA	[153]

Jute fibers, among other natural fibers, are ideal for brake padding applications because of their advantageous properties. While ceramic and metal fibers have reduced strains and stresses compared to jute fibers, they also have drawbacks in other aspects. Ceramic brake pads are costly, whereas metal brake pads are louder and might lead to increased stress and deterioration of the braking rotor. Conversely, natural fibers provide a hopeful substitute. Numerical modeling and finite element analysis can be used to enhance the effectiveness and longevity of brake pads by optimizing the incorporation of natural fibers in their design, while also maintaining environmental friendliness [145].

5.3. Filler

Fillers can be divided into metal types, which include brass chip, copper, zinc, and aluminum powder; alloys; ceramics, including alumina, barium ($BaSO_4$) sulfate, barite, vermiculate, carbon powder, and nickel slag; as well as organic materials, for example, crumb rubber, cashew dust, palm kernel shell, rich husk, and durian seed. Every substance has the potential to contribute 3-60%, according to the percentage of filler utilized for creating a composite brake pad and the targeted performance contribution specifications [22], [67], [87], [88], [91], [94], [108], [149], [154]. Metallic fillers function as heat dissipators, which are responsible for absorbing or transmitting heat in brake components, thus minimizing a high level of heat accumulation in the brake system, avoiding heat damage, and preserving beneficial brake performance [154]. These compounds function to occupy the vacant area between the fibers, limit fade, and boost braking efficiency. They also lower costs and boost brake pad production capacities [14]. Kumar et al. (2022) employed barium sulfate to raise the specific gravity and durability of the brake pad composite, while barite and vermiculate were utilized in order to enhance its thermal and mechanical attributes [88].

Organic substances that consist of crab shell, periwinkle shell, scallop shell, shellfish, and cashew nut shell are plentiful in the environment, cost-effective, readily available for manufacture, possess thermally stable properties, and enhance the brake pad's function pad [125], [129], [132], [155]. Previously study found that palm kernel shell is made of cellulose and lignin, giving it distinctive features and structure as a natural fiber. Palm kernel shells are processed through washing, cleaning, and drying procedures. Crush the material into filler particles ranging in size from 100 to 350 µm, employing a crushing machine. Filler plays a crucial role in enhancing many properties, such as wear rate resistance, flame resistance, friction resistance, compressive strength, oil absorption, and water absorption, due to its optimal composition and uniform distribution [67]. Small particle size has a crucial role in increasing the surface area of particles with the binder, which helps reduce porosity and enhance brake pad effectiveness [98].

5.4. Modifier and Abrasive Material

Composite brake pads are designed to function effectively under extremely high-frequency friction and fluctuating temperatures. Brake pad materials must have high characteristics, such as wear resistance and thermal stability [67]. This can be achieved by using modifiers and abrasive compounds, as indicated in **Table 2**, with sizes ranging from 74 to 500 µm. Abrasive materials enhance friction or interact with oxygen to regulate the interfacial zone. Abrasives help to maintain surface cleanliness and manage friction film accumulation. They also enhance friction, particularly during the initial stages of deceleration [14]. It is important to examine the appropriate composition and size to prevent the hardness from causing damage to the disc rotor of the brake pad [67]. Natural abrasive substances, including sawdust and rice husk, are able to absorb resin, leading to increased density, strong strength, and outstanding friction resistance [90].

To enhance wear and friction endurance, composite brake pads require material modifiers like lubricants and thermally stable compounds. Lubricant substances help reduce mechanical contact and preserve the brake mechanism's integrity. In 2019, Faga et. al. [156] outlined the crucial characteristics of particles that impact their effectiveness as lubricants in composite brake pads. Spherical particles primarily lubricate by rolling more smoothly at the point of contact. The result may boost lubricating efficiency. The size of a particle is crucial as smaller particles are capable of reducing friction by increasing particle density at the interface between particles. The creation of a durable tribofilm at the contact, leading to friction reduction, is directly linked to the material's density. The alignment of material crystals along the "c" axis of graphite in single crystals affects tribofilm production and decreases friction. The relationship between load and friction is linear, with the intercept of the straight line being affected by the particles' morphological characteristics, including aspect ratio and sphericity.

Table 2. Types of modifiers and abrasive material in brake pad composite

Modifier and Abrasive Material	Composition (wt.%)	References
Graphite	10	[22]
Alumina	2	[22]
Steel slag	15	[67]
Silical sand	0-15	[67]
Carbon black	5	[67]
Saw dust	NA	[90]
Rice husk	NA	[90]
Bronze	2	[94]
Metal suphides	1.5	[95]
Chalcopyrite ($CuFeS_2$)	7	[95]
Wollastoniete	10	[95]
Graphite	2.5	[95]
Mica + silica	8	[95]
Fly ash	NA	[139]
Bagasse	NA	[139]
Graphite	NA	[157]
Mica	NA	[157]

According to Sathyamoorthy et al. [157], the material's thermal robustness helps to preserve the brake pad structure by preventing deformation and degradation at elevated temperatures caused by the interaction between the disc and brake pad during intense and unexpected stopping. The sulfide mixture's oxidation results in Fe_2O_3, which enhances wear resilience by acting as an abrasive at higher temperatures. This prevents the breakdown of the binder and the release of free sulfur, thereby preserving its lubricating characteristics [97]. Aluminum has stable fading and recovery because of its flake pattern [158].

6. Fabrication and Properties Test

Composite brake pads are manufactured by a multi-stage process using polymer binder, natural fiber reinforcement, metals, alloys, ceramics, organic fillers, and modifiers or abrasives. Every substance has a specific role and mission to enhance the efficiency of composite brake pads. Ahmed et al. [121] identified graphite as a lubricating agent in brake pads, comprising 9.5% of the composition due to its poor compatibility with resin. Cashew dust, when used as an organic modifier, enhances friction resistance and is compatible with disc pads. Using crumb rubber and vermiculite as fillers can help decrease noise and enhance the durability of brake pads. The unique contact response is a result of a mixture of materials with distinct features. Natural fiber consists of many layers, including cellulose, hemicellulose, lignin, and impurities. Investigators modify the fiber's surface structure by employing chemical, mechanical, and biological treatments. This procedure is intended to generate pore spaces on the fibers' surface, which enable the binder to fill, forming an excellent adhesive connection that enhances the brake pad's physical and mechanical qualities [87].

In 2020, Kumaran et al. extracted fiber from snake grass plants using retting or degumming procedures. This procedure efficiently separates fibers from stems and leaves by eliminating an outer coating and gum-like substance from the leaf surface. Various retting processes are employed, including water retting, chemical retting, enzyme spray retting, and bio-innovative retting. The technique starts by cutting the Sansevieria ehrenbergii leaves from the plant and soaking them in water for four days. The contaminating materials and the outer layer of the leaf are eliminated, and individual fibers are extracted through manual stripping. The fibers were dried in the sun for 8 hours [152]. Various studies have shown differences in fiber size, such as abaca fibers ranging from 1–5 mm [88], mulberry fibers also measuring 1–5 mm [89], fleece fibers at 2 mm [92], and prosopis juliflora fibers spanning from 0.5–5 mm [144]. Fillers derived from natural plants and animals are treated in dry conditions using a crushing machine to get certain sizes like sawdust and rice husk that range from 74–500 µm [67], [90].

By subjecting the ingredient to a mixture-making procedure involving mechanical and magnetic stirring, a homogenous mixture is created. The selection of blending equipment is tailored to the material's properties and desired outcomes. The mixing duration varies according to the material being used: 4 minutes for binder, 10-15 minutes for fiber combination, and 6–30 minutes for powder mixture [22], [85]. Following that, the combination undergoes a manufacturing procedure that plays a crucial role in producing a composite brake pad with accurate dimensions, cost-effectiveness, ease of manufacturing, eco-friendliness, and high performance. Previous studies employed compression molding with pressure settings ranging from 13 to 15 MPa, temperatures between 135 and 150 °C, and a time frame of 8 to 10 minutes. The composite is then allowed to discharge the gases that remain in the pores before undergoing post-curing at a temperature of 150–160 °C for 5–5.5 hours. The ANOVA analysis indicates that curing time and heat treatment time significantly impact the mechanical and tribological parameters. The last step involves grinding the baked pad to provide a smooth finish on the surface using a belt grinder [22], [85], [140]. The process of creating composite brake pads includes choosing the component, finding suitable machinery, and conducting evaluation and examination according to commercial and organizational specifications, as seen in **Figure 6**.

Various standards assets utilized through research and industry consist of American Society for Testing and Materials (ASTM), International Organization for Standardization (ISO), Japanese Industrial Standards Committee (JISD), Society of Automotive Engineers (SAE), and Japanese Automotive Standards Organisation (JASO). This standard ensures that examination results can be easily and systematically matched across various testing facilities and producers, as well as that products meet performance expectations for the automobile sector. Adhering to these guidelines enables researchers and producers to guarantee the safety, reliability, and compliance of composite brake pads with commercial and regulatory standards [22], [87], [88], [98], [103], [154], [157], [159].

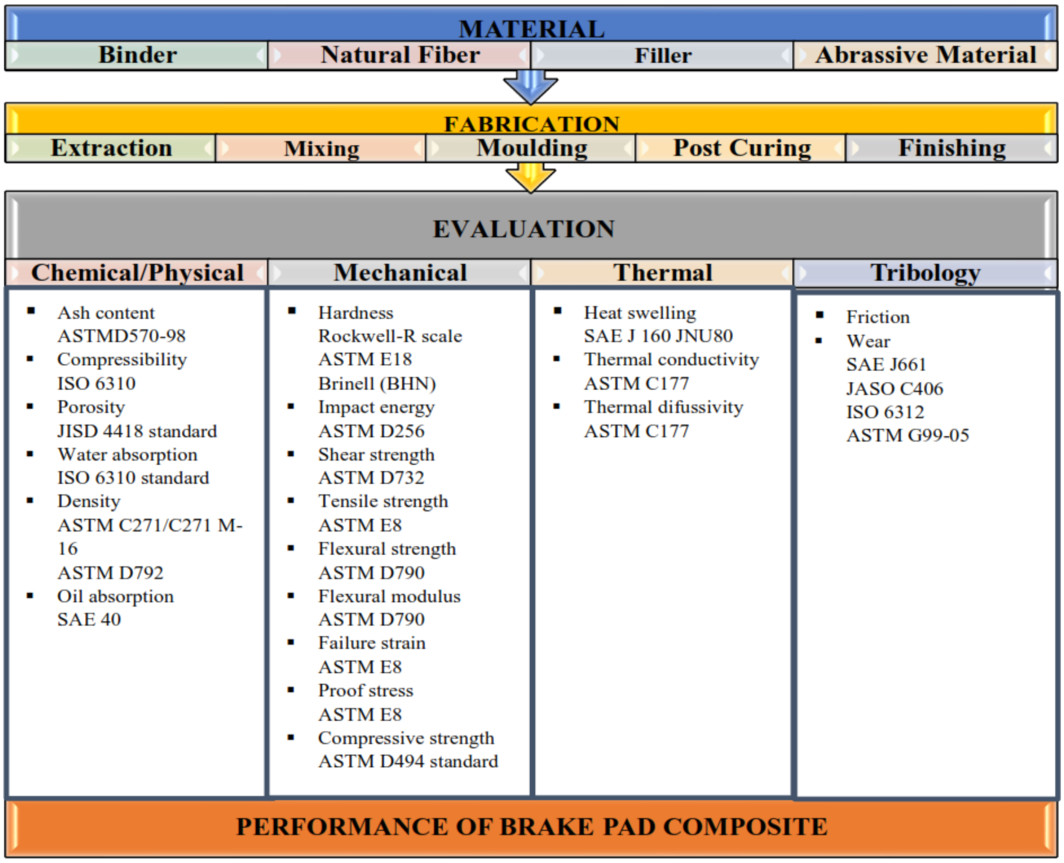


Figure 6. Manufacturing flow of brake pad composite

7. Eco-Friendly Brake Pad Properties

Passengers' vehicle braking technologies use mechanical concepts that rely on interaction between the brake and disc pad to transform kinetic energy into frictional heat, thereby slowing or stopping the vehicle. Composite brake pads possess appropriate mechanical and thermal characteristics and a consistent coefficient of friction pursuant to different conditions like temperature, pressure, and environmental factors that involve dust, water, and anti-freezing agents. They also offer high wear resistance and compatibility with interacting parts. They should optimally function dependably in various extreme situations without generating pollution or noise, and be easily manufacturable at a reasonable cost [143]. Modern braking materials must have a coefficient of friction that is balanced: sufficiently small to avoid tire restriction, yet sufficiently great to ensure effective brake operation while avoiding damage to the disc pads. The brake pad works by ensuring uniform and seamless friction with the disc pad to prevent fractures or any harm to the contact [160].

7.1. Characteristic of Brake Pad Composite

Characterization is crucial for determining the material qualities of brake pads in order to achieve excellent substances and formulas that are suitable for producing brake pads with maximum effectiveness. In 2021, Kumar et al. conducted thermal analysis on free asbestos brake pads made of phenolic resin (25%), flax fiber (2–8%), barite (15–16%), vermiculite (5%), coke (8%), molybdenum disulfide (1-2%), magnesium oxide (4-6%), potassium titanate (5-7%), aluminum oxide (5%), and zirconium silicate (2%). The samples are fabricated in accordance with the FRPC (Fiber-Reinforced Polymer Composite) code based on the fiber composition. Sample degradation was observed above 300°C, resulting in a notable decrease in mass due to the heat breakdown of cellulose and hemicellulose in flax fibers. The composite containing 6% volume of flax fiber had the greatest glass transition temperature, suggesting a robust mechanical connection between the fiber and the matrix. FRPC-6 exhibited superior thermal stability, maintaining stability up to 673.31°C with a weight loss of only 2.14%, outperforming other FRPC samples that degraded at lower temperatures [109]. Another important finding was that DSC and TGA offer detailed insights for determining the thermal characteristics and material makeup of composite brake pads, crucial for choosing the right material for creating efficient and secure braking systems.

Fourier transform infrared spectroscopy (FTIR) is an effective tool for characterizing the chemical reactions between inorganic and organic substances and for assessing the functional groups of various elements. The interactions among various components of the brake pad material reveal prominent bands of banana fiber, phenolic resin, and other constituents within the 2000 cm^{-1} to 400 cm^{-1} range. The absorption bands at 1504 cm^{-1} and 1450 cm^{-1} in the four brake pad materials indicate the stretching of the C=C aromatic ring of the phenolic resin. Lignin and hemicellulose were identified through the C-H stretching of amines at 1370 cm^{-1} and 1241 cm^{-1}. The 1153 cm^{-1} band is attributed to the asymmetric stretching of polysaccharides, primarily induced by cellulose. The absorption band at 1031 cm^{-1} seen in cellulose polysaccharides indicates the stretching vibrations of C-H and OAH. The peak at 1179 cm^{-1} represents the antisymmetric stretching of SO42−, while the peaks at 982 cm^{-1},633 cm^{-1}, 610 cm^{-1}, and 467 cm^{-1} are associated with vibrations from the symmetric stretching of barite. The FTIR spectrum of the brake pad composite indicates a favorable interaction between phenolic resin and banana fiber, attributed to the hydroxyl groups present [103].

Phenolic resin is commonly used as a binding agent in brake pad composites. FTIR investigation has verified the existence of different elemental bonds in phenolic resin, such as O-H, C-H, and C=C. Wave numbers of 3228, 2936, and 1602 cm^{-1} [161]. In 2019, Menapace et al. analyzed the thermal properties of phenolic resin in the manufacturing of composite brake pads. Phenolic resin breaks down in multiple phases at different temperatures. The resin dehydrates at 100°C. Resin polycondensation takes place at temperatures ranging from 150 to 200°C, leading to mass reduction caused by the elimination of constitutional water. At 200°C, a CH_2 methylene group developed, suggesting a bridging reaction between the phenolic rings, and a C=O carbonyl group resulted from the first oxidation. At 300°C, there was a notable mass reduction, peaking at 422°C, indicating the onset of resin decomposition. At 500 °C, the TG curve shows a drop, signifying a total mass loss of around 40%, with the separation of phenol groups happening above 500°C. The Raman spectra at 700°C display peaks related solely to extremely disordered carbon, but at 1200°C, the peak attributed to total resin degradation is absent [162].

7.2. Physical and Mechanical Properties

Natural fiber consists of multiple layers of material, including cellulose, hemicellulose, lignin, and contaminants, which may hinder the bonding across the binder and fiber. The chemical procedure alters the hydrophilic properties of natural fibers to hydrophobic features to enhance association, decrease water absorption, and improve thermal stability [152]. The fiber's ability to interact with water molecules is facilitated by the polar -OH group present in it. Thus, altering these groups decreases the amount of water molecules that attach, resulting in reduced water absorption from the brake pad [144].

The modification of the surface of Allium sativum fiber is able to be achieved through alkaline treatment, benzoylation, and acetylation. The study indicates that surface treatment of fiber has a negative impact of over 30% on various properties, including density, water swell, porosity, heat swell, loss on ignition, hardness, tensile strength, Young's modulus, and elongation at break. Acetylation treatment has a good effect by enhancing the thermal stability of the fiber from 340 °C to 378 °C and increasing surface roughness. The crystalline index and crystal size measured 35.86 and 28 nm, respectively, which were greater than those of other treated fibers. The FTIR analysis indicated that the acetylation treatment effectively eliminated lignin, wax, and hemicellulose from the fiber, revealing a more prominent presence of crystalline cellulose on the surface compared to other treatments. Acetylated fibers treated with ASac exhibit a significantly higher tensile strength of 723.28 ± 2.7 MPa in comparison to fibers treated with other chemicals [87]. Silane treatment of leucas aspera fiber enhances the connection between the matrix and fiber, resulting in an increase in tensile strength from 43 MPa to 56 MPa and hardness from 87 to 93 (Rockwell) [96]. Applying benzoyl chloride to Cyperus pangorei fiber at a concentration of 10% for 2 hours raises the cellulose content, resulting in an increase in density from 1107 kg/m^3 to 1243 kg/m^3 of the composite brake pad. Enhancing the fiber structure enhances the connection between the binder and fiber, resulting in increased hardness from 82.8 to 89.3 (Rockwell), improved shear strength from 42.65 to 48.23 kg/cm^2, and reduced loss on ignition from 34.21 to 27.55% [135].

Note that differences in fiber content are crucial for enhancing the effectiveness of composite brake pads. Optimizing the quantity enhances various mechanical properties and thermal stability [147]. Adding carbon powder to epoxy and banana is able to boost compressive strength from 0.44 to 1.62 MPa, decrease wear rate from 0.065 to 0.021 mg/m, and increase tensile strength from 1.39 to 2.06 MPa [94]. Kumar et. al. [88] conducted a comparative analysis between sabai grass fiber and kevlar fiber, exploring composition differences ranging from 5% to 20%. The physico-mechanical properties show that as the amounts of sabai fiber and kevlar fiber in the polymer composite increase, the amount of porosity, the amount of water retention, and the amount of compressible matter go up, while the amount of ash, hardness, and density goes down [146]. The increase in porosity is likely due to the unequal distribution of fibers in the matrix, which leads to stress accumulation and eventual failure.

In another major study, Vivek et al. [114] assessed how differences in natural fiber composition, namely palm fiber (PF) content ranging from 2–12%, impact the physical, mechanical, and absorption capabilities of brake pads. The investigation's findings indicate that the fiber component quantity significantly influences the brake pad qualities. Small amounts must be achieved for loss of ignition, porosity, heat swell, water, and oil absorption. Water is more likely to be trapped in the composite material than oil because of its ability to penetrate microscopic spaces in the structure of the polymer chain, the capillary action impact between the fiber and the polymer, and the transport of molecules into the micro-gaps of the polymer while using the printing method [127]. Particles forming aggregate and uneven dispersion inside the binder may cause a decrease in hardness value [138]. Using powder metallurgy and sintering to mix phenolic resin, coir fiber, and friction material to make a carbon phase that is meant to be evenly distributed and increase hardness [163].

In 2022, Madnasri et al. [148] produced pineapple leaf fiber using water treatment, while coconut fiber and areca fiber will be prepared using a separation method after drying. Fibers were manufactured with volume fractions ranging from 2% to 10%, and their orientation was altered to random, perpendicular, and 45° angles. The assessment outcomes indicate that the sample oriented at 45° has the highest tensile strength. The piece of material with a volume fraction of 2 vol% exhibited the greatest hardness of 68 HRN. The sample with 10 vol% had the lowest wear of 1.64×10^{-4} mm^2/kg. Specimens oriented at 45° produced the highest tensile strength of 14.5 MPa [140]. The size of the fiber plays a role in the brake pad's physical and mechanical characteristics. Increased size facilitates air entry and entrapment during mixing, leading to pore formation. This flaw type promotes crack propagation and stress concentration, which causes issues [150].

The stopping power of composite brake pads is significantly influenced by the filler and abrasive components' substance combinations and sizes. In 2022, Adetunji et. al. incorporated palm kernel shell, steel slag, silica sand, and carbon black ranging in size from 100 to 350 µm into phenolic resin. The study found that Brinell hardness ranged from 46.25 to 105.50 (BHN) and compressive strength ranged from 92.55 to 115.2 N/mm^2. Additionally, the material has a flame resistance ranging from 32.56% to 97.95%, a coefficient of friction between 0.31 and 0.44, oil absorption levels varying from 0.312% to 0.825%, and water absorption rates ranging from 3.72% to 10.45%. There are several possible explanations for these results, higher concentrations of palm kernel shell in the brake pad formulation enhance the hardness and compressive strength of the pad by expanding the filler's region, which reinforces the brake pad's structure. Increasing the size of palm kernel shell particles decreases pad hardness because larger particles tend to cluster together, creating more empty space and speeding up the failure process. Optimal formulations result in superior performance in hardness, compressive strength, wear resistance, flame resistance, and water and oil absorption tests due to the uniform distribution of materials [67] and the high resin absorption capacity of small particles, leading to increased density within particles [90].

Particle size strongly influences the formation of voids. Ossia et al. [98] experimented with a variety of sizes of coconut peat ranging from 90 to 850 µm. They found that larger particle sizes led to the formation of voids, resulting in a higher absorption of water and oil by 1.4–1.8% and 1.2-2.3%, respectively. A particle size ranging from 90–850 µm decreases hardness and compressive strength by 42–39 BHN and 3.1-2.85 MPa. Nandiyanto et al. [108] conducted a study assessing the suitability of rice husk as a composite material for brake pads, using particle sizes of 250, 500, and 1000 µm. The substantial particle size results in significant empty spaces ranging from 93-245 µm, which diminishes the bonding surface area across the binder and particles. The presence of voids leads to stress concentration, uneven stress distribution, and a reduction in compressive strength from 0.238 MPa to 0.144 MPa. An incorrect friction particle content can lead to the failure to produce oxides that help reduce friction and wear in high load and temperature conditions [131].

Alternatively, Solomon et al. [164] assessed using groundnut shells as a filler material in brake pads. They examined the effects of different molding temperatures (110 °C and 130 °C), molding times (10 min and 20 min), curing times (30 min and 60 min), and particle sizes (150 µm and 350 µm). The samples' water and oil absorption capabilities increased in a clear association with the filler's composition size. The reduction in water and oil absorption rates may be due to enhanced interfacial association between the binder and filler particles, resulting in a reduction in porosity. The curing time, particle size, and temperature during molding all have a big impact on how well the surfaces stick together and how the particles are spread out in the binder. This, in turn, has an effect on the material's physical and mechanical properties [164]. When braking in wet conditions or transitioning from wet to dry conditions, the brake pad initially exhibits inadequate effectiveness while it achieves an acceptable coefficient of friction, which can lead to surface abrasion [165].

7.3. Tribology Properties

The wear mechanism for composite brake pads includes mechanical breakdown from friction, characterized by a bright surface with deep grooves, abrasive wear, and degraded phases. As a result, thermal fatigue manifests in significant surface fissures. Rust forms when metal reacts with carbon and oxygen elements. Thermochemical wear causes phases to fade from extreme heat [104]. Materials with exceptional tribology capabilities, particularly in terms of wear and friction characteristics, are required for composite brake pads.

Krishnan et al. [137] revealed that wear behavior in brake pads is influenced by both temperature and friction frequency of operation. They studied brake pad composites (BPC) reinforced using Areca fiber in combination with various other fibers like acrylic, rockwool, and steel. Areca fiber, chopped into 3 mm pieces, was made with a composition of 5% (BPC1) and 10% (BPC2). The initial fade phase takes place between 93 °C and 289 °C, during which the friction coefficient (µ) rises until it peaks at 130 °C for all friction samples. The BPC1 brake pad composite exhibited a reduction in the coefficient of friction at 205 °C, whereas BPC2 showed a decrease at 150 °C. The reduction in coefficient of friction (µ) at elevated temperatures is due to the deterioration of the organic components in the brake material, leading to the formation of a friction film that lowers the µ value. Both composites fall within the industry-acceptable category of friction levels, which is typically between 0.3 and 0.5. The coefficient of friction of the brake pad composite steadily rises until it reaches 195 °C, then starts to decline. Above 195 °C, the change in µ is slower for BPC2 compared to BPC1, suggesting distinct friction properties. At high temperatures, the BPC1 composite, which has less areca fiber and more barite, has better friction performance than the BPC2 composite.

In 2020, Abutu and colleagues optimized manufacturing variables such as molding pressure (MP), molding temperature (MT), curing time (CT), and heat treatment (HTT) using response surface methodology (RSM). Experimental design is critical in developing composite brake pads made from coconut shell and seashell to meet industrial standards. The optimal performance of coconut shell-based brake pads can be achieved by employing 12 MPa for MP, 100 °C for MT, 6 minutes for CT, and 2 hours for HTT. For peak performance of shell-based brake pads, utilize MP, MT, CT, and HTT at 10 MPa, 160 °C, 12 minutes, and 2 hours. The high-performance brake pad made from optimized coconut shell falls under class H (µ>0.55), whereas the sample made from shell falls under class G (0.45–0.55), making it suitable for both heavy and light vehicles as per Society of Automobile Engineers (SAE) standards. The abrasion on shell-based and commercial samples exhibited broader wear marks in comparison to coconut shell, which displayed smaller wear marks, suggesting superior wear resistance and coefficient of friction. The proportion of errors derived from ANOVA is below 5%, suggesting that the experimental procedure was conducted with minimum noise impact [115].

According to Ilie and Cristescu [81], mechanical contact can lead to extreme temperatures in the material, resulting in fading and delayed color transformations. Prolonged exposure to temperatures exceeding 300 °C will affect the surface of the brake and disc pad. Moreover, the organic components undergo degradation, which subsequently impacts the brake pad's performance. Factors contributing to this phenomenon include fiber presentation, mixing outcomes, matrix composition, porosity, density, and mechanical qualities [88]. Wear qualities signify the extent of wear, while friction describes the degree of friction. The fade cycle illustrates the reduction in braking effectiveness caused by heat buildup from prolonged braking, resulting in increased braking time and distance. The recovery cycle refers to the brake pad's return to its normal friction condition. An increase in fiber quantity leads to suboptimal mixing with the binder, causing the fibers to detach readily and reducing wear resistance. This is also evidenced by the inability to maintain consistent friction performance [88].

In 2022, Kumar et al. [89] mixed binder, mulberry, and other components such as aramid, polyacrylonitrile, alumina, lapinus, potassium titane, graphite, barium, and vermiculite. They found that higher mulberry content led to increased wear resistance. Various metals, such as graphite for lubrication and barium for increased hardness, can reduce friction. A notable event is the formation of a strong interlocking connection between the fiber and the binder, along with even particle distribution [91]. It is important to note that certain materials can react and create a matrix like copper-tin (Cu-Sn) in high-temperature conditions. The matrix is pliable, enhancing stickiness between the disc surface and the brake pad, leading to a higher wear rate [166]. When you choose natural friction materials like Brutia cone pine powder and walnut shell dust, you need to think carefully about how to mix them with other materials to get the right friction and wear resistance values that meet SAE-J661 (Brake Lining Quality Test Procedure) standards [116], [167]. Abrasive particle size is an important factor in the wear process [168].

Modifiers, friction, and abrasive materials are crucial components in enhancing the abilities and longevity of composite brake pads. Graphite plays a crucial role as a lubricant in minimizing friction between the brake and disc pad [104]. Further studies utilized nickel (Ni) to improve friction surfaces' resistance to plastic deformation and facilitate the production of mechanically robust mixed layers and thick tribo-oxide coatings. The constant tribo-film present at the point of contact interface maintains a steady average coefficient of friction throughout different braking circumstances. Excessive nickel can reduce the flexibility of the friction surface, leading to a transition from adhesive wear to delamination as the primary wear mechanism [169]. When incorporating uniform mineral components like quartz, graphite, vermiculite, and barite into composite brake pads, it is important to regulate aspects such as particle size, as it greatly impacts the performance of the brake pads. Friction resistance includes energy transmission between particles and binder, whereas the brake pad's toughness demonstrates the importance of the binding between particles and binder [112]. Graphene significantly stabilizes the coefficient of friction (CoF) over a broad temperature range (80–345 °C) more effectively than composites with graphite. The graphene nanostructure increases surface area, leading to increased thermal conductivity, which aids in stabilizing CoF at elevated temperatures. The Graphene feature also results in a lower fade rate (% fade) [161].

Phenolic resin exhibits a propensity to readily bond with various elements used in composite brake pads, such as copper (Cu) and iron (Fe) metal particles. The metal particles catalyze the decomposition of the phenolic resin, lowering the temperature at which the procedure begins. Prior observations have shown that the inclusion of 20 vol% Fe can lower the beginning temperature of resin disintegration by 40°C, while the addition of 25 vol% Cu can reduce it by 70 °C. Ceramic fillers like bentonite, montmorillonite, and other silicates can enhance the stability of phenolic resins by raising the temperature at which the resin starts to degrade. Silicon and boron have a positive impact on reducing the decomposition rate of phenolic resins, resulting in a higher residue weight at 900 °C [162].

Chung et al. [170] assessed how abrasive materials like ZrO_2 (zirconium oxide), $ZrSiO_4$ (zirconium silicate), Al_2O_3 (aluminum oxide) and Fe_3O_4 (iron oxide) impact the friction resistance of composite brake pads in 2020. The friction coefficient of various abrasive materials can vary during continuous frictional operation, primarily influenced by friction frequency and fluctuating temperature conditions. ZrO_2 material exhibits a reduction in the friction coefficient, suggesting the development of a transfer layer. The ZrSiO4 material exhibits a reduction in the friction coefficient as the contact temperature rises, which is attributed to changes in the material's mechanical characteristics. Al2O3 exhibits a more pronounced reduction in friction coefficient as friction temperature rises and increases with greater friction. In contrast, Fe_3O_4 displays a weaker correlation between friction coefficient and temperature, which might actually decrease with prolonged brake application. Evenly spreading lubricant substances on the friction contact surface helps the chair prolong the resistance of the friction film and reduce friction fluctuations [171].

Natural fiber consists of numerous components, including cellulose, hemicellulose, lignin, and other contaminants. In 2022, Palai and Sarangi [93] altered the surface morphology of Eichhornia crassipes fibers using un-treatment, alkali treatment, and silane treatment classifications. The results indicated that silane treatment eliminated excess lignin, hemicellulose, and wax compounds, enhancing fiber binding with phenolic resin in automobile brakes. Eichhornia crassipes fibers treated with silane exhibited increased thermal stability, with a maximum degradation temperature of 338.2 ℃ and a crystallinity index of 33.17%, surpassing untreated and alkali-treated fibers. Adding silane to Eichhornia crassipes fiber in the brake pad composite made it better at healing and regenerating friction, as shown by a 1.1% drop in the acetone extraction value. The extensive contact area between the fiber and the binder helps prevent fiber delamination and pulling [172]. It also reduces the significant kinetic energy during mechanical friction and sudden temperature increases, thereby hindering fiber connections from being removed from the [151].

The blend of 5% coir natural fiber and 60% slag waste demonstrates the highest friction coefficient of 0.396, the smallest fade rate of 15.40%, and the least friction fluctuations of 0.101 [149]. High loads cause friction, leading to plastic stretching of the composite substance and the creation of a thin polymer film that sticks to the composite interface, impacting the fiber's cross-sectional area. This fragile coating serves as a protective barrier, decreasing the coefficient of friction. Oxide presence decreases oxygen diffusion, enhances load-bearing capacity, and lowers the coefficient of friction. These effects are contingent upon particle properties and the temperature generated during mechanical friction between the brake and disc pad [129]. Particle wear starts when the fibers separate from the binder. As the braking load increases, the fibers and binder continue to break down structurally [173].

Nogueira et al. [174] applied a pin-on-disc setup to assess the tribological characteristics of rice husk friction material containing a significant silica concentration. Rice husk with 6% alumina content is produced under two circumstances, such as non-heat treatment and heat treatment at 600°C. It is then compared with alumina, which contains 6%. The test results indicate that rice husk subjected to uniform heat treatment leads to favorable wear rates and reduced emissions. Even the placement of particles in the binder decreases porosity and enhances friction resistance [99]. A relatively small, rich husk particle size can lead to significant mass loss, a low wear rate, and a reduced high friction coefficient in brake pads due to the easy separation of small particles under braking loads [108]. In 2019, Primaningtyas et. al. found that the huge size of particles causes them to accumulate in one region, leading to stress concentration and decreased brake pad effectiveness. Increasing the amount of rich hush composition has a beneficial effect on enhancing wear resistance [118].

7.4. Thermal Properties

Braking causes a temperature rise due to friction, which leads to the thermal breakdown of organic compounds in the brake pad material. High-temperature disintegration compromises the foundational strength of the brake pad material, leading to inadequate braking, known as brake fade. The tribo layer's characteristics during contact between the brake pad and disc influence the friction coefficient, with a lower predicted temperature increase on the disc surface. Temperature fluctuations are influenced by the fiber composition, the fiber breakdown process, and the brake pad's thermal conductivity [175].

Brake pad materials were analyzed by Thermal Gravimetric Analysis (TGA) to assess their degradation behavior at different temperatures. TGA gives detailed data on disintegration tempo and highest degradation at specific temperatures. In 2021, Bashir et. al. [103] found that brake pads containing banana fiber exhibited three distinct weight loss steps, as seen by three primary peaks in the TGA findings at around 60 °C–85 °C, 490 °C–565 °C, and 730 °C–760 °C. The initial peak at a low temperature signifies the evaporation of moisture within the sample. The second peak observed between 490 °C and 565 °C signifies the breakdown of phenolic and cellulose resins. Phenolic resins remain stable at temperatures up to 300 °C–350 °C but disintegrate outside of this range. The third peak, observed between 730 °C and 760 °C in all samples, indicated lignin breakdown. Lignin functions as a binding material and breaks down slowly throughout a broad temperature span of 180 °C–900 °C. The thermogravimetric analysis results confirm that using banana fiber with phenolic resin as a binder reduced heat degradation of the brake pad material. The thermal resistance of phenolic resin as a binder has been impacted by a large amount of banana fiber.

Thermogravimetric analysis reveals that thermal deterioration is capable of occurring in multiple phases. The initial process begins at 245 °C, resulting in a 10% weight loss attributed to the amount of moisture in the fiber. Heating the abaca fiber composite to temperatures between 245 and 600 °C results in a drop in weight exceeding 73% as a result of hemicellulose loss and gas release. The last phase takes place at a temperature ranging from 600 to 900 °C, leading to a weight decrease of under 9% caused by the decomposition of lignin and cellulose in the abacá fiber. Higher fiber content can enhance thermal durability by causing natural fibers to grow and release hot gases in the composite at temperatures between 40 and 50 °C [88]. Fleece fiber is essential for enhancing brake pad performance due to its exceptional qualities like elasticity, resistance to breaking and fire, and its capacity to create a durable bond with the binder [92].

Several research investigations provide evidence of attempts to enhance the structural integrity of brake pads under varying thermal conditions. Chemical treatment removes non-crystalline components like lignin and hemicellulose. The high concentration of crystalline cellulose hinders and inhibits the discharge of fibers at elevated temperatures [152]. When leucas aspera fiber is treated with silane, the crystalline index goes up by 2.1 times. This makes the structure more uniform, the melting point go up, and the thermal stability get better with a 39% charcoal residue [96]. Additional researchers included vermiculite to enhance isothermal and long-term stability at elevated temperatures [89]. Graphite granules of the correct composition form a protective coating on the surface, which helps maintain heat resistance [104]. The permeable composition of red mud in the brake pad affects heat absorption, aiding in the regenerative mechanism and maintaining frictional barrier function [176].

8. Development and Commercial Brake Pad

Materials used for creating composite brake pads are constantly changing to fulfill requirements regarding effectiveness, protection, and durability. Furthermore, financial and environmental considerations are critical in brake pad manufacturing. Kumar and Ghosh [177] assessed the performance criteria for market items by evaluating the development of brake pads to determine market performance criteria. In order to assess the brake pad composite, repeated-measures ANOVA (Analysis of Variance) were used to make manufacturing factors better, like load, speed, and operational temperature, so that development products work better in terms of how well they transfer heat, how much friction they have, and how quickly they wear out. Researchers like Sethupathy et al. [77] have published information from commercial products, such as a density range of 2.12-2.23 g/cm^3, an S-scale hardness range of 80–94, and a porosity range of 6.1–9.2%. Additional studies provide quality standard data for different products, as shown in **Table 3**. Standardized criteria are crucial for ensuring that the production of composite brake pads meets the requirements and is recognized by customers and manufacturers. The creation of composite brake pads from natural sources aims to reduce the environmental impact caused by metal brake pads, which release pollutant elements harmful to environmental quality, cultivation, and the well-being of individuals [178]. Sustainable composite brake pads have benefits, including eliminating toxicological hazards and decreasing energy consumption. These materials are environmentally friendly and have relatively low manufacturing and production [179].

Table 3. Displays the standard parameters of a commercial brake pad product

Parameter	Value	References
HRB (Rockwell Hardness B)	59.50-66.90 (HRB)	[177]
HB (Brinell Hardness)	101.0 (HRB)	[180]
	102 (HB)	[181]
Water Absorption	1.2%	[98]
Oil Absorption	6.1%	[98]
Coefficient of Friction	0.40-0.99	[91]
	0.35-0.45	[114]
	0.30-0.40	[180]
Friction Stability	Approaching 100%	[114]
Wear Rate	3.80 mg/m	[180]
	3.82 mg/m	[181]
Wear Weight Loss	1.00 g	[67]
Specific Gravity or Density	1.89 g/cm^3	[180]
	1.898 g/cm^3	[181]
	2.47 g/cm^3	[182]
Thickness Swell in Water	0.9%	[180]
Thickness Swell in SEA oil	0.30	[180]
Flame Resistance	Charred ash 9%	[180]
Compressive Strength	111 N/mm^2	[181]

Prior investigations have assessed the possibility of using sustainable substances to develop composite brake pads, focusing on wear weight reduction and the coefficient of friction (CoF), as shown in **Figure 7** and **Figure 8**. Natural fibers and particles can influence the wear rate and coefficient of friction, which falls within the commercial product price range. Composite brake pads derived from natural sources show promising and expanding potential for the future. A low wear rate number is preferred as it signifies a gradual rate of wear. For CoF, both low and high values might be advantageous, depending on the specific application and system design. In certain situations, a low coefficient of friction (CoF) might result in better braking and reduced wear on the brake system. Conversely, in some scenarios, such as car brakes, a high CoF may be preferable for quicker and more efficient braking.

Ünaldi and Recai [183] found that both material formulation and manufacturing conditions significantly influence the density and porosity of composite brake pads. Anova is utilized to optimize all variables for the development of brake pads with exceptional qualities. In 2018, Akıncıoğlu et al. [182] prepared various friction material dusts containing steel fiber, rock wool, kevlar pulp, graphite, phenolic resin, vermiculite, brass, calcium hydroxide, zirconium silicate, metal sulfide, iron oxide, rubber scrap, barites, rubber, petroleum coke, chalcopyrite, mica, and silica. These were incorporated independently using hazelnut shell (HS) and boron oxide (BS), an inorganic compound in the synthetic materials grouping. Brake pads with high thermal conductivity can enhance stopping power by facilitating the faster removal of heat created during braking, resulting in improved braking performance. Excessive heat might result in damage to the hydraulic

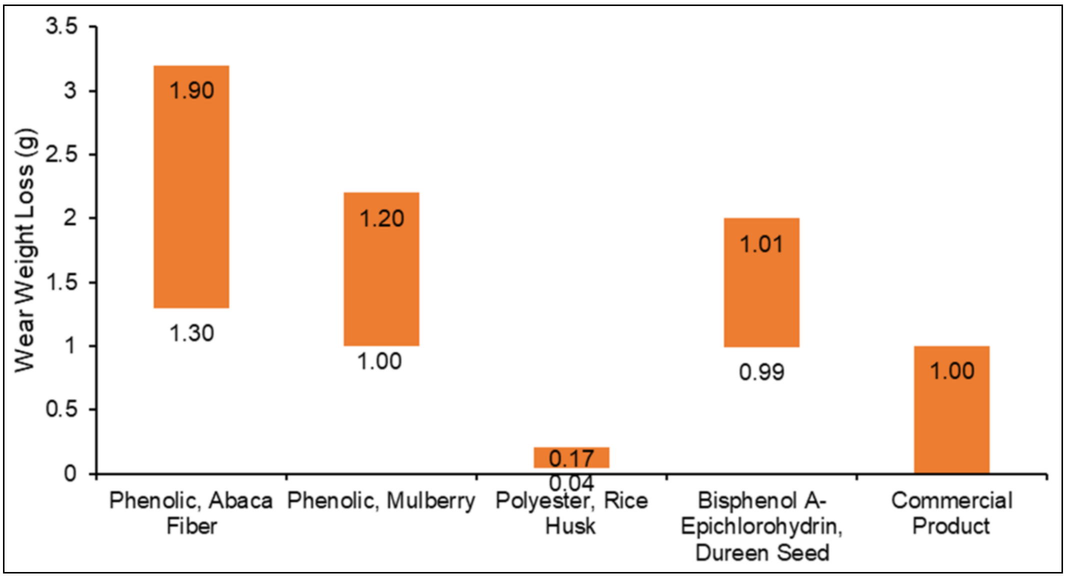


Figure 7. Wear weight loss of development and commercial brake pad composite [88]–[91]

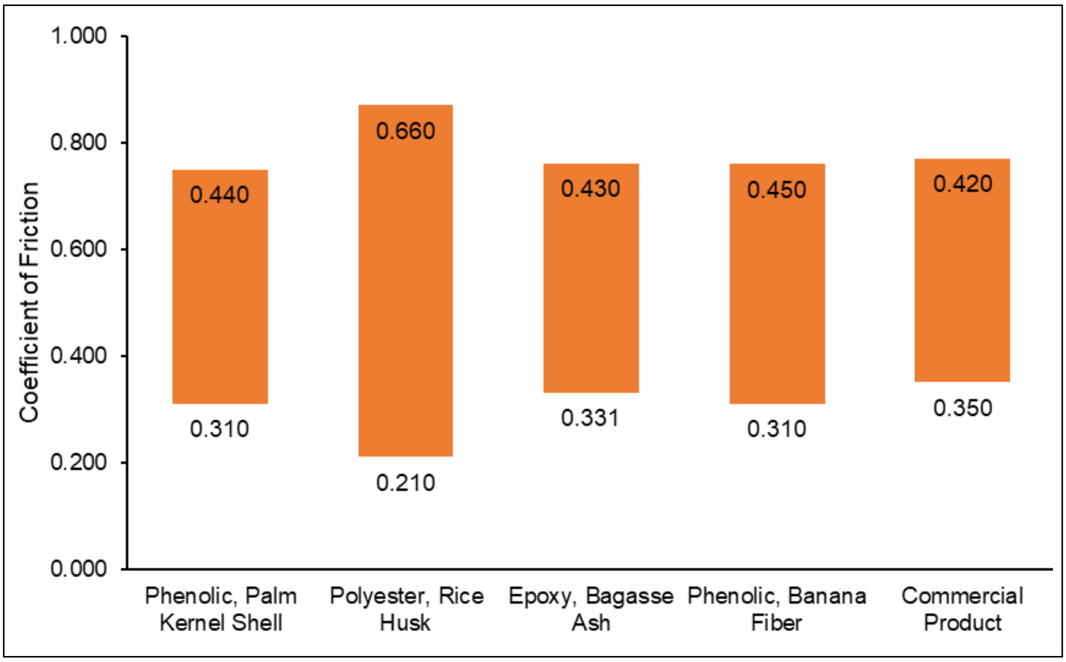


Figure 8. Coefficent of friction in development and commercial brake pad composite [67], [90], [99], [103], [164]

fluid. Thus, it is crucial for the heat conductivity to be in an optimal ratio. Furthermore, as density increases, porosity decreases. Decreased porosity leads to higher thermal conductivity. This finding has found that generally the pore structure in the brake pads hinders heat conduction, leading to increased temperature throughout frictional forces.

The shear force of the brake pads is tested as follows: hazelnut shell (HS) 694 N, baron oxide (BS) 751 N, and commercial (CO) 850 N. These values comply with the ISO 6312 standard, which requires a minimum of 350 N. Compressibility is the extent to which a metal powder can be readily compacted to its specified density. Considerable variances were seen in the compressibility evaluations of HS, BS, and CO brake pads. The HS bearing exhibits the greatest compressibility with a thickness variation of 285 µm, although the BS and CO samples demonstrate similar values. The compressibility was measured at 1.58%, 1.57%, and 1.41% in sequence. It is possible that the close agreement in compressibility data is due to the empty content. The study's findings align with the ISO 6310 standard, which requires the compression value to be under 2% [182]. Adegbola et al. [184] assessed the inherent capabilities of palm kernel shell and bagasse particles in brake pad composites, demonstrating lower density values of 1.65 g/cm3 and 1.43 g/cm3 in comparison to commercial goods at 1.89 g/cm3. The density of the composite brake pad must adhere to requirements since it can impact braking performance, vehicle weight, vibration absorption, heat distribution, and wear resistance. The smaller particle size leads to a decrease in pore quantity because the particles are easily distributed uniformly inside the binder [185].

9. Conclusion

Automotive braking mechanisms rely on complex interactions involving brake pads and discs, necessitating high-quality materials with specific physical, mechanical, tribological, and thermal qualities to enhance effectiveness. An implication of prolonged exposure to high-frequency and high-temperature friction is the possibility can cause mechanical breakdown and thermal weakness, causing compounds to discharge into the surrounding atmosphere. This has the potential to contribute to visible pollution in the form of particle pollution, negatively impacting human and animal health. Heavy metals (Fe, Cu, Co, Cd, Cr, Ni, Pb, Zn, Sb, Mn, and Hg) are the source of particle matter (PM10 and PM2.5). These metals are found in composite brake pads, where they act as a binder, reinforcement, filler, modifier, and abrasive material. Using replacement parts made from fibers and particles from renewable sources like plants and animals has become more popular because it has many benefits, such as being easy to get biologically, making brake pads work better, being eco-friendly, having fewer negative effects on people and animals' health, and supporting a long-term sustainable auto industry. Natural fibers and organic particles are vulnerable to moisture and high temperatures, necessitating surface changes through chemical, mechanical, and biological treatments. Optimizing fabrication parameters such as molding pressure, molding temperature, curing time, and heat treatment to create composite brake pad excellence that fulfills certification and functionality specifications. In addition, natural fibers and organic particles are mixed with modifiers and metal-type abrasive materials to regulate friction resistance, deformation, degradation, and thermal stability. The most obvious finding to emerge from this study is that natural fibers and organic particles are used as friction materials in composite brake pads to meet industry-standard specifications. Another important practical implication is that the wear weight loss is less than 1 g, and the coefficient of friction ranges from 0.30 to 0.99. The results of this study clearly show that fibers and particles present sustainable and environmentally friendly properties but have characteristics that easily bond with water, varied mechanical properties, and limited thermal stability. This phenomenon presents a challenge, so further research needs to optimize fabrication parameters, improve the surface structure of natural materials, develop hybrids of natural fibers and particles, and select other appropriate additional materials to enhance the performance and durability of composite brake pads.

Acknowledgments

The authors would like to thank Universiti Malaysia Pahang Al-Sultan Abdullah, Malaysia, for their generous financial support through research grant No. RDU232715 and UIC231525.

Authors' Declaration

Authors' contributions and responsibilities - A.I.I: writing—original draft, formal analysis; J.P.S.: supervision, formal analysis; M.R.M.R.: Writing- review and editing, validation; T.C.: writing- review and editing, formal analysis; A.E.H.: formal analysis, data curation; J.J.: validation, visualization; D.F.F.: formal analysis, data curation; R.D: visualization, writing- review and editing. All authors have read and agreed to the published version of the manuscript.

Funding – Universiti Malaysia Pahang Al-Sultan Abdullah, Malaysia (Research Grant No. RDU232715 and UIC231525).

Availability of data and materials - All data is available from the authors.

Competing interests - The authors declare no competing interest.

Additional information – No additional information from the authors.

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