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Review

Influence of Natural Fiber Content on the Frictional Material of Brake Pads—A Review

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Abstract: Research into the use of eco-friendly materials, such as natural fibers, in brake pads has gained momentum in the last few decades. This can be attributed to the potential of natural fibers to replace traditional materials in tribological applications such as braking pads. The harmful impact of the commonly-used brake pad materials, such as metal and mineral fibers, on human health and the environment necessitates the development of eco-friendly alternatives. Natural fibers, such as banana peels, palm kernels, and palm slag, have been shown to be a viable replacement for traditional brake pad materials. This article reviews the literature on the use of different natural fibers in brake pads and their impact on the physical, mechanical, and tribological properties. Trends for density, porosity, hardness, coefficient of friction (COF), and wear rate are observed. The recommended formulations to yield the optimum properties, according to the perspective of several studies, are showcased. In addition, the effect of asbestos material and natural fibers on life-cycle assessment and CO_2 emission is highlighted. This article is an attempt to provide a foundation for future researchers in the field of natural fiber-reinforced composites for brake pad applications.

Keywords: brake pads; natural fiber; life-cycle assessment; banana peels; lignocellulose; palm residues; biocomposites

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1. Introduction

The braking system is one of the crucial systems in automobiles, responsible for slowing down or stopping the automobile by converting kinetic energy to thermal energy through friction. For this reason, it is important for brake pads to have a high and stable coefficient of friction [1]. This makes the selection of the appropriate friction material for brake pads of paramount importance and much research has been dedicated to the process of selecting and developing new friction materials. Factors considered in the process of selecting friction materials include the manufacturing process and material requirements. Generally, friction materials can be classified into three categories [2]: (i) metallic brake linings, (ii) carbon−carbon composites, and (iii) organic polymerics (resin bonded).

Metallic brake linings, made of iron or copper, are commonly used in heavyweight and high-speed aircraft, as well as high-speed trains. This is mainly due to the high thermal stability of metallic brake linings, which is a necessary characteristic for these types of applications [3]. Despite their ease of fabrication and low cost, metallic brake linings have a high density, which decreases the system's energy efficiency [2].

The carbon−carbon composite friction materials are primarily utilized in aircraft applications. They are 40% lighter in weight than metallic brake linings and have a high strength at elevated temperatures, twice that of steel. This allows them to have a longer service life. However, the main limitations of carbon−carbon composite materials are their high cost and susceptibility to oxidation [2].

On the other hand, organic polymerics are used in the production of light-duty brakes that are commonly used in normal clutches. Organic polymerics typically consist of 30–40% organic resin, with a wide range of ingredients and formulations. There are four main categories of components used to create organic polymeric materials: binders, fillers, friction modifiers, and reinforcements [2]. As a result, selecting the appropriate organic polymeric friction material needed for a specific application can be a challenging task.

The material of pads is naturally heterogeneous and diverse with a complex formulation [4]. For a century, the primary material used in the production of brake pads has been in the form of a composite material made of a polymeric matrix reinforced with asbestos fibers and other multi-ingredients [5]. Asbestos has good physical and chemical properties, making it stable over a wide range of temperatures, which makes it well-suited for use in friction materials [6]. However, asbestos is a known carcinogenic material and poses significant health risks [5]. As a result, there has been a significant amount of research in this field dedicated to developing asbestos-free composite materials for brake pads by investigating alternative materials to replace asbestos fibers in various polymeric matrix materials. One promising solution presented by this research is the use of natural fibers as an alternative to asbestos-based materials [7]. The use of natural fibers is preferred over synthetic fibers because they are more [7] eco-friendly (environmentally friendly) and cost-effective [8–10].

Natural fibers, also known as lignocellulosic biomass, are becoming as a viable alternative for synthetic reinforcement materials. This can be attributed to their low cost and density, suitable specific strength properties, simplicity of the separation process, the ability to sequester CO_2, and biodegradability [11,12]. Moreover, natural fibers are the most widely estimated abundant biopolymer on Earth, with an estimated annual global production of 1.3×10^{10} metric tons [13,14]. Additionally, natural fibers are renewable and sustainable [15]. These fibers can be obtained from different sustainable sources that are considered waste, such as (i) forest wastes (e.g., branches, unwanted stems, and withered leaves) [16], (ii) industrial wastes (e.g., waste paper and demolished wood) [17], and (iii) agriculture wastes (e.g., palm residues, empty fruit bunch, straw, bagasse, corncob, Nile rose, and stover) [14,18–20]. This mitigates the problem of over-exploitation of resources, especially for the continuous suffering from climate change, and aggravate the global greenhouse gas emissions [21–23]. All of these reasons align with the motivation to reduce reliance on non-renewable mineral resources and the associated carbon footprint used in the production of synthetic fibers [14,15].

The utilization of eco-friendly (green) materials, such as lignocellulose, holds great potential for reducing carbon emissions and addressing environmental toxicity issues [14,24,25]. Lignocellulosic residuals are particularly well-suited for these purposes as they are abundant and renewable biopolymers [14] that have been studied for over 200 applications as sustainable materials. For example, lignocellulosic fibers could be used for comprising construction materials, moderate strength composites, adhesives, packaging, coatings, dental fillings, implants, and drug delivery devices [13,14,16–20,26]. All of these benefits have led several governments to push towards increasing the reliance on lignocellulosic residuals in various applications [27,28]. In addition, the use of lignocellulosic (natural) fibers in frictional materials needed for braking pads has the dual benefits of being a good candidate to replace asbestos fibers and reduce environmental waste. For instance, fruit residuals have been declared as a critical bio-waste source and hence recycling them to produce natural fibers that can be utilized in the manufacturing of some applications, such as braking pads, can significantly reduce environmental waste [29].

The objective of this paper is to provide a comprehensive review of existing research on the synthesis and characterization of natural fiber-based brake pads. The study also examines the impact of varying weight percentages of natural fiber on the mechanical and tribological properties of braking pad materials. Additionally, the paper emphasizes the life-cycle benefits and environmental effects as a result of using natural fiber in braking pad applications.

2. Asbestos Material and Natural Fiber Life-Cycle Assessment

2.1. Asbestos Material Life Cycle Assessment

The use of asbestos has been linked to environmental and potential human health hazards, promoting efforts to find alternative materials. However, many proposed solutions are either extremely energy demanding or not yet fully developed [30], thus becoming endangering by simply moving the environmental influences to a different phase of the asbestos life cycle [31]. To address this, it is important to conduct consistent and quantitative environmental assessments of different scenarios for asbestos-containing waste (ACW) to identify a reliable manner. This is a less environmentally impacting key considering its whole life cycle [31].

Life cycle assessment (LCA) methodology is an environmental management tool used to evaluate the possible environmental impacts of a process or product throughout its entire life cycle [32–34]. Despite its usefulness, there are relatively few LCA studies that have been conducted on different management options for ACW [35]. This can be attributed to the lack of methods for assessing the impact of asbestos emissions on soil, water, and air [36].

Recent years have seen significant advancements in the management of asbestos-containing materials (ACMs), which includes the establishment of a risk map for significant priority of interference and the encapsulation and elimination of ACMs, as well as obtaining ACW end-of-life [31]. To this end, Pini et al. proposed two end-of-life scenarios for ACW in order to reduce it. The first scenario considered thermal inertisation treatment employing an industrial continuous plant. The second scenario considered the disposal of ACW in landfills for hazardous waste [31]. The results obtained are stated in Table 1. Pini et al. proposed for the first-time characterization factor for asbestos fiber and included it in the USEtox 2.0 impact assessment method [31].

Table 1. Life-cycle inventory assessment (LCIA) comparison for the two ACMs scenarios for 150 ton of ACW [31].

Impact Category	Unit	Residual Material Landfill	Thermal Inertisation Treatment (Allocated)	Thermal Inertisation Treatment (Not Allocated)
Human toxicity, cancer	Cases	2.18×10^{-1}	3.33×10^{-3}	5.83×10^{-3}
Human toxicity, noncancer	Cases	1.34×10^{-2}	4.48×10^{-3}	7.85×10^{-3}
Freshwater ecotoxicity	PAF·m^3·day	1.58×10^{10}	1.96×10^{9}	3.43×10^{9}

2.2. Natural Fiber Life-Cycle Assessment

To mitigate the negative effects of ACMs, the characterization factor, which allowed for highlighting that inertisation treatment reliably and quantitatively should be the favored solutions to be adopted by local and national consultants [31]. This is particularly true when the resulting inert material can be used as a secondary raw material, thus reducing the environmental damage [31]. Plant fiber reinforced composites (PFRCs) have been found to be more sustainable compared with synthetic fiber composites based on the life-cycle assessment outcomes [37]. Ramesh et al., at their first look on natural fiber composites [37], also showed that the use of plant fibers as a reinforcing agent in PFRCs has great potential for promoting the sustainability of composites in different applications.

A large amount of fruit residuals from juice industries, food markets, and other industrial processing represents a potential bio-resource with significant environmental implications [38]. This waste produced accounts for a third of fruit waste in the total fruit biomass [39] and poses a significant transportation challenge due to its low bulk density [39]. Traditional compositing methods to deal with the fruit residual, such as direct landfilling, have become increasingly unattainable for environmental issues due to the emissions of methane (CH_4) and carbon dioxide (CO_2) [38,40,41]. These gases are responsible for greenhouse gas (GHG) emissions [42]. One way to address these environmental and economic problems is to convert these residuals into useful materials, such as frictional materials for brake pads. Such utilization of natural fibers not only reduces the harmful environmental impact of asbestos, but also repurposes the fruit waste for economic benefits.

3. Formulation and Manufacturing Process

Several studies have reported that natural fiber-reinforced composite (NFRC) materials showed better tribological and mechanical properties [43–67]. These studies also showed the effect of the adhesion between the ingredients and how that affects the mechanical and tribological properties.

One of the factors that influences the adhesion of fibers is the alkaline treatment applied to them. This treatment is utilized to remove the unwanted elements, such as impurities, from the fiber [68]. The alkali treatment is a cleaning and modifying treatment for the surface of fibers to reduce surface tension and enhance the interfacial adhesion of natural fibers [69,70].

The ingredients of each formulation, fiber content percentage, optimum formulation, fiber treatment, and manufacturing process are shown in Table 2.

Table 2. Illustrates the effect of the natural fiber content, treatment, and manufacturing process on the structure of braking pads [43,44,52,56,57,62,67].

Friction Composite	Other Ingredients	Fiber Content Variation	Optimum Fiber Content	Fiber Treatment	Manufacturing Process	Ref.
Banana fiber/PR	**Parent matrix** (63%) [C, Ca $(OH)_2$, $CaCO_3$, Al_2O_3, MoS_2, Sb_2S_3, MgO, SiC, SW, PAN fiber, PR] [10, 6, 10, 2, 2.6, 2, 3, 3.4, 12, 12%, balance]	0, 7, 14, 21 (Wt.%)	7 Wt.%	-	15 MPa, 150 °C, 10 min.	[43]
	Parent matrix (82%) [($CaCO_3$ and $BaSO_4$), (PAN fiber, $CaSiO_3$, SF), (C, MoS_2, Al_2O_3, SiC, MgO), PR], [30, 29, 23, balance]	4, 8, 12, 16% (Wt.%)	12 Wt.%	-	15 MPa, 150 °C, 10 min.	[44]
	[PR, ((BUNCp), (BCp))] [(5, 10, 15, 20, 25, 30%), balance]	BUNCp, BCp	BCp 30% PR, BUNCp 25% PR	-	-	[52]
palm kernel fibers/ER	[ER, Al_2O_3, C, $CaCO_3$] [(15, 19,23,25,30,40), (5, 0, 10, 5, 5, 6), (5, 5, 10, 5, 5, 29), (40, 70, 30, 35, 20, 15%)]	35, 6, 27, 30, 40, 10% (Wt.%)	10 Wt.%	NaOH soaking for 24 h	100 KN, 25 °C, 2 min	[56]
Palm kernel fibers/PR	[PR, C, Al_2O_3] [35, (35, 30, 25, 20,10), (20, 15, 10, 5, 5%)]	10, 20, 30, 40, 50% (Wt.%)	50 Wt.%	NaOH soaking for 24 h	-	[57]
	[PR, C, Al_2O_3, wheat, Nile rose] [35, (35, 30, 25, 20,10), (20, 15, 10, 5, 5), (3, 5, 5, 10, 10), (2, 5, 10, 10, 15%)]	5, 10, 15, 20, 25% (Wt.%)	-		-	
Palm slag/PR	[PR, C, SF, Al_2O_3] [20, 10, 20, 10%]	40% (Wt.%)	-	-	Hot pressing process	[62]
Palm kernel fibers/PR	**Parent matrix** (46%) [Acrylic fiber, RwF, SF, $Ca(OH)_2$, PR, NBR, CR, CaO, SiC, artificial C, MoS_2, $BaSO_4$] [4, 6, 5, 3, 9, 3, 2, 2, 3, 9, (14, 14, 6), (40, 35, 38%)]	0, 5, 10% (Wt.%)	5 Wt.%	NaOH soaking for 24 h	-	[67]

PR: phenolic resin; ER: epoxy resin; BUNCp: uncarbonized banana peels; BCp: carbonized banana peels; steel Fiber: SF; steel wool: SW; RwF: rockwool fiber; CR: crumb rubber; Wt.%: weight percentage.

4. Influence of Natural Fiber on the Mechanical and Tribological Properties

When natural fibers are used as reinforcement elements, the tribological properties can be improved by controlling the fiber content at certain levels [43–67]. The natural fiber content affects the tribological properties, mainly due to the change in the binder (matrix) to the natural fiber ratio. The binder to the natural fiber ratio affects the adhesion force, which has a direct influence on the tribological properties [71]. The use of natural fibers improves the mechanical properties until a certain point, then the mechanical properties start to decrease. This could be observed for banana fiber and palm kernel fibers with different ingredients and different weight percentage of the fibers. For instance, when this ratio is below an optimum value, the fiber content needed to reinforce the matrix is not enough. In addition, when it is above that optimum value, the fibers will need more binder to bind together. Hence, the deterioration of mechanical and tribological properties is expected in cases when the fiber content is above or below these optimum values.

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. They also measured the porosity, density, hardness, thermal conductivity, compressibility, wear rate, and coefficient of friction (COF) of the prepared composites. Figures 1 and 2 show the testing machines (T-Mc) and standard (St) used by some of the studies to determine the tribological properties, such as COF, as listed in Table 3. These properties are illustrated in Table 3 and Figures 3–7.

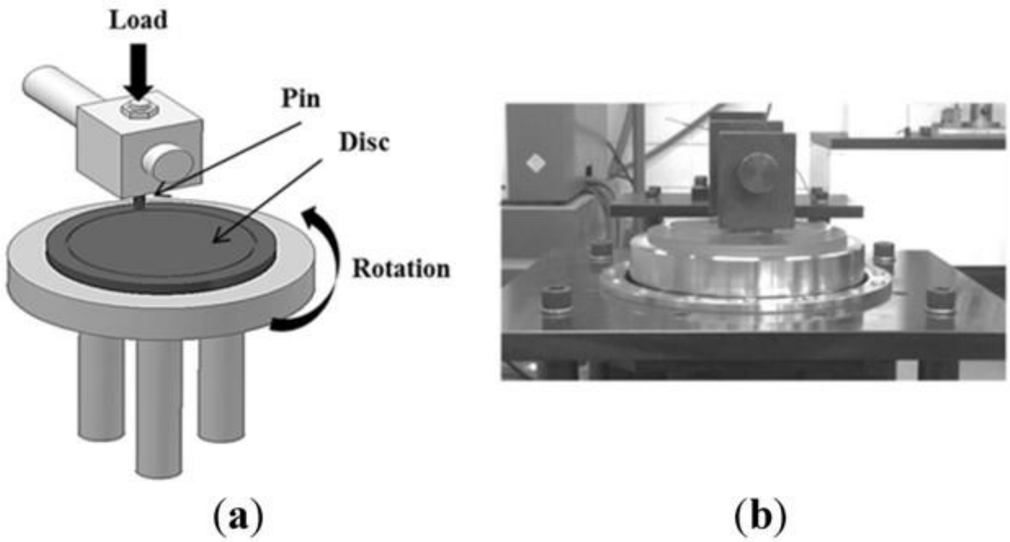


Figure 1. (**a**) The schematic of the pin-on-disc machine and (**b**) pin-on-disc used in the wear rate and measuring COF [72].

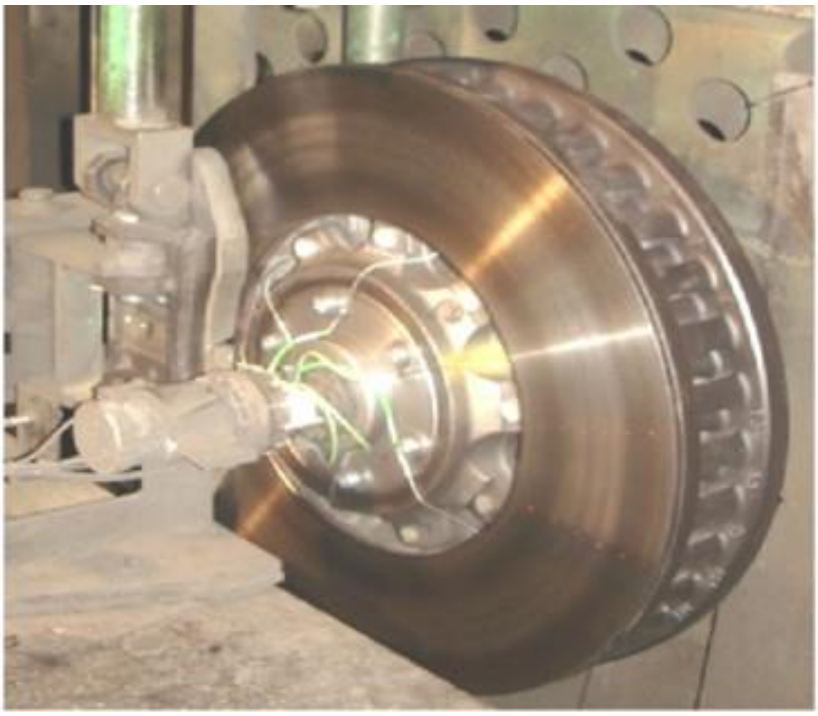


Figure 2. The disc brake machine used for measuring the wear rate and COF [73].

Table 3. Illustrates the effect of natural fiber on tribological and mechanical properties of braking pads [43,44,52,56,57,62,67].

Friction Composite	T-M/St	COF	Wear Rate (WR)	WR Unit	T-M/St	Hardness	T-M/St	Porosity (P%)	T-M/St	Compressive Strength/Compressibility	Thermal Conductivity (TC)	Ref.
Banana fiber/PR	Pin-on-disc- (Figure 1)	-	FWt↑ → WR↑	g	HBN	FWt↑ → HBN↑	-	-	-	-	-	[43]
	Disc brake SAE J661 (Figure 2)	FWt↑ → COF↑ RPM↑ → COF↑	FWt↑ → WR↑ RPM↑→ WR↑, up to certain point then ↓	cm^3/Nm	HRC. ASTM-E18	FWt↑ → HRC↑	-	-	-	-	FWt↑ → TC↑	[44]
	Pin-on-disc- ASTM: G99-05	FWt↓ → COF↓	FWt↓→ WR↓	mg/m	HBN "B" scale	FWt↓→ HBN↑	-	-	Honsfield Tensometer	FWt↓→ σ↑	-	[52]
palm kernel fibers/ER	Inertia dynamotor	FWt↑ → COF↓ up to certain point then↑	FWt↑ → WR↓, up to certain point then↑	mg/m	Inertia dynamometer	FWt↑ → Hardness↑	-	FWt↑→ P%↑.	-	-	No trend	[56]
Palm kernel fibers/PR	Pin on the disc/ ASTM G-99	-	FWt↑ → WR↑, up to certain point then↓	mm^3/N.m	HRC ASTM D-785	FWt↑ → HRC↑	-	-	-	-	-	[57]
			FWt↑ → WR↑			FWt↑ → HRC↑.	-	-	-	-	-	
Palm slag/PR	Pin-on-disc	-	Pressure↑ → WR↓	m^3/m	HRC type E.	Pressure↑→HRC↑	-	-	UTM	Pressure↑ → σ↑	-	[62]
Palm kernel fibers/PR	Chase Test IS2741	FWt↑ → COF↓	-	-	HRC K scale. IS 2742	FWt↓→ HRC↑	JIS D 4418	FWt↑→ P%↑.	-	No trend	-	[67]

↑: increasing, ↓: decreasing, FWt: fiber weight, HRC: Rockwell hardness, HBN: Brinell hardness.

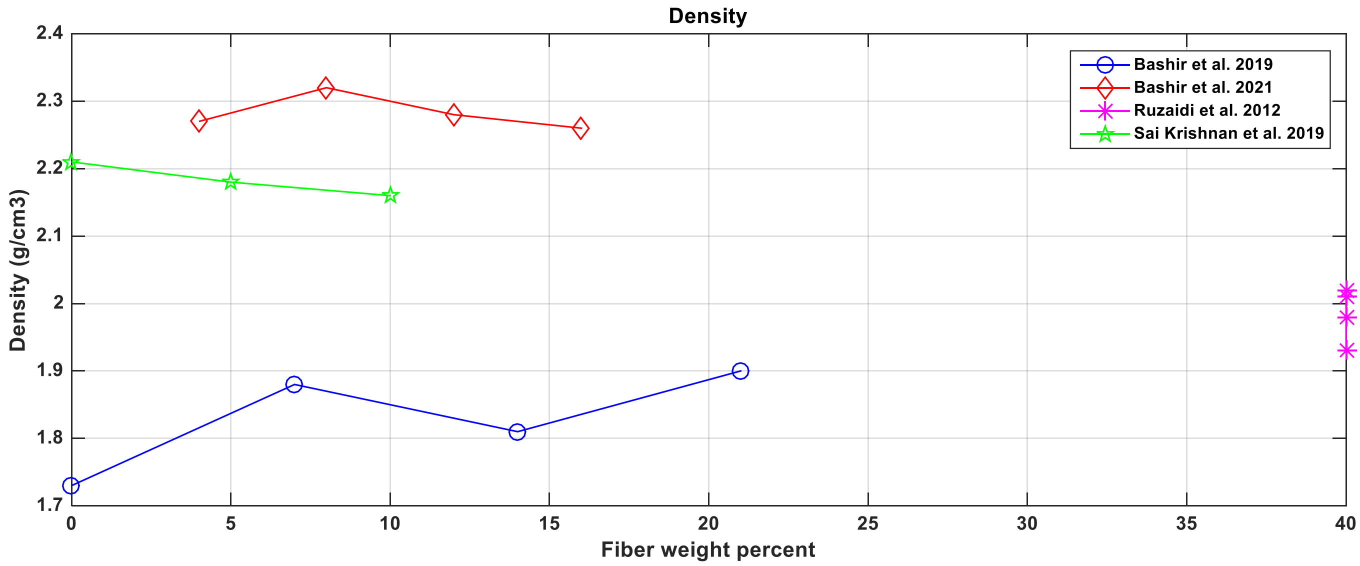


Figure 3. The density variation with variation of fiber weight percentage for different fibers [43,44,62,67].

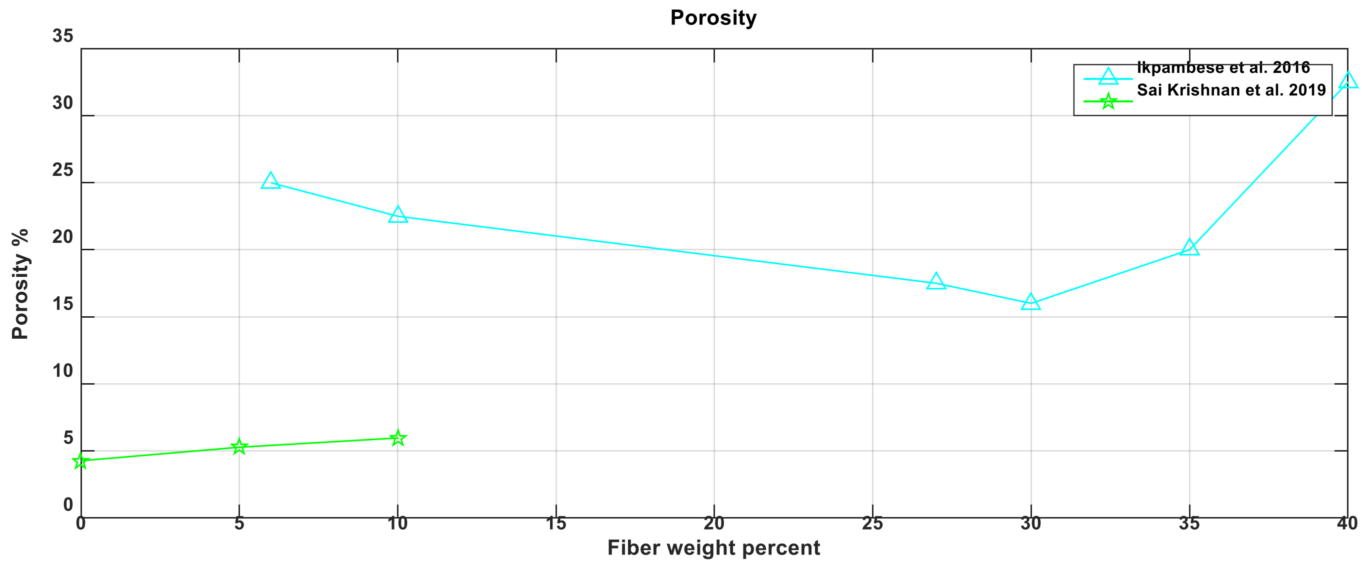
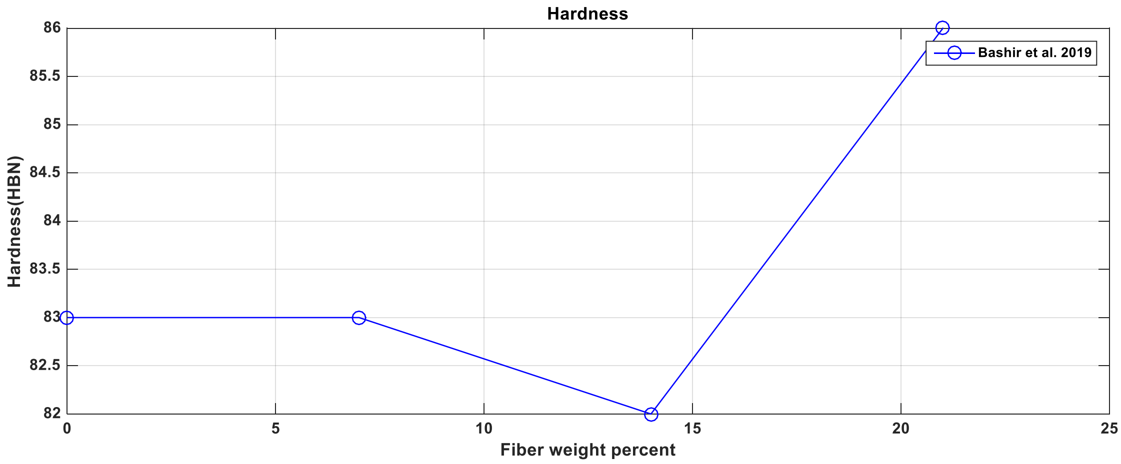
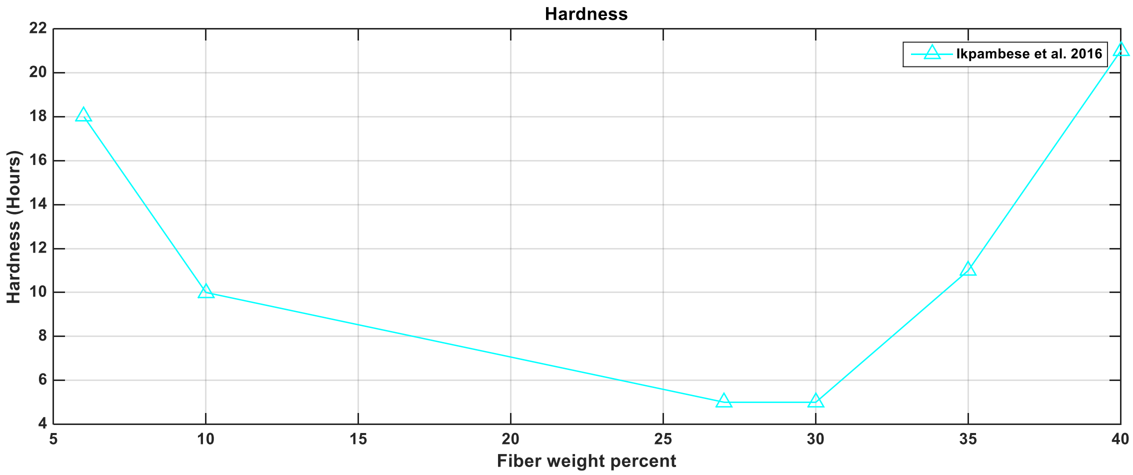


Figure 4. The porosity percentage variation with variation of fiber weight percentage for different fibers [56,67].

In order to provide better comparative observations of the effect of these natural fiber types and their contents on the resulting properties, the results obtained by other researchers are plotted, as shown in Figures 3–7. For example, palm kernel fibers [62] show values of wear rate and hardness, as the fiber content is constant while the pressure used during manufacture varies from 10 to 60 tons. In addition, the inverse relationship between the density and the porosity is quite clear when examining Figures 3 and 4. Moreover, the density increased for banana fiber weight percentages (Wt.%) of 63% and 82% parent matrices, until reaching a certain fiber weight percentage before decreasing. However, the density of the 63 Wt.% composite increased again after the decrease happened at the 14% Wt.% fiber content. Palm kernel with a 54% Wt.% fiber content recorded a density drop when the fiber weight percentage increased. This drop could be due to the change in fillers and the friction modifier MoS4 used (Figure 3).



(a)



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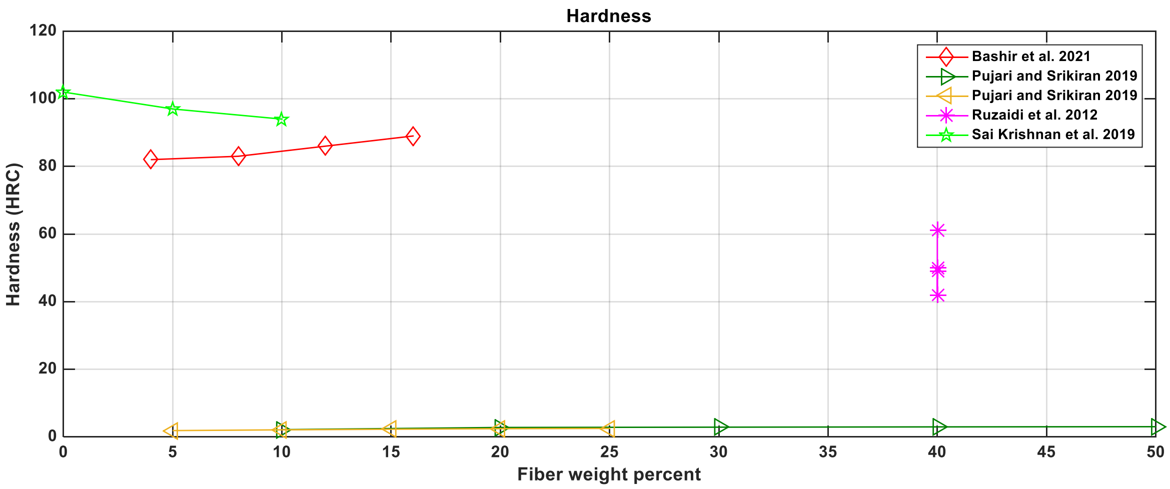


(c)

Figure 5. (**a**) The variation of hardness using the Brinell tester for banana fiber with variation in the fiber weight percentage [43], (**b**) illustrates variation of hardness using inertia dynamotor palm kernel fiber with variation in the fiber weight percentage [56], and (**c**) variation of hardness using Rockwell tester for different fibers with a variation in the fiber weight percentage [44,57,62,67].

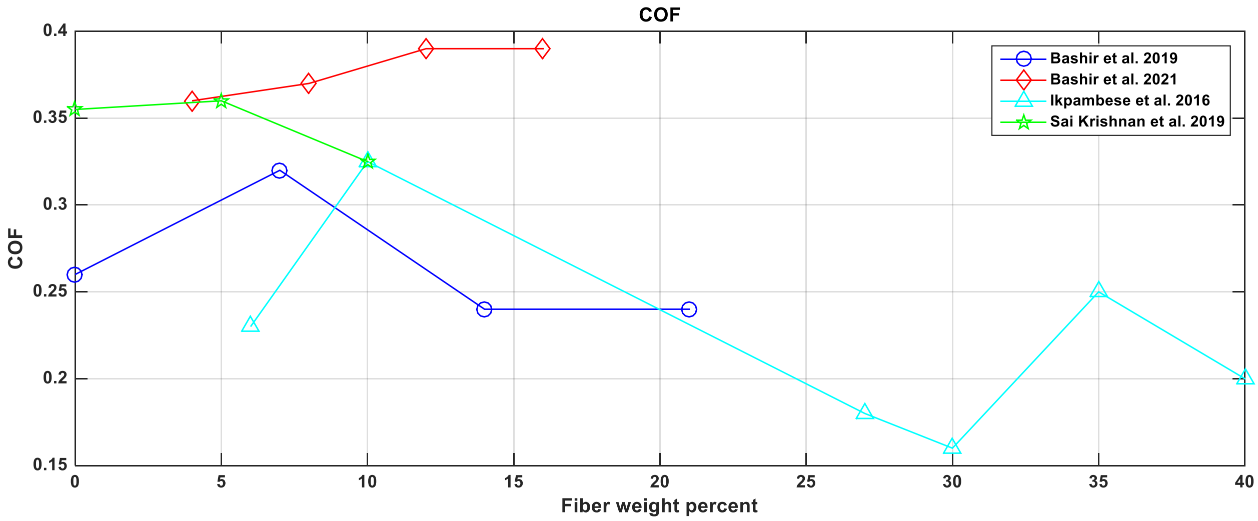
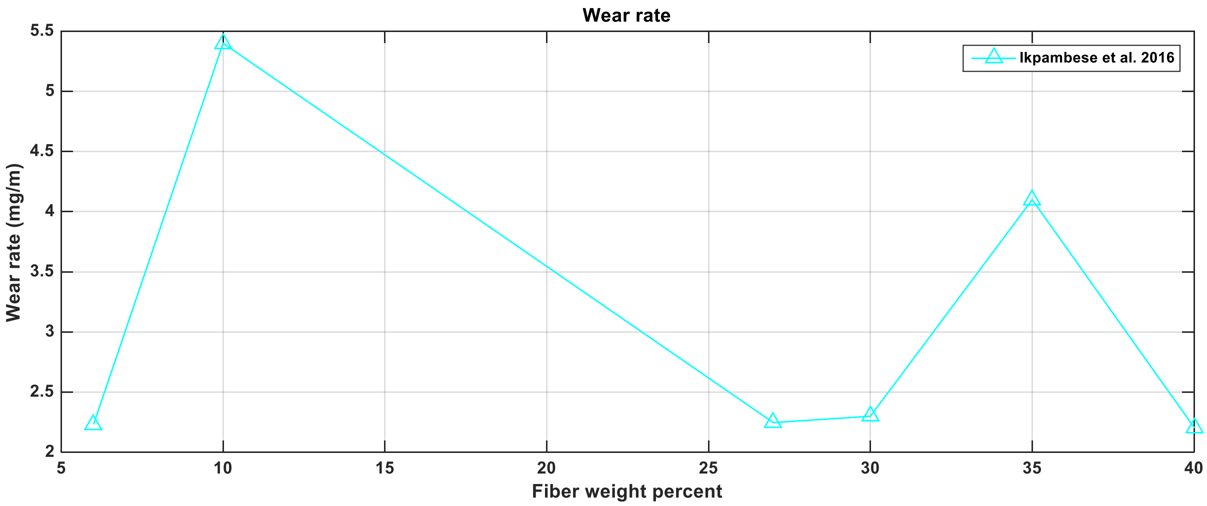
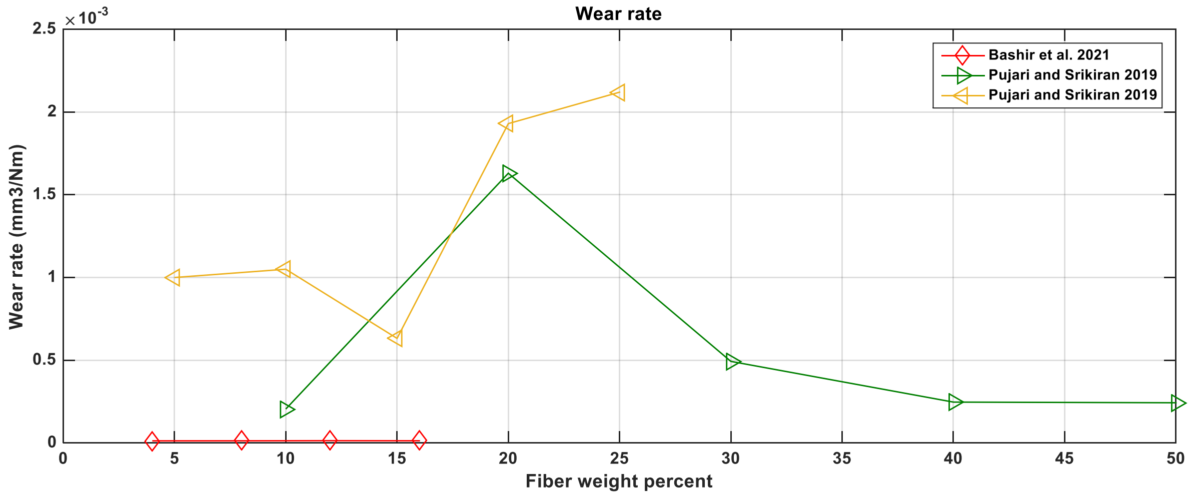


Figure 6. The variation of COF for different fibers with a variation in the fiber weight percentage [43,44,56,67].

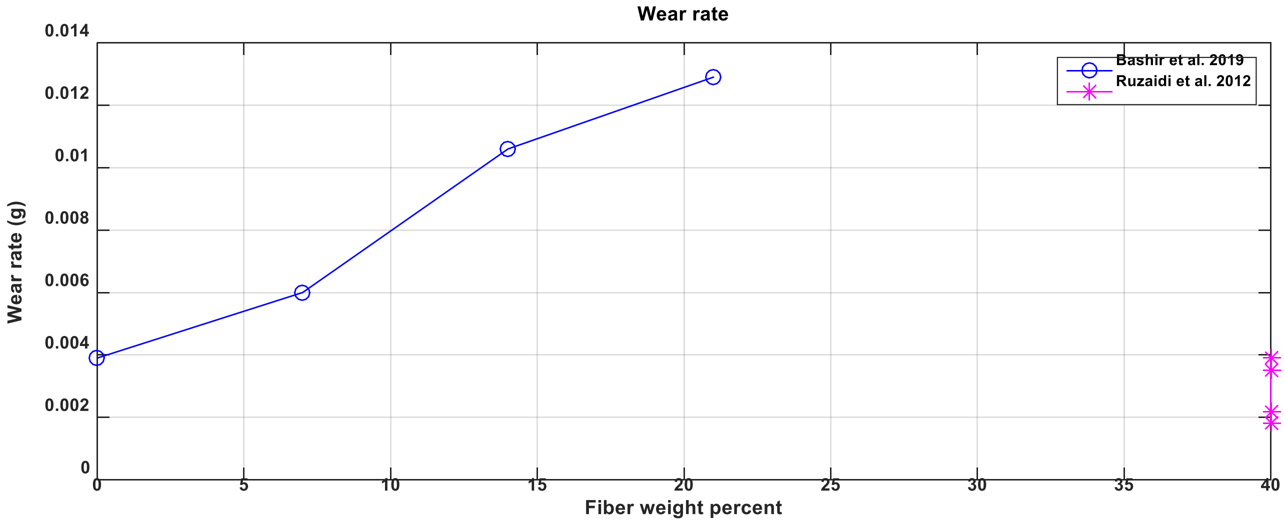


(**a**)



(**b**)

Figure 7. *Cont.*



(c)

Figure 7. (**a**) The variation of wear rate for different fibers for different fiber weight percentages in mg/m [56], (**b**) the variation of wear rate for different fibers for different fiber weight percentage in mm^3/Nm [44,57], (**c**) and the variation of wear rate for different fibers for different fiber weight percentage in g [43,62].

There was a boosting up trend for porosity percentage in the palm kernel of 46% in the parent matrix. It could be observed that the enlargement of the porosity decreased the density value, which could be referred to as the particle size of the palm kernel fibers [56]. This could be attributed to the fact that the particle size of the palm kernel fibers was higher than that of the space filler used [67]. The uniform curing caused a uniform dispersion, which led to a high porosity value [67] (Figure 4). Furthermore, the measured hardness improved for all of the tested natural fiber composites. This improvement was observed to occur with the fiber weight percent rising, except for the case of palm kernel with the 46% parent matrix. The hardness value of each formulation was quite close to the other one and this could be due to applying the same pressure and temperature for the same duration during the hot compaction process [43]. In addition, this rise could be attributed to the cross-linking between the fiber and the resin that takes place during the curing process [44] (Figure 5a). The hardness of the palm kernel with the 46% parent matrix decrease is suggested to occur because of the increase in porosity as the fiber weight percent increased (Figure 5c). The palm kernel of the [56] hardness decayed as the fiber weight percent increased, followed by a jump at 35 and 40% fiber weight percent (Figure 5b). The hardness values of the palm kernel 40% fiber weight percent showed an increase as the compression force used in the fabrication process increased. Increasing the pressure had a role in reducing the voids in the NFRC-based composites. The effect of having a compact and composite material, with a high density and low porosity, is known to improve the mechanical properties significantly [43].

The tribological properties recorded an obvious improvement as the fiber weight percentage increased. Most formulations recorded a trend for enhancement of the properties. The banana fibers recorded a trend of increasing the COF among all of the formulations, except that of the 63% parent matrix (Figure 6). The COF in Figure 6 is the average value for banana fibers [43,44] as it was examined at different temperatures and different loads.

The wear rate in Figure 7 is the average value for the results from several studies [43,44,56,57,62]. An average value was used because of the differences in the testing conditions. The 63% parent matrix recorded an increase followed by a drop, then stability for the COF value. This drop could be due to the failure of bonding between the phenolic resin and the banana fibers. Moreover, it is an indication of the deteriorated

COF for these composites at elevated temperatures [43]. The palm kernel fibers recorded a different COF trend, which is obvious in the graphs. The 46% parent matrix recorded a slight increase followed by a minor drop. This could be attributed to the degradation of the palm kernel fiber at higher temperatures [67]. Ikpambese et al. [56] recorded a decreasing trend followed by an overshot trend, which seems to be different that the results reported in other similar studies. However, this difference could be attributed to the change in the natural fiber weight percent, the absence of a parent matrix, and variations in the ingredients. Furthermore, the results seem to be stable at different ranges, which could be due to the absence of steel fiber [56], as steel fibers play a role in increasing the COF [44,57,74,75].

In general, the wear rate showed trends for both banana and palm kernel. Some of them increased with increasing the fiber weight percent, while others showed a decreasing trend after an initial increase. In addition, some of them showed an increase followed by a decrease and then another increase (Figure 7). For example, the banana fibers with a 63% and 82% parent matrix showed an increase in wear rate as the fiber weight percent increased. This boost could be due to the degradation of the samples at elevated temperatures [43] (Figure 7b,c). Finally, studies that showed an increase followed by a decrease and then an increase were that of palm kernel fiber weight percentages of 5–25% and phenolic resin of 35% weight percent. This could be attributed to the unique adhesion properties between the wheat and Nile rose with the phenolic resin. The formulation that did not contain the Nile rose and wheat showed better results at the same fiber weight percentage, and followed a trend of increasing followed by decreasing, as better wear resistance was obtained through the strong adhesion of natural fibers with resin [71].

The change in the tribological and mechanical properties with changing the binder to a natural fiber ratio and how this could affect the performance of the samples can be observed in Figures 3–7. The optimum value stated by all of these researchers, according to the resulting tribological properties, was for the sample that had almost the same or very close values to that of the asbestos-based brake pad. Table 4 summarizes the properties obtained by each researcher and that of the commercial asbestos-based brake pad [52,62].

Table 4. The optimum formulation in each article relative to the researcher point of view and the commercial pad.

		Banana Peels Optimum Formulations				Palm Kernels			Palm Slag
Properties	**Commercial Pad (Asbestos Base)**	**7 Wt.% & 63% Parent Matrix**	**12 Wt.% & 82% Parent Matrix**	**BCp at 30% Phenolic Resin**	**BUNCp at 25% Phenolic Resin**	**10 Wt.% & 40% Resin**	**50 Wt.% & 35% Resin**	**5 Wt.% & 46% Parent Matrix**	**40 Wt.% at 60 Ton**
Density (g/cm^3)	1.89	1.88	2.28	1.2	1.26	-	-	-	
Porosity	18%	-	-	-	-	22%	-	5.26%	
Wear rate	3.8 mg/m /0.72×10^{-6} mm^3/mm	0.006 g	1.38×10^{-5} mm^3/Nm	4.67 mg/m	4.15 mg/m	3.98	2.4×10^{-4} mm^3/Nm	-	0.89×10^{-6} mm^3/mm
COF	0.3–0.4	0.325	-	0.35	0.4	0.33	-	0.36	
Hardness	101 (Brinell)/ 9.83 (h)	83 (Brinell)	86 (Rockwell)	71.6 (Brinell)	98.8 (Brinell)	10 (h)	2.98 (Rockwell)	97 (Rockwell)	61 (Rockwell)
Compressive strength (MPa)	110			61.2	95.6			-	57.7

5. Conclusions

The use of natural fibers as a reinforcement agent in brake pads can reduce their environmental impact and decrease the toxic effects on human health associated with the use of asbestos. This review paper suggests that the variation of the fiber content can affect the mechanical properties in general and the tribological properties in particular. For instance, the tribological properties of brake pads, such as the coefficient of friction (COF) and wear rate, can be significantly improved by the incorporation of natural fibers at optimal levels. However, the prediction of these new materials' performance and the formulation of trends/correlations of these results. vs. fiber content is a complex process due to several reasons, such as having (i) multi-parameters influencing the measurement process, (ii) different fiber fractions ranges, and (iii) different lignocellulosic sources. Despite these challenges, some trends and relationships have been observed and listed in this review as follows:

1- The density of banana peels increases when the weight percentage of natural fibers is below 10%, then decreases before rising again at a weight percentage of 20%.
2- The porosity generally decreases as the content of the natural fiber in the composite's formulation increases.
3- The hardness of the composites increases for both banana peels and palm kernels, except for the 46% parent matrix and palm kernel as a fiber.
4- The COF increases initially, then decreases and become stable as the weight percentage of natural increases.
5- Only the 46% parent matrix and palm kernels as fiber show a decrease, followed by an increase, as the percentage of other ingredients change, not just the fiber and resin.
6- The wear rate increases as the weight percentage of natural fiber increases, except for palm kernels (10–50%) and 35% phenolic resin.
7- The compression load during processing has an impact on the mechanical and tribological properties.

In summary, this review paper aims to collect the findings from several studies in the literature on the use of natural fiber-reinforced composites (NFRC) as frictional materials for brake pads and pave the road for future researchers in this field. However, future studies specifically focused on the tribological and mechanical properties of NFRC materials are necessary to establish the suitability of this new class of materials for use in brake pad applications.

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