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A Systematic Review of Brake Pad

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Review Article

Abstract

The brake system is a mechanism that allows the vehicle to slow down and remain stationary. Most automobiles uses either one or both disk brake and drum brake system. These brake system components include the brake pedal, brake lines, brake master cylinder, brake booster, brake calipers, brake rotors/drum, and brake pads. The greatest load in the braking of a vehicle falls both on the discs and pads. The friction caused by braking on these parts results in a large amount of heat transfer and particulate emission. Therefore, studies on the brake system have focused on human health, the environment and the economy, in addition to investigating the operation, performance and wear mechanisms of the system. In this study, researchers, citations, keywords, and trending topics of 1,118 studies on brake pad between 1982 and 2023 were investigated by systematic analysis method using R and VosViewer analysis programs. A brief summary of the most cited papers and their topics is given to help researchers who will conduct studies on brakes. These studies focused on wear and emission issues. Non-exhaust emissions have adverse effects on air, aqueous media, roadways and human health. Therefore, it has become mandatory to limit these small particles, which is why they are included in the Euro 7 emission standard. Due to the limitations on braking, future researchers have been informed about the status of non-exhaust emissions.

Keywords: Brake pad, Brake wear, Friction material, Non-exhaust particles, Systematic analysis.

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1. Introduction

In science, which is a set of social and science disciplines that examine claims with a specific curiosity and purpose through experimentation, observation and thought with specific methods, it is of great crucially to share previous research, experiences, methods and results obtained for the production and development of knowledge. Review articles are important in terms of showing the focal points and deficiencies of numerous of studies to researchers with limited time. Review articles, one of the types of scientific publications, have four different types: Traditional review, Systematic review, Meta-analysis and Pooled analysis. Traditional review articles are studies presented in prose by experts on a specific subject, synthesizing findings, conclusions and evaluations by examining various books, journals, articles and proceedings on the subject of research, without following a specific method, compiling information obtained in different ways and from different sources [1].

Traditional review articles, which are the simplest and most widely used method, are deficient in scientific aspects; they may be subjective, they may contain errors, they may contain insufficient research, the criteria for selection of publications may not be clearly stated, the method used may not be defined, they do not contain quantitative evaluations, their results cannot be verified because they cannot be repeated, the results of reviews conducted by different experts on the same subject may be different [2-6].

Systematic reviews are a research method in which studies on a specific topic with similar methods are identified using various selection criteria, scanned in a comprehensive and detailed manner, and based on a comprehensive quality assessment and synthesis of the studies. Systematic reviews are more objective and contain fewer errors. They also contain more information because of more prescriptive, comprehensive, repeatable, the methods and constraints used are clearly specified. In this research method, a critical analysis can be made by compiling the findings of a wide range of studies on a subject [1, 2, 7].

For these reasons, the number of systematic review studies has been increasing in recent years. The process of conducting the systematic review and the issues to be considered are detailed in the studies by Yılmaz [2], Karaçam [1], and Naseri and Malekzadeh [3].

Naseri and Malekzadeh [3] list the stages of systematic review as follows:

- Identifying the research question, keywords and constraints,
- Selection of articles for study,
- Quality evaluation of the studies,
- Obtaining and analysing data,
- Interpretation of results.

In the studies to compare the systematic and traditional review types by Petticrew and Roberts [8] and MacKenzie et al. [9], it is stated that the common points of both methods are the preparation by experts and the presentation of study summaries. It was concluded that they differed from each other in all other criteria and that the systematic analysis was more scientifically reliable.

R and VOSviewer programs are frequently preferred in bibliometric analysis studies across various scientific fields, as it is stated that better data can be obtained from the Web of Science (WoS) index for these programs. The reasons for preferring these programs include their compatibility with the WoS database, graphical presentations, and the enhancement of the study's originality, impact, and understandability.

The brake pad is a part of the vehicle braking system that slows down or prevents the movement of the car by compressing the brake disc and converting kinetic energy into heat energy through friction. Brake pads are composite materials consisting of a mixture of five different components: Reinforcements, which provide mechanical strength; Abrasives, which increase friction and ensure cleanliness between contact surfaces; Lubricants, which maintain frictional properties and reduce wear at high braking temperatures; Binders, which maintain the structural integrity of brake pads under mechanical and thermal stresses; and Fillers, which are used to reduce production costs. Brake pads can be fall into three groups: metallic brake pads with more than 60% metal component content, semi-metallic brake pads with 25-60% metal component content and organic brake pads with more organic component content. The studies on brake pads are generally focused on the wear-friction performance of metallic and organic components, wear particles and the effects of particles on living organisms [10-15].

2. The Purpose

The objective of this study is to quantitatively unveil researchers, citations, journals, keywords, and trending topics in scientific investigations related to brake linings for land, air, and rail vehicles. Thus, instead of a simple review, the aim is to show scientists who are or will be working on brake linings comprehensive and widely studied topics and to guide them quickly to their goals.

In addition to conducive to the literature with regard to its scope, the numerical distribution of publications on brake linings of air, road and railway vehicles by years, distribution by type of publication, keywords, word densities, author analysis, journals, trending topics and number of citations were examined by systematic analysis method. In this context, brief subject summaries of the 20 most cited publications in studies on brake pads between 1982 and 2023 were given in section 6. Since the first article on brake pads indexed by the WoS was published in 1982, this year is accepted as the starting point for this research.

3. Data Sources

In the present era, numerous databases, including Web of Science, Scopus, Google Scholar, PubMed, and others, offer valuable resources for accessing scientific study data. The WoS database was decided on this study by virtue of it is an international and multidisciplinary platform consisting of more than 34,000 journals and more than 155 million records in engineering, social sciences, medicine, and other disciplines, and most importantly, it provides data suitable for bibliometric analysis.

Analysis programs such as Bibexcel, HistCite, VOSviewer, CiteSpace, Gephi, R, etc. are used to provide information about academic trends by formally and quantitatively evaluating and visualizing the existing academic literature of a particular subject. With these bibliometric analysis programs, quantitative findings can be compiled on country, author, university, journal, weak and strong research areas, literature gaps, areas of collaboration, potential opportunities and widespread impacts of outputs.

4. Search Strategy

The opting for keywords to be used in the retrieval of scientific publications for the systematic analysis conducted in this study was established by the authors. While the keywords were determined by the authors, it was aimed to obtain the most relevant results. Because brake pads are a subject of scientific study that has the capability to be published in many fields such as health, agriculture, materials, statistics as well as the automotive field. Different keywords and phrases such as brake, braking, braking system, pad, lining, friction, wear, shoe, etc. were searched in detail to cover research topics such as vehicle braking systems, lining composition, their performance in conjunction with brake discs, and their effects on the environment and living things. It was decided to keep the searching simple to obtain the majority of searching data covering the topics mentioned. On 31.12.2023, the first searching was made in the "All Fields" field with the keywords "brake pad" in the WoS system.

When the words "brake pad" were in quotation marks, the number of publications found was 894 publications, since both words must appear in the publication. Deciding by the authors that this number was insufficient due to the scope of the subject, a search was made without quotation marks in order to reach all publications and the number of publications found was n= 2,258 results from Web of Science Core Collection.

After the keywords were identified and the first search result was obtained, the constraints for removing publications that are not germane to the study topic from the list were determined. It was agreed that the first constriction for the publications in the list should be on "Languages" and publications whose written language is not English are excluded. The next constrictions were decided to be made in the order of "Document Types", "Research Areas", "Citation Topics Meso", "Conference Titles", "Web of Science Categories", "Publication Titles". Even after applying all these constrictions, 20 publications could not be extracted from the list. These 20 publications were found and deleted in the file suitable for analysis downloaded from the WoS system. After a step-by-step restriction process, n=1,118.

The search conducted on certain keywords and constrictions yielded 1,118 documents; 881 articles, 206 proceedings and 31 review papers written by 2,754 different authors in 453 journals, with the oldest publication dated 1982. In addition, 118 authors have more than 5 publications while 2,149 authors have one publication.

5. Analysis of Data

In order to delve into the search results in detail, VOSviewer and R Programs, which are scientific mapping methods, were used. VOSviewer is a highly visual program that enables quantitative evaluation of scan results. The reason why the use of R Program is preferred is that it reports the missing information in the publications procured in the sequel of the search in WoS and can provide different graphics.

The R program reported the missing information such as abstract, keywords, keywords plus, year, etc. of the publications in the search data. The missing information data of the publications were found through detailed searches on the internet and added one by one to the document to be used for the systematic analysis. In analysis programs, data losses below 10% are considered acceptable. In this study, with a missing data rate around 7.4%, its impact on the overall results is negligible. The missing information is due to the publication format of the journals, not due to oversight or incomplete writing. Subsequently, the statistical data used to evaluate scientific achievement were analyzed based on authorship, citations, journals, keywords, and abstracts. Although all Publication Year deficiencies of the publications were corrected, the reason why 83 of the 1,118 publications did not have keywords is that there is no keyword writing requirement in the journal. In the bibliometric analysis study conducted by Cetin and Seyitoglu [16] covering the years 2002-2022, auxetic structures used in the automotive industry were the subject and the Scopus database was used as the data source. As a result of the analysis conducted in that study, it was stated that 2,599 publications were made by 5,161 authors and 5,457 keywords were used. Abdullaev et al. [17] stated that in the bibliometric analysis study on electric vehicles in the Scopus database with the VOSviewer software, 59 keywords were identified according to the frequency value determined as 25 times in 1,074 documents mentioned between 1985 and 2023.

On 31.12.2023, after applying restrictions to the search data obtained from the WoS database, the following data were achieved with the R program; The oldest publication among 1,118 publications is dated 1982, 2,719 Keywords, Annual Growth Rate 12.58%, Document Average Age 7.69, International co-authorships 18.6%, total 18,759 References, 63 single-authored docs, Co-Authors per Doc 3.84 and 19.1 average citation per doc.

The quality of an article is appraised by several criteria for instance the journal impact factor, methodology, innovation, citations, etc. The number of authors and international teamwork with foreign researchers increases the likelihood of visibility and citation by researchers working on similar topics. Citation is recognized as a measure to ascertain the quality and impact of an article, researcher or institution. However, total or average number of citations to the articles varies from one discipline to another, depends on the number of publications and people working in that field, too. The number of the cited articles, which is a quantify of the impact of academic studies, can be evaluated by bibliometrics. It is revealed in the literature that 20% of publications in engineering and technology are cited in the first year of publication, while the average citations per article in physics sciences and engineering disciplines are between 5-20 [18-20].

Citation statistics are important because they are used for academic tenure, promotion and hiring by institutions as well as measuring both a single publication and an author's individual career success [21, 22]. The graph of the total number of articles and mean total citations per year to articles on brake pad by years is given in Figure 1. According to this graph, the article numbers of published on brake pads has been upsurging of late years and a markedly growing interest in the research topic. However, the number of mean citations to all publications by year has decreased compared to before 2008. The reason for this decrease is the 12-fold increase in the number of articles and the diversification of sub-topics. While before 2008, the average number of publications per year was 5, this value increased to 62 after 2010. In addition, since scientists tend to cite older articles in their studies, the mean number of citations for articles before 2008 is higher.

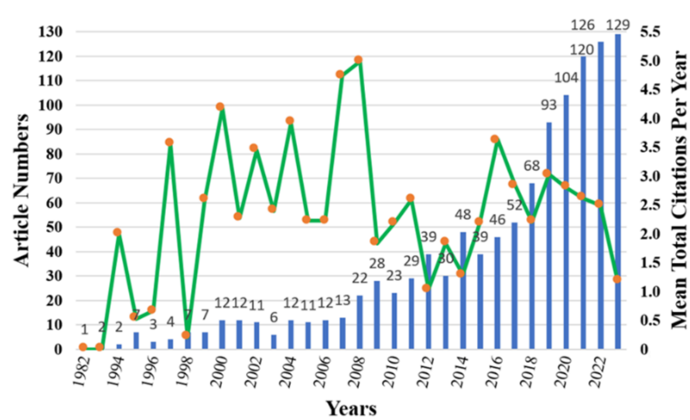

Fig. 1. Total number of articles about brake pads by year and mean citations per year

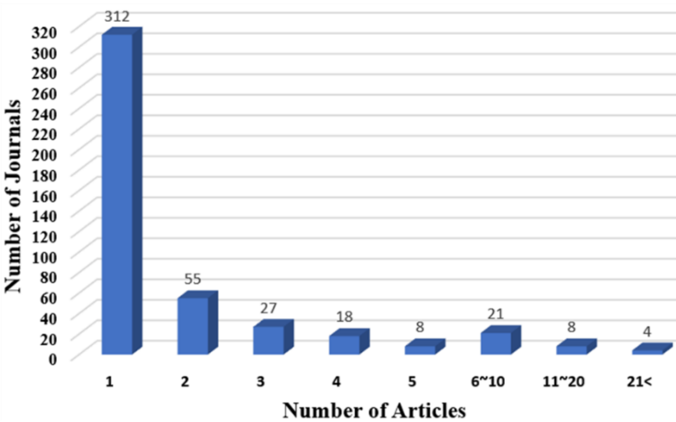

Fig. 2. Number of journals according by the number of articles published about brake pads

Figure 2 shows the number of journals grouped according to the number of articles published on brake pad. There are 453 journals that have published articles on brake pad. Only 1 article was published in 310 journals, 2 articles in 55 journals, 3 articles in 27 journals, 4 articles in 18 journals, and 5 articles in 8 journals. Between 6 to 10 articles were published in 19 different journals. The number of journals publishing more than 11 articles is 12 in total. The interest in the topic, visibility and number of citations to the articles are also affected by the number of articles published by journals on that topic. Therefore, researchers should also publish articles in journals with few publications in order to ensure currency and continuity of the topic.

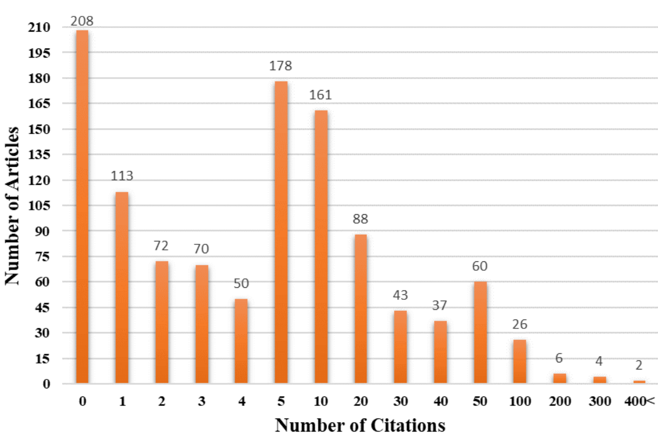

Fig. 3. Number of articles about brake pads by number of citations

The 1,118 articles analyzed in this study was cited total of 21,302 and the average number of citations to an article was 19.05. According to the graph in Figure 3, which shows the number of articles according to the number of citations they have received, 208 articles that have not yet been cited have a rate of 18.6%. In the engineering and technology, the uncitedness rate for the 2006 cohort of WoS indexed papers is 24% [19]. 113 articles have only 1 citation and the citation rate is 10.1%. The number of articles cited between 6 to 10 is 161 (14.4%), the number of articles cited between 11~20 is 88 (7.87%) and the number of articles cited more than 100 is 38 (3.4%) in total. Many articles cited at most once are published in 2022 and 2023. In engineering and technology disciplines, 20% of articles are cited in their first year [19]. Other reasons that prevent articles from being cited are journals that publish one or two articles that do not rank high in searches, articles that do not contain keywords and do not clearly state their aims and results. The high citation number of journals and publications have the effect of increasing their visibility, which in turn affects their citation in other publications.

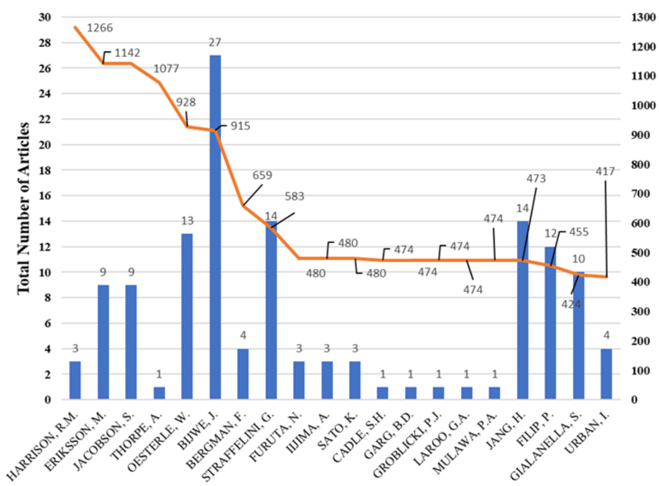

Fig. 4. Authors' total number of publications about brake pads and citations

The performance chart regarding the number of articles of authors who have more than 400 citations is shown in Figure 4. Harrison, one of these authors, received 1,266 citations for his 3 publications, while Eriksson and Jacobson, who have 9 publications, received 1,142 citations. Although some of the researchers have a high number of articles, the citations number of their articles are low. It is thought that the reason for the high number of citations to the articles written by Harrison, R.M., Eriksson, M., Jacobson, S., and Thorpe, A., are the originality of the study subjects, the fact that they are the first studies on this subject, and the variety of co-authors. The accurate and precise interpretation of the research results by these authors in their studies make them followed and respected by other researchers, so they are called scientific gurus.

In Figure 5, the studies with at least 200 times cited among 1,118 publications are given together with their annual average number of citations. The study conducted by Thorpe and Harrison [10] was cited a total of 1,077 times, giving the study an annual citation rate of 67.35. Apeagyei et al. [23] and Adamiec et al. [24] are cited more than 25 times per year, but their total citations are lower than Thorpe's due to year of publication. Although it is not included in the graph, the number of articles that receive more than 10 citations per year is 31. Brief summaries of the 20 most cited articles are given in the next section.

In order to specified the effectiveness of scientific studies, it is remarkable to choose the right keywords used for the evaluation of the article according to many criteria such as views, downloads, citations, etc. Because they are used for indexing articles, finding articles more easily and analyzing them in traditional review, systematic, meta, etc. analysis methods. Therefore, choosing the right keywords is very important [6].

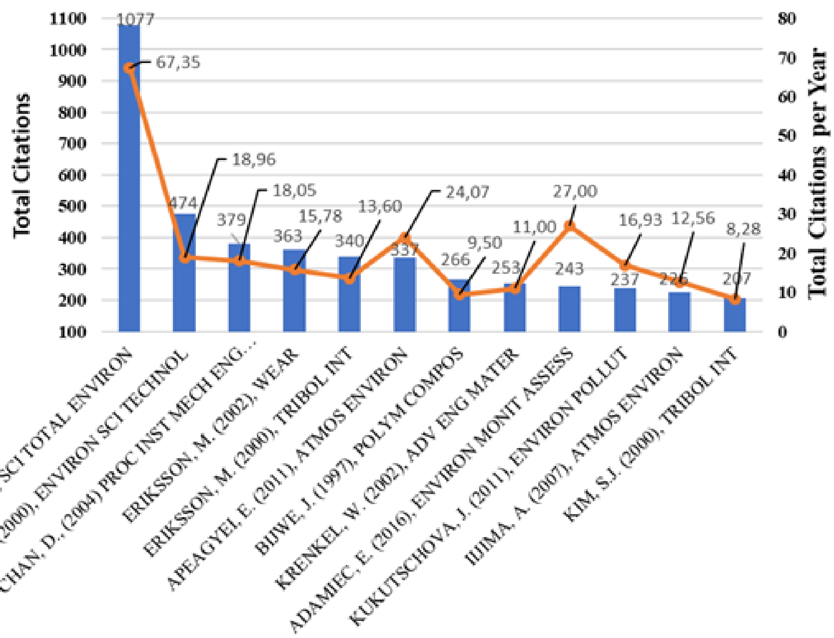

Fig. 5. Most cited articles about brake pads and their average number of citations

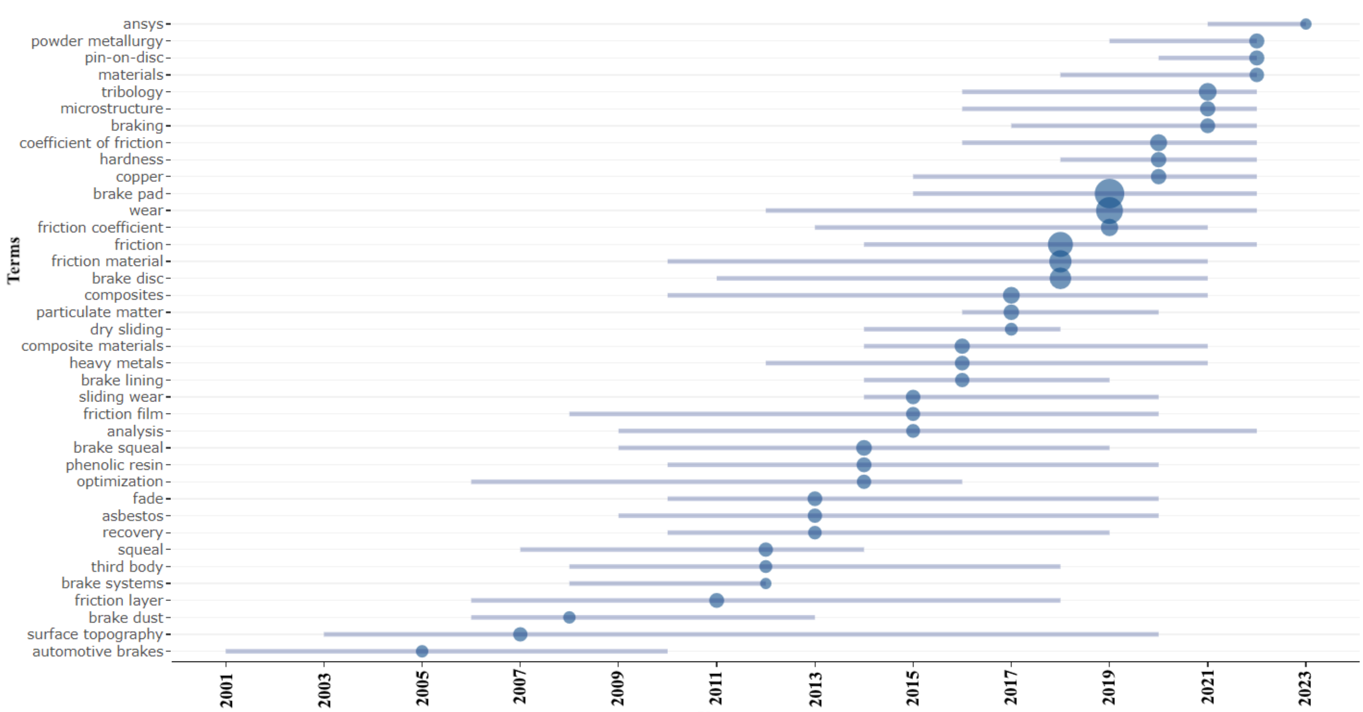

Fig. 6. Trend topics keywords in articles about brake pads

Figure 6 shows the most commonly used words and word groups in article keywords by year. As can be seen in Figure 6, while the keywords such as automotive brakes, disc brakes, surface topography were more preferred among 2000-2010 years, in recent years, the words such as particle size, natural fiber, tribology are more preferred as keywords pursuant to the purpose of the studies. As can be perused from the graphs, the preferred keywords are brake pad, friction material, brake disc, friction coefficient and wear rate, while in recent years, terms such as rigid pad, thermal cracks, absorption capacity, natural fibers, mass loss and shear strength have become popular.

The word cloud created from the keywords of the articles with the VOSviewer program is shown in Figure 7 and the keywords are a word cloud showing 45 words used together in at least 10 documents. The thickness of the line between the keywords indicates that the relationship of co-occurrence is high and that the keywords in the middle are the most preferred ones. According to the color distinction, the preference of keywords according to years can be understood.

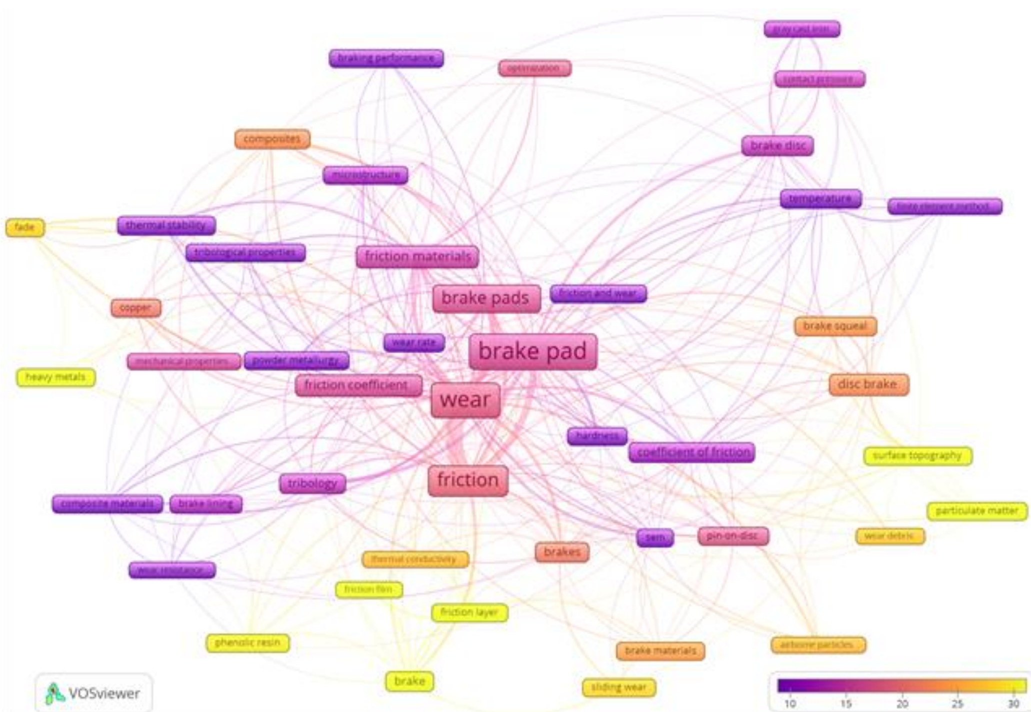

Fig. 7. Co-occurrence of keywords in articles about brake pads

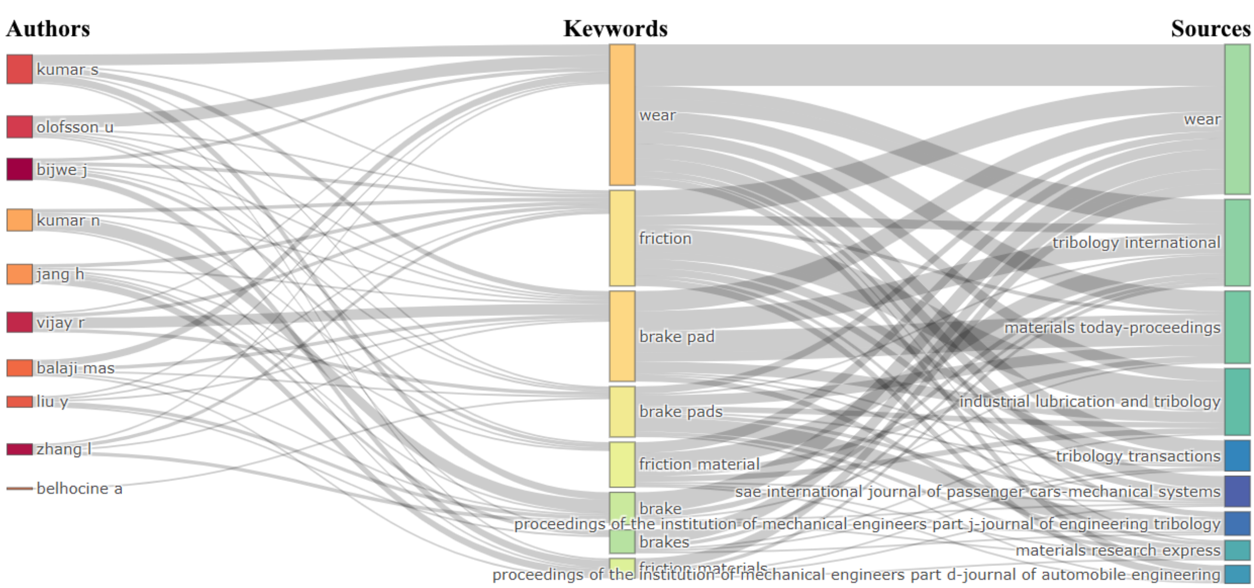

Fig. 8. Sankey diagram of Author-Keyword-Source in articles about brake pads

A Sankey diagram shows the flows and quantities of the observed features with line thicknesses proportional to the flow rate to each other. The width of the lines depicts the level of connection between the features. So, the larger line is the greater amount of flow. The size of the box in the Sankey diagram is the vastness of the connection between the two variables [25].

Figure 8 shows the connection between the three different features (Author-Keyword-Source) with a Sankey diagram. Figure 8 shows the Sankey Plot of the Authors who did the most studies on brake pads (left field), the top Keywords they preferred in their studies (middle field) and the sources in which the articles were published (right field) and all of them have 1-10 items. From the Sankey graph, it is seen that researchers who are connoisseurs in their field and who work on specific topics make certain preferences in terms of keywords and journals. The keyword "wear" was used by 9 authors and in all journals, while the keyword "friction" was used by 8 authors in 9 journals. In the Sankey diagram of 10 authors and keywords, 9 keywords are preferred in the Wear journal and the Tribology International journal, while the Wear journal has a higher selection density.

6. Most Cited Articles

In this section, the objectives, methods, and highlights of the 20 most cited studies on brake pad are mentioned. Our purpose in including this section is to help researchers who will study the subject have information about the general situation and study topics and to decide which parts they should focus on. The 20 most cited studies can be branched into three groups: case studies, review studies and research studies. While 4 studies were conducted as reviews Thorpe and Harrison [10], Chan and Stachowiak [12], Bijwe [26], Krenkel et al. [27], 5 studies were case studies Eriksson et al. [28], Eriksson and Jacobson [29], Österle et al. [30], Eriksson et al. [31], Verma et al. [32], and these studies mainly focused on the development of disc and pad wear and emissions, the phenomenon affecting them and their effects. The purpose, important statements, and study results of the first 20 publications in the list of most cited studies are briefly presented as follows:

In the review study conducted by Thorpe and Harrison [10], relevant studies on trace metals accumulated on roads were examined in order to show the chemical and physical properties, particle sources and non-exhaust trace element profiles resulting from roads. The focal point of the review was on the physico-chemical features of particulate matter rather than the quantity of various source emissions. It was noted that while exhaust emissions from road traffic are significantly reduced by emission control regulation, road vehicles are not able to diminish non-exhaust emissions such as particles from brake, tire and wear particles of road surface, and particles from resuspension following traffic flow. It has been evinced in the literature that the values of such non-exhaust emissions are problematic in the laboratory and in situ as they largely depend on the physical and chemical properties of the particles. It has been emphasized that brake dust particles, identifiable by their Copper (Cu) and Antimony (Sb) content, stand as an exception, and the lack of appropriate tracers makes the precise identification of particles from other sources particularly challenging. Emphasis on the study was placed on the potential of metals like Si, Fe, Ca, Na, Mg, Al, and Sr as markers for road dust. Additionally, it was noted that demolition and construction activities significantly contribute to these elements. Confirming the source of these particles often involves comparisons with local soil and crustal materials.

Adamiec et al. [24] conducted a study to probe and diagnose the heavy metals in urban and highway road dust resulting from non-exhaust emissions in the main sources of which are wear particulates from brake, clutch, road surface and tire, and degradation of road components. It is stated that road dust consists mainly of soil originated minerals (60%), while quartz constitutes 40-50% of minerals originating from soil and trace amounts of organic substances, non-exhaust vehicle emissions and albite, chlorite, microcline and muscovite minerals. Ba, Cd, Cr, Cu, Fe, Ni, Pb, Se, Sr, Zn, Ti and Pd metals selected in the study were analyzed on various sizes of crumbled road dust and brake pad dust (20 to >250 μm) using inductively coupled plasma-mass spectrometry, inductively coupled plasma (ICP)-optical emission spectroscopy and atomic absorption spectroscopy. Sieved dust from twenty samples of each type was subjected to Student's t-tests for comparative analysis. The deductions of SEM-EDS analyses performed on maximum dust fraction of 20 μm from brake pads and tires expressed the dasein of Cu, S, Si and Zn in tire dust, and Al, Cr, Cu, Fe, Mg, S, Si, Zn, Zr and Ca in brake pad dust. Hence Cr, Cu, and Ti are widely acknowledged as significant tracers of brake pad emissions. Dense concentrations of Cr, Cu and Ti, have been emphasized that brake wear contributes substantially to road dust pollution, that urban dust exhibits higher pollution levels compared to highway dust because of driving conditions and braking frequency, as much as the lack of air circulation in the city, and that fine road dust has significant impacts on human health as much as the environment. Urban roads and highways are significantly polluted with Cr, Cu and Ti, and brake pad and tire wear promote greatly to road dust pollution, and the bulk sample analysis were concluded that brake dust is densely contaminated with Fe, Ba, Ti, Cu, Zn, Pb and Cr, that the highest concentrations of the metals studied are found in the lowest fractions of brake dust (<20 and 20-56 μm) and that the >250 μm fraction in road dust is attributed to geogenic sources and is not linked to dust from brake systems.

Apeagyei et al. [23] examined the heavy metals distribution in the road dust in Massachusetts and hypothesized that the composition and concentration of road dust are subject to significant variations based on factors such as traffic type, road class, and geographical location. Analysis of road dust and the concentration of Iron (Fe), Titanium (Ti), Copper (Cu), Barium (Ba) and Zirconium (Zr) among the 22 metals identified in the study to estimate metals in road dust associated with vehicle traffic and to determine which metals from brake and tire wear, respectively, showed that Fe was always highly associated with Cu and Ba. The study results were interpreted as brake wear contributing to road dust, brake wear dust fractions being affected by traffic density and driving behavior, and Zn concentrations resulting from both brake and tire wear at traffic lights and stop signs are high.

Garg et al. [33] on brake pad wear investigated particulate matter size and composition in a brake dynamometer at four wear circumstances using seven brake pad formulations much used. It has been stated that the front brakes cover 70% of the braking load in vehicles, and at least using of one fibrous material (steel fibers, aramid fibers and potassium titanate fibers) in brake pad formulations is worrisome in terms of fiber emissions. It was figured out in the study that approximately 35% of the mass loss in the brake pad was emitted as PM in the air, and in the analysis of PM in the air, it was determined that very little breathable fiber and 18% were carbonaceous material. It was concluded that, approximately, 86% and 63% of airborne PM were PM10 (particle size less than 10 µm) or PM2.5 (2.5 µm) in diameter, respectively, with brake wear being the main source of copper found in the urban environment.

In a review study conducted by Chan and Stachowiak [12] encapsulating the present ingredients for brake friction material for dry and wet braking used in automotive. It was stated that graphite in lamella shape has enhanced lubrication properties while graphite in dust form can dispensate the heat produced during braking dramatically. It was also stated that in addition to focusing on the fuel efficiency and emissions of vehicles, the concentration should be on making brakes lighter and not releasing any toxic and carcinogenic substances into the atmosphere during use, and this can be accomplished by increasing environmental conscience.

Xiao et al. [34] have been investigated the copper metal matrix composite (Cu-MMC) in terms of mechanical properties and microstructure. Cu-MMC brake pads were produced by powder metallurgy method for high-speed trains in the time of emergency stop-braking between 300-380 km/h speeds with a full-scale dynamometer, taking into account their braking performance. When confronting organic friction materials to metal matrix composites are typically able to persevere higher temperatures and therefore can be utilized at temperatures above 1000 °C. Cu-MMC has been expositioned magnificent tribological features during downhill braking, parking braking and stop braking. The following results were obtained in the experiments; the static friction coefficient was approximately 0.4, the utmost brake temperature of disc surface was 566 °C, the wear rate was 0.20 cm3/MJ, the shear strength of the produced sample was 16 MPa and the bond strength betwixt the friction material and the support plate was 37 MPa. They concluded that Cu-MMC displayed distinguished features and could provide the technical demands, eliminating the problems of fragmentation and separation in high-speed train brake pads.

Kukutschová et al. [35], discussed in the article the chemistry and structural features of wear particles emancipated from commercially applicable low-metallic brake pads used in the EU and US markets carried out to brake dynamometer tests. The particles emanated during the experiments were collected and analyzed using proper techniques. The results indicated the release of particles ranging between 10-20 µm into the air, the number of nanoparticles (<100 µm) was three times higher than microparticles, the nanoparticles released, increased when the disc temperature reached 300 °C, and nanoparticles were mostly in the form of ultrafine in all fractions. It has been verbalized that the temperature of the friction surface is a determining factor in the size distribution of wear particles released into the air, it is not easy to discriminate Sn, Cu and other metals/oxides in diffraction measurement, and PIXE analysis reveals the existence of Sn, Cu, Fe, S, and Zn in all fractions.

The study made by Eriksson et al. [31], has been widely cited as it acquaints on the nascence of tribological contact between pad and disc in automotive brakes. In the article, the events that occur between the brake disc and pad and their consequences are analyzed by considering the parts, components, chemical and physical conditions. In automobile brakes, it is stated that the pad to disc overlap is 10-15%, the pad is pressed against the brake disc with a pressure of around 1.2 MPa when the force applied to the pedal is about 5 kN, in extreme cases the pressure can be close to 10 MPa and the power loss in the brake pad during hard braking exceeds 30kW. It has been stated that in vehicle brakes, dry sliding contact occurs at approximately 50% of the vehicle speed, and the load on the contact plateaus increases with the instantaneous elastic compression of the pad at sudden pressure increase. The continuous wear of the disc is notably influenced by the presence of harder components in the brake pads. This wear will initially polish the surface of the disc, allowing it to better conform to the pad, increasing around 15-20% of the pad area is covered by the number of contact plateaus. The pressure applied from the pedal to the pad does not act on the entire pad surface, but only on the areas of the contact plateau. Uneven wear due to the inhomogeneous structure of the pad and disc will initially result in a wavy surface, reducing the actual contact area and resulting in contact plateau problems. The location, size and irregularity of the actual contact points were explained as a result of deformation and wear of the pad as well as the disc surface not being smooth. Since the actual contact area will be small (50-500 µm wide) during the pressure increment, the coefficient of friction will also be low. It has been stated that since the temperature of the pad increases during braking, the temperature difference of the surface facing the disc and the rear part will be high, causing the pad to bend convexly, thus causing an unequal pressure distribution, resulting in a reduction in the pressure on the front and rear edges and uneven wear. It has been stated that local pressure changes during the compression of the pad may cause local pressure changes by causing the pad or disc to bend as a result of vibrations such as brake squeal in the brake system. As the disc and pad undergo heating during braking, several factors, including the chemical reactivity of their surfaces, changes in mechanical properties (such as thermal softening), alterations in the pad structure (such as the decomposition of polymer components), and the propensity for wear debris to contaminate and adhere to both surfaces, collectively impact the composition and tribological properties of the wear surfaces. The contact dynamics between the cast iron brake disc and the organic brake pad are unique to their material combination, setting them apart from most other tribological contacts. This distinctive behavior arises from the interplay of mechanical properties within the brake disc and pad components. The pad area is intricately structured with numerous contact plateaus, each surrounded by low zones. These lowlands remain permanently out of sliding contact, while the actual contact area is concentrated in small points confined to the plateaus. Although plateaus exhibit a relatively long lifespan, the actual contact areas are in constant flux due to wear, deformation, and surface roughness of the disc surface. It is stated that the friction coefficient can vary between 0.3-0.6 due to the different mechanisms between the pad and the brake disc, as the friction coefficient changes due to contact surface changes.

In their study on the tribological surfaces of organic brake pads, Eriksson and Jacobson [29] underscored that the scarcity of publications on the surface properties of brake pads is attributed to the multitude of components, variations in surface roughness, and diverse mechanical characteristics of these components. They also highlighted the necessity for employing different measurement techniques to address these challenges. Their situation analysis study was a highly cited study due to its detailed information and comments about the wear surfaces of organic pads. They stated that the power loss in each front brake pad resulting from the high heat generated during hard braking in an ordinary family car could exceed 80 kW. Pearlitic gray cast iron, which generally contains 3-4% carbon by weight, is preferred as the disc material because it has the desired at appropriate values properties of thermal, mechanical, wear, damping, and low cost, ease of casting and machining. Compared to other types of materials, the tribological behavior of organic pad materials often exhibit special properties or peculiarities, such as an extremely low tendency to seize even at high loads, temperatures and sliding speeds, a friction that is relatively independent of environmental conditions, a large increase in stopping friction, and friction hysteresis. On the brake pad surface, there are both primary and secondary plateaus within the contact areas. The formation of primary plateaus is initially attributed to the lower removal rate of mechanically stable and wear-resistant components within the pad. While in the second stage, these protruding hard phases can constitute agglomeration sites for the expansion of secondary plateaus, and secondary plateaus cannot exist without the support of the primary plateaus. Since secondary plateaus can grow after primary plateaus are formed, the interpretation is that the size and mechanical properties of secondary plateaus depend on the specific contact conditions, including growth at high pressures and temperatures and degradation at low temperatures. Because of the tribological contact in brake pads is multifaceted and complex being that the structure of the pad material, it has been stated that a better understanding of tribological surfaces and their effect on the friction state will facilitate the development of better braking performance and can provide a basis for practical numerical friction modelling.

In order to reveal the mechanisms that degrade the friction layer, wear particles and wear mechanisms, Verma et al. [32] used a pin-disc rig to investigate the tribological features and wear mechanism of brake pad that is made of Non-Asbestos Organic (NAO) against a cast iron disc at different loading circumstances and a constant sliding speed. The essential wear mechanism on the disc surface is tribo-oxidation, with the main supplement of iron oxide hematite and adhesion formed. In the study, it was emphasized that environmental concerns have become a significant issue due to the fine particles formed by the wear processes between the disc and pad, and it was stated that approximately 35% of disc-pad emissions are emitted as PM mixed into the air and 86% of these particles are estimated to be fewer than 2.5 μm. A combination of wear and abrasion through brittle fragmentation is effective on the pin surface. Fragments influence to either abandon the tribological system or become captured between the coupling surfaces by debris from the disc and appressed to form secondary plateaus. The entire wear process and the resulting formation of wear particles vacating the tribological system is governed primarily by the breakdown of secondary plateaus. It has been emphasized that of plateaus have been described: well-compacted plateaus, which tend to form rather large areas rich in copper, and less compacted plateaus, which tend to form quite small fragments consisting of less copper. It has been commented that metallic copper is crucial in providing a superior quality of secondary plateaus regarding wear behavior.

Iijima et al. [36] investigated the concentrations of wear particles and metallic elements formed at 200, 300 and 400 °C disc temperatures at a deceleration acceleration of 3 ms-2 in a brake dynamometer of three different commercially sold brake pads and discussed the estimation of antimony (Sb) emission from brake wear dust. The number agglomeration and aerodynamic diameter (Dp) of wear powders were computed using an aerodynamic particle sizer spectrometer, wear powders were collected using an Andersen low-volume sampler, and the concentrations of Ba, Cu, Fe, K, Sb, Ti and Zn metallic elements in size-sorted dusts were gauged by ICP-AES and ICP-MS. It was stated that the number dispersion of brake wear dust peaks at 1 and 2 μm Dp values, while the particle size improves with increasing disc temperature. The results obtained from the experiments indicate that the features of brake wear dusts are consistent with the properties of fine particulate matter in Sb-enriched air, about 90% of the brake wear dusts are in a small size range (<2.5 μm), and the dissipations of Ba, Cu, Fe, Sb, Ti and Zn are very identical to the total mass dispersion of brake wear powders. According to these results, it was interpreted that the proportion of Sb in automotive brake wear dusts may be one of the leading sources of Sb-enriched airborne particulate matter.

Dong et al. [37] examined the short-term transient and spatial isotope changefulness of Cu, Zn and Pb, which have an impact on urban PM10 compiled from different traffic levels in central London, and traffic emissions from tires and brakes, road paint, manhole covers. It is targeted to discover the effectiveness of potential sources, including road surfaces such as asphalt and asphalt surface, and road dust. In order to promote study of source distribution PM10 samples and their possible sources were classified in terms of enrichment factors of Ba, Cr, Fe, Ni, Sb and V metals. The enrichment factors, concentrations of Cu and Zn in PM10 were noted to be greater at sampling location where the high traffic is get jammed, coupled with other elements from traffic-related sources, involving Ba, Fe, Cr and Sb. In accordance with the study results, in PM10, the major source of Cu is non-exhaust emissions, the main sources of Zn are dust on roads and non-exhaust sources from traffic, and anthropogenic sources such as recycled gasoline and road dust remain important in terms of lead.

Verma et al. [38] investigated the development of the friction layer of a brake pad and the effect of elevated temperature on the friction layer and wear in a pin-on-disc test setup. While the wear test was carried out at 25-350 °C disc temperatures, the wear traces remaining on the pin and disc surfaces were analysed, the stable friction layer formed on the pin surface was interpreted as evidence of a mild wear regime, and it noted a shift from mild to severe wear, with the transition occurring at a temperature of 170 °C. Based on the study results, it was evaluated by thermogravimetric analysis that the wear traces on the discs were caused by the disc tribo-oxidation and wear fragments resulting from the wear of the pin material, and that the observed tribological behavior was greatly impacted by the thermal degradation of the phenolic binder. As the wear behavior at high temperatures, resulting from braking circumstances, is largely influenced by the content of the friction materials, it is crucial to select components that ensure acceptable braking conditions, elevated temperature stability, and consequently, lower wear rates. It has been stated that another important issue affecting the tribological behavior of contact systems is the jamming of wear residues enclosed by the sliding surfaces, eliciting to the friction layer formation, which is effective in determining the frictional behavior of the mating surfaces. The nature of the friction films at various temperatures and the stability of them are crucial for understanding the formation of wear particles, and the deterioration of the lining structure at high temperatures is a major problem germane to the thermal breakdown of phenolic resins, and this incidence is commensurate with the literature. The main transformations related to resin decomposition are reported to be in the temperature range 250-475 °C. In accordance with the literature, the thermogravimetric analysis (TGA) results revealed that the thermal breakdown of the phenolic binder in the pad material initiated with a minor mass reduction (0.04%) at 90 °C. The main decomposition (3.77%) commenced around 280 °C, and the maximum decomposition rate occurred at 415 °C. Being in rapport with the Raman spectroscopy results, the existence of carbonaceous outputs on the worn pin surfaces at elevated temperatures is in the sequel thermal breakdown of the phenolic binder, but the heating and shear stresses caused by the friction closely linked with tribological tests affect the decomposition kinetics.

Krenkel et al. [27], in which the development process of gray cast iron to ceramic composite brake discs was mentioned, different modifications of C/C-SiC composites and the properties of newly developed brake discs were mentioned. In the realm of both vehicles and mechanical engineering, gray cast iron has become the predominant choice for brake discs due to its cost-effectiveness and stable tribological properties. However, it is important to note that gray cast iron has a high density, limited corrosion stability, and its tensile strength is significantly temperature-dependent. As brake discs made of gray cast iron typically fail due to thermally induced cracks rather than inadequate strength, there has been a development of cast iron alloys with lower strength but enhanced thermal conductivity. While lighter brake discs with high thermal conductivity can be produced with metal matrix composites (MMC) based on aluminum and ceramic particles with densities of 2.8 to 3.0 g/cm^3, the application range is limited to approximately 400 °C. Much lighter and more thermally stable carbon/carbon (C/C) composites have been developed for weight-sensitive vehicles such as aircraft and racing cars. However, the fact that the coefficient of friction is quickly affected by humidity and temperature changes and their low abrasion resistance have foreclosed their use as brake disc material in trains and passenger cars or emergency brakes of lift and cranes. Due to their lower coefficient of thermal expansion, high thermal conductivity, and medium modulus, C/C-SiC materials exhibit magnificent thermal shock stability. Moreover, their strength at elevated temperatures surpasses that at room temperature. Since ceramic brake discs consist of at least two parts, namely a CMC (Ceramic Matrix Composites) friction ring and a metallic crucible, the weight saving compared to single-piece cast iron brake discs is approximately 50% and therefore the C/C-SiC density (2 g/cm^3) is slightly lower than assumed when make comparison the density of gray cast iron (7.2 g/cm^3). Following the development process in recent years, C/C-SiC brake discs are now ready for use in high-performance automobiles and are said to have advantages over existing brakes, including deformation stability, extremely low wear rates, high coefficients of friction, improved corrosion resistance, non-fading properties, and reduced unsprung mass.

In the study by Bijwe [26] which reviewed the latest developments in non-asbestos fiber-reinforced pad materials, the discussion encompassed the components of composite friction materials, desired properties, functions, and recent advancements. In friction materials, definitions such as effectiveness, fade, load and speed sensitivity, performance criteria, wear mechanisms, friction material classification were mentioned. The normal no-fading high operating temperatures of various friction materials are 300-350°C for organic materials, 400°C for semi-metallics and 700°C for carbon composites. It has been stated that the normal operating temperature of the front brake disc in passenger vehicles is 150-250°C and for the pads it is above 370°C. In conclusion, it was emphasized that future efforts should not only focus on composite formulation and evaluation, but also on understanding tribo mechanisms, developing wear models, critically analyzing the simultaneous effect on friction and wear, and focusing more on a scientific approach rather than trial and error for multi-component formulations.

In their study, Kim and Jang [39] investigated the wear and friction characteristics of friction materials consist of modified novolac or straight novolac resin, reinforced with aramid pulp in a pin-on disc device. Six brake pad specimens were produced using varying proportions of phenolic resin, aramid pulp, potassium titanate, barite, and graphite. The production involved a series of steps including mixing, pre-forming, hot press molding, and heat treatment processes. Thermal analysis (TGA/DTA) was employed to investigate the samples thermal decomposition, while differential scanning calorimetry (DSC) determined the glass transition temperature, and Rockwell-S measurements were used to adjudicate the hardness values. Disc surface temperature, rotating speed, pressure, and friction force were measured in the experiments. The experiments were conducted using two distinct test modes: a constant initial temperature (mode I) and a constant interval test (mode II). Test mode I: conducted at initial temperature of 50°C, 800 rpm for 300 seconds under 0.98 MPa braking pressure. Test mode II: It involved in a 50-second drag with 30-second intervals under 0.98 MPa braking pressure and was repeated 10 times in serriedly. The study noted that wear is influenced by various factors, including temperature, load, speed, properties of the mating materials, and the durability of the transfer layer. It was stated that the wear resistance of the samples was evaluated by the wear rate (normalized the amount of wear with the energy) given during the friction test to compare the samples wear resistance. According to the experimental results, it was stated that the friction stability and wear resistance varied significantly according to the type of phenolic resins and the relative amount of resin and aramid paste. The friction materials with modified novolac resin showed better friction stability and the differential thermogravimetry (DTG) curve obtained from the modified resin showed higher decomposition temperatures than the plain resin. Generally, the fluctuation in the coefficient of friction is attributed to changes in the actual contact area between the mating materials, the strength of the binder resin, and the frictional properties of the components at elevated temperatures. Meanwhile, the wear rate is contingent on the friction level, porosity, heat resistance of the binder resin, mechanical strength, and the temperature profile during the drag test.

Österle et al. [30] performed scanning electron microscope (SEM) equipped with an energy-dispersive X-ray spectrometer (EDS), photoelectron spectroscopy (XPS) and Cross-sectional transmission electron microscopy (XTEM) combined with selected area diffraction (SAD) analysis to investigate the formation, chemical and microstructural changes of the pad surface, cross-sections and wear particles due to friction and wear in brakes. These analyzes were carried out at constant nominal contact pressure, friction speed and time on a brake pad sample. SEM image of the pad surface after the test; TEM, SAD and EDS spectrum of wear particles; XTEM micrograph, SAD pattern and EDS spectrum analyzes were applied to show the crack friction layer. A model explaining the formation of a plate made of the third-body material, is mentioned. In automotive industry applications, polymer matrix composites (PMC), cast iron and steel discs are used as brake pads, barite, vermiculite, antimony sulfide and quartz phases can be noticeable by different colors using polarized light, the microstructure of the third body material. It has been stated that TEM along with EDS and SAD is required to define the crystallography and brake fading is the gradual decline of the friction coefficient at high speeds and contact pressures. The major wear mechanism is the separation of filler particles from the organic binder, assisted by local degradation of the phenolic resin during heating, the increase in the coefficient of friction at the beginning of the experiment, the formation and growth of the areas, as well as chemical and microstructural changes have an important role. It is concluded that wear particles including nanocrystalline alloy barite must stem from the so-called third body material and that delamination wear of the pad is the dominant mechanism leading to alloy barite patches on the surface even during very low speed reciprocal sliding where temperature does not play any role. The essential wear mechanism is the separation of filler subgrain from the organic binder, which is undergirded by the local deterioration of the phenolic resin throughout the calefaction. The increase in the friction coefficient at the first moments of the experiment indicates that chemical and microstructural changes play a critical role as well as the formation and growth of contact areas. It is concluded that delamination wear of the pad is the dominant mechanism leading to alloy barite patches on the surface even during very low speed reciprocal sliding where temperature does not play any role.

Eriksson et al. [28], in a study to elucidate the mechanisms that cause brake squeal in order to develop silent brake pads, produced two metal fiber reinforced organic type pads and investigated the number, dimensions and total contact area of the contact plateaus and the squeal arises from the interaction between surface topography and brake pad pressure. The main frequency of the sound generated during the experiments was recorded as squeal if it was between 500-20000 Hz and above 88 dB, and the 'squeal index' a function of brake pressure and temperature, was used to indicate the number of generated squeals. The sound in a squealing brake was caused by plateaus formed by the sliding contact of the brake pad against the disc. These plateaus are composed of the harder pad components and are constantly changing due to pad wear and deformation during braking. The size and number of contact plateaus depend on the brake pressure applied and to the contact temperature, these two factors have the strongest influence on brake squeal. It has been observed that with increasing pressure, the total plateau area increases while the contact plateaus number decreases, the contact plateaus are formed at low pressures consist of metal fibers or abrasive particles, and the size of the plateaus increases due to soft graphite and organic materials at 15 and 20 bar. The results showed that pads with a large number of small contact plates (maximum 0.01 mm^2) tend to produce more squeal, and low pressures have little effect on them. The size of contact plateaus is minimally influenced by disc temperature and brake squeal generation since the hard phases of the pads are mechanically stable up to 200 °C.

In their study on the impact of Antimony trisulfide (Sb_2S_3), utilized as a lubricant component in brake pads, on human health, von Uexküll et al. [40] conducted X-ray diffraction analysis. At the beginning of the study, the areas of use, toxicology and potential effects of antimony were mentioned. Then, the objective of the study was to ascertain the chemical presence and solubility in physiological fluid to determine whether antimony is used in brake pads, whether antimony dust in brake pads is respirable and whether Sb is in toxic form. It has been stated that the health risk of Sb depends on the particle size, chemical presence and solubility in brake emissions, and that brake pads can be described as consumer products because they are left to biological cycles, and therefore materials with defined positive health and environmental properties should be used. As a result of the study, the presence of antimony (Sb) in both brake pads and the associated dust, that it was in higher concentrations in disc brake pads than in drum brake pads, and that inhalation of a certain amount of brake dust is contingent on environmental conditions and occupational exposure situations. In addition, it has been stated that Sb in brake dust exhibits a better solubility in tartaric acid than Sb_2S_3, and although this cannot be determined with certainty, there is an oxidation to Sb_2S_3 during the braking, and the less toxic Zn, Mg and Mn can be used instead of Sb.

Uyyuru et al. [41] investigated the tribological behavior of stir-cast Al-Si/SiCp brake discs using the pin-on-disc device. Scanning electron microscopy (SEM) was used to perused the topography and morphology of worn surfaces and debris, while the chemical contents of wear products were attained using electron probe microanalyzer (EPMA) and X-ray diffraction (XRD) techniques. In the study, firstly, information was given about brake discs, Metal matrix composites (MMCs) and the materials used in the experiments. It has been stated that wear consists of three stages: first overcoming the roughness of the disc surface, then accretion of the tribo-layer, and finally the material transfer processes. As a result, it was observed that the wear rate increased and the friction coefficient decreased as the applied normal load increased, both the wear rate and the friction coefficients changed in proportion to the sliding speed, and the tribo-layer on the disc surface had a heterogeneous structure with the formation of a tribo-layer during the wear tests.

Österle and Urban [42] used the focused ion beam (FIB) technique, LM (light optical microscopy), SEM/EDX, TEM/EDX/Electron diffraction analyses to characterize the superficial layers (friction layers and films) in the micro contact areas of a 50% metal-containing (semi-metallic) polymer matrix composite (PMC) brake pad. In the study, in which one, two or three layers are defined depending on the component of the pad, the friction layer formation process is explained with the support of the literature. The study concluded that the large shear stresses that occur during the speed matching of the pad and the disc exhibits high secondary electron emission during FIB scanning, resulting in the observed bright contrast of the contact areas. Simultaneously, the metallic components undergo oxidation wear, leading to the formation of nanocrystalline debris. It has been indicated that some of the wear residues remain in the contact area, filling the pits and forming a discontinuous friction layer, the friction films contain sulfur, but no crystalline sulfur is detected, and zinc is transferred to the disc.

Xin et al. [43] conducted experiments to assess the friction properties of brake composites reinforced with sisal fiber and resin. Tests were conducted on a disc at six different temperatures, maintaining a speed of 2.0 m/s for a duration of 10 minutes. Friction and wear properties of sisal fiber reinforced brake composites with different contents were examined in terms of tribology and wear characteristics at different friction temperatures. At the end of the study, it was stated that the resin and sisal fiber ratio of 3:4 had a high friction factor, low wear rate and strain energy accumulated in sisal fibers, and the wear behavior was basically shear wear in sisal fibers and fatigue cracking in resin occurs at low friction temperatures. Sisal fiber has also been stated to have a "cleaning" function with carbon-type materials during the corrosion process, and sisal possesses the potential to serve as an ideal replacement fiber for asbestos.

Sandahl et al. [44] investigated the effect of brake pad emission and copper dissolved in water on juvenile coho salmon. In the study, after mentioning the increase in human population and urbanization, the damage caused by automobiles to the environment and the effects of copper on aquatic environments were mentioned. Within the comprehension of the experimental study, the supply of coho salmon eggs, growing conditions, preparation of the chemical alarm stimulus and copper-containing exposure solutions were explained in detail. It was stated that copper exhibits neurobehavioral toxicity in fish, traditional neurophysiological recordings were used to investigate the effect of copper exposures on the conventional system of juvenile coho salmon, and the sensitivity and response of fish to the predation cue were assessed through computer-assisted video analysis of their behavior. Electrophysiological and behavioral estimations were examined utilizing ANOVA to test for statistical discrepancies among groups, testing for concentration-dependent associations Fisher's exact test (for freezing responses), or regression analysis were employed. The researchers determined that brief exposure to dissolved copper resulted in diminished sensitivity among juvenile coho salmon. This compromised sensory function, in turn, slowed down their predator avoidance behavior. Additionally, runoff containing copper in rainwater showed the potential to induce chemosensory deprivation in exposed salmon, leading to increased mortality from easier predation.

7. Conclusions

This study conducted a literature review using the systematic analysis method to assist scientists undertaking research on brake pads, to ensure their rapid progress and to show that they can make more effective scans scientifically focused on the subject instead of classical literature review. The restrictions applied to the search criteria are explained in the introduction of the article and will not be repeated here.

Since journals are indexed by keywords, these should be chosen carefully rather than randomly, prioritizing words or phrases that enhance the study's visibility. For this purpose, assistance can be sought from experienced scientists who are knowledgeable about the subject. Writing a keyword allows it to be evaluated in analysis programs. Since some of the articles did not have keywords within the scope of the study, they were not taken into consideration. While analyzing article data, the inability of the programs to distinguish the singular and plural forms of keywords (such as Brake-Brakes, Composite-Composites, etc.) created a handicap. In addition, due to the spelling difference between the authors' native language and English (such as Osterle-Österle, Uexkull-Uexküll, etc.), spelling the authors' names differently in some articles may cause minor errors in the analysis. In our study, these errors were noticed and necessary corrections were made in the analysis document. When the most cited publications on brake pads are examined, it is seen that the studies explaining the formation and development of wear and friction mechanisms in counter parts materials are highly cited. In recent years, due to the increasing interest in emissions, there has been an increase in studies on the environmental impact of pad and tire wear. It is predicted that the importance of non-exhaust emission studies will increase as vehicles with ICE start to be replaced by EVs. Especially for electric vehicles, since they have more vehicle mass than a normal ICE car, their inertia is very high. More torque is required to eliminate this inertia. A high torque value can also lead to increased wear on tires and brake pads, causing them to reach the end of their life prematurely. Although the regenerative braking system for brake pads seems to be a life-extending system, there are people on forum sites where electric vehicle drivers share their experiences, stating that the regenerative braking system causes the vehicle to slow down (in a way that the driver is not used to) and that they therefore deactivate the system.

The Euro 7 emissions regulation, which will be implemented for new light-duty vehicles on July 1, 2025, and will be the strictest standard ever, also addresses particulate emissions (PM2.5 and PM10) from brakes and tires. One quarter of the most detrimental PM2.5 emissions in urban areas are attributed to road traffic, but there are no standards in place to measure or regulate non-exhaust PM emissions. The limit for brake particulate emissions in the Euro 7 standard is targeted to be reduced to 7 mg/km by 2035 and to 3 mg/km from 2035 onwards. It is envisaged by the authors that the main means of strategies for compliance with the Euro 7 regulation will be mitigation, electrification instead of mechanical, development of new materials for pads and tires. Although the study conducted by the Organization for Economic Co-operation and Development (OECD) concluded that electric vehicles will emit 3% to 8% more PM 2.5 from brakes and tires due to their weight, emission correction factors are specified in the Euro 7 regulation to encourage the transition to electric vehicles. Emission correction factors ratios for conventional ICE vehicles 1:1, battery EV 0.15, plug-in hybrids (PHEVs) of 0.3, conventional hybrids (HEVs) 0.4 and mild hybrids at 0.6. The report reveals that the quantity of non-exhaust particulate matter released from automobiles worldwide is expected to increase by 53.5% by 2030 [45-46].

Conflict of Interest Statement

The authors declare that there is no conflict of interest in the study.

CRediT Author Statement

Mahmut Ünaldı: Conceptualization, Visualization, Investigation, Methodology, Data curation, Software, Writing - Review & Editing.
Ayhan Uyaroğlu: Conceptualization, Investigation, Visualization, Writing - Original draft preparation.

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