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APPLICATIONS OF PIEZOELECTRIC MATERIALS IN MODERN CAR INDUSTRY AND FUTURE TRENDS

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ABSTRACT

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Keywords: Piezoelectricity, ceramic piezoelectric materials, lead-zirconate-titanate (PZT), lead-free piezoelectric ceramics, piezoelectric powders, ceramic powders preparation, solid-state method, sol-gel method, co-precipitation method, multilayer piezoceramic, fuel injectors, knock sensors, self-powered sensors, piezoelectric energy harvesting, modern energy

This research paper presents a comprehensive examination of piezoelectric materials and their application in modern automobiles. The paper contributes novel insights into the modern car industry by elucidating the fundamental principles and classifications of piezoelectric materials, investigating the methodologies for preparing piezoelectric powders and performing sintering operations, scrutinizing the adverse consequences of lead usage, surveying recent progress in the development of lead-free piezoelectric materials, evaluating the distinct applications of piezoelectric materials in modern automobiles, and appraising the prospect of piezoelectric materials in addressing the 7th sustainable development goal. A triangulation research approach comprising literature review, expert interviews, and pre-set criteria analysis is used to achieve the research goals, with a pre-set criteria analysis employed for each individual research goal to construct a comprehensive appraisal of piezoelectric materials discussed in each specific context. The study's findings can be applied by car manufacturers in several ways, including evaluating the applications of piezoelectric materials, making better decisions on material selections, reducing environmental impact, and moving toward sustainable development. Additionally, the research has generalizable results, as the structure of the findings could be applicable to future research on other smart materials, facilitating a more systematic approach to their application in various fields.

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1 INTRODUCTION

This introduction section covers the importance of piezoelectric materials in the automotive industry, the research goals, research problem and questions, methods to be used, scope, as well as expected contribution.

1.1 Background and motivation

Piezoelectric materials play an important role in electronic devices such as actuators, sensors, accelerators, ultrasonic motors, transducers, filters and resonators, and micro electromechanical systems (Uchino, 2017, p. 156; Zhao et al., 2019, p. 4). The automotive industry has been a significant beneficiary of the piezoelectric materials, which are applied in various components of modern cars. In particular, piezoelectric materials have found widespread use in knock sensors and fuel injectors. Many of these electronic devices are essential to the proper functioning of modern cars. Although numerous studies have been carried out, potential challenges from both manufacturability and sustainability aspects are still prominent. Therefore, in order to understand how piezoelectric devices are used in modern cars and how to possibly solve the challenges that the industry is facing, it is necessary to understand the theoretical background of the functionality of piezoelectric materials and to investigate the manufacturability aspects of the raw materials and manufacturability of some typical products i.e. knock sensors and fuel injectors. Along with the study of some commercial materials that are practically applied in modern cars, future trends and sustainability aspects related to piezoelectric materials are to be discovered.

1.2 Goal of the research

The goals of this paper consist of the following:

- To describe the theoretical background and the functionality of piezoelectric materials
- To investigate the manufacturability aspects of piezoelectric materials and the manufacturability of the products i.e. knock sensors and fuel injectors
- To study the sustainability and environmental aspects related to piezoelectric materials
- To review some commercial materials practically applied in modern cars
- To explore future trends from the point of view of piezoelectric materials

1.3 Research problem and research questions

There might be a lack of knowledge in the community of car industries that the manufacture of piezoelectric materials presents numerous challenges. These include the difficulty of understanding and describing the materials' composition and manufacturing processes that occur in different settings, as well as the environmental impacts presented by the use of detrimental chemical elements and the need for sustainable methods of recycling. This research seeks to address this complex problem by exploring the practical and research-related issues relating to the functionality and application of piezoelectric materials in modern cars.

"Why piezoelectric materials are so important to modern cars" is the main research question of this paper, with an additional sub-research question "how piezoelectric materials affect the functionality of knock sensors and fuel injectors"

1.4 Research methods

This paper will investigate the use of piezoelectric materials in modern cars through a triangulation research approach combining literature review, expert interviews and pre-set criteria analysis. Literature review will be utilized to achieve each of the five research goals. Expert interviews will be conducted to obtain both general direction and specific information for the research. Pre-set criteria analysis will be implemented to construct an extensive assessment of piezoelectric materials discussed in particular scenarios.

1.5 Scope

This paper aims to examine the use of piezoelectric materials in modern cars, with a particular focus on fuel injectors and knock sensors. In terms of manufacturability, this paper will be limited to reviewing the ceramic powders preparation and sintering processes. In addition, the relationship between the application of piezoelectric material and the 7th sustainable development goals (i.e. affordable and clean energy) will also be evaluated.

1.6 Expected contribution

This paper is expected to offer the modern car industry new and substantial knowledge, including explaining the fundamental principles and categories of piezoelectric materials, exploring the techniques for preparing piezoelectric powders and sintering processes, identifying the negative effects of lead, highlighting recent advancements in lead-free materials, reviewing specific utilizations of piezoelectric materials in modern cars, and assessing the potential of using piezoelectric materials to address the 7th sustainable development goal.

2 LITERATURE REVIEW

This thesis contains a comprehensive literature review structured according to the five research goals. Specifically, the review will be organized into the following subsections: 2.1 theoretical background and functionality of piezoelectric materials, 2.2 manufacturability investigations, 2.3 sustainability and environmental aspects related to piezoelectric materials, 2.4 commercial products practically applied in modern cars, and 2.5 future trends. Each subcategory will be carefully developed to address the relevant research questions and to provide a thorough understanding of the topic at hand.

2.1 Theoretical background and the functionality of piezoelectric materials

The following section will discuss the principles of piezoelectric effect and provide an overview of the categories of piezoelectric materials.

2.1.1 Principles of piezoelectric effect

Piezoelectricity is a phenomenon exhibited by certain materials, whereby mechanical deformation or pressure can be converted into electrical energy, and conversely, electrical energy can be transformed into mechanical deformation (Wang, 2017, p. 77). This unique property is due to the crystal structure of these materials, which features asymmetrical arrangements of atoms, leading to the generation of an electric field in response to mechanical deformation, and vice versa (Behera, 2022, p. 44). As such, piezoelectric materials are capable of producing an electric charge when subjected to mechanical stress, while the application of an electric field can result in mechanical deformation of the material (Carvalho et al., 2021, p. 473; Li et al., 2018a, p. 1).

Both effects exhibited by piezoelectric materials are based on electric polarization. In a piezoelectric material, the crystal structure contains electric dipoles that are disorderly oriented in the absence of an external stimulus. However, when subjected to a mechanical force, the dipoles align themselves in a particular direction, resulting in an electric charge (Mishra et al., 2019, p. 3; Li et al., 2018b, p. 1).

2.1.2 Categories of piezoelectric materials

Piezoelectric materials can be classified into three main categories, namely ceramic piezoelectric materials, polymer piezoelectric materials, and composite piezoelectric materials.

2.1.2.1 Ceramic Piezoelectric Materials

Ceramic piezoelectric materials are generally polycrystalline materials with perovskite crystal structure and the materials exhibit significant anisotropy, with their physical properties varying based on the direction of the applied electric field (Mishra et al., 2019, p. 9; Carvalho et al., 2021, p. 474). The materials are distinguished by their exceptional piezoelectric characteristics, with lead-zirconate-titanate (PZT) regarded as one of the most important piezoceramic that has been widely used in various applications (Zhao et al., 2019, p. 4). Other examples of ceramics include potassium niobate ($KNbO3$) and barium titanate ($BaTiO3$) (Jacob et al., 2018, p. 7).

Most of the piezoelectric ceramics in the market are based on lead zirconate titanate (PZT) because of its high performance characteristics and low cost. The crystalline structure of PZT, characterized by the compositional formula ABO3, is particularly suitable for achieving high piezoelectricity. With a certain level of forming flexibility in addition to the exceptional performance of PZT, it is one of the most favorable material for use in multilayer technology (Uchino, 2017, p. 95).

2.1.2.2 Polymer Piezoelectric Materials

Polymeric piezoelectric materials offer numerous advantages over ceramics. Polymer piezoelectric materials are flexible materials that can undergo significant mechanical deformation while maintaining their piezoelectric effect. Polymer piezoelectric materials are also lightweight and cost-effective, suitable for relatively low-cost and low temperature manufacturing processes. Due to their flexibility, polymeric piezoelectric materials can be shaped easily to meet specific requirements, making them attractive for various application (Sezer and Koç, 2021, p. 7).

There is a long history of studying piezoelectric polymers, dating back to the early 20th century. However, it was not until Kawai's work in 1969, in which a film of polyvinylidene fluoride (PVDF) was drawn and poled, that the strong piezoelectric effect in polar polymers was first revealed. Since then, PVDF and its copolymers have been extensively researched and developed for use in various applications. Currently, they are considered the most important piezoelectric polymers, and research efforts are ongoing to improve their performance while addressing sustainability concerns (Uchino, 2017, p. 14).

2.1.2.3 Composite Piezoelectric Materials

Composite piezoelectric materials are a class of smart materials that combine ceramics or polymers with other materials to exploit their respective properties (Wei et al., 2018, p. 17). Piezoelectric composites typically consist of a piezoelectric ceramic filler incorporated in a piezoelectric polymer matrix, and the properties of the composite can be tailored to specific applications by adjusting the proportion of materials (Carvalho et al., 2021, p. 478). These materials provide several advantages, including low acoustic impedance, high coupling factors, mechanical flexibility, favorable matching with human tissue, and a wide bandwidth, coupled with a low mechanical quality factor. As a result, piezoelectric composites are well-suited for applications such as medical diagnostic ultrasonic transducers and underwater sonar (Behera, 2022, p. 52).

2.2 Manufacturability investigations

This section discusses the various techniques employed for the preparation of piezoelectric powders and an overview of the sintering process, covering three prevalent methods for the preparation of piezoelectric powders, including the solid-state method, sol-gel method, and co-precipitation method. Additionally, the significance of sintering in ceramic powder preparation is highlighted. This section also explains the applications of piezoelectric materials in modern cars, particularly piezoelectric knock sensors and fuel injectors. The process involved in the preparation of PZT, a ceramic piezoelectric material widely used both applications, is presented in detail, which includes raw material preparation, mixing, calcination, and sintering. Finally, the manufacturability of multilayer piezoceramic, used as an actuator in piezoelectric fuel injectors, is examined with economic considerations.

2.2.1 Ceramic powders preparation

There are typically two quintessential steps involved in the fabrication of piezoelectric materials: ceramic powders preparing and molded structures sintering (Uchino, 2017, p. 385). This part endeavors to present a discourse on prevalent techniques employed for the preparation of piezoelectric powders and provide an overview of the sintering process.

2.2.1.1 Solid-state method

The conventional solid-state reaction method is a popular technique for producing ceramics, such as PZT, for large-scale practical applications (Wu, 2018, p. 42). This method involves mixing constituent materials in powder form, which may include several types of metal oxides (Jeshurun et al., 2021, p. 2). To ensure the quality of the mixture, the composition proportion should be accurately calculated and each constituent should be carefully weighed. The mixture is then subjected to calcination at relatively high temperatures, allowing for the development of the piezoelectric property as the corresponding crystal structure is formed in the pre-sintering stage under these conditions (Wu, 2018, p. 42).

2.2.1.2 Sol-gel method

The method involves the generation of a gel through the dissolution of a molecular precursor, typically a metal alkoxide, in a solution of either water or alcohol, followed by a hydrolysis or alcoholysis reaction, during which the precursor is transformed into a gel through the application of heat and stirring. Upon completion of the hydrolysis or alcoholysis reaction, the resultant gel typically contains a significant amount of moisture and must undergo drying processes appropriate to the desired application and properties. When dealing with alcoholic solutions, a common drying method involves burning off the residual alcohol. Following the drying stage, the gels are subjected to powdering and calcination (Bokov et al., 2021, p. 1).

2.2.1.3 Co-precipitation method

In this method, the constituents of the piezoelectric ceramic are initially dissolved in a solvent, following which a precipitating agent is introduced to the solution to create a gel. Subsequently, the gel is calcined to obtain the desired ceramic powder. This method has been implemented to produce lead-free piezoelectric ceramics such as Cs3Bi2xSb2–2xI9 (Goel et al., 2017, p. 7; Chen et al., 2020, p. 1).

2.2.2 Sintering

Sintering is a crucial process in the preparation of ceramic powders, as it is the process by which ceramic powders are converted into dense and hard materials with desirable properties. Typically, powders shaped in pellets are subjected to high temperatures that are lower than the melting point of the material. During this process, pores are primarily eliminated, resulting in a significant improvement in density. Several factors, such as sintering temperature, sintering aids and sintering atmosphere, can affect the physical properties of ceramics during the sintering process (Cen et al., 2021, p. 1-3). Moreover, the influence of sintering atmosphere on the internal structure of piezoelectric materials is a critical factor in enhancing their piezoelectric properties. Furthermore, the optimization of sintering temperature is remarkbly important. Various sintering aids, such as oxides and compounds, have been used in recent years, and their effects on the electrical properties of ceramics have been reported (Ul et al., 2019, p. 8). Different sintering techniques, such as hot-pressing sintering, microwave heating, and spark plasma sintering, have been used to improve the microstructure (Mégret et al., 2020, p. 1).

The following section will investigate the manufacturability of piezoelectric knock sensors and fuel injectors, which are two of the major applications of piezoelectric materials in modern cars.

2.2.3 Knock sensor and PTZ preparation

A knock sensor is a device used in internal combustion engines to detect and monitor engine knock, an unwanted phenomenon that occurs when the fuel-air mixture in the combustion chamber detonates rather than burns smoothly, resulting uncontrolled pressure waves that can damage the engine. Piezoelectric knock sensor converts the acoustic waves generated by the engine knocking into an electrical signal through piezoelectric effect. This signal is then sent to the control unit to adjust the engine's ignition timing and prevent engine damage (Laganá et al., 2018, p. 469-471).

PZT (lead zirconate titanate), a ceramic piezoelectric material, is utilized in various applications in modern cars, including knock sensors as a transducer and fuel injectors as an actuator. The preparation of PZT involves several steps, including raw material preparation, milling, calcination, and sintering. These steps determine the microstructure and properties of the PZT material, which ultimately govern its performance and reliability (Uchino, 2017, p. 394-395).

The first step in PZT preparation is the preparation of the raw materials. The raw materials typically used include lead oxide (PbO), zirconium oxide (ZrO2), and titanium oxide (TiO2). The purity of the raw materials is critical for the quality of the final product, so they are usually carefully selected and purified (Bochenek et al., 2020, p. 2).

The next step is mixing the raw materials. The mixing process is typically performed using a ball mill, which mixes the raw materials together and creates a mixture of powders. The mixing time, speed and ball-to-powder ratio are critical factors that affect the quality of the final product (Yue et al., 2017, p. 2).

Then the mixed powder is conventionally calcined in a furnace at a high temperature of around 800-900°C. However, recent studies have shown that this step can be effectively replaced with high-energy ball milling, if implemented in the previous step. High-energy ball milling generates sufficient impact energy to initiate chemical reactions, thereby facilitating the removal of volatile impurities and formation of a stable crystal structure at room temperature (Bochenek et al., 2020, p. 2).

High-energy ball milling also obviates the necessary step of milling after calcination in order to break down any agglomerates and create a fine powder. The materials present in a powder form, which is then shaped into the desired geometry using techniques such as pressing. The shaped PZT body is then sintered in a furnace at a high temperature to create a dense ceramic material. (Siddiqui et al., 2020, p. 1).

2.2.4 Fuel injector and multilayer piezoelectric actuator

A fuel injector is a device that delivers fuel into an internal combustion engine. The major function of fuel injectors is to set up a valve regulated by the engine's control unit to ensure precise timing and volume of fuel injection. When the control unit sends an electrical signal to the injector, it opens the valve and allows pressurized fuel to spray into the engine's combustion chamber. The amount of fuel delivered is precisely controlled to ensure optimal engine performance, fuel efficiency, and emissions. The design of the fuel injector is critical for achieving proper fuel atomization and spray pattern, which can significantly impact engine performance and emissions. Therefore, fuel injector design and optimization are essential for modern engines to meet increasingly stringent environmental and efficiency standards (Ma et al., 2021, p. 1-3).

Piezoelectric materials have been to proven be effective as an actuator of the valve. When an electrical current is applied to the crystal, it deforms and causes the valve to open, allowing fuel to flow into the engine. The deformation of the crystal is reversible, allowing the valve to close when the current is removed. Piezoelectric fuel injectors offer precise control over fuel flow, allowing for more efficient combustion and reduced emissions (Panda et al., 2023, p. 1&8).

To enhance the performance, multilayer ceramic actuators (MLCAs) are designed to generate larger displacements than single-layer actuators by using a multilayer structure as the driving element. Multilayer piezoceramic manufacturing processes involve the creation of thin layers of piezoceramic material, which are then stacked together to form a multilayer structure (Wu, 2018, p. 477).

One common process for manufacturing multilayer piezoceramic involves tape casting, where the ceramic material is mixed with a binder and then cast into thin sheets. Solvent is a critical component of tape casting slurries as pores and cracks may form if the evaporation rate is too high or the boiling point is too low. Common solvents used in tape casting slurries include methyl ethyl ketone (MEK), ethanol/isopropanol, and acetone. Binders are also an essential component of tape casting slurries as they hold the primary powder particles together after casting, maintain the strength of each layer, and increase its formability. Common binders used in tape casting slurries include Polyvinyl alcohol, Polyvinyl butyral, and Acrylic resin (Ren et al., 2018, p. 3). Once dried, the sheets are cut into precise dimensions before being stacked together with an adhesive layer between each sheet (Zhang et al., 2019, p. 6).

The effectiveness of a multilayer ceramic actuator (MLCA) is contingent upon three primary factors: the piezoelectric ceramics that drive the actuator, the layers of the MLCA, and the internal electrodes. The internal electrodes are vital constituents of MLCAs, and they have a considerable impact on their effectiveness. Platinum (Pt) is a preferred electrode material due to its suitability for co-firing with ceramics. However, its high cost renders it impractical for most piezoelectric actuators. Therefore, two primary electrode systems are commonly utilized in commercial MLCAs: silver (Ag) and palladium (Pd) alloy, and base metal internal electrodes such as nickel (Ni) or copper (Cu) (Wu, 2018, p. 478).

2.3 Sustainability and environmental aspects related to piezoelectric materials

Lead-based piezoelectric ceramics, e.g. PZT, are commonly used as the key component in a wide range of actuators, sensors, and transducers. However, the inherent toxicity of lead poses significant environmental and health hazards, which necessitates the exploration of lead-free alternatives (Zhao et al., 2019, p. 4). This section will review the adverse impacts of lead as well as the recent advancements and challenges in the development of lead-free piezoelectric materials.

2.3.1 Detrimental effect of lead

Lead is a hazardous heavy metal that could generate negative environmental impacts (Nain and Kumar, 2020, p. 2). The presence of lead in the environment can have far-reaching and long-lasting effects on both wildlife and human health. For example, lead could contaminate soil (Q. Yang et al., 2018, p. 1) through waste disposal of piezoelectric materials containing PZT. This can result in the uptake of lead by plants, leading to its accumulation in the food chain (Rai et al., 2019, p. 366). Lead can also contaminate various water sources, such as drinking water, groundwater, etc. This can lead to serious health problems for humans and animals that consume the contaminated water (Carolin et al., 2017, p. 1). In addition, wildlife can be exposed to lead through the food chain, as well as through direct contact with contaminated soil and water (Nkwunonwo et al., 2020, p. 6). As the concentration of lead in the food chain builds up, the risk of human over intaking increases, which may result in neurological and immune system damage as well as the development of cancer (Nain and Kumar, 2020, p. 1-2).

2.3.2 Achievements and challenges in the development of lead-free piezoelectric materials

Regarding the detrimental effect of lead, it is important to minimize lead releases into the environment in order to protect the health of the planet and its inhabitants. There are several lead-free piezoelectric materials that have been developed in recent years according to Wu (2018), including:

Piezoelectric Materials Based on Alkali Niobate

The materials based on alkali niobate are composed of solid solutions of $KNbO_3$, $NaNbO_3$, and related compounds (Tan et al., 2019, p. 1). These materials have evolved over time, with significant advancements in the study of their electrical properties and physical mechanisms. Matthias discovered the ferroelectric properties of $KNbO_3$ materials, while Vousden proposed an antiferroelectric model for $NaNbO_3$. The binary system of $KNbO_3$–$NaNbO_3$ (KNN) was first explored by Shirane et al. The different phase transition temperatures for these materials, and the study of phase boundaries, are currently a major area of research.

$Bi_{0.5}Na_{0.5}TiO_3$-Based Piezoelectric Materials

The compound Bismuth sodium titanate (BNT, $Bi_{0.5}Na_{0.5}TiO_3$) was first discovered to have a rhombohedral structure by Smolenskii et al. in 1960. Since then, BNT materials have gained attention due to their high remnant polarization. However, it is challenging to produce a pure BNT ceramic with desirable piezoelectric properties due to its high conductivity and large coercive field, leading to poor piezoelectricity. As a result, chemical modification has become a common approach to improve the piezoelectric behavior of BNT materials. There have been significant advancements in terms of piezoelectric and strain properties (Yan et al., 2020, p. 1-2). However, the existence of the depolarization temperature limits the practical use of these materials in piezoelectric devices. Notably, BNT-based ceramics have been found to have a large strain under high electric fields, which outperforms lead-based ceramics. Consequently, much attention has been focused on modifying the strain and studying the underlying mechanism of BNT-based materials.

BaTiO3-Based Piezoelectric Materials

The barium titanate (BaTiO3, BT) material is the first perovskite to produce lead-free piezoelectric ceramics. However, for many years, the conventional solid-state reaction method can result only week piezoelectric effect from observation. Nonetheless, advancements have been made in this material. In 2009, Ren et al. discovered a significant piezoelectric effect (d33 of 620 pC/N) in lead-free Ba(Ti0.8Zr0.2)O3-(Ba0.7Ca0.3)TiO3 (BCT-BZT) ceramics with a novel phase boundary. In addition, new properties, such as the electrocaloric effect, have also been discovered in BT-based materials.

2.3.3 Other environmental concerns

While the shift towards lead-free piezoelectric materials may address the adverse effects of lead, it is important to note that it may also introduce new environmental concerns. Since the primary source of bismuth and its oxide is as a byproduct of lead smelting, bismuth based piezoelectric materials may have a more negative impact on the environment than PZT due to the added challenges posed by the processing and refining steps required for the extraction. Additionally, the higher energy cost associated with recycling bismuth compounds makes it less favorable in comparison to lead. Therefore, bismuth based piezoelectric materials may not present a clear advantage over PZT in terms of environmental sustainability (Ibn-Mohammed et al., 2018, p. 4922&4936).

2.4 Commercial products practically applied in modern cars

This section aims to study the application of piezoelectric materials in two key components of modern automobiles, namely fuel injectors and knock sensors, through reviewing some commercially available products i.e. CRI3 piezo injector from Bosch and several knock sensors from various manufacturers. By exploring the use and benefits of these materials, a deeper comprehension of the characteristics of piezoelectric materials may be realized.

2.4.1 Bosch CRI3 piezo injector

The CRI3 piezo injector is a third-generation high-performance fuel injector designed for use in premium cars and light duty vehicles. The injector is controlled by a piezo ceramic actuator that expands when voltage is applied. The piezo actuator comprises numerous layers of piezo ceramic, which undergo expansion of a few thousandths of a millimeter upon voltage application. This expansion prompts the movement of the jet needle, resulting in extremely brief reaction times and small pre-injection quantities (Bosch Mobility Solutions, 2023).

The injectors can operate at pressure levels ranging from 2,000 bar to 2,700 bar, and they have a modular construction that can be customized for different applications based on factors such as lifetime, nozzle design, and injector length. Fuel is conveyed to the injector through the high-pressure connection from the rail and is regulated through the electrical connection. The fuel-return line facilitates the drainage of the return flow quantities generated during the injection process back into the tank (Bosch Mobility Solutions, 2023). The CRI3 piezo injector permits highly accurate and versatile fuel injection into the engine cylinder, allowing for brief injection intervals, with the potential for up to ten individual injections per cycle. This versatility in injection process design results in a reduction in fuel consumption, CO_2 emissions, as well as other pollutants and noise emissions (Bosch Automotive Myanmar, 2022). Moreover, the integration of the piezo actuator into the housing facilitates a slimmer injector design in comparison to solenoid valve injectors, thereby reducing the spatial requirements for installation (Bosch Mobility Solutions, 2023). The CRI3 piezo injector has been utilized in Mercedes-Benz ("Bosch Common Rail Injector (CRI3) (Piezo) for Mercedes Benz," 2023) and BMW (Ades Diesel, 2023) diesel engines, such as the C-CLASS (W204) C 350 CDI (204.023) 265 HP Saloon (06.2011-01.2014) and E-CLASS Coupe (C207) E 350 CDI 265 HP Coupe (04.2011-) as well as 3 (F30, F80) 335 d xDrive 313 HP Saloon (11.2012-) and X5 (F15, F85) xDrive 40 d 313 HP Closed Off-Road Vehicle (12.2013-).

2.4.2 Knock sensors

The engine management system of contemporary automobiles is a sophisticated technology that oversees the entire combustion process, utilizing advanced technologies to regulate various components and computer modules, thereby ensuring optimal vehicular operation. As a preeminent Original Equipment (OE) manufacturer, Delphi Technologies proffers a comprehensive assortment of engine sensors aimed at enhancing emissions control, fuel economy, and drivability, upheld by exacting OE development and product validation procedures. The knock sensors developed by Delphi Technologies are engineered to ensure optimal ignition timing and prevent engine knock, communicating with the Engine Control Module (ECM) to modulate ignition timing and optimize engine performance, while reducing the risk of damage to internal engine components.

Furthermore, these sensors feature a sealed design capable of withstanding humidity, salt spray, and automotive fluids (Delphi Technologies, 2023).

Knock sensor is a crucial component for ensuring smooth fuel burning and preventing engine damage from detonation. The testing regimen of Hitachi Astemo knock sensors exceeds typical operating conditions and they are made from premium-grade raw materials with tight tolerances and high repeatability. Hitachi Astemo knock sensors are designed for increased sensitivity to engine ping and vibration, and they feature the most updated knock-sensing technologies. These sensors are available for millions of vehicles and calibrated to each exact application for optimal engine efficiency. Hitachi Astemo knock sensors offer good quality at an excellent price and are a reliable choice for vehicle owners who value high-quality components (Hitachi Astemo Americas, 2023).

The knock sensors manufactured by Standard® exhibit a high degree of flexibility, capable of detecting knock frequencies up to 1000 Hz, thereby accommodating variations in engine knock frequency across a wide range of vehicular conditions. The production process incorporates an automated data acquisition system that oversees the sensor output, ensuring it generates the requisite voltage output within the specified frequency range. To ensure seamless functioning, all units undergo a 100% accelerometer vibration test (Standard, 2023).

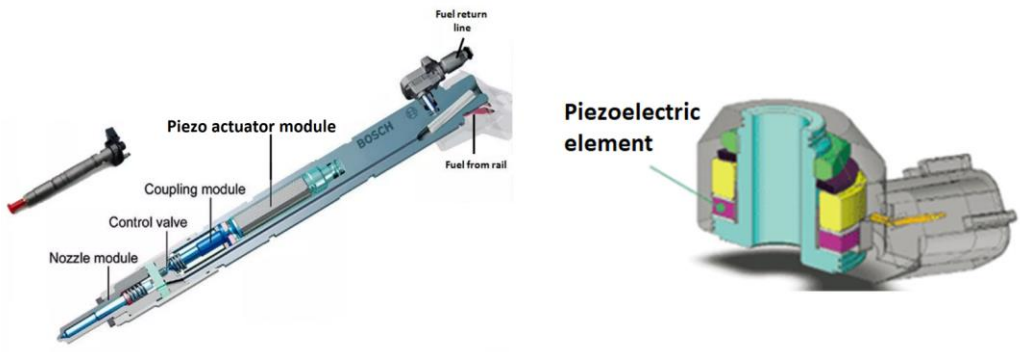

Figure 1 Schematic diagram of Bosch CRI3 (Luca Nurchi, 2016) and Piezoelecrtric element in a knock sensor (NGK SPARK PLUG CO., LTD., 2023)

2.5 Future trends

This section discusses future trends related to the use of piezoelectric materials in modern cars from the perspectives of sustainability and modern energy, with an emphasis on energy harvesting as well as the opportunities and challenges that may arise.

2.5.1 Sustainable and modern energy

In the year 2015, the United Nations General Assembly adopted the Sustainable Development Goals (SDGs) or the 2030 Agenda for Sustainable Development as a guiding framework for global collaboration aimed at attaining a sustainable future for the planet. Energy constitutes a crucial domain of focus within the SDGs, with emphasis primarily directed towards the 7th Sustainable Development Goal (SDG7) that endeavors to guarantee universal access to affordable, reliable, sustainable, and modern energy (McCollum et al., 2018, p. 1-2).

The pressing concern of climate change has further accentuated the significance of a worldwide energy transition, in consonance with the objectives of SDG 7. Universal attainment of contemporary energy services through sustainable means can help restrict the escalation of global surface temperature and mitigate greenhouse gas emissions. This warrants substantial technological breakthroughs in renewable energy, which is perceived as a crucial stimulus for facilitating this transition (Gielen et al., 2019, p. 1-2).

2.5.2 Energy harvesting

The increasing demand for clean and sustainable energy has underscored the necessity for exploring alternative energy strategies (Zhang et al., 2017, p. 1). In this context, energy harvesting with piezoelectric materials has emerged as a promising area for advancement in the modern car industry (Z. Yang et al., 2018, p. 676).

2.5.3 Piezoelectric materials as a key component

Piezoelectricity is a promising technique for energy harvesting applications (Dudem et al., 2018, p. 1). The efficacy of piezoelectric materials in generating electrical output from applied strain energy accounts for the significance of its employment. These materials are also easily integrated into different devices, making them a suitable choice for a sustainable power source. The most common type of piezoelectric material used for power harvesting is the piezoceramic, PZT, although it is highly brittle and limited in its applied situations. Other piezoelectric-based materials such as PVDF (Narita and Fox, 2018, p. 3) also have applications in power harvesting. Technological advancements in the integration of piezoelectric materials into different systems hold the potential for significant progress towards sustainable energy harvesting (Askari et al., 2018, p. 12).

2.5.3.1 Mechanisms

Piezoelectric energy harvesting (PEH) has emerged as a significant topic of study, garnering widespread attention from researchers. This is largely attributed to the advantages it offers, including its simple architecture and high power density. However, piezoelectric energy harvesting (PEH) devices have limitations in terms of acceleration magnitudes and frequency range of environmental vibration sources, leading to low power generation. To improve performance and increase the operating bandwidth, advanced methodologies are required to maximize their potential (Liu et al., 2018, p. 15-16).

There are five mainstream mechanisms for performance enhancement: (1) multi-degree-of-freedom (multi-DOF) harvesting mechanism, (2) frequency-up-conversion mechanism, (3) bi-stable nonlinear mechanism, (4) mono-stable nonlinear PEH mechanism, and (5) hybrid harvesting mechanism. Each approach has its advantages and disadvantages, and research is ongoing to improve the effectiveness of the methods applied under specific situation for maximizing the performance of PEH devices (Liu et al., 2018, p. 15-24)

2.5.3.2 Other challenges

While performance enhancement for different types of harvesting mechanisms has been carried out, challenges from other perspectives are still remarkable. For example In order to fulfill the piezoelectric demands of the future, it is imperative to cultivate piezoelectric materials that exhibit exceedingly elevated piezoelectric d_{33} coefficients, surpassing 600 pC N^{-1}. Additionally, the manufacture of nanogenerators must align with industrial high-volume production processes to enable their application and integration into self-powered devices (Mahapatra et al., 2021, p. 63).

2.5.4 Self-powered sensors and intelligent transportation systems

The automotive industry has shown an increasing inclination towards the employment of small-scale sensors for safty and control functions. However, the incorporation of additional sensors on each vehicle presents a significant challenge to the connectors and cabling of sensor modules. The contemporary vehicle is composed of cables that exceed a length of 4 km, resulting in added weight, significant space occupation, and reduced overall reliability. One possible solution to address these issues is the adoption of wireless sensors. However, their limited battery capacity impedes long-term automated operation. To overcome this limitation, researchers have focused on harvesting the deformation and vibration energy of operating vehicles, thereby enabling energy harvesters to effectively substantially prolong battery life and achieve lifelong autonomous operation of small-sized sensor modules. Piezoelectric energy harvesting (PEH) along with other energy-harvesting techniques has been proposed for various applications in powering the sensors (Z. Yang et al., 2018, p. 675-676).

In addition, the swift advancement of electric cars and self-driving technology has led to the detection of traffic congestion and the provision of optimal alternative routes to drivers (Kumar et al., 2019, p. 15). This development enables intelligent transportation systems in smart cities to be realized through the utilization of IoTs. Consequently, there is an increased demand for additional sensors. To address energy management challenges, energy harvesting is emerging as a promising solution that helps prolong the lifespan of low-power devices and reduces reliance on conventional power sources (Ejaz et al., 2017, p. 1).

Looking forward, the potential for energy harvesting in automotive industry is immense, particularly as 5G technology continues to develop. With increased connectivity and data transmission speeds, energy harvesting could be used to power a variety intelligent transportation systems (Liu et al., 2021, p. 7-8).

2.6 Mid-summary

Section 2.1 provided an overview of the principles of piezoelectric effect and the three categories of piezoelectric materials: ceramic, polymer, and composite, including their characteristics, advantages, and applications. Section 2.2 discussed the techniques used for the preparation of piezoelectric powders and an overview of the sintering process, including the solid-state method, sol-gel method, and co-precipitation method, with a focus on the preparation of PZT and the manufacturability of piezoelectric knock sensors and fuel injectors for use in modern cars. Section 2.3 discussed the environmental impact of lead and the development of lead-free piezoelectric materials such as alkali niobate, Bismuth sodium titanate (BNT), and barium titanate (BT), as well as the challenges and advancements in their production, while also highlighting that the shift towards lead-free materials may introduce new environmental concerns. Section 2.4 discusses the use of piezoelectric materials in fuel injectors and knock sensors in modern cars, reviewing commercially available products such as the Bosch CRI3 piezo injector, Delphi Technologies knock sensors, Hitachi Astemo knock sensors, and Standard knock sensors, and their features and benefits. Section 2.5 discussed the future trends related to the use of piezoelectric materials in modern cars for sustainable and modern energy, energy harvesting, self-powered sensors, and intelligent transportation systems.

3 RESEARCH METHODS

This section provides an explanation of the research methodology employed in this study, namely triangulation. Literature search, expert interviews, and pre-set criteria analysis constitutes the triangulation. In addition, an account of the reliability analysis has been conducted to ensure the trustworthiness of the research findings.

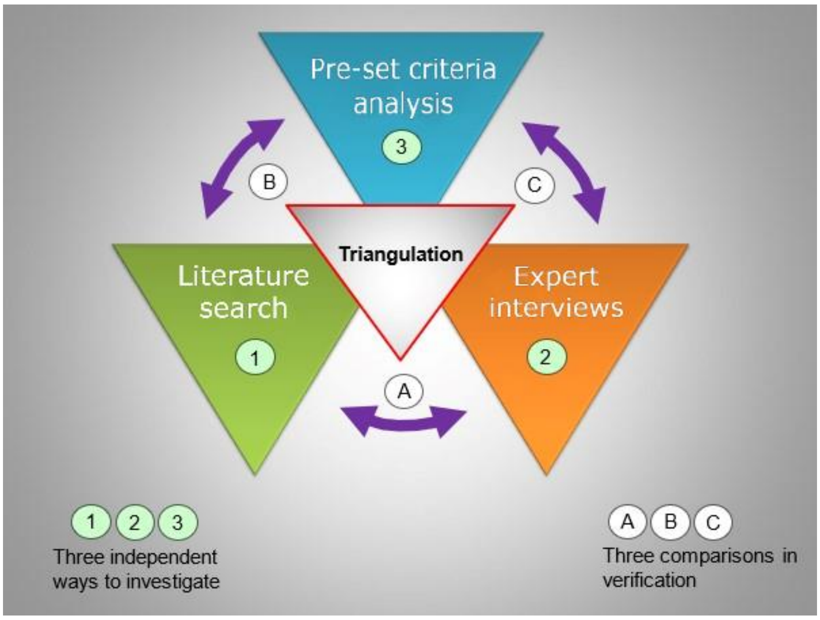

Figure 2 Triangulation

3.1 Triangulation

The present study will undertake an investigation into the utilization of piezoelectric materials in modern automobiles, utilizing a triangulation research approach that amalgamates literature review, expert interviews, and pre-set criteria analysis. The literature review will serve as a means of fulfilling individual research objectives. Expert interviews will be carried out to acquire both directional advice and specific information relevant to the research. Furthermore, pre-set criteria analysis will be employed to construct a comprehensive appraisal of piezoelectric materials discussed in specific contexts.

3.2 Literature search

The implementation of information searching will be carried out for each research goals. To optimize the search results, various keywords pertaining to the research goals will be identified and developed, and search operators such as quotation marks and truncation symbols will be employed. In the event that the retrieved results do not yield the desired information, further options for refinement, such as expanding the relevance criteria and broadening the scope of information sources, will be explored.

3.3 Expert interviews

To elicit a comprehensive understanding of the research problem, expert interviews will be conducted at different phases of the study. These interviews will serve the dual purpose of acquiring both general and specific information related to the research goals. Moreover, these interviews will aid in validating the questions formulated for the pre-set criteria analysis. Furthermore, the integration of expert insights and feedback into the research process will enhance the accuracy and credibility of the research findings.

3.4 Pre-set criteria analysis

This research employs a predetermined set of criteria to conduct a systematic analysis of references. The analytical process involves a series of well-defined stages, beginning with the formulation of a comprehensive set of criteria that is tailored to the specific research goals. The criteria employed in this study are established on a comprehensive evaluation of various factors, including commercial considerations, public concerns, and expert advice. Next, a set of questions is developed, with a focus on technological, social, and economic aspects, to guide the analysis of the relevant references. Finally, the information extracted from relevant reference is meticulously matched with the formulated questions to identify the most pertinent insights and to ensure a consistent and coherent analytical framework. An principle model table is provided below.

Table 1 Pre-set criteria principle model

Criteria	Reference [1]	Reference [2]	Reference [3]
Which ones are discussed?			
Which technological aspects are discussed?			
Which social aspects are discussed?			
Which economical or business oriented aspects are discussed?			

3.5 Reliability analysis

In order to ensure the reliability of this paper, various measures will be taken into consideration. Firstly, only references published within the last seven years will be used in this study. Additionally, references have been selected from reputable scientific databases such as Elsevier and Springer. Moreover, bibliometric measures such as SNIP, SJR, and Site Score, which are available through Scopus, have been utilized to assess the credibility of the sources used in this paper. Furthermore, at least three references about the same issue have been compared, and different types of references have been used. Finally, a total number of more than 50 references have been employed to support the findings in this study.

4 RESULTS

The results consist of three subcategories which are scientific contribution, concrete applications, and generalizable results. Each will be evaluated subsequently.

4.1 Scientific contribution

This research paper contributes novel insights to the modern car industry of why piezoelectric materials are so important to modern cars and how piezoelectric materials affect the functionality of knock sensors and fuel injectors by elucidating the fundamental principles and classifications of piezoelectric materials, investigating the methodologies for synthesizing piezoelectric powders and performing sintering operations, scrutinizing the adverse consequences of lead usage, surveying recent progress in the development of lead-free piezoelectric materials, evaluating the distinct applications of piezoelectric materials in modern automobiles, and appraising the prospect of piezoelectric materials in addressing the 7^{th} sustainable development goal.

In addition, a pre-set criteria analysis is employed for each individual research goals to construct a comprehensive appraisal of piezoelectric materials discussed in each specific contexts. A demonstration is included in the results section and more are attached in appendix.

4.2 Concrete applications

The modern car industry could use the information provided in this research in several ways:

- Evaluating the Applications of Piezoelectric Materials: The research paper evaluates the distinct applications of piezoelectric materials in modern automobiles. Car manufacturers can use this information to determine which car parts or components would benefit the most from the integration of piezoelectric materials.

- Making Better Decision on Material Selections: The research paper highlights the impact of the various stages of the manufacturing process on the final product's performance, enabling car manufacturers to make informed decisions regarding material selection.
- Reducing Environmental Impact: The research paper scrutinizes the adverse consequences of lead usage in piezoelectric materials. As a result, the car industry could move towards lead-free piezoelectric materials to reduce the environmental impact of car production.
- Moving toward sustainable Development: The research paper appraises the prospect of piezoelectric materials in addressing the 7th sustainable development goal. The car industry can use this information to develop and implement sustainable practices in the production of automobiles.

4.3 Generalizable results

The study's findings regarding the application of piezoelectric materials in modern cars could potentially serve as a framework for examining the use of other smart materials. Given that smart materials share traits in common, it is likely that similar areas of consideration may apply across various types of smart materials. Consequently, the structure of the results obtained from this study could be applicable to future research on other smart materials, facilitating a more systematic approach to their application in various fields.

5 DISCUSSION

The discussion will be carried out with a multi-dimensional approach encompassing various aspects, which are comparison and connections with former research, objectivity, reliability, assessment of the results, key findings, novelty value of the results, generalization and utilization of the results.

5.1 Comparison and connections with former research

The current research paper appears to provide more comprehensive insights into the fundamental principles and classifications of piezoelectric materials, as well as more detailed information on the methodologies for synthesizing piezoelectric powders and performing sintering operations. The paper also examines the adverse consequences of lead usage and evaluates the potential of lead-free alternatives, which may not have been covered in previous research. Additionally, the paper's focus on the sustainable development goal and its potential for generalizable results suggest that the research goes beyond previous work on piezoelectric materials in modern cars. The paper's framework for examining the use of smart materials in various fields may also provide a foundation for future research on the topic. Overall, the current research paper appears to expand upon previous work on piezoelectric materials in modern cars and provides new insights and potential directions for future research.

5.2 Objectivity

In order to achieve a high level of objectivity, this study employs a triangulation research approach, integrating a literature review, expert interviews, and pre-set criteria analysis. Along with the literature review, through which most of the information is gathered, expert interviews were conducted at various phases of the study to gain a comprehensive understanding of the research problem, acquire both general and specific information related to the research goals, validate the pre-set criteria analysis questions, and enhance the accuracy and credibility of the research findings. In addition, systematic analyses of references are carried out through well-defined analytical processes using pre-set criteria tailored to specific research goals, which were established based on a comprehensive evaluation of commercial considerations, public concerns, and expert advice.

5.3 Reliability

The present research has completed the necessary measures to ensure its reliability. Firstly, the inclusion of only sources published within the last seven years has been strictly adhered to. Secondly, reliable scientific databases such as Elsevier and Springer were used to select sources. Thirdly, the credibility of sources has been evaluated using bibliometric measures such as SJR, SNIP, and Site Score, available through Scopus. Moreover, more than 50 references have been employed to support the findings. Finally, at least ten references regarding the same research goal are compared and different types of references are utilized, thereby increasing the reliability of this research.

5.4 Assessment of the results

The results presented in this research paper appear to be well-organized. The paper's scientific contribution is considerable, as it provides insights into the importance of piezoelectric materials in modern cars and their impact on knock sensors and fuel injectors. The paper accomplishes this by detailing the fundamental principles and classifications of piezoelectric materials, discussing methodologies for preparing piezoelectric powders, and examining the adverse consequences of lead usage. Additionally, the paper's concrete applications are relevant and potentially impactful. By evaluating the distinct applications of piezoelectric materials in modern automobiles, the paper provides car manufacturers with the information they need to make informed decisions about which car parts or components would benefit most from the utilization of piezoelectric materials. Similarly, the paper's discussion of the impact of various stages of the manufacturing process on product performance enables car manufacturers to make informed decisions regarding material selection, potentially leading to more sustainable practices in car production. Finally, the paper's potential for generalizable results is perceptive. The framework presented in this study could potentially serve as a foundation for examining the use of other smart materials, enabling a more systematic approach to their application in various fields. Overall, based on the information provided, it seems that this research paper has made a valuable contribution to the field of modern car industries and has the potential to influence future research on smart materials.

5.5 Key findings

Several key findings have emerged from this research. Firstly, piezoelectric materials play a crucial role in modern automobiles, particularly for knock sensors and fuel injectors. Secondly, the adverse environmental impact of lead usage in piezoelectric materials can be mitigated by adopting lead-free alternatives. Thirdly, the synthesis and sintering of piezoelectric powders are critical stages in the manufacturing process that significantly impact the final product's performance. Fourthly, piezoelectric materials have diverse applications in modern automobiles, and informed decisions can be made by car manufacturers regarding their integration. Fifthly, piezoelectric materials have the potential to address the 7th sustainable development goal. Finally, the framework presented in this study could serve as a potential foundation for examining the use of other smart materials in various fields.

5.6 Novelty value of the results

The research paper appears to have significant novelty value, as it provides new insights into the importance of piezoelectric materials in modern cars and their impact on knock sensors and fuel injectors. The paper accomplishes this by detailing the fundamental principles and classifications of piezoelectric materials, discussing methodologies for synthesizing piezoelectric powders, and examining the adverse consequences of lead usage. Additionally, the paper evaluates the distinct applications of piezoelectric materials in modern automobiles, enabling car manufacturers to make informed decisions regarding their integration. The paper also highlights the impact of various stages of the manufacturing process on product performance and suggests using lead-free alternatives to reduce the environmental impact of car production. Finally, the paper's potential for generalizable results could enable a more systematic approach to the application of smart materials in various fields.

5.7 Generalization and utilization of the results

The results of this study, which focus on the use of piezoelectric materials in modern cars, may serve as a potential framework for exploring the application of other types of smart materials. Since smart materials share common characteristics, it is plausible that comparable factors may apply to other smart materials in diverse areas. Consequently, the structure of the findings obtained in this study could be transferable to future research on other smart materials, enabling a more comprehensive approach to their use in various fields.

5.8 Topics for future research

Future research could explore several topics related to the application of piezoelectric materials in cars. For example, the integration of piezoelectric materials with other emerging energy harvesting technologies, such as thermal energy harvesting and photovoltaic energy harvesting. Such integration could lead to improved energy efficiency with enhanced safety features. Another area of research could be the optimization of piezoelectric energy harvesting systems, which could involve improving the efficiency and scalability of these systems.

6 SUMMARY

This thesis presents a comprehensive examination of piezoelectric materials and their applications in modern automobiles. The study's methodology involved a triangulation research approach consisting of a literature review, expert interviews, and pre-set criteria analysis. The research paper contributes novel insights to the modern car industry by discussing the fundamental principles and classifications of piezoelectric materials, preparing piezoelectric powders and performing sintering operations, scrutinizing the adverse consequences of lead usage, surveying recent progress in the development of lead-free piezoelectric materials, evaluating the distinct applications of piezoelectric materials in modern automobiles, and appraising the prospect of piezoelectric materials in addressing the 7th sustainable development goal. The findings have practical implications for car manufacturers, including the ability to evaluate applications of piezoelectric materials, make informed decisions regarding material selection, reduce environmental impact, and move towards sustainable development. Furthermore, the study's structure and findings have generalizable results that could potentially be applicable to future research on other smart materials, enabling a more systematic approach to their application in various fields.

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Appendix 1 Pre-set criteria: “Functionality of different types of piezoelectric materials”

Criteria	Advanced Piezoelectric Materials (Uchino, 2017)	A comprehensive review on the state-of-the-art of piezoelectric energy harvesting (Sezer and Koç, 2021)	Piezoelectric Materials, in: Advanced Materials (Behera, 2022)
Which ones are discussed?	Ceramic and Polymer Piezoelectric Materials	Polymer Piezoelectric Materials	Composite Piezoelectric Materials
Which technological[12] aspects are discussed?	PZT; piezoelectric performance; multilayer technology	Flexibility; low weight	high coupling factors; low acoustic impedance; good matching with human tissue; mechanical flexibility
Which social aspects are discussed?	Sustainability concerns	Low temperature manufacturing	n/a
Which economical or business oriented aspects are discussed?	Low cost	Cost-effective	n/a

[1] The articles Wang (2017), Behera (2022), Carvalho et al. (2021), Li et al. (2018a), Li et al. (2018b), and Mishra et al. (2019) all discuss the principles of the piezoelectric effect. Wang (2017) discusses the mechanical deformation and electrical energy conversion that occurs in piezoelectric materials. Behera (2022) covers the use of an asymmetrical structure to enhance the piezoelectric properties of a material. Carvalho et al. (2021) discuss the mechanical deformation and electrical energy conversion aspects of the piezoelectric effect. Li et al. (2018a) and Li et al. (2018b) delve into the electric dipoles arrangement and polarization that contribute to the piezoelectric effect. Finally, Mishra et al. (2019) examine the dipole arrangement in piezoelectric materials.

[2] In addition to the information presented in the table, Mishra et al. (2019), discuss ceramic piezoelectric materials, specifically the crystal structure of these materials. Carvalho et al. (2021) also discuss ceramic piezoelectric materials, focusing on the anisotropy of these materials. Zhao et al. (2019) discuss the exceptional piezoelectric characteristics of PZT and their application. Jacob et al. (2018) discuss ceramic piezoelectric materials, particularly the use of barium titanate ($BaTiO_3$) and potassium niobate ($KNbO_3$). Uchino (2017) talks about the discovery of a strong piezoelectric effect in polyvinylidene fluoride (PVDF) and its potential applications. Wei et al. (2018) and Carvalho et al. (2021) mention properties combination to enhance the performance of composite piezoelectric materials.

Appendix 2 Pre-set criteria: “Manufacturability aspects of piezoelectric materials related to the manufacturability of piezoelectric knock sensors and fuel injectors”

Criteria	Visualization Experiment and Numerical Analysis of Cavitation Flow Characteristics in Diesel Fuel Injector Control Valve with Different Structure Design (Ma et al., 2021)	High strain lead-free piezo ceramics for sensor and actuator applications: A review (Panda et al., 2023)	Identification of combustion and detonation in spark ignition engines using ion current signal (Laganá et al., 2018)
Which ones are discussed?	Fuel injector	Fuel injector	Knock sensor
Which technological[3456] aspects are discussed?	Fuel atomization; volume control; spray pattern; engine performance	Piezoelectric actuator; reversible deformation	Engine knock monitoring; signal conversion
Which social aspects are discussed?	Emission	Reduced emissions	n/a
Which economical or business oriented aspects are discussed?	Fuel efficiency	Efficient combustion	Engine damage prevention

[3] The articles by Uchino (2017), Wu (2018), Jeshurun et al. (2021), Bokov et al. (2021), Goel et al. (2017), and Chen et al. (2020) all discuss various aspects of powder preparation for the fabrication of piezoelectric materials. Uchino (2017) covers topics such milling and calcination. Wu (2018) discussed the solid-state method and calcination, while Jeshurun et al. (2021) mentioned mixing metal oxides. Bokov et al. (2021) uses the sol-gel method for powder preparation, and Goel et al. (2017) uses the co-precipitation method. Chen et al. (2020) discusses the preparation of lead-free piezoelectric ceramics powders.

[4] The articles by Cen et al. (2021), Ul et al. (2019), and Mégret et al. (2020) all discuss the fabrication of materials, with a particular focus on sintering. Cen et al. (2021) discussed sintering processes, while Ul et al. (2019) mentioned the temperature and sintering aids used in the process. Mégret et al. (2020) discussed various sintering techniques, including hot-pressing sintering, microwave heating, and spark plasma sintering, and their application to different materials.

[5] The articles by Bochenek et al. (2020), Yue et al. (2017), and Siddiqui et al. (2020) all discuss the technological aspects of PZT preparation. Bochenek et al. (2020) discusses raw material preparation and high-energy ball milling, while Yue et al. (2017) discussed the milling process using a ball mill. Siddiqui et al. (2020) mentioned the calcination and sintering process involved in PZT preparation.

[6] The articles by Ren et al. (2018) and Zhang et al. (2019) discussed the technological aspects of multilayer ceramic actuators, specifically the fabrication process involving tape casting, cutting, and stacking.

Appendix 3 Pre-set criteria: “Detrimental effects of lead and lead-free piezoelectric materials”

Criteria	**Heavy metals in food crops: Health risks, fate, mechanisms, and management. (Rai et al., 2019)**	**Advances in lead-free piezoelectric materials (Wu, 2018)**	**Life cycle assessment and environmental profile evaluation of lead-free piezoelectrics in comparison with lead zirconate titanate (Ibn-Mohammed et al., 2018)**
Which ones are discussed?	Pb	KNbO3, NaNbO3, BNT, BT	Pb, Bi, PZT
Which technological[7] aspects are discussed?	n/a	Ferroelectricity discovery of KNbO3; Piezoelectric enhancement of BNT; Significant piezoelectric effect discovery in BT	lead smelting; processing and refining steps required for the extracting bismuth
Which social aspects[8] are discussed?	Plants as food contaminated by Pb in soils	n/a	n/a
Which economical or business oriented aspects are discussed?	Food chain management	n/a	cost associated with recycling bismuth compounds

[7] In addition to the information presented in the table, the articles by Tan et al. (2019) and Yan et al. (2020) both discuss alkali niobate based materials, with Tan et al. focusing on the composition of these materials and Yan et al. discussing advancements in strain properties.

[8] In addition to the information presented in the table, the sources discuss environmental and health hazards associated with Pb (Zhao et al., 2019), negative environmental impacts (Nain and Kumar, 2020), soil contamination (Yang et al., 2018), water contamination and associated health problems for humans and animals (Carolin et al., 2017), wildlife contamination and food chain contamination (Nkwunonwo et al., 2020), and health problems for humans (Nain and Kumar, 2020).

Appendix 4 Pre-set criteria: “Piezoelectric materials applied in automotive commercial products”

Criteria	**(Bosch Mobility Solutions, 2023)**	**(Bosch Automotive Myanmar, 2022)**	**(Delphi Technologies, 2023)**	**(Hitachi Astemo Americas, 2023)**	**(Standard, 2023)**
Which ones are discussed?	CRI3 piezo injector	CRI3 piezo injector	Knock sensor	Knock sensor	Knock sensor
Which technological aspects are discussed?	piezo ceramic actuator; brief reaction times; small pre-injection quantities; compatibility	high accuracy injection;	ignition timing optimization; engine knock prevention; Drivability	preventing engine damage; optimal engine efficiency	wide operational frequency range
Which social aspects are discussed?	n/a	reduction in CO_2 emissions, noise emissions	emissions control	n/a	n/a
Which economical or business oriented aspects are discussed?	n/a	reduction in fuel consumption	fuel economy	smooth fuel burning; good quality at an excellent price	n/a

Appendix 5 Pre-set criteria: “Sustainable and modern energy with piezoelectric energy harvesting in future cars”

Criteria	Connecting the sustainable development goals by their energy inter-linkages (McCollum et al., 2018)	The role of renewable energy in the global energy transformation (Gielen et al., 2019)	A comprehensive review on piezoelectric energy harvesting technology: Materials, mechanisms, and applications (Liu et al., 2018)	High-Performance Piezoelectric Energy Harvesters and Their Applications (Yang et al., 2018)
Which ones are discussed?	Sustainable and modern energy	Sustainable and modern energy	Energy harvesting Mechanisms	Self-powered sensors
Which technological[9] aspects are discussed?	n/a	technological breakthroughs in renewable energy	piezoelectric energy harvesting (PEH); simple architecture; high power density; performance improvements	wireless sensors powering; self-powered sensors
Which social aspects are discussed?	Sustainable Development Goals	climate change; help restrict the escalation of global surface temperature; mitigate greenhouse gas emissions	n/a	n/a
Which economical or business oriented aspects are discussed?	affordable, reliable, sustainable, and modern energy	energy transition	n/a	battery life enhancement

[9] In addition to the information presented in the table, Zhang et al. (2017) discussed alternative energy strategies that could be achieved through the use of piezoelectric materials. Yang et al. (2018) and Dudem et al. (2018) both pointed out energy harvesting with piezoelectric materials. Narita and Fox (2018) mentioned the use of polyvinylidene fluoride (PVDF) in power harvesting applications. Askari et al. (2018) discussed the integration of piezoelectric materials into different systems. Liu et al. (2018) delved into the topic of Piezoelectric energy harvesting (PEH), presented various ways for performance improvements. Mahapatra et al. (2021) brought up piezoelectric d33 coefficients and high-volume production processes. Liu et al. (2021) talked about connectivity and data transmission speeds. Kumar et al. (2019) discussed the use of piezoelectric materials for traffic congestion detection and provision of optimal alternative routes.