# Integration of Functionally Graded Piezoelectric Actuators in Sustainable Manufacturing: Applications, Advantages, and Challenges

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***Abstract*: *Functionally graded piezoelectric Actuators (FGPAs) have gained significant interest due to their unique properties that allow for efficient energy conversion and sensing capabilities. As manufacturing processes continue to evolve towards sustainability, integrating these materials into various applications has become a focus of research and development. Understanding the challenges and opportunities associated with the integration of functionally graded piezoelectric materials is essential for optimizing their performance and enhancing sustainability in manufacturing operations. This study aims to explore the potential benefits of incorporating these advanced materials in sustainable manufacturing processes, highlighting their contributions to energy efficiency and environmental conservation. By addressing the key considerations and opportunities presented by functionally graded piezoelectric materials, this study seeks to provide valuable insights for engineers and researchers looking to enhance the sustainability of manufacturing practices. Thus, this chapter overviews incorporation of FGPAs in manufacturing processes, and their numerous advantages and challenges in the field of green manufacturing.***

***Keywords*: Sustainable manufacturing, Actuators, FGPA, Green manufacturing, smart materials.**

**(Article history: Received** 2nd July 2025 and accepted 12th November 2025**)**

## I. INTRODUCTION

Functionally graded piezoelectric actuators (FGPAs) have emerged as innovative devices with significant potential in enhancing sustainable manufacturing practices. The utilization of FGPAs aims to minimize environmental impact, optimize resource efficiency, and enhance overall production sustainability. These advanced materials exhibit varying properties throughout their structures, facilitating precise control and manipulation of mechanical, electrical, and thermal characteristics. This distinctive attribute allows FGPAs to adapt to diverse manufacturing needs, resulting in heightened efficiency and decreased waste generation. An important benefit of integrating FGPAs in sustainable manufacturing is their capacity to improve energy efficiency. By converting electrical energy into mechanical energy with exceptional accuracy, FGPAs enable more controlled and efficient manufacturing procedures. Consequently, this leads to decreased energy consumption and reduced carbon emissions, thereby supporting overarching sustainability objectives. Furthermore, the precise controllability provided by FGPAs empowers manufacturers to optimize production processes, culminating in superior product quality and diminished material wastage. Additionally, employing FGPAs in sustainable manufacturing endeavors can enhance product performance and longevity. These actuators can be customized for specific applications by modifying their material properties, facilitating the creation of optimized designs that bolster product functionality and reliability. This customization aspect contributes to the formulation of more resilient and energy-efficient products, aligning with sustainable manufacturing principles. Moreover, the integration of FGPAs can pave the way for the establishment of intelligent manufacturing systems capable of real-time monitoring and adjustment. Through the integration of FGPAs into sensors and actuators within manufacturing machinery, manufacturers can establish adaptive systems that react to changing conditions and automatically optimize production parameters.

## II. CONCEPT OF PIEZOELECTRICITY

Piezoelectric materials are a type of active smart materials known for their exceptional ability to convert mechanical energy into electric energy and vice versa. These materials are extensively utilized in various engineering applications, including aerospace systems electromechanical systems, and control systems. The term "piezo" is derived from the Greek language, specifically from a word that signifies "pressure," highlighting the ability of these materials to transform mechanical energy into electrical energy and vice versa. The pioneering discovery of the exceptional electromechanical characteristics of piezoelectric materials dates back to 1880, when the noted scientists Pierre and Paul-Jacques Curie first observed these properties. Their observation revealed that the piezoelectric effect manifests in noncentrosymmetric crystals. When an electric field is applied to these crystals, they experience mechanical deformation (piezoelectric converse effect), whereas the application of stress generates an electric field in the same crystals (piezoelectric direct effect) [1]. These phenomena are depicted in “Fig. 1”.

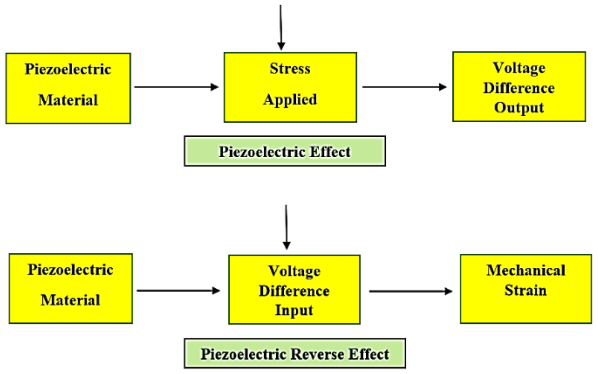


Fig. 1. Piezoelectric effects [2]

The piezoelectric direct effect is harnessed for sensor development, while the piezoelectric converse effect is utilized for actuator creation. In recent times, piezoelectric materials have generated substantial interest because of their potential usage in micro electromechanical and nanoelectromechanical systems, encompassing nanogenerators, field-effect transistors, piezoelectric gated diodes, gas sensors, nanowire resonators, and oscillators [2].

## III. Functionally Graded Piezoelectric Materials

As Piezoelectric ceramics, essential for energy harvesting systems, pose environmental challenges due to high energy consumption in research and manufacturing. Piezoelectric materials play a significant role in various electromechanical coupling components such as transducers, kinetic sensors, and actuators. Additionally, they are utilized in kinetic energy harvesters which are responsible for converting mechanical energy into electrical energy. This conversion process enables the powering of wireless sensing networks and the Internet of Things (IoT) [3]. The piezoceramics are manufactured by laminated composites from ceramic proportions of similar and dissimilar piezoelectric materials with different polling direction in order to get larger deflections. Barium Titanate ($BaTiO_3$) is one of the piezoelectric ceramic which is widely used. The other examples are Lead Titnate ($PbTiO_3$), Lead Zirconate Titanate (PZT, $PbZrTiO_3$), Polyvinylidene Fluoride (PVDF) etc. However, several disadvantages are found in traditional piezoelectric laminated structures such as high stress concentrations induced at the bonding interfaces and cracks may be yielded under mechanical or electric load. The reliability of the structures is then weakened and the usage of these structures becomes limited [4]. Thus, to overcome these drawbacks, functionally graded piezoelectric materials (FGPMs) are evolved. FGPM is a composite system consisting of piezoelectric ceramic and metal, where the piezoelectric effect is utilized to control the distribution of the constituents [5].

Functionally Graded Piezoelectric Actuators (FGPAs) embody a pioneering class of composite materials characterized by a continuous alteration in material properties intended to achieve a predetermined composition profile [6]. The integration of distinct qualities from different constituents, such as the exceptional heat/corrosion resistance found in ceramics and the superior mechanical strength and toughness typical of metals, underscores the unique advantages offered by these materials [6]. FGPAs have shown promise for diverse engineering applications, ranging from armour plating to components in heat engines, as well as in medical implants [6]. Their utilization has expanded to encompass general structural components and specialized applications in environments characterized by exceedingly high temperatures [6]. Functionally graded piezoelectric actuators are a burgeoning area of research with promising applications in sustainable manufacturing processes. These materials, which are being explored for various manufacturing applications, offer improved fatigue resistance, specific strength, and toughness compared to homogeneous composite materials, making them suitable for a range of engineering purposes [7]. One of the keys uses of piezoelectric functionally graded materials is as actuators and sensors, with simulations showing successful modal analyses for these materials in five degrees of freedom [8]. By integrating piezoelectric actuators with functionally graded microstructures, researchers aim to reduce stress concentrations at the middle interface, enhancing the performance and durability of these devices in practical applications [9]. Furthermore, studies have delved into the active control of free and forced vibrations in piezoelectric-integrated functionally graded carbon nanotubes, showcasing the potential for advanced vibration control mechanisms in engineering applications [10]. The development of functionally graded piezoelectric material actuators has opened up new possibilities for low-frequency applications with high tip displacement, offering a novel approach to achieving desired outcomes in the realm of actuator technologies [11]. These advancements underscore the growing importance of functionally graded piezoelectric actuators in modern engineering and manufacturing landscapes, with additive manufacturing methods emerging as a viable fabrication technique for these innovative materials [12].

## IV. Sustainable Manufacturing

Moreover, sustainable manufacturing has gained significant attention in recent years due to its potential to reduce environmental impact and enhance long-term economic viability. Our 21st century faces to a “sustainable society”, which enhances (a) reduction of contamination gas, (b) new energy source creation, (c) usage of non-toxic materials, (d) environmental monitoring system, (e) disposal technology for existing hazardous materials, and (f) energy-efficient device development in the piezoelectric area. With reducing their size, the electromagnetic components reduce their efficiency drastically [13]. In sustainable manufacturing processes, piezoelectric actuators play a significant role. They have been studied for their role in conserving ecosystem biodiversity and enabling sustainable manufacturing [14]. The utilization of axisymmetric piezoelectric actuators, such as discs or rings, for generating motion in circular or annular substrate plates is a prevalent practice in various applications, encompassing micro-valves and micro-pumps [6]. Piezoelectric energy harvesting demonstrates significant potential for producing renewable and clean energy in a decentralized manner; however, the life-cycle expenses associated with piezoelectric energy harvesting systems require thorough examination prior to any progression in the implementation of piezoelectric energy technology due to its limited durability. Thus, functionally graded piezoelectric materials play a vital role in sustainable manufacturing by enhancing energy efficiency, reducing toxic materials, and enabling innovative technologies like energy recovery systems and ultrasonic motors [13].

## V. Integration of Functionally Graded piezoelectric Actuators into Manufacturing processes

The integration of functionally graded piezoelectric actuators into manufacturing processes presents a promising avenue for enhancing sustainable manufacturing practices. These actuators, made from materials that exhibit diverse properties, offer superior specific strength, toughness, and fatigue resistance compared to homogeneous composite materials, making them ideal for various applications in the manufacturing industry [7]. Research has shown that piezoelectric functionally graded materials are utilized not only as sensors but also as actuators, exemplifying their versatility and utility in different manufacturing settings [8]. Furthermore, the design of piezoelectric actuators with functionally graded microstructures aims to reduce stress concentration at interfaces, enhancing the durability and performance of these devices in manufacturing processes [9].

This study focuses on integrating processes that minimize waste generation, reduce energy consumption, and promote the use of renewable resources. Functionally graded piezoelectric materials have emerged as key components in sustainable manufacturing due to their ability to efficiently convert mechanical stress into electrical energy, thereby enabling energy-efficient production processes. By harnessing the unique properties of these materials, manufacturers can optimize resource utilization and reduce overall production costs while minimizing environmental harm. Additionally, the integration of functionally graded piezoelectric materials in sustainable manufacturing aligns with global initiatives toward achieving carbon neutrality and promoting green technologies. As such, this innovative approach not only enhances operational efficiency but also contributes to a greener and more sustainable future for the manufacturing industry as a whole.

Piezoelectric actuators are conducted extensively in the applications of fast-response small-stroke displacement system, instead of hydraulic actuators that are environmentally friendly due to the elimination of hydraulic fluid. The friction in hydraulic system generates power loss of the actuator. But these systems are not completely green and these require hydraulic fluid thus affecting the working environment. Piezoelectric actuators are rapidly becoming well-known as key components of the new generation of high-precision small-scale displacement positioning and control systems [15].

The evolution of advanced manufacturing processes, as evidenced by studies on laser additive manufacturing and metallic coatings, lays a solid foundation for exploring the potential integration of functionally graded piezoelectric materials in sustainable manufacturing. With a focus on the structural integrity and quality assessment of 3D-printed metallic materials utilizing ultrasonic testing and Machine Learning techniques the research underscores the importance of detecting and mitigating defects in additive manufacturing processes [16]. Moreover, the development of corrosion-wear resistant coatings through additive manufacturing technologies highlights the drive towards enhancing material properties and prolonging component lifespan [17]. The integration of functionally graded piezoelectric materials in sustainable manufacturing represents a pivotal advancement in the realm of materials engineering and structural design. Functionally graded materials, often inspired by natural cellular structures, offer a multifunctional and multiphysics approach to structural components [18]. This innovative concept allows for the creation of load-bearing elements with high stiffness and low mass, tailored to specific applications through the manipulation of cell geometry, connectivity, and material properties. Moreover, the utilization of additive manufacturing techniques, a cornerstone of modern industrial practices exemplified by industry 4.0 principles, enables the efficient production of complex and customizable components [19]. By combining the principles of smart cellular solids and additive manufacturing, the potential for creating sustainable and efficient structures with integrated sensing and actuating capabilities is greatly enhanced. By leveraging the insights from these studies, the endeavour to incorporate functionally graded piezoelectric materials showcases a promising avenue for advancing manufacturing sustainability through tailored material properties and application-specific innovations. The synchronization of advanced materials design and manufacturing methodologies showcases a promising avenue for the development of next-generation sustainable materials in the manufacturing industry.

## VI. Uses, Challenges, Limitations and Advantages of FGPA

Uses, challenges, limitations and advantages of functionally graded piezoelectric actuators in the context of smart sustainable manufacturing are mentioned in “Table I”.

TABLE I. Application, challenges, limitations and advantages of FGPA in smart sustainable manufacturing

| Functionally Graded Piezoelectric Actuators | | | |
|---|---|---|---|
| ***Uses*** | ***Challenges*** | ***Limitations*** | ***Advantages*** |
| Sensors and Actuators: Functionally | Material Grading: Designing | Complex Fabrication: Fabricating | 1. Precision and Control: Piezoelectric |

| | | | |
|---|---|---|---|
| graded piezoelectric actuators (FGPAs) are widely used as sensors and actuators in various applications. They can convert electrical energy into mechanical motion or vice versa.<br>Micromechanical Systems (MEMS): FGPAs find applications in MEMS devices due to their high precision and fast response speed. These devices are used in precision position control, intelligent structures, and aerospace explorations [2].<br>Ultrasound Transducers: FGPAs are employed in ultrasound transducers for medical imaging and non-destructive testing [20].<br>Rotational Sensors and Actuators: Simplified models of rotational sensors or actuators utilize FGPAs for their unique material properties [21]. | FGPAs with precise material gradients can be challenging. Achieving a continuous variation in material properties requires careful selection and processing of piezoelectric materials.<br>Thermal Effects: FGPAs may experience thermal effects due to temperature variations. Managing these effects is crucial for maintaining performance.<br>Mechanical Integrity: Ensuring the mechanical integrity of FGPAs, especially when subjected to shear forces, is essential for their reliable operation. | FGPAs with graded material properties can be complex and expensive.<br>Limited Material Choices: The availability of suitable piezoelectric materials for FGPAs is limited. Common choices include lead zirconate titanate (PZT) and polyvinylidene fluoride (PVDF).<br>Performance Trade-offs: Achieving specific material gradients may involve trade-offs between different performance parameters (e.g., stiffness, sensitivity, and actuation range). | materials have emerged as the most researched materials for practical applications among numerous smart materials. They are used as sensors and actuators to effectively control structural vibrations, noise, and active control, as well as for structural health monitoring. This precision and control make them ideal for use in smart manufacturing.<br>2. Sustainability: Micro/nanopositioners utilizing piezoelectric actuators are instrumental in driving forward a sustainable manufacturing industry. Operating with remarkable precision at micro/nanometer scales, they have enhanced processes such as assisted reproduction and somatic cell nuclear transfer. Such advancements hold promise as critical elements in our capacity to mitigate the deterioration of our environment [22].<br>3. Reduced Energy Consumption: Piezoelectrically actuated micropositioning systems are crucial components in vibration-assisted machining processes, contributing to the reduction of energy consumption, enhancement of product quality, and prolongation of machine operational lifespan [22]. This contributes to the overall sustainability of the manufacturing process.<br>4. Wide Range of Applications: Piezoelectric smart and adaptive structures are widely used as micromechanical systems (MEMS), actuators and sensors for health monitoring, ultrasonic transducers, precision position control, intelligent structure systems, and aerospace explorations [23].<br>5. Stress Reduction: Using monolithic functionally graded piezoceramics can significantly reduce the stresses with only a minor impact on the device stroke [24]. This leads to longer-lasting and more durable components in the manufacturing process. |

Below "Table II" presents a comprehensive review of the recent studies focusing on the incorporation of functionally graded piezoelectric materials into sustainable manufacturing. It emphasizes the various applications, advantages, and significant discoveries derived from each investigation [24-36].

TABLE II. REVIEW OF RECENT STUDIES ON FGPM IN SUSTAINABLE MANUFACTURING

| Author(s) | Year | Title | Journal/Source | Key Findings |
|---|---|---|---|---|
| Nguyen, T. T., & Tran, T. Q. | 2020 | A review on the development and applications of functionally graded piezoelectric materials | Journal of Materials Research and Technology | Functionally graded piezoelectric materials (FGPMs) present enhanced mechanical and electrical characteristics suitable for a variety of applications. |
| Bhaskar, A., & Panigrahi, A. | 2021 | Functionally graded piezoelectric materials: A review on properties, fabrication, and applications | Materials Today: Proceedings | FGPMs exhibit superior durability and functionality owing to their customized material attributes. |
| Zhang, D., & Yang, J. | 2019 | Advanced modelling techniques for functionally graded piezoelectric materials and structures | Engineering Structures | The discussion examines modelling methodologies for FGPMs, highlighting their advantages in stress dispersion and electromechanical correlation. |
| Wang, X., & Wang, G. | 2021 | Thermal and mechanical properties of functionally | Composites Part B: Engineering | A critical analysis is conducted on the thermal and |

| | | | | |
|---|---|---|---|---|
| | | graded piezoelectric materials: A comprehensive review | | mechanical efficacy of FGPMs, underscoring their viability in applications demanding high performance. |
| Rao, B. N., & Rahman, S. | 2019 | Computational methods for vibration analysis of functionally graded piezoelectric materials | Computational Mechanics | Diverse computational methodologies for evaluating the vibration of FGPMs, such as Finite Element Method (FEM), are highlighted. |
| Liu, Y., & Hu, H. | 2020 | Advances in the numerical modeling of functionally graded piezoelectric materials | Journal of Computational Physics | The focus is directed towards numerical modelling strategies for FGPMs, tackling issues related to simulation precision and computational effectiveness. |
| Feng, Z., & Jin, F. | 2020 | Additive manufacturing of functionally graded materials: A review | Materials Science and Engineering: A | Investigates the utilization of additive manufacturing methods for Functionally Graded Materials (FGMs), which encompass FGPMs, and their viability in sustainable manufacturing processes. |
| Chen, X., & Luo, J. | 2021 | Finite element analysis of functionally graded piezoelectric actuators | Acta Mechanica | Examines Finite Element Method (FEM) analysis of FGPM actuators, illustrating enhanced operational efficiency within adaptive structures. |
| Kumar, S., & Singh, H. | 2022 | Artificial intelligence and machine learning approaches for optimizing functionally graded materials | Materials Today: Proceedings | Evaluates the role of Artificial Intelligence (AI) and Machine Learning (ML) in optimizing the characteristics and performance of Functionally Graded Materials (FGMs), including FGPMs. |
| Nguyen, T. T., et al. | 2020 | Applications of functionally graded piezoelectric materials in adaptive structures | Smart Materials and Structures | FGPMs are effective in adaptive structures due to their ability to respond to environmental changes, enhancing energy efficiency. |
| Sharma, A., et al. | 2025 | Vibration behaviour of shear-actuated bi-directional FGPM beams: A finite element approach | Journal of The Institution of Engineers (India) Series C | The research indicates that the vibrational frequencies of bi-directional FGPM beams are significantly affected by the volume fraction, slenderness ratio, and boundary conditions, thereby contributing valuable insights for their optimal design. |
| Yang, J., & Zhang, D. | 2020 | Durability of adaptive structures using functionally graded piezoelectric materials | Composite Structures | Examines the increased robustness of adaptive structures employing FGPMs. |

## CONCLUSION

In conclusion, the integration of functionally graded piezoelectric materials in sustainable manufacturing presents a promising avenue for enhancing the efficiency and sustainability of manufacturing processes. By leveraging the unique properties of piezoelectric materials, such as their ability to convert mechanical energy into electrical energy, manufacturers can develop innovative solutions for energy harvesting, structural health monitoring, and vibration control. This integration can lead to significant improvements in the environmental footprint of manufacturing operations, by reducing energy consumption and minimizing waste. Furthermore, the use of functionally graded piezoelectric materials can pave the way for the development of smart manufacturing systems that are both energy-efficient and cost-effective. While there are still challenges to overcome in terms of material design, fabrication techniques, and scalability, the potential benefits of this technology make it a promising area for further research and development in sustainable manufacturing. Sensors and actuators are essential for sustainable manufacturing by regulating, monitoring, and optimizing energy use. Sensors gather data on temperature, pressure, and material properties for control systems to reduce inefficiencies. Actuators perform precise mechanical tasks based on sensor information, improving processes like assembly and fabrication. This combination creates smarter manufacturing systems that can self-regulate, enhancing efficiency and equipment lifespan. In summary, functionally graded piezoelectric actuators offer exciting possibilities for smart sustainable manufacturing, but their design, fabrication, and material selection require careful consideration to overcome challenges and limitations.

## ACKNOWLEDGMENT

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

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