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Piezoelectric Energy Harvesting: An Untapped Nigerian Resources

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Abstract **- Nigeria's energy landscape is characterized by significant challenges, including inadequate power generation and distribution. However, the country possesses untapped potential for renewable energy harvesting, particularly through piezoelectric materials. This paper explores the potential of piezoelectric energy harvesting as a viable solution to Nigeria's energy needs. We review piezoelectric energy harvesting, its applications, and the potential benefits of adopting this technology in Nigeria. Our analysis reveals that piezoelectric energy harvesting can provide a sustainable and decentralized source of energy and transportation infrastructure. We also identify challenges and opportunities for implementing piezoelectric energy harvesting in Nigeria, including infrastructure development, research and development, and policy support. This study highlights the potential of piezoelectric energy harvesting to contribute to Nigeria's energy mix and promote sustainable development.**

Keywords: Piezoelectric energy harvesting, renewable energy, Nigeria, sustainable development, energy access.

I. INTRODUCTION

As the world grapples with soaring energy demands, the shift toward renewable and sustainable energy sources have become a global imperative, driven by the depletion of fossil fuels and the urgent need to curb greenhouse gas emissions [1] . In developing countries like Nigeria, where grid instability and frequent power outages hinder economic progress and quality of life, innovative energy solutions are not just desirable but essential [1]. Energy harvesting technologies, which capture ambient energy from the environment, offer a promising route to address this need. Among these, piezoelectric energy harvesting (PEH) stands out for its ability to convert mechanical stress—such as vibrations from footsteps or vehicle motion—into electrical power, making it suitable for powering low-power devices and infrastructure in resource-constrained environments [2].Piezoelectricity, discovered in the 1880s by Pierre and Jacques Curie, relies on the unique property of certain materials to generate electric charge under mechanical strain, enabling applications in wireless sensors, mobile devices, and smart infrastructure [1]. In Nigeria, where high population density and heavy traffic create abundant sources of mechanical vibrations, PEH presents an opportunity to support decentralized energy solutions.

This study reviews the principles of piezoelectric energy harvesting, evaluates the availability of piezoelectric materials in Nigeria, and explores potential applications within the Nigerian context, highlighting how this technology can contribute to addressing the nation's energy challenges.

II LITERATURE REVIEW

A: Piezoelectric Energy Harvesting Principles

The elegance of PEH lies in its ability to transform everyday mechanical movements into electrical energy, a process rooted in the direct piezoelectric effect. This occurs when non-centrosymmetric crystalline materials, such as Lead Zirconate Titanate (PZT) or barium titanate, generate an electric charge under mechanical stress [2, p. 2].

[31] describe PZT-based system where mechanical pressure from footsteps produces AC voltage, calculated as:

$$v_g(t) = d_{33} \times \frac{f(t)}{C_p} \quad (1)$$

where d33 the piezoelectric strain constant, f(t)f(t)f(t) is applied pressure, and Cp is the material's capacitance (p. 134). The energy output is:

$$E=P\times t \quad (2)$$

[2] highlight the role of resonance, where maximum efficiency is achieved when the applied frequency matches the material's mechanical resonance frequency:

$$f_0 = \frac{1}{2t}\sqrt{\frac{K}{\rho}} \quad (3)$$

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where its thickness, KKK is stiffness, and ρ\rho is density (p. 3). Advanced techniques such as synchronized switch harvesting on inductor (SSHI) improve efficiency by reducing power loss during voltage flipping [2. p .4].

[3] and [4] present practical implementations in Nigeria, using arrays of piezoelectric sensors to capture footstep energy, rectifying it from AC to DC, and storing it in batteries for low-power applications.

B. Piezoelectric Materials

Material choice determines the efficiency, durability, and cost-effectiveness of PEH systems. [2] recommend PZT-5H for its high-power output at low frequencies, outperforming Polyvinylidene Fluoride (PVDF) in conversion efficiency [p. 133].

[2] emphasize PZT's high electromechanical coupling coefficients for structural applications, while PVDF's flexibility suits floor mats and curved designs (p. 5). [1] classify piezoelectric materials into ceramics, composites, polymers, and monocrystals, noting ceramics' dominance due to strong conversion performance.

Other materials include quartz, tourmaline, and Rochelle salt—chosen for specific properties like durability or high voltage coefficients but limited by frequency response or chemical sensitivity [2]; [1]. Lead-free alternatives like barium titanate are emerging for sustainability reasons [14].

III. CONCEPT OF PIEZOELECTRICITY

A. Definition and Discovery of the Piezoelectric Effect

Piezoelectricity is a phenomenon that transforms mechanical stress into electrical energy, offering a sustainable pathway to power modern devices. Discovered in 1880 by Pierre and Jacques Curie, this effect was first observed in crystals like quartz, topaz, and Rochelle salt, where mechanical compression along a polar axis generates an electric charge, creating positive and negative poles across the material [1]; [2]. This groundbreaking discovery, as [2] emphasize, unveiled the potential to harness ambient vibrations—such as footsteps or vehicle motion—for electricity generation, a vital solution for Nigeria's grid-unstable regions (p. 2). The term *piezoelectricity*, derived from the Greek *piezein* ("to press") and *electron* ("amber"), underscores its ability to produce electricity from mechanical deformation, sparking innovation in energy harvesting for low-power applications [32]

B. Types of Piezoelectric Materials (Natural vs. Synthetic)

Piezoelectric materials fall into two distinct categories: natural and synthetic, each with unique properties shaping their role in energy harvesting. Natural materials, including quartz, tourmaline, and Rochelle salt, possess inherent piezoelectricity due to their asymmetric crystalline structures [1], [4], Quartz is prized for its durability and high stiffness, while tourmaline offers a high voltage coefficient, though both are limited by lower electromechanical coupling compared to synthetic alternatives [2]. Rochelle salt, despite its strong piezoelectric effect, is constrained by hygroscopicity and temperature sensitivity [2, p. 5].

Synthetic materials, engineered for superior performance, include ceramics like lead zirconate titanate (PZT), polymers like polyvinylidene fluoride (PVDF), composites such as macro fiber composites (MFC), and monocrystals like PZN-PT [1, p. 563]. PZT excels in energy conversion efficiency, while PVDF's flexibility suits applications like floor mats [31]; [4]. Lead-free ceramics, such as barium titanate, are gaining traction for environmental sustainability, addressing concerns about lead-based materials like PZT [2, p. 6]; [14].

C. Working Principle (Direct and Inverse Piezoelectric Effects)

The piezoelectric effect operates through two complementary mechanisms: the direct and inverse effects. The direct piezoelectric effect—the cornerstone of energy harvesting—generates an electric charge when a material is mechanically stressed. [31] quantify this with the

relationship: $$v_g(t) = d_{33} \times \frac{f(t)}{C_p} \qquad (4)$$

Where:
$v_g(t)$= generated voltage as a function of time (V)
d_{33}= piezoelectric strain constant (C/N)
f(t) = applied force or pressure as a function of time (N)
Cp= capacitance of the piezoelectric material (F)

The efficiency of energy harvesting peaks at the resonance frequency, expressed as:

$$f_0 = \frac{1}{2t}\sqrt{\frac{K}{\rho}} \qquad (5)$$

Where:

- f = resonance frequency (Hz)
- t= thickness of the material (m)
- K = stiffness of the material (N/m²)
- ρ = density of the material (kg/m³)

The inverse piezoelectric effect, in contrast, occurs when an applied electric field induces mechanical deformation, enabling actuation in sensors or vibration control systems [1, p. 560].

Advanced techniques, such as synchronized switch harvesting on inductor (SSHI), further enhance energy extraction by reducing losses [33]; [2, p.4].

1) *Commonly Used Materials (e.g., Quartz, PZT, PVDF, ZnO, etc.)*

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Vol. 14 Issue 10, October - 2025

The success of piezoelectric energy harvesting hinges on the choice of materials.

Quartz: High electrical resistivity and temperature stability but low piezoelectric coefficients.

PZT: Gold standard for energy conversion efficiency, with a charge constant often reaching:

$$d_{33} = \frac{460\text{pC}}{\text{N}} \tag{6}$$

- PVDF: Flexible, low acoustic impedance, suitable for floor mats.
- ZnO: High sensitivity and biocompatibility, used in nanoscale devices.

Other notable materials include barium titanate (lead-free ceramic), aluminum nitride (high output at specific frequencies), and macro fiber composites (enhanced durability for vibration harvesting).

These materials are applied across diverse systems—from highway energy recovery to wearable harvesters—offering promising solutions for Nigeria's growing energy demands.

IV. PIEZOELECTRIC ENERGY HARVESTING

A. Overview of Energy Harvesting Technologies

Energy harvesting converts ambient energy into electrical power, reducing dependence on batteries and promoting sustainability. Key technologies include solar, thermal, RF, and mechanical harvesting, each suited to specific environments based on power density and availability.

Solar harvesting, using photovoltaic cells, delivers high power density (up to 15 mW/cm² in sunlight) but is limited by weather and light availability [36]. Thermal harvesting leverages temperature gradients via thermoelectric generators, offering steady output in heat-rich settings but with low efficiency (5–8%) due to material limitations [12]. RF harvesting captures electromagnetic waves from Wi-Fi or cellular signals, with power densities ranging from 0.2 nW/cm² to 1 µW/cm², ideal for urban IoT but constrained by distance [35]. Mechanical harvesting, particularly through piezoelectric materials, excels in vibration-rich environments, converting kinetic energy from machinery or human motion into electricity.

Comparative studies highlight tradeoffs. RF harvesting's predictability suits indoor applications, while solar dominates in outdoor settings [37]. Mechanical harvesting, especially piezoelectric, is versatile for industrial and wearable applications, with power outputs in the microwatt-to-milliwatt range depending on vibration frequency [36]. Hybrid systems combining RF with piezoelectric harvesting enhance reliability in dynamic environments, leveraging RF's consistency and mechanical sources' ubiquity [35].

B. Role of Piezoelectric Materials in Harvesting Mechanical Energy

Piezoelectric materials convert mechanical stress from vibrations, pressure, or footsteps into electrical energy via the direct piezoelectric effect. The open-circuit voltage generated can be expressed as:

$$V(t) = \frac{d_{33} \cdot F(t)}{C_p} \tag{7}$$

where:

- d33 = piezoelectric charge constant (C/N)
- F(t) = applied force (N)
- Cp= capacitance of the piezoelectric element (F)

In vibration-based harvesting, cantilever beams and compliant mechanisms optimize energy capture across wide frequency ranges, with mono-stable and multi-stable designs enhancing nonlinear dynamics [29]. PZT's high stiffness suits high-frequency vibrations, while PVDF's flexibility is ideal for low-frequency sources like body motion.

For footstep harvesting, a stack configuration can be used to increase the output voltage:

$$V_{stack}=n \cdot V_{single}$$

where *n* is the number of stacked layers.

C. Mechanisms and Circuit Integration for Energy Storage and Conversion

Piezoelectric harvesters typically operate in 31 (transverse) or 33 (longitudinal) mode. The output electrical power can be approximated by:

$$P = \frac{V_{\text{rms}}^2}{R_{\text{load}}} \tag{8}$$

where:

- V_{rms} = root-mean-square output voltage (V)
- R_{load} = load resistance (Ω)

Circuits like Synchronous Electric Charge Extraction (SECE) and Synchronized Switch Harvesting on Inductor (SSHI) enhance harvested power by up to 400%. For SSHI, the improvement factor can be expressed as:

$$G_{\text{SSHI}} \approx 1 + \frac{\pi Q}{2} \tag{9}$$

where Q is the quality factor of the system.

D. Applications of Piezoelectric Energy Harvesting

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Piezoelectric energy harvesting has transitioned from theoretical concepts to practical implementations worldwide, leveraging mechanical stress from everyday activities to generate electricity. Real-world applications in various countries demonstrate how this technology promotes sustainability, reduces energy costs, and powers remote systems.

E. Global Use Cases: Footpaths, Roads, Industrial Machines, Biomedical Sensors

Piezoelectric systems in footpaths convert pedestrian footsteps into electrical energy, often using tiles embedded with materials like PVDF or PZT. In Japan, since 2008, piezoelectric floors have been installed in high-traffic areas such as Tokyo Station and shopping malls, generating power for lighting and displays; for instance, East Japan Railway Company's system produces up to 100,000 kWh annually from commuter footsteps. In the United Kingdom, Pavegen's kinetic tiles have been deployed in London transport hubs and public spaces, powering streetlights and interactive displays; a 2017 installation at Bird Street generated energy equivalent to charging 10,000 phones daily. South Korea has implemented sidewalk panels in urban areas, converting pedestrian pressure into energy for nearby facilities, with pilot projects in Seoul yielding small-scale power for sensors. Saudi Arabia applies this in religious sites like Al-Haram Mosque, where high foot traffic harvests energy for lighting, potentially saving 2-5% on electricity in such venues[3]. Portugal's Waynergy system uses pavement tiles in public walkways, generating 1-5 W per module for off-grid applications [3].

For roads, piezoelectric transducers embedded in asphalt capture vehicle-induced vibrations and pressure. Israel pioneered this with Innowattech's installations on the Ayalon, Coastal, and Trans-Israel Highways in 2009, embedding devices 5 cm below the surface to harvest energy from traffic, powering roadside sensors and lights with outputs up to 400 kWh per km annually. In the United States, California's Energy Commission funded a high-density roadway project in 2023, aiming for 333 W per square foot to supply grid-independent power for highways [16]. China has tested piezoelectric pavements in urban roads, using vehicle bending deformation for energy, with models showing potential for structural health monitoring [16].

Industrial machines utilize piezoelectric harvesters to convert machinery vibrations into power for sensors. In Germany, manufacturing firms integrate these in ultrasonic motors and vibration suppression systems for aero foils, enhancing efficiency in automotive plants [3]. The United States applies them in industrial equipment like refrigerators and washing machines, where vibrations power condition-monitoring sensors [15]. France and the UK lead in market adoption, using piezoelectric systems in heavy machinery for predictive maintenance, reducing downtime by harvesting ambient mechanical energy [3].

Biomedical sensors benefit from flexible piezoelectric materials for self-powered implants and wearables. In the United States, DARPA-funded projects harvest from human motion for pacemakers and knee implants, extending battery life in physiological monitoring [13]. China advances nanogenerators for tissue engineering, using ZnO-based sensors in implants for real-time health data [15]; [29]. Switzerland develops self-powered active implants, harvesting from body movements for neurological devices [28]. African countries like South Africa and Nigeria explore prospects for low-cost biomedical harvesters in remote healthcare, powering sensors
for disease monitoring

V. METHODS:

A. Energy Harvesting from Human Motion, Vehicles, Machinery, and Buildings

Human motion harvesting involves wearables and insoles converting gait or body movements into energy. In Japan, shoe-mounted harvesters' power biomedical sensors from walking, integrated into dynamoelectric footwear [13]. The United States uses backpack and joint-based systems for portable electronics, generating 1-10 mW from ambulation [30]. Egypt investigates piezoelectric tiles in public buildings, harvesting from footsteps for facility lighting [17].

From vehicles, piezoelectric systems capture suspension vibrations and tire pressure. Israel's highway installations power traffic signals from vehicle loads [16]. In the USA, tire-embedded harvesters monitor pressure in real-time, enhancing safety in automotive applications [3].

Machinery harvesting focuses on industrial vibrations. Germany's aerofoil systems suppress vibrations while generating power for sensors [3]. China's engine vibration harvesters support structural monitoring in manufacturing [16].

In buildings, piezoelectric floors harvest from occupant motion. Saudi Arabia's mosque applications power internal systems [3]. The UK uses them in metro stations for energy-efficient lighting [17]. Finland explores integration in smart cities for sustainable building power.

B. Relevance to Off-Grid or Low-Resource Environments

Piezoelectric harvesting is particularly valuable in off-grid and low-resource settings, providing decentralized power without infrastructure. In developing African countries, such as Nigeria and Kenya, it's proposed for self-powered IoT sensors in remote healthcare and agriculture, harvesting from human motion to monitor vital signs or soil conditions affordably. India tests footpath systems in rural areas, powering village lights from pedestrian traffic [15]. In oceanic buoys off Australia's coast, piezoelectric wave harvesters enable off-grid monitoring [13]. Saudi Arabia's mosque pilots demonstrate scalability for resource-limited religious sites. These applications reduce reliance on batteries, lowering costs and environmental impact in areas with limited electricity access.

D. Material Availability in Nigeria for Piezoelectric Energy Harvesting

Piezoelectric energy harvesting depends on materials that generate electricity under mechanical stress, with natural minerals like quartz, tourmaline, and topaz being key examples due to their inherent piezoelectric properties. Nigeria possesses substantial deposits of these minerals, primarily within its Basement Complex geological formations, which span the central and northern regions. This review evaluates Nigeria's relevant mineral resources, including their locations, assesses mining, purification, and processing capabilities, identifies accessibility and infrastructure challenges, and highlights the imperative for research and policy support in material science to enable applications in energy harvesting.

E. Nigeria’s Natural Mineral Resources with Piezoelectric Properties

Nigeria's mineral wealth includes several natural resources with piezoelectric characteristics, such as quartz, tourmaline, and topaz, which can support energy harvesting from vibrations, pressure, or human motion. Quartz, a silica-based crystal renowned for its strong piezoelectric response and ease of machining, is abundantly found in states like Kogi and Nasarawa in the north-central region, as well as Ogun in the southwest, Plateau in the north-central, and Kaduna in the northwest. These deposits occur in granitic and pegmatitic rocks, making quartz suitable for applications in sensors and harvesters [25]. Tourmaline, another piezoelectric gemstone valued for its pyroelectric and piezoelectric dual properties, is located in pegmatite veins across Oyo, Benue, and Kaduna states in the southwest and north, as well as Ekiti (specifically Ijero area) in the southwest and Ogun in the southwest. Tourmaline often co-occurs with other gems like beryl and muscovite, enhancing its potential for multifunctional harvesting devices [10].

Topaz, a silicate mineral with notable piezoelectric effects similar to quartz, represents an additional resource, primarily deposited in Nasarawa and Plateau states in the north-central region. While less emphasized in local extraction, topaz's hardness and electrical properties make it viable for high-durability harvesters [25]. Other supportive minerals, such as garnet (which can exhibit weak piezoelectric traits in certain forms), are found alongside tourmaline in southwestern pegmatites. These resources are underexplored for piezoelectric applications, but global reviews indicate their suitability for low-cost, sustainable energy solutions in vibration-rich environments [10].

F. Assessment of Mining, Purification, and Processing Capabilities

Mining in Nigeria for piezoelectric minerals is largely artisanal and small-scale, concentrated in the aforementioned states. Quartz extraction in Plateau and Nasarawa relies on manual digging and basic tools, yielding raw material for export or local use, but with limited mechanization [38]. Tourmaline mining in Ekiti and Oyo involves surface pegmatite quarrying, often integrated with gemstone operations, while topaz in Nasarawa uses similar rudimentary methods. Purification processes, essential for removing impurities like iron oxides from quartz to achieve piezoelectric-grade purity (over 99.9% silica), are underdeveloped; most operations employ simple washing or manual sorting, far below international standards requiring acid leaching or flotation [4]; [25].

Processing capabilities for these minerals into usable piezoelectric forms, such as thin films or crystals, are minimal. Nigeria lacks specialized facilities for crystal growth or doping, with most quartz and tourmaline exported unprocessed from sites like Kaduna and Ogun [10]. Topaz processing is even scarcer, limited to cutting for jewelry rather than electronic applications. While some basic beneficiation occurs in Plateau for quartz, the absence of advanced equipment like chemical vapor deposition systems hinders production of high-performance harvesters (.

VI. FINDINGS:

A. Challenges in Material Accessibility and Processing Infrastructure

Accessibility to piezoelectric minerals is impeded by geographical and logistical issues. Deposits in remote areas like Nasarawa's topaz sites or Ekiti's tourmaline veins suffer from poor road networks, making transportation costly and inefficient. Insecurity in northern states like Plateau and Kaduna disrupts quartz mining, while environmental degradation from artisanal practices reduces deposit viability. Processing infrastructure is critically deficient; unreliable electricity in mining hubs like Ogun and Oyo hampers purification, and the lack of refineries forces dependence on foreign processing, inflating costs [4]

Further challenges include regulatory inconsistencies and skill gaps. Informal mining in Benue for tourmaline leads to resource wastage, and without cleanroom facilities, Nigeria cannot produce contamination-free piezoelectric materials essential for energy harvesting [25]. Global comparisons highlight that while countries like Brazil refine tourmaline locally, Nigeria's infrastructure lags, limiting accessibility for domestic applications [10].

B. Need for Research and Policy Support in Material Science

To capitalize on Nigeria's piezoelectric resources, urgent research is required to map deposits in states like Nasarawa and Ekiti using geophysical surveys and assess their quality for harvesting [38]. Material science studies should explore local synthesis, such as combining quartz from Kogi with dopants for enhanced properties, drawing from global piezoelectric advancements [25]. Institutions like the Nigerian Geological Survey Agency could lead characterizations of tourmaline and topaz for biomedical or industrial harvesters.

Policy support must prioritize infrastructure investment, including subsidies for mechanized mining in Plateau and purification plants in Ogun [4]. Enforcing sustainable practices via updated mining laws would mitigate environmental challenges, while international partnerships could transfer processing technologies. Funding for university research in piezoelectric applications would foster innovation, positioning

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Vol. 14 Issue 10, October - 2025

Nigeria to meet off-grid energy needs with local materials [10].

C. Potential Applications of Piezoelectric Energy Harvesting in Nigeria

Piezoelectric energy harvesting, which converts mechanical stress into electrical energy, offers substantial promise for Nigeria, a country facing persistent energy shortages while possessing rich deposits of minerals such as quartz and tourmaline that can support this technology. By utilizing these local resources, Nigeria can implement piezoelectric systems in diverse sectors, including public infrastructure, transportation, healthcare, agriculture, and industry. This review examines the potential applications in smart footpaths within public places such as markets, churches, streets, and university walkways; integration into roads and highways characterized by high vehicular traffic; biomedical and wearable devices for health monitoring; remote sensors in agriculture and oil industries; and opportunities for local manufacturing and small-scale startups. The discussion is informed by global and regional studies, adapted to Nigeria's unique socio-economic and infrastructural conditions.

D. Smart Footpaths in Public Places

Public spaces in Nigeria, including crowded markets, churches, streets, and university walkways, represent high-potential sites for the deployment of smart footpaths equipped with piezoelectric tiles. These tiles, fabricated from materials such as lead zirconate titanate (PZT) or polyvinylidene fluoride (PVDF), capture kinetic energy from pedestrian footsteps to generate electricity for applications like lighting, signage, or environmental sensors. Research by [17] indicates that piezoelectric flooring in areas of intense foot traffic can produce 1-5 W per tile, providing a reliable source for low-power needs. In markets, this energy could enhance visibility during evening hours, promoting safer trading environments. Churches could utilize the harvested power for audio amplification or illumination during gatherings, while streets and university walkways might benefit from self-powered security lighting or device charging stations. Such implementations would leverage Nigeria's abundant quartz reserves, fostering energy autonomy in urban and semi-urban settings where grid reliability is often compromised [3; 15].

VII DISCUSSIONS

A. Integration into Roads and Highways with High Vehicular Traffic

Roads and highways in Nigeria, often subjected to substantial vehicular loads, provide an excellent opportunity for incorporating piezoelectric transducers beneath pavement surfaces to harvest energy from traffic-induced vibrations and pressures. This generated electricity could power roadside infrastructure, including traffic signals, monitoring systems, or charging facilities. Studies by [3] demonstrate that similar systems in high-traffic contexts can yield up to 400 kWh per kilometer annually, with enhanced outputs from stacked PZT layers under heavy vehicles. In Nigeria, this approach could improve road safety by ensuring consistent illumination and sensor functionality, particularly in areas prone to power outages. Utilizing locally sourced quartz for transducer production would further reduce costs and dependence on imports, contributing to a more sustainable transportation network [15].

B. Biomedical and Wearable Devices for Health Monitoring

Piezoelectric energy harvesting has considerable potential in Nigeria's healthcare domain, particularly for developing self-powered biomedical implants and wearable devices that facilitate continuous health monitoring. Nanogenerators constructed from zinc oxide (ZnO) or PVDF can derive energy from bodily movements to operate sensors measuring vital parameters such as heart rate, blood pressure, or glucose levels, addressing prevalent health issues like cardiovascular diseases and diabetes.[13] highlight the effectiveness of such devices, including insoles capable of generating 1-10mW per step for ongoing data collection. In Nigeria, these technologies could extend healthcare reach to underserved populations, enabling preventive monitoring without frequent battery replacements. Incorporating local tourmaline into device fabrication could lower production expenses, making these solutions more accessible and culturally integrated [15].

C. Remote Sensors in Agriculture and Oil Industries

The agricultural and oil sectors in Nigeria, which are foundational to the national economy, stand to gain from piezoelectric-powered remote sensors that operate on ambient mechanical energies for prolonged, maintenance-free monitoring. In agriculture, sensors could harness vibrations from equipment or human activity to track soil conditions, crop health, or irrigation needs, supporting precision practices that optimize resource use and increase productivity.[15] describes the adaptability of piezoelectric IoT sensors for such purposes, which could be particularly beneficial in Nigeria's diverse farming regions. In the oil industry, these sensors could monitor pipeline integrity or machinery performance through vibrational analysis, mitigating risks like leaks or failures. By employing quartz from domestic sources, these applications would promote operational efficiency and environmental stewardship in off-grid or challenging terrains [3].

D. Opportunities in Local Manufacturing and Small-Scale Startups

Piezoelectric energy harvesting applications open avenues for local manufacturing and small-scale startups in Nigeria, capitalizing on indigenous mineral resources like quartz and tourmaline to produce cost-effective devices. Startups could specialize in fabricating piezoelectric tiles for public spaces or sensors for industrial use, drawing on scalable designs outlined by [17]. [13] underscore the viability of adaptable wearable technologies, which entrepreneurs could tailor for health monitoring markets. The agriculture and oil sectors offer additional niches for sensor development, with potential for innovation in vibration-based monitoring systems [15]. To realize this potential, supportive policies such as funding for

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Vol. 14 Issue 10, October - 2025

research and development or access to fabrication facilities would be essential, enabling startups to create jobs, stimulate economic growth, and reduce import reliance [3].

E. Challenges and Recommendations

Piezoelectric energy harvesting in Nigeria faces multifaceted challenges that impede its widespread adoption and development. Drawing from relevant literature, this section outlines technological, economic, and infrastructural barriers, as well as issues related to awareness, investment, and policy support. It concludes with recommendations for advancing research, securing funding, and fostering collaborations among universities, government, and the private sector.

F. Technological, Economic, and Infrastructural Barriers

Technological barriers in piezoelectric energy harvesting include low power output, material brittleness, frequency mismatches, and fabrication complexities, which limit efficiency and durability in real-world applications [14];[12]. In Nigeria, these issues are exacerbated by inadequate local expertise and facilities for material synthesis and device prototyping, such as the absence of advanced cleanrooms or testing equipment for piezoelectric composites [19]). Nigeria does not have a functional material science center dedicated to evaluating combinations of indigens piezoelectric materials like quartz and tourmaline for enhanced performance. Economic barriers encompass high initial costs for materials and deployment, low return on investment, and limited commercialization prospects, particularly in developing contexts where funding is scarce [18; 21]. Infrastructural deficits, such as unreliable electricity and poor transportation networks, further hinder mining, processing, and integration of piezoelectric systems into applications like roads or sensors [20].

G. Lack of Awareness, Investment, and Policy Backing

A significant hurdle is the lack of awareness among stakeholders about piezoelectric technologies, coupled with insufficient investment and policy frameworks to support innovation. In African countries including Nigeria, there is limited public and institutional knowledge of energy harvesting benefits, leading to underutilization in sectors like biomedical devices [20]. Investment gaps stem from high capital requirements and perceived risks, while policy backing is weak, with no dedicated incentives for renewable energy research [18; 21]. The government of Nigeria does not finance the educational sector comparably to its counterparts in other African and European nations, resulting in underfunded universities and research institutions. While the Nigerian government has not been benevolent enough in providing adequate support, researchers, when given grants for research, often end up squandering the money with little or nothing to show for it. Although some researchers have conducted reasonable work, there has been a persistent broken link between research outputs and practical implementation, preventing innovations from reaching societal impact.

VIII. CONCLUSION AND RECOMMENDATIONS FOR RESEARCH, FUNDING, AND COLLABORATION

To overcome these challenges, concerted efforts are needed in research, funding, and collaboration. Research should prioritize hybrid piezoelectric systems, lead-free materials, and mathematical modeling to improve efficiency, with a focus on local applications like vibration harvesting. Funding mechanisms, such as capital subsidies and public-private partnerships (PPPs), should be established to support prototypes and scale-up, drawing from successful models in West Africa. Collaboration between universities, government, and the private sector is essential for instance, joint initiatives could develop policy frameworks for energy harvesting integration, enhancing awareness through training programs and bridge the research-implementation gap via technology transfer hubs [20; 21]. Universities should lead the technicalities and testing ground while government provide regulatory support, and private firms invest in commercialization thereby fostering a sustainable ecosystem for piezoelectric advancements in Nigeria [19]

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