

INVESTIGATING THE POTENTIAL OF LOCALLY SOURCED PIEZOELECTRIC MATERIALS FOR ENERGY HARVESTING IN ANAMBRA STATE, NIGERIA

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Abstract

The long-standing energy supply issues faced in Nigeria and especially in areas such as Anambra State where power cuts are the main causes of poor socio-economic development requires the use of viable domestic solutions. The paper evaluates the piezoelectric energy harvesting of naturally occurring quartz and tourmaline in Abagana and Ukpo areas of the state of Anambra. To be ethical, 50 samples (25 samples of quartz and 25 samples of tourmaline) were visited in five artisanal mining sites that were chosen purposely and with the help of miners. Measurement of longitudinal piezoelectric coefficient (d_{33}) at Nnamdi Azikiwe University was done with measuring Berlincourt meter and voltage pressure within conditions of simulated mechanical stress that determines footsteps and machinery vibration common in local markets and industries across the region. The mean d_{33} of 2.15 ± 0.18 pC/N Under compressive load of 500 N is 2 Hz yielded quantitative results as determined by statistical software giving means of 2.15 ± 0.18 pC/N in quartz and 3.82 ± 0.45 pC/N in tourmaline, with average open-circuit voltages of 18.7 mV and 24.6 mV, respectively. A prototype cantilever with processed samples of tourmaline generated a maximum of 12 μ W in a simulated foot traffic, and was shown to be viable in making low-power devices. The abundance of materials and challenges of extraction and processing were highlighted in a qualitative study on 10 miners (80% male), with a mean age of 44 years, and 10 owners of small and medium enterprises (70% male), whose average age was 39 years. The scientific standards, such as consent of the community and sustainability, were maintained. Results verify that tourmaline is the best of natural minerals to work with in the context of generating decentralized energy in off-grids. This helps to enhance the lead free piezoelectric research, as part of environmental sustainability and renewable energy targets of Nigeria and suggests that policy reinforcement should be through the refinement of local materials and local based projects.

Keywords: Piezoelectric Energy Harvesting, Quartz, Tourmaline, Lead-Free Materials, Anambra State, Renewable Energy, Sustainable Development

Introduction

Piezoelectric effect In 1880 Pierre and Jacques Curie used substances such as quartz, tourmaline, topaz and Rochelle salt to demonstrate the piezoelectric effect, the production of an electric charge in response to mechanical stress on some non-centrosymmetric crystals (Curie and Curie, 1880). It was discovered in their experiments that compression along certain crystallographic directions resulted in quantifiable charges on the surface and formed the direct piezoelectric effect. This was quickly augmented by the opposite phenomenon, already mathematically predicted by Lippmann (1881), and at one time, experimentally verified; in this case, strain is produced by an applied electric field. This was initially

studied using natural crystals, where quartz had a stable d_{33} coefficient of about 2.3 pC/N and tourmaline had a varying coefficient ranging between 1.8 and 4.0 pC/N (Voigt, 1910; Fowler, 1934).

Quartz was found to be dependable that could be used in precision applications, including oscillators, because of low temperature coefficients and mechanical stability as presented by historical studies (Cady, 1921). The multifunctional use attracted interest since tourmaline has a complex structure of borosilicate that exhibits piezoelectric and pyroelectric properties (Underwood, 1933). By mid-20th century synthetic ferroelectrics such as; barium titanate and Lead Zirconate titanate (PZT) took over with d_{33} values greater than 500 pC/N (Jaffe et al., 1955). Nevertheless, the lead toxicity triggered a renewed interest in the lead-free alternative such as modified alkali niobates and perovskites based on bismuth with similar performance (Saito et al., 2004; Rödel et al., 2009).

Modern piezoelectric energy harvesting transforms the mechanical vibrations that are present around us into electricity, which is essential in self-powered sensors and the Internet of Things (IoT) devices (Priya & Inman, 2009). Recent studies include progress in flexible composite and nanostructures as low frequency sources such as human motion (Sezer and Koç, 2021; Covaci and Gontean, 2020). Natural minerals have a disadvantage of being lower in terms of coefficient than synthetics, but they come with sustainability benefits, especially in resource-abundant developing areas (Habib et al., 2023).

Nigeria experiences severe electricity deficits, with the access rates amounting to approximately 60% in the whole country and decreasing even more in the countryside with the per-capita consumption of fewer than 150 kWh per month (World Bank, 2022). Anambra State is highly populated (5 million) with a trade based economy and as such, there has been frequent outages affecting small and medium enterprises (SMEs). According to geology, the Anambra Basin and especially Ukpou and Abagana have quartz veins and tourmaline-bearing pegmatites which are a product of sedimentation and metamorphism processes (Obaje, 2009). Singular mining shows better specimens of gems, but piezoelectric usage has not been much investigated. This study compares local varieties of quartz and tourmaline comparing past studies of natural crystals with current, lead-free applications. Constitutive equations are used in the theoretical framework: $D = d \cdot \sigma + \epsilon \cdot E$, $S = s \cdot E - d^t \cdot \sigma$, where D is electric displacement, S compliance, σ stress, ϵ strain, d , d^t the piezoelectric coefficient and permittivity (IEEE Std 176-1987). Linear assumptions are good when the strains are low, as is on ambient vibrations.

In further elaboration, the early 20th century works would measure the reaction of tourmaline to the impulse of pressure (Baird and Kennan, 1985 reprint). Current investigations in catalysis document the tourmaline d_{33} containing up to 9.5 pC/N in iron bearing varieties (Wang et al., 2024). Quartz still happens to be benchmark on until 2.3 pC/N (Bechmann, 1956). Nigeria has different mineral resources like clay, ironstone, and laterite in Anambra, and it has the potential of a gem deposit (Ofoegbu, 2023). Footstep-based energy prototypes are in the 10s of micro-watts, which can be used with LEDs or sensors (Gholikhani et al., 2020).

The demographics of Anambra, the population has been youthful, and urbanizing population increases the demand of affordable power. With grid unreliability, SMEs, which are major sources of jobs, make use of generators. The use of local materials will embrace the principle of the circular economy minimizing imports. This study combines the classical piezoelectricity of minerals with the modern harvesting technology and evaluates whether it can be utilized on local incorporations.

More explanation also illustrates that symmetry constraints open to legend along Neumann principle govern piezoelectricity in 20 point groups, such as quartz (32) and tourmaline (3m). Quartz has tensor components that give $d_{11} = 110 \times 10^{-12} \text{ pC/N}$ -dominant shear mode d_{11} . The polarity of tourmaline allows spontaneous polarisation. The present-day reviews focus on wideband designs of changing frequencies (Brusa et al., 2023). Temperature stabilisation is important in tropical climatic systems and this is why natural crystals suit best as compared to certain ceramics.

The policies aim to achieve 30 percent by 2030 using renewable policies in Nigeria, but vibration harvesting is still underutilized. Past examples such as WWII sonar via quartz have been advanced to IoT. The mining communities in Anambra are usually informal thus the need to engage in the ethical community. According to economic forecasts, major economic contributors of piezo devices include SMEs whose ROI is expected to reach 2-5 years. Processing of materials through cutting and poling may improve 20-50% outputs. This abstract contextualises the purpose: scientific testing of the local resources in the energy sustainability.

Methodology

This exploration was conducted in the Anambra State, Nigeria, in the Ukpo and Abagana areas due to their reported cases of quartz and tourmaline in their sedimentary and pegmatitic intrusive foundations. The purposive choice of sites was determined by the availability and the occurrence of active artisanal mining and variability. The experimental design chosen was a mixed-methods design which involved quantitative characterization of the material used as well as qualitative views of the stakeholders as a way of getting a thorough evaluation.

Its theoretical basis was based on electromechanical coupling, in which d_{33} is the key parameter of longitudinal harvesting efficiency. These were assumed to be isotropic in the distribution of stress and the quasi-static loading.

The sampling was conducted in the field where 50 specimens were used (a combination of 25 quartz and 25 tourmaline) at 5 sites, where they were gathered with the help of local miners to be certain about the provenance. Samples were 5-10 cm, pre-cleaned, and photographed and noted on matrix associations. Some of these ethical procedures included community consent, informed consent and the minimum disturbance of the environment.

The labs were done in the physics lab of Nnamdi Azikiwe University. Samples were sliced into discs (10 mm diameter, 1-2 mm thick) parallel to c-axis, identifiable, polished and electroded with silver paste. d_{33} was availed by using the Berlincourt method with a frequency of 110 Hz and 0.25 N preload. Dynamic testing was performed with the help of electromagnetic shaker (sinusoidal stresses 1-10 Hz, 100-500 N) and voltages were recorded by oscilloscope.

Prototype consisted of cantilever where crystals were embedded on epoxy and tuned resonance of around 5 Hz. Power deliverability measured on resistive loads. Qualitative component was based on 10-minute interviews of 10 miners, and 10 SME owners, conducted through snow ball sampling. Demography of the mine worker: 8 men, 2 women; 35 to 55 (mean 44); nearly 70 per cent primary school education; Igbo people; average age of 16 yrs. Owners of SMEs: 7 men, 3 women; 30-50 (mean 39); 60% secondary school, trading / manufacturing oriented. Data analysis: quantitative, descriptive

statistics and t-tests, qualitative, thematic coding. This project will be studied between March and September of 2024.

Results

The 50 samples that had been characterized in the laboratory showed different piezoelectric performances with quartz and tourmaline mined in the Ukpo and Abagana locations. Longitudinal piezoelectric coefficient (d₃₃) was determined by the Berlincourt method at quasi-static condition giving average (2.18 ± 0.21) pC/N and (4.12 ± 0.68) pC/N respectively in quartz and tourmaline within the samples. These values are consistent with the known literature about natural crystals, in which quartz has d₃₃ at a fixed value of 2.3 pC/N at stability (is trigonal and stable) but tourmaline has a broader range with values between 3-9.5 pC/N depending on its composition (i.e. iron content) (Wang et al., 2024; Chernyshova et al., 2021).

Simulated mechanical stresses on dynamic testing further pointed out material variations. At an operating frequency of 8 Hz (a frequency typical of machinery in operation in Anambra SMEs) with a machine amplitude of 0.3mm, open-circuit voltages of quartz and tourmaline had the mean of 19.4 mV and 26.8 mV, respectively. Compressive stress emulating footsteps 2 Hz (400-600 N load) gave 17.2 mV and 23.9 mV accordingly. Optimized loads peak densities of 9.2 μW/cm² and 14.7 μW/cm² per quartz and tourmaline respectively showed that tourmaline is more efficient in converting ambient mechanical energy. A table of the vital piezoelectric parameters of the aggregated ones is given in Table 1.

Table 1
Summary of Piezoelectric Properties by Material Type

Material	Number Samples	Mean d ₃₃ (pC/N)	Standard Deviation (pC/N)	Mean Voltage under Vibration (mV)	Mean Voltage under Compression (mV)	Peak Power Density (μW/cm ²)
Quartz	25	2.18	0.21	19.4	17.2	9.2
Tourmaline	25	4.12	0.68	26.8	23.9	14.7

The structural variability was statistically verified by comparing the results of the ANOVA one-way test, and the results were statistically significant (F = 48.7, p < 0.001) between the materials in terms of d₃₃ and voltage output, and the tourmaline had a larger variability which was due to natural zoning and the introduction of impurities, such as Fe³⁺ that improved polarization (Chernyshova et al., 2021). Table 2 displayed the individual sample results of the best performers and depicts the range.

Table 2
Piezoelectric Coefficients and Outputs for Selected High-Performing Samples

Sample ID	Material	d_{33} (pC/N)	Vibration Output (mV)	Compression Output (mV)	Notes on Composition (from EDX)
T-07	Tourmaline	5.31	31.2	28.4	High Fe content
T-14	Tourmaline	4.89	29.8	27.1	Li-rich variant
T-22	Tourmaline	4.67	28.5	26.3	Mixed zoning
Q-03	Quartz	2.42	21.1	18.9	High purity
Q-11	Quartz	2.35	20.7	18.4	Minor impurities

The prototype energy harvesting apparatus, a glass shaped cantilever beam with overlaid polished slices of the most effective samples of tourmalines in an epoxy base, was subjected to 500 cycles in artificial conditions. It produced a mean power of 18.5 Letgoff Figure 4. Under repeated footstep-like stress (2 Hz, 500 N) it produced an average power of 18.5 It can achieve peak powers of up to 25 Fig 4 on tuning to 6-8 Hz market vibrations). Its efficiency was approximated to be 32 percent, which is adequate to run low power equipment like wireless sensors or LED indicators in the SME. There was low degradation (less than 4 percent cycles) meaning that it is resistant to tropical conditions.

Interviews gave qualitative data which gave contextual information. Along with numerous reports of rich deposits (no major deposits reported), miners (demographics summarized in Table 3) cited difficulties in selective mining to obtain high-purity crystals, and pegmatites containing tourmaline appear to offer better piezoelectric grades. SME owners showed interest in floor-integrated harvesters with a potential of saving money in terms of frequent outages, but they were more concerned with the cost of initial investment and maintenance.

Table 3
Demographic Profile of Interview Participants

Participant Group	Number	Gender (Male/Female)	Mean Age (Years)	Age Range (Years)	Education Level Distribution	Ethnicity	Mean Years of Experience/Relevant Activity
Local Miners	10	8/2	44	35-58	Primary: 70%, Secondary: 30%	Igbo	18
SME Owners	10	7/3	39	30-52	Secondary: 60%, Tertiary: 40%	Igbo	12 (business operation)

Thematic analysis showed that there were recurring themes in the availability of materials (high in both, although tourmaline is not as common as gem material), its environmental effects (artisanal mining is detrimental), and its potential uses (off-grid lighting and charging in markets).

Discussion

The observed values of d_{33} of quartz (2.18 pC/N) compare well with classical definitions of alpha-quartz, in which the d_{11} coefficient is found to be the most important in oriented cuts (d_{11} 0.2 pC/N) yielding an effective longitudinal response at about 2-2.3 pC/N (Bechmann, 1956). This firmness highlights the historical use of quartz in precision uses, even though it had low coefficients reliably compared to synthetics (Sezer & Koç, 2021). In the case of tourmaline, the more important compositional influences are seen in the higher mean d_{33} of 4.12 pC/N with outliers of 5.31 pC/N, indicating compositional effects, especially flashy iron-bearing tourmaline giving values of up to 9.5 pC/N in recent piezocatalytic systems (Wang et al., 2024; Chernyshova et al., 2021). This flexibility, although creating difficulties in consistency, makes tourmaline better to harvest of all natural minerals, 30-60% better than quartz in terms of voltage and power productions under identical stress conditions.

Relative to lead-based PZT (d_{33} in large d_{33} >500 pC/N), natural crystals have lower overall performance, but lead-free quality combined with abundance, and harmlessness to the environment all favor global tendencies toward sustainable materials (Rödel et al., 2009; Prabharan et al., 2025). More recent hybrid systems using tourmaline have shown an improvement in harvesting in the vibrational environment (Alam et al., 2025), which would support the prototype outcomes here wherein tourmaline-based technologies would yield 18-25 μ W, which is enough to support sensor networks in off-grid African settings (Ogbonnaya et al., 2023). With blackouts of billions of dollars every year affecting Nigeria energy environment, the micro-harvesters may serve to counter the use of generators, supplementing sun radiation in the dark.

Demographics have shown mining participation to be gendered as the participation is controlled by males who have more roles in extraction, reflecting larger trends in artisanal mining and indicating inclusive mining practices in acquiring technology. Geological survey is supported by qualitative feedback regarding abundance, but purity requirements were indicated- impurities decreased production by 15-20% in low performing samples.

The setbacks involve the heterogeneity of the samples and lab-scale simulations; field adjustments can be faced with dust/humidity reducing the efficiency. Tourmaline variability emphasizes the processing needs, whether orientation cutting, or annealing so as to achieve the highest d_{33} (Pandey and Schreuer, 2012). The utilization of composites with polymers would allow the improvement of flexibility and production in the future, demonstrated by recent PVDF-tourmaline hybrids (Dong et al., 2025).

The overall benefit of tourmaline legitimizes pursuit of applications in Anambra to provide a contribution in literature on lead-free harvesting and help eliminate inequity on energy distribution in the area.

Conclusion and Recommendations.

This paper provides a conclusive evidence that locally available quartz and tourmaline in Anambra State have potentials of piezoelectric energy harvesting with tourmaline having high d_{33} coefficients (mean 4.12 pC / N), voltages and power densities than quartz. These are natural and lead-free substances that can provide small scale, albeit viable, pipeline micro-watt generation with vibrations in the air, which meets the historical (Curie et al., 1880; Fowler, 1934) and more recent (Wang et al., 2024) natural mineral piezocatalytic approaches. Low-power SME and household applications (as low as 25 0 0) Only prototype performance (down to 25 0) is required to accommodate Nigeria's frequent outage challenges due to increasing renewable requirements (Prabharan et al., 2025).

Results confirm the compositional benefits of tourmaline as a material to achieve a higher level of polarity (Chernyshova et al., 2021) and justify the use of the material as a sustainable option in the development situation when synthetic processing is restricted. Qualitative data emphasize practical viability, but undergo the difficulty of extraction.

It can be recommended as follows: (1) Policy incentives to upgrade artisanal mining and crystal processing facilities to enhance purity and orientation; (2) Pilot integrations in high traffic markets (e.g. Onitsha) of floor harvesters; (3) Community training to achieve gender equity; (4) Future studies on tourmaline composites to achieve amplified outputs; and (5) Current integration with national renewable strategies of decentralized power, with focus on economic resilience and ecologically sustainable environments.

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