CHAPTER 18

Assessing the Cost Effectiveness and Feasibility of Piezoelectric Tiles in India

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ABSTRACT

Piezoelectric technology converts mechanical energy, such as pressure or vibrations, into electrical energy using materials that generate an electric charge when stressed. However, current research on this technology faces several challenges, such as limited data, feasibility issues, implementation challenges, and a lack of studies needed for real-world implementation. This study aims to evaluate the feasibility and effectiveness of piezoelectric tiles, as this technology could help achieve the Sustainable Development Goals (SDGs) by supporting clean energy and sustainable urban development. As part of the research, field visits were conducted at high-footfall metro stations like Ghatkopar, Airport Road, and Andheri stations in Mumbai. These observations and footfall count analysis helped identify suitable locations for installing the tiles. The project analyzed footfall data from these areas to estimate the potential energy generation and studied the economic & location feasibility by analyzing installation and construction costs. The goal is to understand whether piezoelectric tiles can be scaled up and have a significant impact in India. If widely adopted, this technology could support the achievement of SDG-9 by driving innovation in industry and improving infrastructure. The findings will determine if piezoelectric tiles are a cost-effective solution for creating sustainable and efficient energy, which can power street lighting, public transport systems, and other urban infrastructure.

Keywords: Piezoelectric tiles; Renewable energy; Sustainable urban development; Green India movement; Cost-effectiveness.

1.0 Introduction

India's rapid industrialization and urbanization have significantly increased its energy demands, reaching 1,553.9 TWh in 2022-23 (CEA). While the government has promoted renewable energy sources such as solar, wind, and hydro, innovative solutions like footstep-generated energy using piezoelectric tiles offer a promising complement. Piezoelectric technology converts mechanical pressure into electricity, making it suitable for densely populated areas like metro stations, railway hubs, and shopping centers.

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This study evaluates the feasibility and cost-effectiveness of implementing piezoelectric tiles in Indian metro stations by analyzing energy generation potential, economic viability, and adaptability. “India has achieved 95% of its 175 GW renewable energy target set in 2015,” declared RK Singh, Minister of Power and New and Renewable Energy, in Parliament (cnbctv18, 2023). By 2026-27, non-fossil fuel capacity is expected to reach 57.4%, with further growth to 68.4% by 2031 (Singh, 2022). The government aims to reduce fossil fuel reliance to 30% by 2047 (Puri, 2020). While large-scale renewable projects are crucial, decentralized solutions like piezoelectric tiles can provide localized power. Metro stations in Mumbai, Delhi, and Bangalore, with millions of daily commuters, present a viable setting for energy harvesting. Each step can generate 5-10 watts (Sharma, 2016), enabling lighting, display screens, and ticketing systems to operate sustainably (Chandra, 2022).

Large renewable projects like solar and wind require significant land, making urban implementation difficult. Piezoelectric tiles offer an alternative by harnessing continuous foot traffic to generate electricity, unlike solar panels dependent on sunlight. Successful applications in Shibuya Station, Tokyo, and O’Hare Airport, Chicago, highlight their potential. However, adoption in India is still in its infancy, necessitating further exploration of energy output, costs, and long-term durability (Chaudhary, 2022). Piezoelectric tiles, composed of materials like quartz and ceramics, generate electricity when pressure is applied a principle discovered by Pierre and Jacques Curie in 1880 (Sciencefacts, 2024). Advances in nanotechnology have improved their viability, yet high initial costs for production, installation, and maintenance remain significant barriers (Chandra, 2022). Mechanical wear and exposure to dust and moisture may further reduce efficiency (Deekshitha, 2024).

Additional financial concerns include energy storage and conversion complexities (Anand, 2021). Limited large-scale pilot projects in India hinder research, making economic comparisons with solar and grid power essential (Naderipour, 2021) This research assesses the feasibility of piezoelectric tiles in metro stations, particularly in high-footfall locations such as Ghatkopar, Andheri, and Airport Road in Mumbai. By evaluating pedestrian flow, energy generation potential, and economic viability, this study aims to determine whether piezoelectric tiles provide a cost-effective alternative to other renewable sources. Additionally, it explores policy interventions and economic incentives to promote their adoption. However, limitations exist, as findings are based on case studies, pedestrian traffic data, and simulations rather than extensive field trials (Dagdeviren, 2014). Factors such as variations in pedestrian movement and environmental conditions may impact efficiency (Nakamura, 2019). Field experiments and interdisciplinary research are needed for practical validation and technology enhancement.

Piezoelectric technology in flooring systems has gained global traction due to its potential to generate electricity from mechanical stress, particularly in high-footfall areas such as airports and railway stations (Ramakrishna, 2014). In India, where energy expenses constitute 52% of industrial costs (Anand, 2019), the rising electricity demand necessitates sustainable alternatives like piezoelectric tiles (Yingyong, 2021).

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These tiles align with India's emissions reduction goals and infrastructure sustainability targets (Shanmugam, 2020). Their development traces back to the discovery of piezoelectricity by Jacques and Pierre Curie in 1880, with advances in ceramics and polymers improving their efficiency (Smith, 2014). Research across the UK, Netherlands, and Japan has demonstrated their viability in high-traffic areas, influencing commercialization prospects in India (Jones, 2016) (Haertling, 1999) (Praharaj, 2023) (Nakamura, 2019). Current research on piezoelectric tiles focuses on energy harvesting potential, material durability, and urban integration. Studies show significant energy generation in high-footfall locations such as stadiums and metro stations (Glynne, 2018) (Roy, 2015). Material advancements highlight trade-offs between ceramic and polymer-based tiles, balancing durability and efficiency under India's diverse climates (Tiwari, 2019). The feasibility of integrating these tiles into urban infrastructure remains debatable due to economic constraints and policy gaps (Ramanathan, 2022) (Rao, 2023). Global and Indian case studies, including projects at O'Hare International Airport and Delhi Metro stations, reveal both promise and challenges related to installation costs and maintenance (Kumar, 2021) (Gupta, 2022) (Sustainable Energy Solution at O'Hare International Airport., 2019). Despite the promise of sustainable energy, challenges include technological limitations, economic feasibility, and policy frameworks (Johnson, 2019).

The lack of research on social acceptance and long-term environmental impacts in India presents further obstacles (Mukherjee, 2022). While some argue high installation costs hinder widespread adoption (Singh, 2021), others believe advancements in materials and government support could make the technology viable (Patel, 2020) (Kumar, 2020). Addressing these barriers through interdisciplinary research, pilot projects, and strong policy measures could enhance India's green energy transition (Agarwal, 2021) (Sharma, 2023) (Gupta, 2022). This research will examine pedestrian footfall as well as the potential for power generation through piezoelectric tiles in metro stations to find out whether or not these tiles can be implemented. This study investigates the cost-effectiveness of installing and generating energy through piezoelectric tiles in comparison with conventional forms of energy generation. In addition, the research presents a detailed comparison of solar, wind, and piezoelectric energy solutions on economy, environment, and technology dimensions. By understanding how much energy can be produced from piezoelectric technology and if it can be economically feasible, the research would study what role such technology could play toward India's clean energy goals. The results will help set the stage for understanding better sustainable urban energy solutions and for future policy formulation regarding the adoption of piezoelectric tiles in metros.

2.0 Research Methodology

This research adopts a structured and systematic methodology to assess the feasibility and cost-effectiveness of piezoelectric tiles in metro stations as a sustainable energy alternative. The methodology integrates multiple research techniques, including bibliometric and thematic

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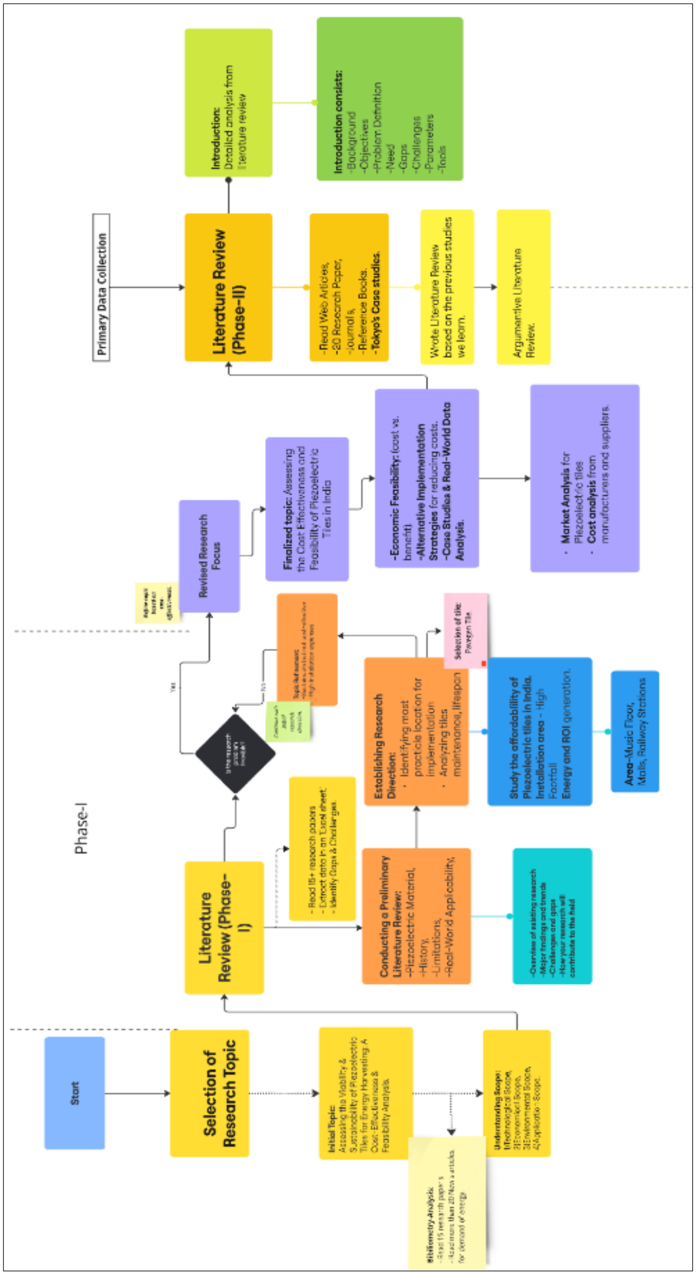
analysis, comparative assessments, and field surveys, to develop a comprehensive understanding of the technology's practicality in the Indian metro system.

Figure 1: Flowchart of Research Methodology



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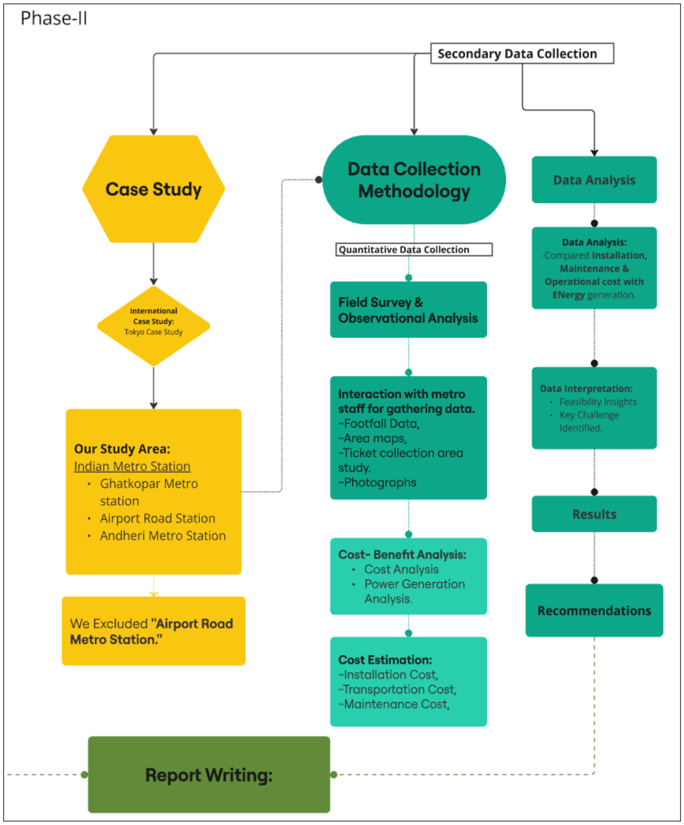

A bibliometric analysis of 15-20 research papers, case studies, and industry reports provided insights into the properties, applications, efficiency limitations, and economic considerations of piezoelectric materials. Thematic analysis was then employed to categorize key findings, identify literature gaps, and highlight challenges such as unproven large-scale implementation, integration with metro infrastructure, high initial investment costs, and long-term durability concerns. A major issue that emerged was the lack of real-world case studies on the use of piezoelectric tiles in high-footfall areas like Indian metro stations. While international projects, such as Tokyo Metro's piezoelectric floor-tile system, provide reference points, they do not account for the unique infrastructural, economic, and environmental conditions of Indian metros. The detailed structure of our methodology is shown in the research methodology flowchart (Figure 1).

Field surveys at Mumbai's Ghatkopar, Andheri, and Airport Road metro stations analyzed foot traffic patterns, commuter density, and energy harvesting potential. Observations covered peak and off-peak movement, environmental factors like dust and moisture, and mechanical stress on tiles. Discussions with metro staff highlighted concerns about durability, maintenance, and high installation costs. Metro authorities favored solar power over

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piezoelectric tiles due to cost-effectiveness and reliability issues, as foot traffic fluctuations raised doubts about consistent energy generation. Additionally, secondary data collection involved analyzing technical reports and case studies from existing piezoelectric installations worldwide. Studies on energy conversion efficiency, material performance, and real-time energy utilization highlighted limitations in large-scale applications. Despite the potential of piezoelectric tiles, findings from site visits and literature review indicate that while they may contribute to supplementary energy generation, they are unlikely to serve as a primary power source due to cost and efficiency constraints. The integration of hybrid energy solutions, combining piezoelectric technology with solar panels, may offer a more sustainable alternative.

Ultimately, the study concludes that although piezoelectric flooring holds promise, its economic and technical feasibility in Indian metro stations remains uncertain. Further advancements in material efficiency and cost reduction are needed to make this technology a viable option for public infrastructure projects.

3.0 Results

The ticket collection areas at Ghatkopar and Andheri metro stations were selected for footfall analysis and power estimation due to their high commuter concentration. These areas ensure uniform pressure on the proposed piezoelectric tiles, maximizing energy generation potential. Based on station staff data and manual recordings, Andheri receives approximately 700,000 daily commuters, while Ghatkopar accommodates around 300,000. Footfall was divided among the ticket machines, with each machine handling an estimated 19,444 footfalls at Andheri and 11,111 at Ghatkopar. With a 65% activation efficiency and 5 Joules of energy generated per footstep, the energy produced at Andheri is approximately 0.972 kWh daily, while at Ghatkopar, it reaches 0.416 kWh. This energy can power LED lighting or signage within the station. Initially, triangular piezoelectric tiles were planned due to their structural efficiency. However, the ticketing area's rectangular layout led to uneven foot traffic distribution. Installing triangular tiles would have incurred high costs due to excessive cutting and installation efforts. Instead, the peripheral sections were covered with regular tile pieces, optimizing costs without affecting efficiency. This improved sustainability and economic feasibility while ensuring precise tile placement under high-footfall zones.

4.0 Prototype Design

The proposed piezoelectric tile prototype (as shown in Figures 2 & 3) is designed to efficiently harvest kinetic energy from foot traffic in high-footfall areas such as metro stations. The tile system follows a modular structure, ensuring scalability, durability, and ease of maintenance. The prototype consists of triangular-shaped tiles, arranged in a repeating modular pattern. The triangular design enhances load distribution and structural stability while

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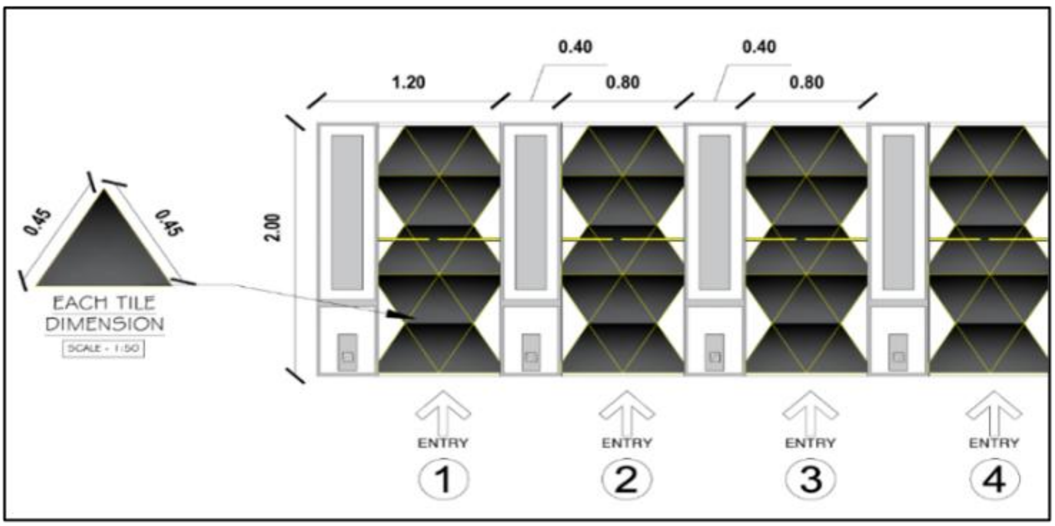
maximizing the number of active pressure points for energy generation. Each tile is composed of multiple layers: a top layer made of a durable, high-friction surface to withstand constant pedestrian movement, a middle layer with a flexible mechanical structure that enhances footstep impact transfer, and a bottom layer embedded with piezoelectric transducers arranged in a structured grid pattern to convert mechanical pressure into electrical energy.

The working mechanism of the prototype is based on the piezoelectric effect, where mechanical stress from foot traffic induces an electrical charge in the piezoelectric material. When a pedestrian steps on the tile, the generated energy is transferred to a power conditioning circuit, which stabilizes and stores it in an integrated battery or capacitor. The system is further connected to a central energy management unit, allowing real-time energy monitoring and grid integration. Initial simulations and testing suggest that each footstep generates approximately 0.105 mW, which, when accumulated over thousands of daily footsteps, contributes to an overall energy generation of 1.388 kWh/day for both metro stations. However, challenges such as low per-step energy output, wear-and-tear, and high initial costs (₹4.88 Cr for Ghatkopar and Andheri stations) limit the large-scale implementation of this technology. While the prototype successfully demonstrates a proof of concept, further advancements in material efficiency, energy storage integration, and hybrid energy solutions (e.g., combining with solar energy) are essential to enhance its feasibility as a practical renewable energy source.

Figure 2: Popup of Tile Installation Design at Andheri & Ghatkopar



Tile Selection: Based on various research studies and a comparative analysis of the tile products listed in Table 1, including lifespan and cost comparisons, Pavegen tiles were chosen for our study due to their efficiency, flexibility, and smart technology integration.

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Figure 3: Tile Installation Design

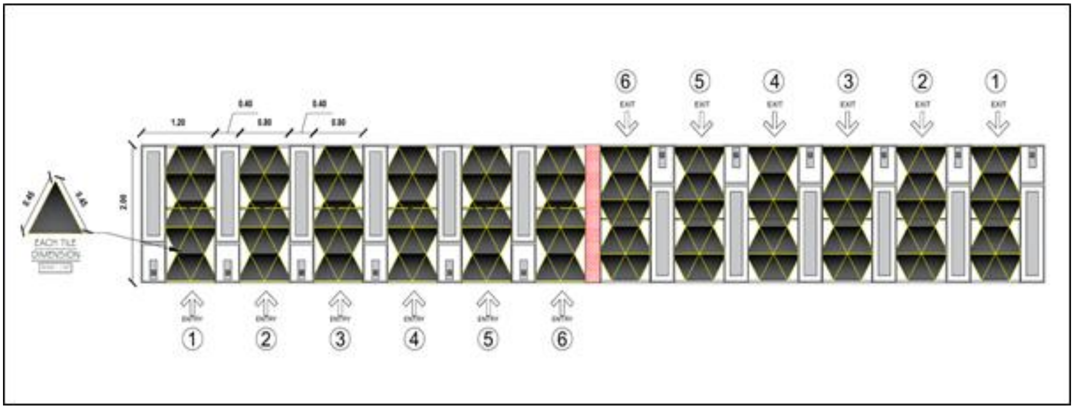

Table 1: Tile Comparison based on Various Product Types

Sr. No	Product Type	Tile Size / Dimensions	Energy Produced	Price (US$)	Estimated Lifespan	Source
1	Waynergy Floor Tiles	40×40 cm	10 W per step	451.5	20 years	Rodrigues, 2011
2	SEF Tiles	75×75 cm or 50×50 cm	Up to 30 W continuous, avg 7 W per step	1693	15 years	Solban & Moussa, 2019
3	Pavegen Tiles	45 x 45 x 45 cm	5 W	395	20 years	Pavegen, 2021
4	EAPs	Sheets	1 W	Not available	20 years	Balouchi, 2013
5	Sound Power Tiles	50×50 cm	0.1 W per 2 steps	270.9	20 years	Hassan et al., 2014
6	Parquet PVDF Layers	Thickness: 10 µm	2,100,000 W per pulse (70 kg load)	Not available	20 years	Elhalwagy, 2017
7	Drum Harvesters - Piezo Buzzer	40 mm - 25 mm	2,463,000 W (35.6 mW for 70 kg)	56.4	20 years	Mishra et al., 2015
8	Power Leap (PZT) Tiles	60×60 cm	500,000 W per step	Not available	20 years	Balouchi, 2013
9	HEF	75×75 cm or 100×200 cm	Up to 250 kWh per year per tile	1693	20 years	Solban & Moussa, 2019

Each tile generates 5W per step and has a 20-year lifespan, making it a long-term solution. While PZT ceramic tiles generate higher power, Pavegen tiles offer real-time data analytics and modular designs, making them suitable for metro stations, airports, and shopping centers. These tiles have been successfully used in projects like Mercury Mall in London, demonstrating their capability to power signage and lighting through pedestrian movement.

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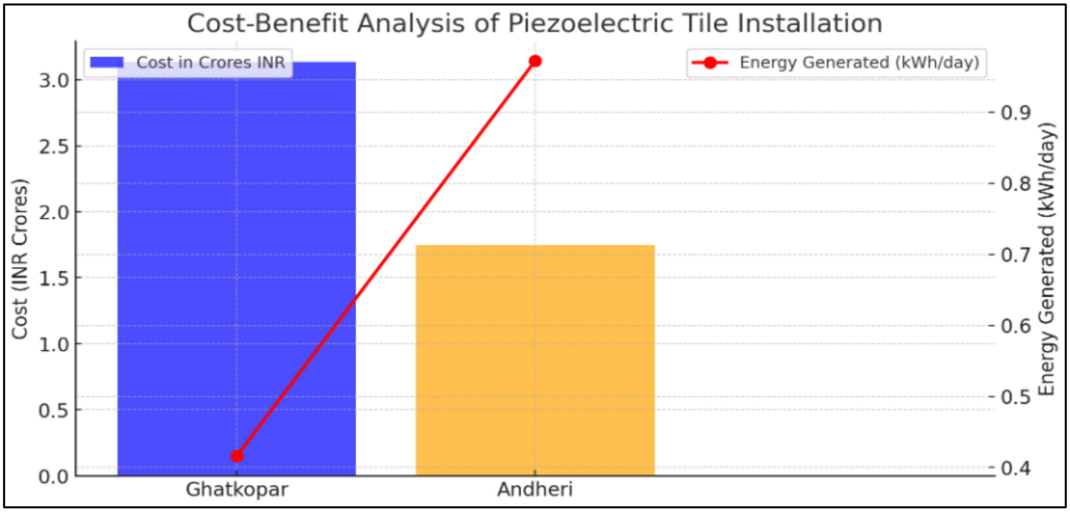
Footfall Analysis: Observational studies at the ticketing hubs of Ghatkopar and Andheri metro stations recorded passenger movement patterns. Ghatkopar handles 300,000 commuters daily, while Andheri manages nearly 700,000. These numbers highlight the necessity for efficient infrastructure and management to accommodate such high commuter volumes.

Power Estimation: The ticket collection zones were identified as the areas of maximum foot traffic, ensuring optimal pressure on the tiles. Based on peak and off-peak hour footfall intensity, energy generation potential was estimated as follows:

Figure 4: Cost Benefit Analysis



Tile and Machine Area Calculation:

Equation 1: Area of equilateral triangle

Area of an equilateral triangle: $(\sqrt{3} / 4) * \text{side}^2$

- Tile Size: 450 mm = 0.45 m
- Tile Area: sq. meters
- Machine Area: converted to meters: sq. meters
- Tiles per Machine: 14

Energy Generation:

- Energy per Step: 5 Watts = 5 Joules
- Operating Hours: 17 hours/day
- Footfall per Machine: at Ghatkopar; at Andheri
- Total Energy: Joules at Ghatkopar; Joules at Andheri
- Energy in kWh: kWh at Ghatkopar; kWh at Andheri

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Cost Estimation: The cost of installing piezoelectric tiles was calculated based on tile pricing, shipping, and labor expenses. The total tile requirement was 882 tiles, with an average cost of ₹35,550 per tile. The costs for both stations are estimated as follows:

Table 2: Ghatkopar & Andheri Energy Generation Data

Parameter	Ghatkopar	Andheri
Total Footfall	300,000	700,000
Machines	27	36
Tiles/Machine	14	14
Total Tiles	378	504
Footfall/Machine	11,111	19,444
Total Energy (J)	15,00,000	35,00,000
Energy (kWh)	0.416	0.972
Total Tile Weight (kg)	11,340	15,120

Table 3: Ghatkopar & Andheri cost Estimation Data

Expense Component	Ghatkopar (₹)	Andheri (₹)	Total (₹)
Tile Cost	1,34,37,900	1,79,17,200	3,13,55,100
Shipping Charges	87,31,800	87,31,800	1,74,63,600
Installation Cost	21,500	21,500	43,000
Total Cost	2,21,91,200	2,66,70,500	**4,88,61,700**

Shipping was calculated based on standard charges for 17,640 kg of tiles at ₹990 per 1000 kg. Installation costs included five workers at ₹1,000 per day and two experts at ₹3,000 per day, completing the project in three days.

As shown in Figure 3, our study represents that this project needs "High Initial Cost", mainly due to the expensive nature of piezoelectric technology & shipping charges. To make this project more financially viable partnerships with technology providers, government subsidies, or future advancements in cost-effective piezoelectric material could be explored.

5.0 Comparative Evaluation of Renewable Technologies: Solar, Wind with Piezoelectric Sensor Energy

A comparative analysis of solar, wind, and piezoelectric tiles was conducted based on key factors such as energy output, cost, land use, scalability, and environmental impact as shown in Table 4. While solar and wind energy proved to be more efficient and cost-effective, piezoelectric tiles stood out for their ability to integrate into existing urban infrastructure. However, their lower energy output and higher cost per kWh limit their large-scale feasibility.

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Piezoelectric tiles generated significantly less energy (1.388 kWh/day for metro stations at Ghatkopar and Andheri) due to low energy harvesting per footstep (5J/step). This requires a high volume of foot traffic to produce meaningful energy. Additionally, installation costs (₹4.88 Cr for metro stations) were considerably higher compared to the energy output, making piezoelectric tiles less viable compared to solar and wind alternatives, which offer greater energy efficiency at a lower cost.

Table 4: Comparative Analysis between Renewable Alternatives

Aspect	Solar	Wind	Piezoelectric Tiles
Energy Output	150-200 kWh/m² annually	6-8 million kWh/year (3 MW turbine)	5-20 kWh/day (1,825-7,300 kWh/year)
Carbon Footprint	20-70 grams CO_2/kWh	10-20 grams CO_2/kWh	20-30 grams CO_2/kWh
Land Use	50-100 acres per 1 MW	Requires spacing between turbines	Installed on existing sidewalks/floors
Cost	₹75000-85000 per kW	₹4 crore per MW	₹35,550 per tile
Maintenance	25+ years, minimal upkeep	Regular servicing needed	Prone to wear, especially in monsoons
Public Engagement	Invisible infrastructure	Invisible infrastructure	Visible, sparks curiosity and awareness
Ideal For	Large-scale adoption (rural, open land)	Coastal areas with consistent winds	Urban areas with high foot traffic
Energy Generation (Annual)	Dependent on area (e.g., 150-200 kWh/m² annually)	6-8 million kWh per turbine/year	1,825 - 7,300 kWh/year (high-traffic areas)
Space Efficiency	Requires large land areas for solar farms	Takes up minimal ground area, but requires spacing	Installed in existing spaces (sidewalks, metro floors, etc.)
Environmental Impact	Requires significant raw materials like silicon	Low environmental impact due to simpler materials	Moderate impact due to polymers and metals used
Scalability	High scalability, especially in open land	Scalable in areas with enough wind resources	Limited scalability in low-traffic areas but feasible in urban settings
Installation Time	Relatively fast, but depends on the scale	It takes longer to install due to the turbine size	Quick installation in existing urban spaces
Noise	No noise generation	It can be noisy due to moving parts	No noise generation

Real-world challenges further limit the feasibility of piezoelectric tiles. High foot traffic leads to faster wear and tear, increasing maintenance costs. Energy storage remains a concern due to the small energy output, requiring advanced battery technology for effective utilization. Moreover, the high initial investment (₹35,550 per tile) makes large-scale adoption difficult. To

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improve feasibility, research into better materials and alternative storage solutions is needed. A hybrid approach integrating solar panels with piezoelectric tiles could enhance efficiency, and field testing in urban areas should be conducted before broader implementation.

6.0 Conclusion

This research evaluates the feasibility of piezoelectric tiles as a renewable energy source for metro stations, comparing them with solar and wind energy alternatives. The findings indicate that piezoelectric tiles generate minimal energy (1.388 kWh/day for both stations) due to low energy harvesting per footstep, making them less efficient compared to solar and wind energy. Additionally, the high installation cost (₹4.88 Cr for Ghatkopar and Andheri stations) makes them economically unviable, as their energy output is too low to justify the investment. Wear-off issues, high maintenance needs, and energy storage challenges further limit their practicality. In contrast, solar energy proves to be more cost-effective and scalable, especially in urban environments with abundant sunlight. Wind energy also remains a steady alternative, provided suitable locations are available.

To explore the practical implementation of this technology, a prototype piezoelectric tile system was designed and tested. The modular triangular tile design, as shown in Figure X, enhances load distribution and optimizes energy harvesting by incorporating piezoelectric transducers in a structured grid pattern. While the prototype successfully demonstrated the feasibility of footstep-induced energy generation, the low power output per step and durability concerns remains key limitations.

Despite these challenges, piezoelectric tiles present an innovative approach to energy generation and could become more viable with technological advancements in material durability, energy storage, and hybrid integration with solar or kinetic energy systems. The study highlights the need for further research and field testing to optimize piezoelectric technology for practical use. While it is not currently a feasible large-scale energy solution for metro stations, hybrid approaches combining piezoelectric tiles with solar panels could enhance energy efficiency and sustainability in the future.

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