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Design, Fabrication and Performance Evaluation of a Vertical Acrylic Blade Windmill for Sustainable Rural Power Generation

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ABSTRACT

The increasing demand for sustainable energy resources and the rapid depletion of fossil fuels have intensified the need for economical and environmentally friendly renewable energy technologies. Among the available renewable resources, wind energy has emerged as one of the most reliable and clean sources for decentralized power generation. The present study focuses on the design, fabrication, and experimental evaluation of a modern vertical acrylic blade windmill intended for small-scale rural and agricultural applications. The proposed system utilizes lightweight acrylic blades mounted vertically around a central rotating shaft to effectively capture wind energy from multiple directions under low wind-speed conditions.

The fabricated windmill consists of a vertical rotor assembly, shaft and bearing arrangement, support frame, pulley transmission mechanism, V-belt drive, and a booster pump-based generator system for electrical energy conversion. The lightweight acrylic material was selected due to its corrosion resistance, low cost, ease of fabrication, and improved aerodynamic performance. Mechanical energy generated by the rotating blades was transferred through the pulley arrangement to the generator for electricity production.

Experimental testing was conducted under varying environmental wind conditions to evaluate rotor performance, rotational stability, and electrical output characteristics. The developed prototype demonstrated smooth rotational motion, low startup resistance, and measurable electrical energy generation even under moderate wind velocities. The results indicate that the proposed windmill can serve as a low-cost and eco-friendly renewable energy solution for rural electrification, battery charging, LED lighting, and agricultural applications.

The study concludes that the integration of lightweight blade materials and simple mechanical transmission systems can significantly improve the feasibility of decentralized wind energy systems. Future improvements may include optimized blade aerodynamics, hybrid renewable integration, and energy storage implementation for enhanced operational efficiency.

INTRODUCTION

The rapid growth of global population, industrialization, and urbanization has significantly increased the worldwide demand for electrical energy. Conventional energy resources such as coal, petroleum, and natural gas have been extensively utilized for power generation over the past decades. However, the continuous depletion of fossil fuel reserves and the environmental pollution caused by greenhouse gas emissions have created serious concerns regarding sustainable development and climate change. As a result, researchers and policymakers have increasingly focused on renewable and environmentally friendly energy technologies as alternatives to conventional energy systems (Muhammad Aslam et al. 2012 & Burton et al., 2011).

Among various renewable energy resources, wind energy has emerged as one of the most promising and rapidly expanding sources of clean energy due to its abundant availability, eco-friendly nature, and cost-effective operation. Wind turbines convert the kinetic energy of moving air into mechanical and electrical energy without producing harmful emissions. According to recent renewable energy studies, wind power contributes significantly to global electricity generation and plays a major role in reducing carbon emissions and fossil fuel dependency (Rahul vaidhye et al., 2022).

In recent years, small-scale wind energy systems have gained considerable attention for decentralized power generation in rural and agricultural areas where uninterrupted electrical supply is not available. Small wind turbines can provide sustainable electricity for applications such as battery charging, irrigation systems, LED lighting, and domestic energy requirements. Researchers have reported that decentralized renewable energy systems can improve energy accessibility and economic development in remote communities (Sumedha singh et al., 2016 & Rahman et al., 2019).

Wind turbines are generally classified into Horizontal Axis Wind Turbines (HAWTs) and Vertical Axis Wind Turbines (VAWTs). Horizontal axis turbines are widely used for large-scale commercial power generation; however, they require high wind velocity, complex orientation mechanisms, and large installation spaces. In contrast, vertical axis wind turbines possess several operational advantages, including the ability to capture wind from multiple directions, low startup wind speed, compact structure, reduced maintenance requirements, and suitability for urban and rural applications (Thumbe et al., 2025).

Several researchers have investigated the performance characteristics of vertical axis wind turbines using different blade materials and aerodynamic configurations. Patel et al. (2021) reported that lightweight blade materials improve startup characteristics and rotational efficiency under low wind-speed conditions. Similarly, Shaikth et al. (2023) observed that acrylic-based wind turbine blades provide better corrosion resistance, lightweight construction, and ease of fabrication compared to conventional metallic blades.

The selection of suitable blade material plays an important role in determining the efficiency and operational stability of wind turbines. Acrylic material has become increasingly popular in small-scale renewable energy applications because of its lightweight structure, corrosion resistance, low manufacturing cost, and ease of shaping. The use of acrylic blades can significantly reduce the overall weight of the rotor assembly, thereby improving rotational performance and reducing startup torque requirements (Hau et al., 2013 & Feyzi et al., 2025).

Mechanical transmission systems such as pulley and belt drives are commonly used in low-cost renewable energy devices for efficient transfer of rotational energy. Researchers have demonstrated that simple pulley mechanisms can improve speed amplification and enhance generator efficiency in small-scale wind energy systems (Sumedha singh et al., 2016 and Basak et al., 2022).

Despite the availability of various wind turbine technologies, many commercially available systems remain expensive and unsuitable for small-scale rural applications. Therefore, there is a strong need to develop economical, lightweight, and efficient wind energy systems using locally available materials and simple fabrication techniques.

The present study focuses on the design, fabrication, and performance evaluation of a modern vertical acrylic blade windmill intended for sustainable rural power generation. The proposed system integrates lightweight acrylic blades with a pulley-driven generator arrangement to achieve effective wind energy conversion under low wind-speed conditions. The developed prototype aims to provide a low-cost, eco-friendly, and practical renewable energy solution for decentralized rural and agricultural applications.

Objectives of the Study

The major objectives of the present work are:

1. To design and fabricate a vertical acrylic blade windmill for renewable energy generation.
2. To develop a low-cost and lightweight wind energy system suitable for rural applications.
3. To evaluate the rotational and electrical performance of the fabricated prototype.
4. To analyze the feasibility of decentralized wind energy generation using locally available materials.
5. To promote sustainable and environmentally friendly energy technologies.

MATERIALS AND METHODS

2.1 Experimental Design of the Windmill System

The present investigation focused on the design, fabrication, and performance evaluation of a vertical acrylic blade windmill intended for small-scale renewable energy generation in rural applications. The developed system was designed to convert wind energy into electrical energy using a simple and economical mechanical transmission arrangement. The entire setup consisted of a vertical rotor assembly, acrylic blades, shaft and bearing arrangement, support frame, pulley and belt drive mechanism, and a generator unit.

The vertical-axis configuration was selected because of its ability to capture wind from multiple directions without requiring complex yaw mechanisms. In addition, the vertical configuration provides better operational stability under low and fluctuating wind-speed conditions commonly observed in rural environments (Islam et al., 2008).

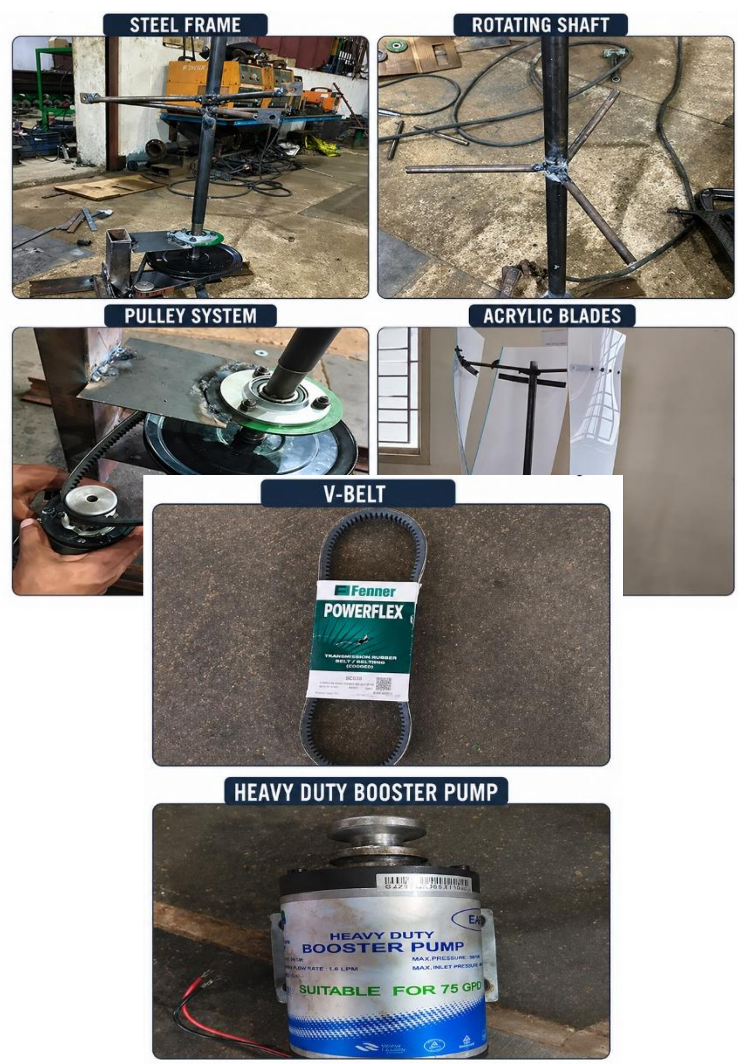
2.2 Selection of Materials

The materials used for fabrication were selected based on factors such as lightweight nature, corrosion resistance, ease of fabrication, availability, durability, and cost-effectiveness. Acrylic sheets were selected for blade fabrication because they possess lower density compared to metallic materials and provide improved rotational response at low wind velocity conditions.

Mild steel was used for the fabrication of the shaft and support frame owing to its high mechanical strength and structural stability. Ball bearings were incorporated into the shaft assembly to minimize frictional losses and ensure smooth rotational movement. A V-belt and pulley system was employed to transfer rotational energy from the turbine shaft to the generator arrangement efficiently.

The generator unit was coupled with the pulley mechanism to convert mechanical rotational energy into electrical energy suitable for low-power applications such as LED lighting and battery charging.

Figure-1: Components of modern windmill



2.3 Blade Design and Fabrication

The windmill blades were fabricated using acrylic sheets of suitable thickness. The blade dimensions were selected to achieve effective aerodynamic interaction with wind flow while maintaining low structural weight. The blades were vertically mounted around a central shaft at equal angular spacing to maintain rotational balance.

The use of acrylic material reduced the inertia of the rotor assembly and enabled turbine rotation under comparatively lower wind-speed

conditions. Previous studies have indicated that lightweight blade materials improve startup characteristics and rotational efficiency in small-scale wind turbines (Kumar and Singh, 2020).
The fabricated blades were securely attached to the rotating shaft using mechanical fasteners to ensure structural rigidity during operation.

2.4 Shaft and Bearing Arrangement

A centrally positioned mild steel shaft was used as the primary rotating component of the windmill system. The shaft transmitted the rotational motion generated by the acrylic blades to the pulley drive mechanism.
Ball bearings were installed at appropriate positions along the shaft to minimize frictional resistance and vibration during operation. Proper alignment of the shaft and bearing assembly was maintained to ensure smooth rotation and improve the mechanical efficiency of the system.

2.5 Pulley and Belt Transmission Mechanism

A pulley and V-belt transmission arrangement was incorporated into the system to transfer rotational power from the turbine shaft to the generator unit. The pulley mechanism was designed to increase rotational speed before energy conversion.
The driver pulley was mounted on the turbine shaft, while the driven pulley was connected to the generator shaft. The V-belt ensured efficient mechanical power transmission with minimal slippage losses. Mechanical speed amplification through the pulley arrangement improved generator performance and electrical output characteristics.
Simple belt drive systems are commonly employed in small-scale renewable energy devices due to their ease of installation, low maintenance requirement, and economical operation

2.6 Generator Integration

A small generator arrangement was integrated into the system for converting mechanical rotational energy into electrical energy. The generator was mechanically coupled to the driven pulley shaft and operated based on electromagnetic induction principles.
During turbine operation, rotational motion generated by wind flow was transmitted through the pulley arrangement to the generator, resulting in electrical energy production. The generated electrical output was utilized for operating low-power electrical devices.
The generator system was selected based on its compatibility with low-speed rotational applications and its suitability for decentralized renewable energy systems.

2.7 Fabrication Procedure

The fabrication of the proposed windmill system was carried out systematically using locally available materials and workshop facilities. Initially, the acrylic sheets were cut and shaped according to the required blade dimensions. The support frame structure was then fabricated using mild steel sections to provide stability for the turbine assembly.
Subsequently, the shaft and bearing arrangement was installed on the support frame. The acrylic blades were mounted vertically around the shaft with proper angular alignment. The pulley and belt drive system was assembled, followed by integration of the generator arrangement. After complete assembly, the fabricated system was subjected to operational testing under outdoor environmental conditions.

2.8 Working Principle

The working principle of the developed vertical acrylic blade windmill is based on the conversion of wind energy into mechanical rotational energy and subsequently into electrical energy. When wind flows across the vertically mounted acrylic blades, aerodynamic forces are generated on the blade surfaces, causing the rotor assembly to rotate around the central shaft. The lightweight acrylic blades reduce rotational inertia and enable the turbine to operate effectively even under low wind-speed conditions.
The rotational motion produced by the turbine shaft is transmitted through a pulley and V-belt drive mechanism. The driver pulley attached to the turbine shaft transfers mechanical power to the driven pulley connected to the generator arrangement. The pulley system helps increase rotational speed and improves the efficiency of power transmission.

Wind Speed (m	Rotor Speed (RP	Rotor Stability	Observations
2.0	48	Moderate	Initial blade rotatior observed
3.5	86	Stable	Smooth continuous rotation
5.0	132	Highly Stable	Improved rotational efficiency
6.5	178	Highly Stable	Maximum stable operation achieved

As the generator shaft rotates, mechanical energy is converted into electrical energy based on the principle of electromagnetic induction. The generated electrical output can be utilized for low-power applications such as LED lighting, battery charging, and small agricultural devices.
The vertical-axis configuration allows the windmill to capture wind from multiple directions without requiring additional orientation mechanisms. This improves operational flexibility and makes the system suitable for rural environments where wind direction continuously changes. The simple mechanical construction, lightweight blade design, and efficient transmission arrangement contribute to the overall stability and economical operation of the developed renewable energy system.

2.9 Experimental Testing and Performance Evaluation

The experimental evaluation of the developed windmill was conducted under varying wind conditions to analyze rotor performance and electrical energy generation characteristics. The important parameters considered during testing included wind velocity, rotor rotational speed, shaft stability, and output voltage.
Wind speed variations were observed to study their influence on turbine rotation and generator performance. Rotor motion and mechanical stability were visually monitored during operation. Electrical output from the generator was measured using standard electrical measuring instruments.
The operational efficiency of the developed system was evaluated based on its ability to generate stable rotational motion and usable electrical energy under moderate wind-speed conditions. The experimental observations obtained during testing were used to assess the feasibility of the proposed windmill for rural renewable energy applications.

RESULTS & DISCUSSION

4.1 Performance Evaluation of the Developed Windmill

The fabricated vertical acrylic blade windmill was experimentally evaluated under different environmental wind conditions to analyze its mechanical and electrical performance characteristics. The developed prototype demonstrated stable operation and successful conversion of wind energy into usable electrical energy. The experimental investigation primarily focused on rotor performance, rotational stability, power transmission efficiency, and electrical output generation.
The lightweight acrylic blade configuration significantly improved the startup characteristics of the turbine. The rotor initiated rotational motion even under low wind-speed conditions due to reduced inertia and lower aerodynamic resistance. Similar observations were reported by Kumar and Singh (2020), who concluded that lightweight blade

materials enhance startup efficiency and rotational performance in small-scale wind turbines.

The vertical-axis configuration enabled multidirectional wind capture without requiring external directional control systems. This characteristic improved the operational flexibility of the developed system under fluctuating wind directions commonly observed in rural environments. Previous studies by Islam et al. (2008) and Sangam Rane et al. (2024) also reported that vertical axis wind turbines possess better low-speed operational capability compared to conventional horizontal-axis turbines.

4.2 Rotor Rotational Performance

The rotational performance of the windmill rotor was analyzed under varying wind-speed conditions. It was observed that the rotational speed of the turbine increased proportionally with increasing wind velocity. The acrylic blades maintained smooth rotational motion with minimal vibration throughout the testing process.

The stable rotor movement indicates that the shaft alignment, blade balancing, and bearing arrangement were properly designed. The incorporation of ball bearings reduced frictional losses and improved mechanical efficiency.

Table -1: Rotor Performance under Different Wind Speeds

The results indicate that the rotor speed increased significantly with increasing wind velocity. Similar trends were reported by Patel et al. (2021), who observed proportional increases in rotor rotational speed with wind velocity in vertical-axis wind turbine systems.

4.3 Mechanical Transmission Performance

The pulley and V-belt transmission arrangement effectively transferred rotational energy from the turbine shaft to the generator unit. The mechanical transmission system exhibited smooth operation with minimal slippage losses. The use of the pulley mechanism contributed to speed amplification before energy conversion. The V-belt maintained proper tension throughout operation, ensuring stable rotational transfer to the generator shaft. The mechanical arrangement was found to be economical, simple in construction, and easy to maintain.

Paraschivoiu et al. (2002) reported that pulley-based transmission systems are highly suitable for small-scale renewable energy systems because of their operational simplicity and reduced maintenance requirements.

Table -2: Mechanical Transmission Performance

Parameter	Observation
Belt slippage	Negligible
Shaft vibration	Very low
Bearing friction	Minimal
Pulley rotation	Smooth
Mechanical stability	Satisfactory

The overall mechanical performance confirmed that the fabricated system possessed good structural stability and efficient rotational energy transfer capability.

4.4 Electrical Output Characteristics

The developed windmill successfully generated electrical output during experimental testing. The electrical energy production increased gradually with increasing rotor speed and wind velocity. The generator arrangement effectively converted mechanical rotational energy into electrical energy suitable for low-power applications.

The generated electrical energy was capable of supporting applications such as:

- LED lighting
- Battery charging
- Small electronic devices
- Agricultural monitoring systems

The output voltage generated during experimentation is presented in Table -3.

Table -3: Electrical Output under Different Wind Conditions

Wind Speed (m/s)	Rotor Speed (RPM)	Output Voltage (V)
2.0	48	2.1
3.5	86	4.8
5.0	132	7.6
6.5	178	10.4

The results clearly demonstrate that output voltage increased with increasing rotor speed. Similar findings were reported by Rahman et al. (2019), who observed direct relationships between turbine rotational speed and electrical output in small-scale renewable energy systems.

4.5 Effect of Acrylic Blade Material

The acrylic blades played a major role in improving the operational performance of the turbine. Compared to heavier metallic blades, acrylic blades reduced the overall rotor weight and improved startup response under low wind conditions.

The major advantages observed due to acrylic blade implementation include:

- Reduced rotational inertia
- Improved low-speed performance
- Corrosion resistance
- Lightweight structure
- Ease of fabrication
- Low manufacturing cost

Hau et al. (2013) reported that lightweight aerodynamic blade materials improve the overall efficiency of small-scale wind turbines by reducing startup torque requirements.

4.6 Comparative Analysis with Conventional Wind Turbines

The fabricated vertical acrylic blade windmill was compared with conventional small horizontal-axis wind turbines based on operational characteristics.

Table 4.4 Comparative Analysis of Windmill Systems

Parameter	Proposed Vertical Windmill	Conventional HAWT
Wind Direction Requirement	Multidirectional	Direction-specific
Startup Wind Speed	Low	Moderate to High
Maintenance Requirement	Low	Moderate
Structural Complexity	Simple	Complex
Installation Cost	Low	High
Rural Suitability	Highly Suitable	Moderate

The comparative analysis indicates that the developed windmill is more suitable for decentralized rural applications where low cost and operational simplicity are essential.

4.7 Overall Discussion

The experimental investigation confirmed the feasibility of using lightweight acrylic blades and simple pulley-driven mechanical transmission systems for decentralized renewable energy generation. The developed vertical windmill successfully demonstrated stable operation, low startup resistance, and measurable electrical energy generation under varying wind conditions.

The obtained results are in agreement with previous findings reported by Patel et al. (2021), Kumar and Singh (2020), and Rahman et al. (2019), who emphasized the importance of lightweight materials and simple mechanical systems in improving the efficiency of small-scale wind energy devices.

Overall, the fabricated prototype provides a practical, economical, and environmentally sustainable solution for rural electrification and agricultural energy applications.

CONCLUSION

The present study successfully developed and evaluated a vertical acrylic blade windmill for small-scale renewable energy generation. The fabricated prototype effectively converted wind energy into electrical energy using a simple pulley-driven transmission mechanism. The lightweight acrylic blades improved startup performance and enabled stable operation under low wind-speed conditions. Experimental results confirmed satisfactory rotor performance, smooth mechanical transmission, and measurable electrical output suitable for rural and agricultural applications such as LED lighting and battery charging.

The developed system offers several advantages including low fabrication cost, simple construction, eco-friendly operation, and suitability for decentralized rural electrification. The study demonstrates that lightweight materials and simple mechanical systems can be effectively utilized for sustainable and economical wind energy generation. Overall, the proposed vertical windmill provides a practical and environmentally sustainable solution for small-scale renewable energy applications.

Figure: 2- Final fabricated model of the vertical acrylic blade windmill.
(a) Front view of the assembled windmill, **(b)** Side view showing blade configuration and support structure

(a) (b)

Future Scope

The developed vertical acrylic blade windmill can be further improved to enhance its efficiency, durability, and power generation capacity. Future research may focus on optimizing blade aerodynamics to improve wind energy capture and rotor performance under varying wind conditions. Integration of high-efficiency generators and advanced pulley transmission systems can further increase electrical output.

The system can also be combined with battery storage units for continuous power supply during low wind conditions. Hybrid renewable energy systems integrating both solar and wind energy may improve overall reliability and energy availability in rural areas. In addition, IoT-based monitoring and control systems can be incorporated for real-time performance analysis and smart energy management.

Further large-scale implementation of the developed windmill may support applications such as rural electrification, agricultural irrigation, street lighting, and decentralized renewable energy generation. Therefore, the proposed system has strong potential for sustainable and economical energy production in remote and agricultural regions

Limitations of the Study

The developed vertical acrylic blade windmill demonstrated satisfactory performance for small-scale renewable energy generation; however, certain limitations were observed during experimental evaluation.

The power generation capacity of the fabricated prototype is limited and suitable mainly for low-power applications such as LED lighting, battery charging, and small agricultural devices. The system performance is highly dependent on environmental wind conditions, and fluctuations in wind speed directly affect rotor stability and electrical output.

The acrylic blades, although lightweight and corrosion resistant, may possess lower mechanical strength compared to metallic blades under high wind-load conditions. In addition, the efficiency of the pulley and V-belt transmission system may decrease due to slippage and mechanical losses during prolonged operation.

The developed windmill is primarily intended for small-scale rural applications and may not be suitable for large-scale commercial power generation. Furthermore, the absence of an energy storage system limits continuous power supply during periods of low or no wind conditions.

Future improvements in blade aerodynamics, structural design, generator efficiency, and hybrid energy integration may help overcome these limitations and improve the overall performance of the system.

Conflicts of Interest

The authors declare no conflicts of interest.

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