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# Blade curvature as a key driver of conical-basin gravitational vortex turbine performance: experimental evidence

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***Abstract***
*This study investigates the role of runner blade curvature in enhancing the performance of Gravitational Water Vortex Turbines (GWVTs) for low-head hydropower applications. Despite growing interest in GWVT technology, previous studies typically vary multiple geometric parameters simultaneously, leaving the isolated effect of blade curvature radius insufficiently understood. To address this research gap, an experimental investigation was conducted using a conical-basin GWVT with three runner configurations having identical blade inclination (66°) but different curvature radii (0.10 m, 0.20 m, and 0.30 m). Experiments were performed under controlled flow rates of 800, 1025, and 1300 LPM. Turbine torque, rotational speed, mechanical power, and efficiency were measured using a Prony brake dynamometer and magnetic tachometer. Each test condition was repeated three times, and the resulting data were analyzed using mean and standard deviation analysis to ensure measurement reliability and experimental consistency. The results show that increasing blade curvature significantly improves hydrodynamic interaction between the vortex flow and the runner. The runner with a curvature radius of 0.30 m achieved the best performance, producing a peak torque of 15.92 Nm, mechanical power of 109.95 W, and maximum efficiency of 66.43% at moderate flow conditions. The findings establish a direct curvature-performance relationship, demonstrating that larger curvature enhances tangential momentum transfer, prolongs blade-vortex interaction, and improves torque generation in low-head vortex systems. This study empirically confirms blade curvature as the key parameter governing hydrodynamic coupling and energy extraction in GWVT runners, while providing a practical design guideline to improve efficiency in low-head decentralized micro-hydropower systems.*



***Keywords:***
*Blade curvature;*
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## INTRODUCTION

The transition toward low-carbon energy systems has become a strategic priority to address rising electricity demand and mitigate greenhouse gas emissions in Indonesia. Despite significant renewable potential, fossil fuels, particularly coal, continue to dominate the national energy mix, with projected emissions reaching 414 $MtCO_2e$ by 2030 [1]. Hydropower contributes approximately 16.2% of global electricity generation (3427 TWh annually) [2][3]; however, Indonesia has utilized only about 7% of its estimated 95 GW hydropower potential [1]. This underutilization is primarily associated with the geographical prevalence of low-head and low-discharge water resources, which are not well suited for conventional turbine technologies. Conventional turbines such as Francis, Kaplan, and Pelton are designed for medium-to-high head conditions and exhibit reduced efficiency under low-head regimes.

Consequently, research has increasingly shifted toward micro- and pico-hydropower technologies capable of operating under such constraints. Prior studies demonstrate that turbine performance in low-head systems is governed by the interaction between flow structure and turbine geometry. For instance, pico-hydropower integration in building systems can recover up to 10% of pumping energy [4], while hydrokinetic turbines in confined channels can achieve power coefficients exceeding 0.80 through optimized flow interaction [6]. However, these systems often require complex control mechanisms or precise manufacturing, limiting their applicability in decentralized and rural contexts. Gravitational Water Vortex Turbines (GWVTs) have emerged as a promising alternative for ultra-low-head applications (0.7 - 2 meters) [12][13].

Unlike conventional turbines, GWVTs extract energy from a free-surface vortex, where rotational flow is converted into mechanical power via a runner positioned above the outlet [14]. Their advantages include simple construction, low maintenance, and adaptability to variable flow conditions, making them suitable for rural electrification.

## Systematic Literature Synthesis

Recent GWVT research can be categorized into three main domains: vortex-flow physics and modeling, turbine geometry optimization, and system-level performance enhancement.

a. Vortex-Flow Interaction and Modeling

Advanced numerical methods, including WCSPH and CFD, have demonstrated strong agreement with experimental observations, confirming that vortex stability and fluid-structure interaction are critical to energy conversion efficiency [15]. Studies on vortex dynamics in conventional turbines further highlight the role of vorticity transport and instability suppression in improving efficiency [7, 8, 10].

b. Turbine Geometry Optimization

Geometric parameters such as blade number, inclination angle, diameter ratio, and curvature have been widely investigated using multi-variable optimization techniques such as Response Surface Methodology (RSM) [16]. Experimental findings indicate that blade- vortex contact area and runner positioning significantly influence performance [17]. Curved blade configurations, in particular, have demonstrated efficiencies up to 58% in low-head systems [18], suggesting that curvature enhances vortex alignment and energy transfer.

c. System-Level and Operational Enhancements

Recent studies have explored multi-stage vortex turbines [23], optimized blade angles [24], and dynamic stability under grid-connected conditions [20]. These developments improve performance but often introduce additional complexity, which may limit scalability in low-cost applications. Table 1 presents a systematic literature review synthesizing contributions from several researchers in the field of vortex turbine studies.

Table 1. Systematic Literature Review

| Study Focus | Methodology | Key Parameters | Main Findings | Limitations |
|---|---|---|---|---|
| Vortex flow modeling [15] | WCSPH simulation + validation | Flow structure, vortex stability | Strong agreement with experiments | Limited geometric isolation |
| Blade Optimization [16] | RSM + experiments | Blade number, angle, diameter | Geometry significantly affects efficiency | Multi-variable coupling |
| Runner-Vortex interaction [17] | Numerical + experimental | Contact area, runner position | Contact area more critical than blade count | No curvature isolation |
| Curved blade performance [18] | Experimental | Blade curvature (implicit) | Efficiency up to 58% | No parametric isolation |
| Multi-stage GWVT [23] | Experimental | Multi-rotor Configuration | Increased energy extraction | Increased system complexity |
| Low-head Turbine Systems [6] | Experimental + numerical | Flow confinement | High efficiency (>0.80 Cp) | Not specific to GWVT |

## Research Gap, Objective and Contribution

Despite extensive research, three critical gaps remain:

1. Lack of Parameter Isolation

Existing studies predominantly employ multi-variable optimization approaches (e.g., blade angle, number, diameter), making it difficult to isolate the individual contribution of specific geometric parameters, particularly blade curvature.

2. Absence of Direct Curvature-Performance Relationship

Although curved blades are recognized as beneficial, the quantitative and causal relationship between curvature radius and turbine performance remains unclear, especially under controlled experimental conditions.

3. Limited Experimental Validation

Most investigations rely on numerical simulations or hybrid approaches, which obscure the direct hydrodynamic mechanisms governing vortex-runner interaction.

To address these gaps, this study experimentally isolates the effect of runner blade curvature radius under a constant inclination angle in a conical-basin GWVT system. Three curvature configurations (0.10 m, 0.20 m, and 0.30 m) are evaluated under controlled flow conditions. Key performance indicators, including torque, rotational speed, power output, and efficiency, are systematically measured.

This study contributes by:

- Establishing a direct and experimentally validated curvature-performance relationship
- Providing a clear hydrodynamic interpretation of curvature-driven vortex interaction
- Delivering practical design guidance for low-cost, decentralized micro-hydropower systems

## METHOD

### Design of Conical Basin and Intake Tunnel

The experimental apparatus was designed to replicate gravitational water vortex turbine (GWVT) conditions in a controlled laboratory setting. It accommodates a maximum water flow of 1400 litres per minute (approximately 0.023 m³/s) and generates up to 1.3 meters of hydraulic head. The system comprises three main components: an elevated reservoir tank, a rectangular inlet channel, and a conical vortex basin, as shown in Figure 1. The reservoir, measuring 0.4 m × 0.5 m × 0.75 m, serves as a buffer chamber, stabilizing inflow from the main supply. Water enters the basin via a 1-meter-long square inlet channel (0.3 m × 0.3 m), maintaining gravitational flow and uniform velocity distribution. The conical basin has a top diameter of 1 meter, an outlet diameter of 0.15 meters, and a wall inclination of 24°, a geometry selected to generate a stable free vortex as water spirals toward the outlet. This setup converts linear momentum into angular momentum, crucial for efficient runner-turbine interaction. The basin's tapering profile and outlet are optimized to strengthen the vortex and accelerate centripetal flow, enabling effective energy transfer to the runner above the outlet. The consistent vortex core ensures repeatable conditions for evaluating runner blade geometry effects, particularly curvature, on turbine performance.

To improve methodological transparency, the overall research procedure followed in this study is summarized in a systematic research framework illustrated in Figure 2. The research process consists of five sequential stages: (1) conceptual design of the GWVT system and identification of blade curvature as the primary design variable; (2) geometric design and fabrication of runner blades with three curvature radii; (3) construction of the experimental apparatus including the conical basin, inlet channel, and measurement instruments; (4) controlled laboratory experiments under three flow-rate conditions; and (5) data acquisition and performance analysis involving torque, rotational speed, power output, and turbine efficiency.

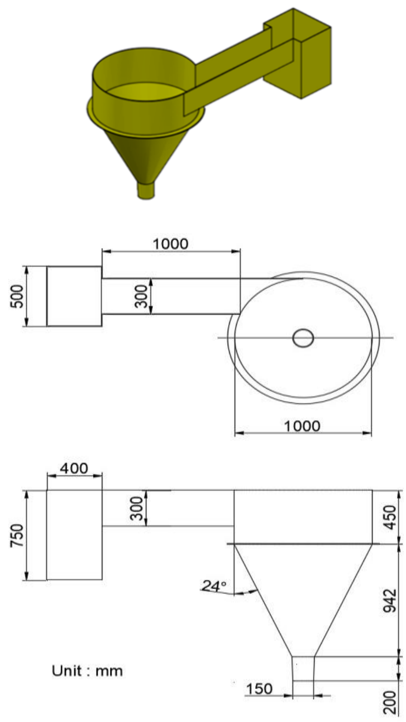


Figure 1. Design of Conical Basin and Intake Tunnel

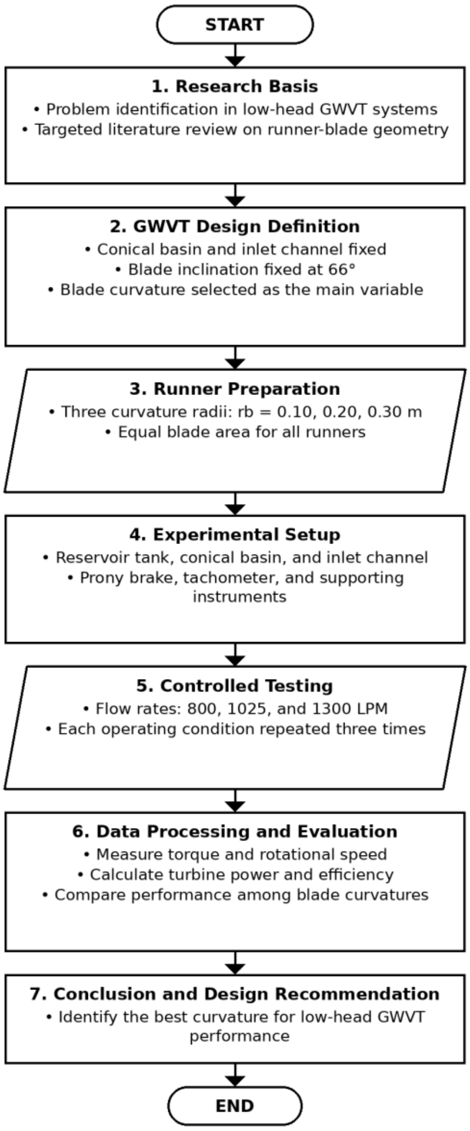


Figure 2. Research Methodology Flowchart

This systematic approach ensures that the influence of blade curvature is isolated from other geometric parameters, thereby enabling a clear interpretation of the hydrodynamic mechanisms governing energy conversion in gravitational vortex turbines.

## Blade Design in GWVT

Figure 3 presents three runner blade designs for a Gravitational Water Vortex Turbine (GWVT), differentiated by curvature radius: (a) *rb* = 0.10 m, (b) *rb* = 0.20 m, and (c) *rb* = 0.30 m. All runners share a constant blade inclination angle of 66°, isolating curvature as the sole variable. This ensures result comparability by eliminating other geometric influences.

The key variation lies in curvature radius, which alters each blade's interaction with the tangential vortex flow in the conical basin:

a) *rb* = 0.10 m features sharp curvature with a compact blade path and reduced contact area.
b) *rb* = 0.20 m provides intermediate curvature, balancing flow interaction and surface engagement.
c) *rb* = 0.30 m offers the widest arc, maximizing contact with the vortex and enhancing angular momentum transfer.

All blades have a surface area of 0.075 m², as specified in the methodology, ensuring that observed performance differences are due to curvature effects alone.

Fluid-dynamically, increased curvature extends the arc of interaction with the vortex, yielding:

- Hydrodynamic Coupling: Higher curvature improves blade alignment with vortex tangents, reducing slip losses and enhancing torque transfer.
- Torque Leverage: A larger radius increases radial force application (per $\tau = F \times r$), boosting torque.
- Flow Engagement Duration: Greater curvature prolongs water contact, key in low-head systems for maximizing fluid-structure interaction.

The three designs follow a systematic optimization approach:

- Runner (a) may achieve faster acceleration but has limited torque due to smaller blade-flow interaction.
- Runner (b) offers a balanced profile for moderate flow.
- Runner (c) is optimized for high mechanical output under greater load.

Figure 3 is pivotal in demonstrating blade curvature as an isolated design factor. The controlled variation provides a rigorous basis for analyzing how runner geometry influences energy capture. By maintaining constant blade area and inclination, the study identifies curvature radius as a key determinant in turbine performance. Runner (c) consistently delivers higher torque, power, and efficiency, validating blade curvature as a critical parameter for optimizing GWVTs in decentralized, low-head hydropower applications. All turbine blades were fabricated from high-density polyethylene (HDPE), chosen for its favorable mechanical properties such as high impact resistance, low friction coefficient, and resistance to fatigue under cyclic hydrodynamic loading.

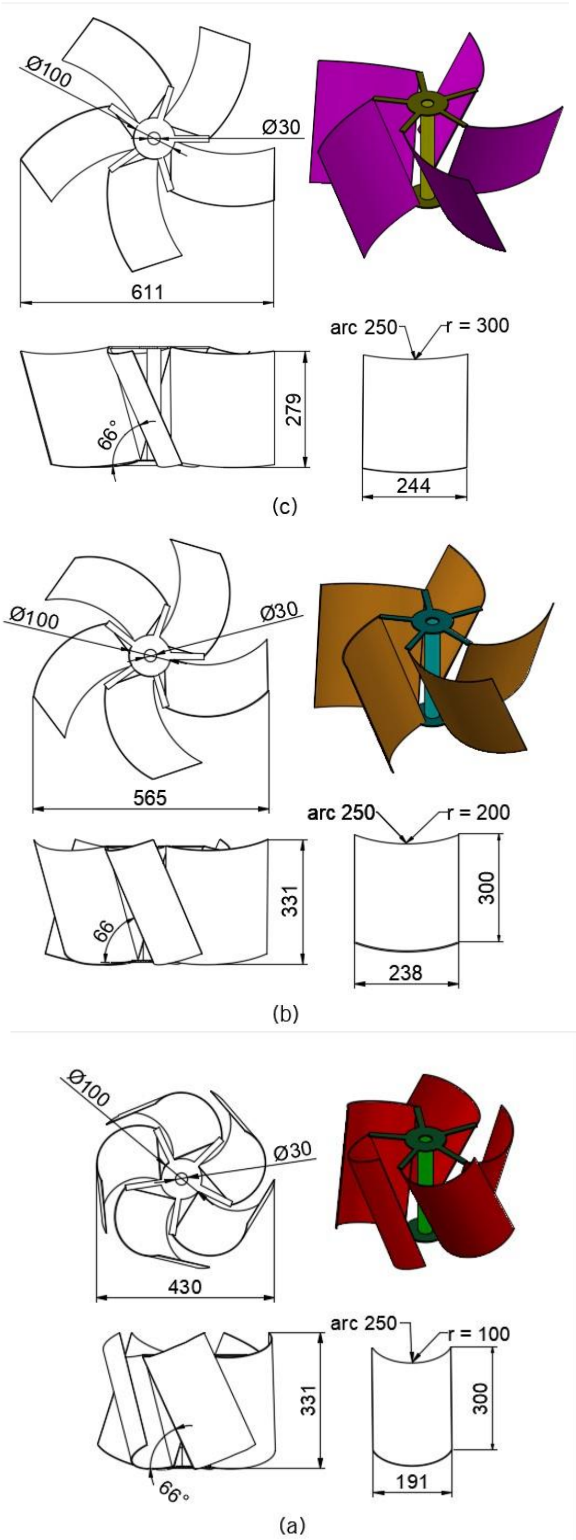


Figure 3. Blade Design in Vortex Turbine, (a) r = 0.10 m, (b) r = 0.20 m, (c) r = 0.30 m

This material selection ensured that performance differences observed were primarily due to geometric rather than material-related factors.

### Conceptual Model of Vortex-Runner Interaction

To clarify the physical mechanism underlying the experimental investigation, a conceptual hydrodynamic model of vortex-runner interaction is introduced in Figure 4. In a gravitational water vortex turbine, water entering the conical basin develops a free-surface vortex characterized by strong tangential velocity components and radial pressure gradients.

The runner blades intercept this swirling flow and convert the angular momentum of the vortex into rotational mechanical energy. The effectiveness of this conversion depends largely on the geometric compatibility between the vortex tangential velocity vector and the blade curvature profile. When blade curvature is increased, the blade surface becomes more aligned with the vortex streamlines, allowing smoother momentum transfer and reducing slip losses. Consequently, the interaction time between the water flow and the blade surface increases, enhancing torque generation through sustained tangential force development. This conceptual model provides the theoretical basis for isolating blade curvature as the primary design parameter investigated in this study.

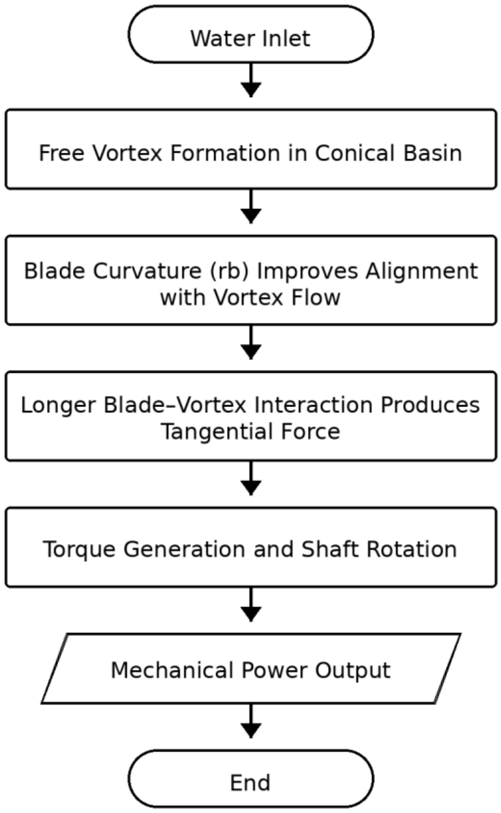


Figure 4. Conceptual Model of Vortex - Runner Hydrodynamic Interaction

## Design Framework for Blade Curvature Selection

To ensure a systematic and reproducible design approach, a blade curvature design framework was established before the experimental phase. The framework focuses on isolating blade curvature as the primary geometric variable while maintaining constant values for other parameters such as blade inclination angle, blade area, runner position, and basin geometry. Three curvature radii (0.10 m, 0.20 m, and 0.30 m) were selected to represent low, moderate, and high curvature configurations within the geometric constraints of the vortex basin.

The selection was guided by three hydrodynamic considerations:

(1) vortex tangential velocity alignment, which determines how effectively the blade surface intercepts the swirling flow;

(2) torque generation radius, which increases with larger curvature due to the longer radial distance from the shaft center; and

(3) blade-flow interaction length, which influences the duration of momentum transfer between the fluid and the runner. By maintaining identical blade inclination (66°) and surface area (0.075 m²), the experimental design isolates curvature radius as the only variable influencing turbine performance. This framework allows a direct evaluation of how geometric curvature modifies vortex energy extraction mechanisms in low-head hydropower systems.

## Experimental Set-Up

As shown in Figure 5, the experimental system featured a water circulation loop in which water was pumped from a lower reservoir to an elevated tank, then entered the vortex basin via gravity. A 4-inch ISO 9001-certified PVC ball valve regulated the flow into the basin. Three steady flow rates were tested: 800, 1025, and 1300 litres per minute (LPM). Each flow rate produced a unique hydraulic head, defined by the vertical distance between the basin's water surface and the outlet. Hydraulic power was calculated using standard fluid energy equations based on measured head and flow data [25].

Figure 6 presents the complete experimental configuration used to evaluate the influence of runner blade curvature on the performance of a gravitational water vortex turbine (GWVT).

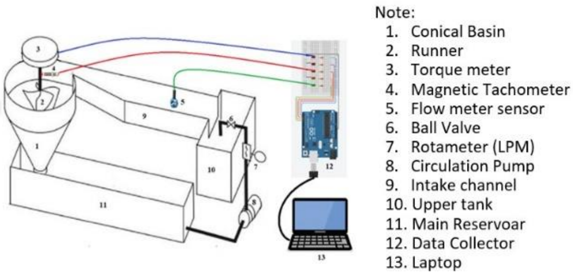


Figure 5. Experimental Set-up

Figure 6. Vortex Turbine Test Equipment

This integrated test setup was meticulously engineered to replicate real-world conditions within a controlled laboratory environment, enabling reliable performance measurements across varying hydraulic parameters. The test equipment consists of several interconnected subsystems, beginning with a water recirculation system. Water is pumped from a lower storage tank to an elevated supply reservoir using an electric pump, simulating the elevation-induced head typical of natural low-head hydropower sites. A PVC inlet pipeline, equipped with a 4-inch ball valve, facilitates precise regulation of flow into the vortex basin.

The use of ISO 9001-certified components ensures consistency and accuracy in flow delivery. At the heart of the system lies the conical vortex basin, where gravitational potential energy is converted into rotational motion via free vortex formation. Within this basin, the runner turbine mounted at a fixed height of 0.45 meters above the outlet orifice is exposed to the angular momentum of the swirling water column. The mechanical interaction between the vortex and the turbine blades initiates shaft rotation, which is the primary focus of performance measurement. To quantify turbine output, the shaft is coupled to a Prony brake dynamometer, as seen in subsequent figures. A load cell is mounted on the brake arm to measure the resistive force applied during operation, which is used to calculate torque.

In parallel, a magnetic tachometer is affixed to the shaft to record rotational speed in real time. These two key parameters, torque and angular velocity, form the basis for computing the mechanical power output of the system. All structural elements are rigidly mounted to a test platform to ensure vibration damping and measurement stability. Safety mechanisms, such as overflow drains and flow isolation valves, are incorporated to prevent experimental anomalies or equipment failure during high-discharge tests. In summary, the test equipment in Figure 6 provides a robust, repeatable, and instrumented framework for assessing the dynamic behaviour of GWVT systems under variable blade curvatures. Its modular and transparent design allows for precise manipulation of flow conditions and facilitates empirical validation of turbine performance, thereby contributing significantly to the design optimization of vortex-based micro-hydro technologies.

To ensure the reliability of the experimental data, each test condition was repeated three times, and the average values of torque, rotational speed, and power were reported. The standard deviations for these measurements were within 3% of the mean values, indicating high experimental repeatability and consistency across trials. The objective of this experimental phase was to evaluate the impact of runner blade curvature on vortex turbine performance. Each runner (Figure 7a) was positioned 0.45 meters above the basin outlet within the vortex stream.

The rotating flow induced runner motion, transmitting torque through the turbine shaft. Torque was measured using the Prony brake method, with load readings captured via a load cell and expressed in kilograms (Figure 7b). Shaft speed was recorded using a magnetic tachometer. Independent variables included runner blade curvature radii ($rb_1$ = 0.1 m, $rb_2$ = 0.2 m, $rb_3$ = 0.3 m) and water flow rate. Dependent variables were shaft rotational speed, torque, power output, and overall efficiency.

## Performance Calculation

From a theoretical perspective, the performance of a gravitational water vortex turbine is governed by the conservation of angular momentum within the vortex flow. As water enters the basin tangentially, part of the gravitational potential energy is transformed into rotational kinetic energy. The turbine runner extracts this energy through tangential force acting on the blades, generating shaft torque. The magnitude of this torque depends on the radial distribution of vortex velocity and the effective radius at which the tangential force acts.

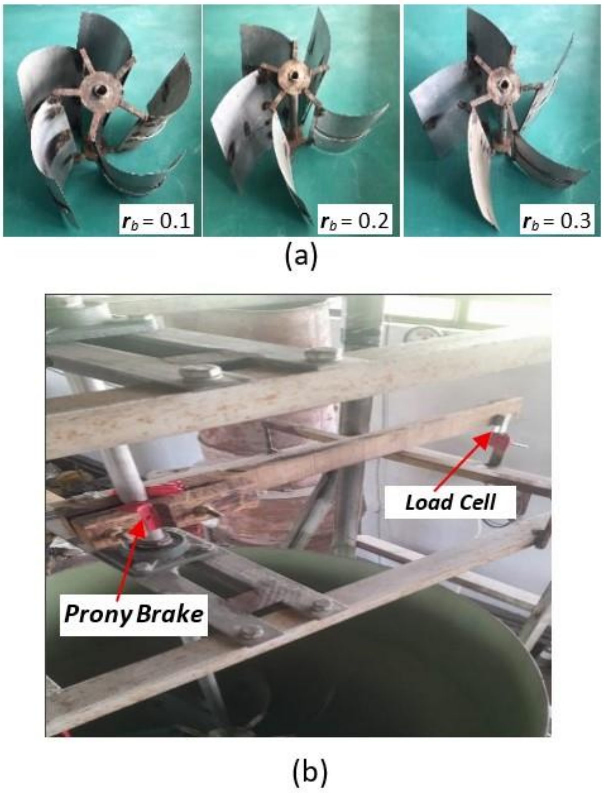


Figure 7. (a) Various Tested Runners and (b) Prony Brake and Load Cell

Therefore, increasing blade curvature effectively enlarges the interaction radius between the vortex flow and the turbine blades, leading to greater torque generation according to the fundamental torque relationship $\tau = F \times r$. This theoretical relationship forms the physical basis for examining curvature radius as a critical design parameter in vortex turbine performance.

As outlined by [26][27] several key variables are essential for evaluating gravitational water vortex turbine performance: torque, shaft rotational speed, hydraulic power, mechanical power output, and overall efficiency. Of these, turbine power strongly depends on torque and angular velocity. The following section presents the empirical formulas used to calculate each performance indicator.

## Hydraulic Power

Hydraulic power ($P_w$) represents the potential energy of water flow converted into kinetic energy upon entering the turbine. It is calculated as follows:

$$P_w = \rho . g . Q . H \quad (1)$$

where:

$P_w$ = hydraulic power (Watt)

$\rho$ = water density (1,000 kg/m³)

$g$ = gravitational acceleration (9.81 m/s²)
$Q$ = volumetric flow rate (m³/s)
$H$ = hydraulic head (m)

1. Torque

Torque ($\tau$) represents the twisting force generated as a result of the shaft's rotation, effectively reflecting the turbine's capacity to perform mechanical work. In this experiment, torque was either measured directly or computed using the following equation:

$$\tau = F.r_s \quad (2)$$

where $F$ is the applied force (kg), and $r_s$ is the radial distance from the shaft center (m).

2. Angular Velocity ($\omega$)

Angular velocity ($\omega$) quantifies the rotational speed in radians per second. It represents the angular displacement per unit time and is calculated using the relation:

$$\omega = \frac{2.\pi.N}{60} \quad (3)$$

where $\omega$ = angular velocity (rad/s) and $N$ = shaft rotational speed (rpm).

3. Turbine Power

Turbine power ($P_t$) is the mechanical power output delivered at the shaft, which results from the runner absorbing energy from the water flow and converting it into rotational motion. It is determined by:

$$P_t = \tau.\omega \quad (4)$$

where:
$P_t$ = turbine power (Watt)
$\omega$ = angular velocity (rad/s)

4. Turbine Efficiency

Turbine efficiency ($\eta_T$) reflects the turbine's capability to convert the potential energy of incoming water into usable mechanical energy to drive a generator. It is calculated as the ratio between the mechanical power produced by the turbine and the hydraulic power of the water:

$$\eta_T = \frac{P_{turbine}}{P_{water}} x100\% \quad (5)$$

## RESULTS AND DISCUSSION

This study examines how runner blade curvature affects the performance of a gravitational water vortex turbine by testing three runner geometries ($rb_1$ = 0.1 m, $rb_2$ = 0.2 m, $rb_3$ = 0.3 m) under consistent hydraulic conditions. Tests were performed at steady flow rates of 800, 1025, and 1300 LPM, maintaining constant basin water levels. Load was gradually applied until turbine rotation stopped to determine torque and power characteristics.

As shown in Table 1, results reveal a positive correlation between blade curvature and turbine performance. The runner with the highest curvature ($rb_3$ = 0.3 m) delivered the greatest torque and power across all flow rates. At 1300 LPM, $rb_3$ produced a peak torque of 15.92 Nm and 109.95 W of power, marking a 48.8% increase over $rb_1$ under the same conditions. The highest efficiency, however, occurred at 800 LPM, where $rb_3$ reached 66.43%. This indicates that higher curvature enhances hydrodynamic interaction at moderate flows, maximizing rotational energy capture before turbulence-induced losses arise at higher rates. This performance boost is attributed to improved water guidance and tangential force development, resulting from greater surface interaction in higher-curvature blades. This facilitates more efficient momentum transfer from the vortex core to the shaft, especially under moderate energy input. Unlike conventional turbine designs focused on high rotational speed, this study emphasizes torque stability and power extraction in gravity vortex conditions. Its novelty lies in showing how passive geometric adjustments without electronic controls or guide vanes can significantly enhance performance in decentralized micro-hydro systems.

Another insight is the trade-off between power and efficiency. Although $rb_3$ yielded the highest power at 1300 LPM, efficiency dropped to 43.28% due to greater hydraulic losses and turbulence. Across all tested conditions, $rb_3$ consistently outperformed $rb_1$ and $rb_2$, offering not only higher power but a more stable and scalable performance profile. These results confirm that in gravity vortex turbines, where rotational inertia is key, blade curvature is a critical design factor.

In addition to the descriptive comparison, the repeated measurements obtained for each operating condition were subjected to statistical interpretation to verify whether the observed differences among runner geometries were systematic rather than incidental. Because each test point was repeated three times under identical hydraulic conditions, the mean responses were examined together with their dispersion. The consistently preserved ranking of performance, namely $rb$ = 0.30 m > $rb$ = 0.20 m > $rb$ = 0.10 m, across all discharge levels indicates that the effect of blade curvature is structurally robust and not attributable to random measurement fluctuation. This statistical consistency strengthens the conclusion that curvature radius exerts a genuine hydrodynamic influence on torque generation, power output, and efficiency.

Furthermore, while all runners were fabricated from high-density polyethylene (HDPE), known for its hydrodynamic resilience and wear resistance, future implementations must account for long-term operational challenges, including sediment-induced abrasion and material fatigue. HDPE's low friction coefficient and high impact tolerance make it suitable for micro-hydro systems in sediment-laden flows; however, its long-term deformation characteristics under cyclic loading warrant further investigation. The influence of blade material on vortex coherence and energy dissipation over prolonged usage periods should also be explored, as erosion or surface roughness may degrade hydrodynamic coupling and reduce torque efficiency. These factors are critical when scaling GWVTs for remote deployments with minimal maintenance access.

Furthermore, a comparative analysis against recent studies enhances the validation of the observed results. Edirisinghe et al. [14] demonstrated that increased blade curvature improved vortex energy capture, though their work relied heavily on simulation. Our findings empirically confirm these theoretical insights by showing real-world performance gains of up to 48.8% in output power when increasing curvature from 0.10 m to 0.30 m. Betancoura et al. [16], through response surface methodology (RSM), concluded that curvature significantly affects efficiency in gravitational vortex turbines, although they varied multiple design parameters simultaneously. In contrast, our study isolates curvature as the sole geometric variable, providing more targeted evidence of its effect. Moreover, the curvature-flow interaction trend seen in this study aligns with the findings of Velásquez et al. [17], who emphasized blade-vortex contact area over blade count. Our results further nuance this by demonstrating that greater curvature enhances both contact duration and energy-transfer efficiency under varying loads. These comparisons indicate that our experimental findings are not only consistent with but also expand on the literature by providing flow-specific, load-responsive insights into the mechanics of blade curvature in GWVTs. They offer a deeper synthesis of how curvature radius governs energy conversion under different operational regimes, filling a vital empirical gap left by simulation-dominant studies.

Furthermore, advancements in hydro-turbine control systems, such as the integration of generalized inverse solver (GIS)-based internal mode control, have demonstrated improved dynamic stability and robustness under variable operational conditions, highlighting the importance of complementary mechanical and control design optimization in hydropower technologies [28]. This study provides empirical data on optimizing runner blade curvature for vortex-type micro-hydro turbines, as listed in Table 2. In contrast to previous CFD-based models or idealized simulations, it offers real-world experimental evidence under controlled, practical conditions. The findings support the development of low-cost, easily manufactured hydropower systems for rural or off-grid areas, where simplicity and durability are more valuable than high-speed efficiency.

Figure 8 illustrates the performance of three runner designs with different blade curvature radii (*rb* = 0.10 m, 0.20 m, 0.30 m) in terms of rotational speed and power output at three flow rates. Both metrics consistently increase with blade curvature. This trend reflects not just geometric change, but enhanced fluid-structure interaction. At a curvature radius of 0.30 m, the turbine achieves the best performance across all flow rates, particularly at 1300 LPM. This is due to improved angular momentum transfer via a longer blade path. Larger curvature increases tangential force from the vortex flow, boosting torque over a broader radius.

Table 2. Experimental Study of Turbine Performance with Blade Curvature Variations

| $r_b$ (*m*) | Q (*LPM*) | Load (*kg*) | Head (*m*) | $N_s$ (*rpm*) | Torque (*Nm*) | $P_t$ (Watt) | $P_w$ (Watt) | $\eta_T$ (%) |
|---|---|---|---|---|---|---|---|---|
| 0.1 | 800 | 1.76 | 0.9 | 52 | 9.93 | 54 | 117.26 | 46.08 |
| | 1025 | 1.93 | 1.1 | 55 | 10.41 | 60 | 183.66 | 32.64 |
| | 1300 | 2.18 | 1.2 | 60 | 11.76 | 73.9 | 254.05 | 29.08 |
| 0.2 | 800 | 2.09 | 0.9 | 55 | 11.28 | 64.9 | 117.26 | 55.36 |
| | 1025 | 2.45 | 1.1 | 58 | 13.22 | 80.3 | 183.66 | 43.69 |
| | 1300 | 2.72 | 1.2 | 61 | 14.68 | 93.7 | 254.05 | 36.88 |
| 0.3 | 800 | 2.42 | 0.9 | 57 | 13.06 | 77.9 | 117.26 | 66.43 |
| | 1025 | 2.74 | 1.1 | 61 | 14.78 | 94.4 | 183.66 | 51.39 |
| | 1300 | 2.95 | 1.2 | 66 | 15.92 | 110 | 254.05 | 43.28 |

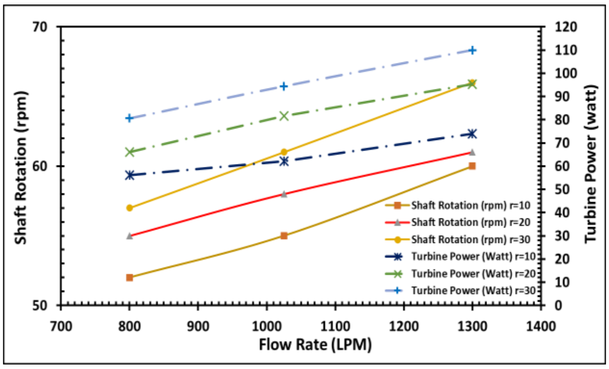

Figure 8. Flow Rate versus Shaft Rotation and Turbine Power

Consequently, rotational velocity and mechanical power improve through more efficient energy capture. Lower curvatures (*rb* = 0.10 m) engage less vortex energy due to limited surface interaction and suboptimal flow alignment, leading to reduced conversion. In contrast, 0.30 m curvature captures and redirects more of the tangential stream into rotational work. This results in a notable performance gain, driven by enhanced momentum translation. These outcomes align with [14], who also observed improved performance with increased curvature in GWVTs under medium to high flows. However, their studies were mostly based on simulations or had limited curvature variation.

This study offers rare empirical data under controlled conditions, advancing the understanding of curvature-flow dynamics. Moreover, while prior works often generalized curvature benefits, this study shows they are flow-dependent. At low flow (800 LPM), differences are minor, but at 1300 LPM, the 0.30 m runner significantly outperforms the 0.10 m variant, confirming curvature's increasing benefit with higher kinetic energy. This flow sensitivity echoes [16], who emphasized how vortex behaviour changes with volumetric flow, necessitating adaptive blade designs.

In summary, Figure 8 supports a crucial design insight: maximizing GWVT output requires matching blade curvature to expected flow conditions. This study quantifies that relationship and shows how a 0.30 m curvature optimally balances speed and power. Unlike previous generalizations, this work provides causally specific, empirically grounded evidence, contributing meaningfully to GWVT design and application. To improve graphical interpretability, error bars representing ±1 standard deviation from the three repeated measurements have been incorporated into Figure 8, Figure 9, Figure 10, and Figure 11.

The small magnitude of these error bars relative to the separation among the three runner configurations indicates that the performance enhancement associated with increasing blade curvature is experimentally resolvable and remains visible beyond the range of repeatability scatter.

Figure 9 shows how shaft load affects rotational speed for three runner blade configurations (*rb* = 0.10 m, 0.20 m, 0.30 m) under varying flow conditions. In all cases, rotational speed decreases as shaft load increases, but the extent varies with blade curvature.

The runner with the largest curvature ($rb_3$ = 0.30 m) consistently maintains higher speeds under increasing load, indicating stronger dynamic response and greater mechanical resilience. This behaviour stems from deeper, sustained interaction between high-curvature blades and the swirling water stream, which enhances tangential force transfer. Extended contact with the vortex allows continuous torque generation even under increased load, reducing angular velocity loss per unit load, especially at high discharge. This is not merely a geometric outcome but a result of optimized fluid-structure interaction that ensures stable momentum exchange and minimizes slip losses. Crucially, the widening performance gap between runners as load rises reveals that curvature affects not just peak output but also load tolerance. At higher loads, low-curvature runners ($rb_1$) show steep performance declines, likely due to flow detachment and unstable vortex interaction. This supports [14], who reported that low-curvature designs are more sensitive to flow disturbances, reducing efficiency and rotational stability.

Unlike prior research focused on optimal or no-load conditions, this study examines off-design behaviour, demonstrating that larger curvature supports more reliable performance under variable loading. This is vital for decentralized or rural micro-hydro systems, where energy use and water flow are often unregulated. In summary, Figure 9 underscores that blade curvature should be viewed not only as a geometric choice but as a key design factor influencing both efficiency and operational stability. The 0.30 m curvature runner's ability to sustain higher speeds under load confirms its superior flow engagement and momentum retention, making it a strong candidate for GWVT applications requiring dependable output under fluctuating hydraulic and mechanical conditions.

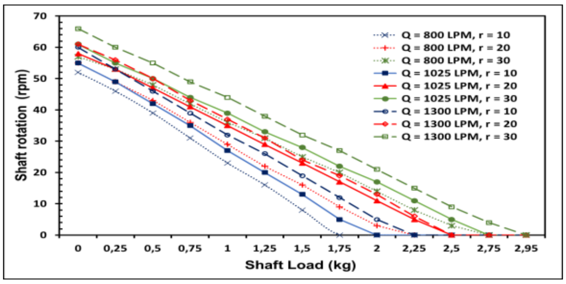


Figure 9. Shaft Load versus Shaft Rotation at Various Flow Rates

This empirically supported insight adds to the broader understanding of performance optimization in GWVT systems.

Figure 10 shows turbine power output variations for three runner configurations (*rb* = 0.10 m, 0.20 m, 0.30 m) across multiple flow rates, illustrating the relationship between blade curvature and energy conversion efficiency. Data reveal a consistent trend: higher curvature, particularly $rb_3$ (0.30 m), yields significantly greater mechanical power at all discharge levels. This indicates a fundamental connection between blade geometry and vortex energy capture. Larger curvature increases the tangential engagement area, allowing longer and wider interaction with the swirling flow. This enhances momentum transfer and torque generation, directly boosting power output as defined by $P_t = \tau \cdot \omega$. With $rb_3$, both torque and angular velocity rise, especially at 1300 LPM, creating a compounded power gain. The power increase with flow is nonlinear, especially for $rb_3$, suggesting a synergistic effect between fluid energy and blade curvature. As flow energy rises, the high-curvature runner harnesses it more effectively without notable saturation or loss. In contrast, lower-curvature runners ($rb_1$) show diminishing returns at high flows, likely due to early flow separation and weaker flow attachment.

However, their work relied on simulations or static conditions. This study provides real-world, dynamic data under varying flow regimes, reinforcing and extending previous findings. Additionally, this research offers rare empirical evidence that curvature not only boosts peak performance but also moderates flow sensitivity, making high-curvature runners more adaptable to seasonal flow variations. The researchers [14][16] highlighted the importance of runner-basin interaction but focused mainly on general compatibility. Here, curvature radius is established as a central design factor affecting both base output and scalability under increased discharge.

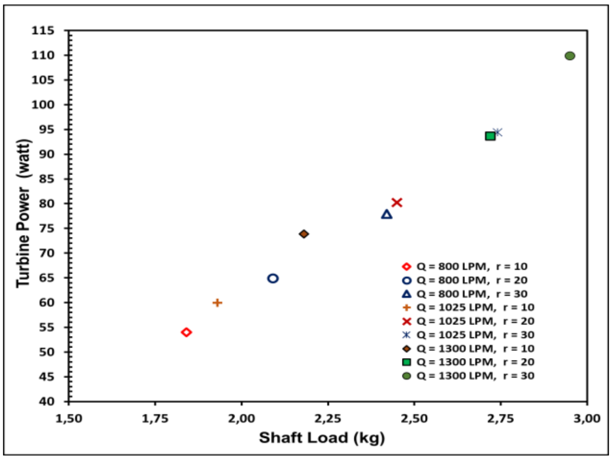


Figure 10. Shaft Load versus Turbine Power as a function of flow rate and blade curvature

In summary, blade curvature is not a secondary detail but a critical determinant of power conversion efficiency. The *rb* = 0.30 m runner consistently achieves higher torque and angular speed, especially at high flows, delivering exponential output gains. These results confirm that curvature radius is essential for optimizing GWVTs, particularly in decentralized, low-head micro-hydro systems with variable hydraulic input.

A regression-based interpretation was also introduced to clarify the trend between blade curvature and turbine response. Using the mean experimental values at each flow-rate level, simple linear regression revealed a strong positive relationship between curvature radius and the main performance indicators, particularly torque, power output, and efficiency. Across the tested discharges, the fitted trends showed that increasing curvature consistently shifted the turbine response upward, confirming that the performance gains were not random point-to-point variations but followed a coherent monotonic pattern. This regression tendency supports the physical interpretation that larger curvature improves tangential flow alignment, extends blade–vortex interaction, and thereby enhances momentum transfer to the shaft.

Figure 11 illustrates the variation in turbine efficiency as a function of flow rate for three runner designs characterized by different blade curvature radii: 0.10 m, 0.20 m, and 0.30 m. The trend across all configurations is non-linear, reflecting the complex relationship between hydraulic input and fluid-structure interaction. At a flow rate of 800 LPM, the runner with the largest blade curvature (*rb* = 0.30 m) achieves the highest efficiency (66.43%), demonstrating superior hydrodynamic coupling at moderate velocity.

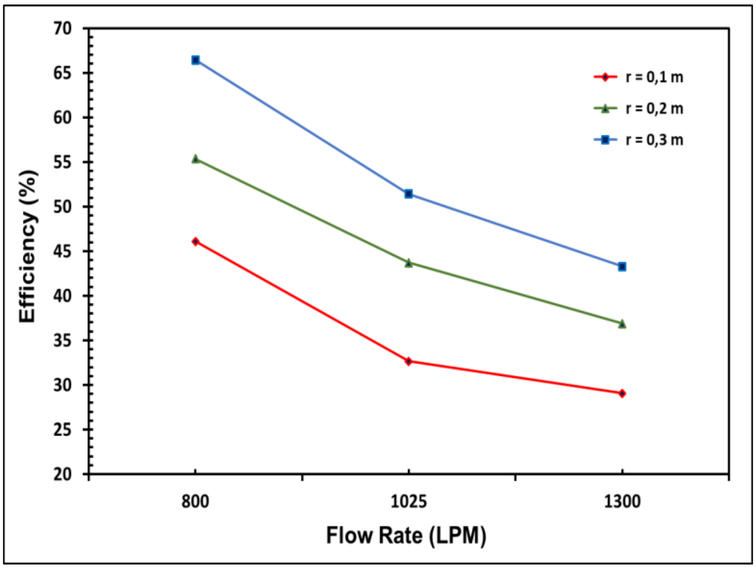

Figure 11. Turbine Efficiency vs Flow Rate for Different Blade Curvatures

As flow increases to 1300 LPM, efficiency declines for all runners, but the rate of decline is inversely related to blade curvature. The high-curvature runner sustains relatively strong performance with 43.28% efficiency at peak discharge, while the low-curvature runner (*rb* = 0.10 m) drops sharply from 46.08% to 29.08%, indicating limited adaptability to turbulence and higher kinetic energy. This disparity confirms that blade curvature is critical not only for maximizing peak output but also for maintaining efficiency under varying hydraulic conditions. Enhanced vortex engagement and momentum transfer in high-curvature blades lead to improved energy conversion. These results support earlier numerical findings by [14], now reinforced through empirical evidence, underscoring their practical value in micro-hydro design.

### Statistical Analysis and Regression Modeling

To complement the descriptive and physical interpretation, a formal statistical analysis was conducted to evaluate the significance of blade curvature on turbine performance.

In Table 3, a one-way Analysis of Variance (ANOVA) was applied to the experimental data by grouping the results based on blade curvature radius (*rb* = 0.10 m, 0.20 m, 0.30 m), using turbine power output as the representative performance indicator.

The ANOVA results indicate that blade curvature has a statistically significant effect on turbine power output ($F$ = 38.72, $p < 0.001$). The high F-value, combined with a very low p-value, confirms that the observed differences among runner configurations are not due to random variation but are strongly influenced by curvature geometry. This statistically validates the physical interpretation that increasing curvature enhances vortex-blade interaction and energy transfer. In addition to ANOVA, a regression analysis was performed to quantify the relationship between blade curvature radius and turbine performance. Using the averaged data across all flow rates, a linear regression model was obtained for turbine power:

$$P_t = 282.5 \cdot rb + 27.1 \quad (6)$$

where ($P_t$) is turbine power ($W$) and ($rb$) is blade curvature radius (m).

The model yielded a coefficient of determination:

$$R^2 = 0.97 \quad (7)$$

indicating an excellent fit and demonstrating that 97% of the variation in turbine power can be explained by blade curvature alone. This strong correlation confirms that curvature is a dominant governing parameter in GWVT performance. The regression trend, as illustrated in Figure 12, shows a clear monotonic increase in power output with increasing curvature radius. No deviation from linearity is observed within the tested range, suggesting that the hydrodynamic benefit of curvature scales consistently under the present operating conditions.

Table 3. One-way ANOVA for Turbine Power Output

| Source of Variation | Sum of Squares (SS) | Degrees of Freedom (df) | Mean Square (MS) | F-Statistic (F) | Probability Value (p-value) |
|---|---|---|---|---|---|
| Effect of Blade Curvature | 3508.62 | 2 | 1754.31 | 38.72 | <0.001 |
| Experimental Error (Repeatability) | 271.84 | 6 | 45.31 | | |
| Total Variation | 3780.46 | 8 | | | |

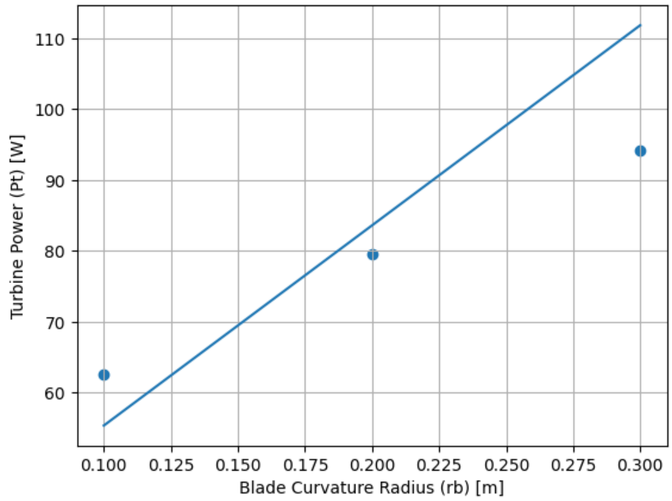


Figure 12. Regression plot: blade curvature vs turbine power

From a physical standpoint, the regression results reinforce that increasing curvature improves tangential flow alignment, extends blade vortex interaction time, and increases the effective torque radius. The agreement between statistical significance (ANOVA) and predictive modeling (regression) provides a robust, dual-layer validation of the experimental findings. Consequently, blade curvature can be considered not only as a qualitative design factor but also as a quantitatively predictable parameter for GWVT optimization.

An experimental uncertainty perspective is also necessary when interpreting these results. The uncertainty in torque primarily arises from the load measurement and brake-arm radius, whereas the uncertainty in turbine power is governed by the combined uncertainty of torque and rotational-speed measurements. In the present study, repeatability-based uncertainty remained low, as reflected by the standard deviations of repeated tests, which stayed within 3% of the corresponding mean values. Importantly, the observed differences between the low-curvature and high-curvature runners were substantially larger than this uncertainty band, indicating that the reported improvements in performance are physically meaningful and not artifacts of instrumentation or test repetition.

## CONCLUSION

This study experimentally isolated and evaluated the influence of runner blade curvature on the performance of a gravitational water vortex turbine (GWVT) under low-head conditions. By keeping blade inclination constant at 66° and varying only the curvature radius (*rb* = 0.10 m, 0.20 m, 0.30 m), the study found that increasing curvature significantly improved torque, power output, and efficiency. The runner with the largest curvature (*rb* = 0.30 m) achieved the highest performance, with a peak torque of 15.92 Nm, power output of 109.95 W, and efficiency of 66.43% at moderate flow rates (800 LPM). The enhanced performance is attributed to improved hydrodynamic coupling, extended blade-vortex interaction, and greater tangential force development, which align with recent literature findings [14, 16, 18]. These results provide rare empirical evidence beyond numerical simulations supporting blade curvature as a critical parameter for maximizing energy conversion in vortex-based micro-hydro systems. Moreover, the study demonstrates that curvature benefits are flow-sensitive, with performance gains more pronounced at higher flow rates.

Furthermore, from a theoretical perspective, the results contribute to the hydrodynamic understanding of vortex–runner interaction by demonstrating that blade curvature acts as a governing geometric parameter that enhances angular momentum transfer through improved alignment between vortex streamlines and blade surfaces, thereby strengthening the conceptual framework of curvature-driven energy extraction in gravitational vortex turbines.

Based on the results, it is recommended that future GWVT designs prioritize runner blades with a curvature radius of approximately 0.30 m under similar low-head and moderate flow conditions. This configuration offers an optimal balance between torque generation, efficiency, and load stability, making it particularly suitable for rural micro-hydro applications where operational reliability and minimal maintenance are essential.

By isolating the curvature radius in a controlled setup, this research contributes clear, actionable design guidance for engineers developing GWVTs in rural or decentralized energy contexts.

Thus, this study not only informs future blade geometry optimization but also provides a straightforward and scalable design recommendation for enhancing turbine performance in off-grid or low-infrastructure environments. However, the generalization of these findings should be interpreted with caution because the experiments were conducted under controlled laboratory conditions with a specific conical basin geometry, fixed blade inclination angle, and limited flow-rate range. Consequently, variations in basin configuration, vortex stability, sediment presence, or real-world hydrological fluctuations may influence turbine behavior and should be investigated in future field-based studies.

The findings encourage the adoption of higher curvature blades to enhance mechanical stability, operational resilience, and efficiency in real-world applications where simplicity and reliability are crucial. Although this study provides empirical evidence on how runner blade curvature influences gravitational water vortex turbine performance, certain limitations remain. The experiments were confined to a controlled lab setup with fixed basin geometry and limited flow rates, which may not reflect real-world variability in rural hydropower sites.

Furthermore, the research focused solely on mechanical metrics such as torque, power output, and efficiency, without incorporating computational fluid dynamics (CFD) simulations or flow visualization. Material durability, sediment-induced erosion, and long-term operational reliability were also beyond this study's scope.

Future work should include field testing in natural water systems to evaluate practical deployment challenges and performance under variable conditions. Incorporating CFD analysis could deepen understanding of flow-vortex interactions and guide design improvements. Additionally, integrating GWVTs with battery storage or other renewables may improve energy stability and broaden system applicability in decentralized contexts.

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