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Performance Evaluation of a Recyclable Bottle-Blade Overshot Waterwheel for Low-Head Low-Flow Pico Hydropower Applications

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Abstract

This study presents the design and performance evaluation of an innovative bottle blade overshot waterwheel specifically developed for pico hydropower generation in low-head and low-flow conditions. The waterwheel incorporates a lightweight, portable structure with turbine blades constructed from recycled plastic bottles, offering a sustainable and cost-effective solution that also facilitates easy maintenance and reduces plastic waste. Experimental testing was conducted using a water test rig equipped with a Prony brake system, operating under water heads of 0.4 meters and 0.5 meters with flow rates of 0.015 m^3/s and 0.02 m^3/s. System performance was evaluated based on the fundamental principles of mass, momentum, and energy conservation. Two configurations of the waterwheel, using four and eight bottle blades respectively, were tested to assess the influence of blade quantity on energy conversion efficiency. Key performance indicators included rotational speed (n), angular velocity (ω), torque (τ), tangential force (FT), lift force (FL), blade velocity ratio (U divided by v), mechanical power output (Pmech), mechanical efficiency (ηmech), and electrical efficiency (ηelec). Results were analyzed using graphical performance curves and a nomographic method to visualize the effects of operational parameters. The results demonstrate that both the hydraulic head and the number of blades significantly influence performance. The eight-blade configuration operating at a water head of 0.5 meters and a flow rate of 0.02 m^3/s exhibited the highest performance, achieving a mechanical power output of 48.58W, a mechanical efficiency of 49.11%, and an electrical efficiency of 24.03%. This condition corresponded to an angular velocity of 19.48 rad/s, a torque of 2.49 Nm, and tangential and lift forces of 11N and 16.25N respectively. In conclusion, the bottle blade overshot waterwheel demonstrates significant potential for decentralized renewable energy generation in remote or resource-constrained areas, offering an environmentally responsible and technically viable solution for pico hydropower applications.

1. Introduction

Access to electricity is fundamental to human development, enabling essential functions such as lighting, communication, and the operation of household and agricultural equipment [1]. Despite significant global progress in electrification, many rural and remote communities remain disconnected from national grids due to infrastructural limitations, geographic barriers, and economic constraints [2]. As a result, these communities often depend on diesel-powered generators, which are expensive to operate, contribute to environmental degradation, and are not sustainable in the long term [3,4].

The increasing urgency to reduce global carbon emissions and reliance on fossil fuels has intensified the search for cleaner, renewable energy alternatives [5,6]. Among available options, hydropower remains one of the most mature and reliable forms of renewable energy [7]. It offers high efficiency, long operational lifespans, and relatively low maintenance compared to other systems [8]. Small-scale hydropower technologies, particularly mini, micro, and pico hydropower systems, have emerged as attractive decentralized energy solutions [9,10]. These systems are well-suited to off-grid communities because they provide localized energy generation with minimal environmental impact [11].

Pico-hydropower systems, typically producing less than 5 kilowatts, are especially promising for applications in isolated areas with limited water resources [12]. They operate with high reliability and low maintenance, while also minimizing ecological disruption [13]. Overshot waterwheels, a specific category of pico-hydropower devices, are particularly effective in converting potential energy from falling water into rotational mechanical energy, even under relatively low head conditions [14]. These systems function using simple mechanical principles and are recognized for their robustness, ease of construction, and cost-effectiveness [15].

However, most existing overshot waterwheel systems are designed to operate at heads greater than one meter, and their performance tends to decline sharply under sub-meter head conditions [16]. This presents a critical technological gap, as many rural irrigation canals, small streams, and agricultural runoff channels in developing regions feature heads below one meter and flow rates under $0.02m^3/s$. These ultra-low hydraulic inputs render conventional turbines and waterwheels either inefficient or economically impractical [17]. While recent studies have explored unconventional materials such as plastic or aluminum for waterwheel construction, very few have systematically evaluated modular, portable designs incorporating recycled materials specifically for these conditions.

Addressing this gap, the present research introduces a novel, low-cost, and environmentally sustainable overshot waterwheel system. The system uses recycled polyethylene terephthalate (PET) plastic bottles as turbine blades, fixed onto a modular frame designed for portability and easy assembly. The design is optimized for ultra-low head conditions between 0.4 and 0.5 meters and flow rates between 0.015 and 0.02 cubic meters per second. This study integrates circular economy principles into renewable energy development by transforming plastic waste into functional mechanical components, thereby enhancing both environmental and social sustainability.

The system's performance was evaluated through a series of laboratory-scale experiments using a controlled water test rig. A Prony brake system and standard instrumentation were employed to measure torque, angular velocity, and mechanical power output. Parametric analyses were conducted to investigate the influence of flow rate, head, and blade configuration on system efficiency. A performance nomogram was also developed to visualize relationships among key operational parameters, including efficiency, torque, and the velocity ratio between blade movement and incoming water.

Nomenclature

PET	polyethylene terephthalate
PP	polypropylene
PC	polycarbonates
PE	polyethylene
Q	flow rate
H	water head
ρ	water density
g	gravitational acceleration
$P_{potential}$	potential power
P_{mech}	mechanical power output
P_{elec}	electrical power output
η_{mech}	mechanical efficiency
η_{ele}	electrical efficiency
τ	torque
ω	angular velocity
n	rotational speed
F_L	load force
F_T	tension force
F	force
U	tangential velocity of blade
v	water velocity
B4	four-blade configuration
B8	eight-blade configuration
A_c	area of water channel
SDG	Sustainable Development Goals

2. Related Research and Research Gap

Pico-hydropower systems, with a maximum generation capacity of 5kW, are commonly deployed in rural and mountainous areas to meet local energy needs [15, 16]. In Malaysia, the widespread availability of small rivers—largely driven by the country's tropical climate and annual rainfall exceeding 3,000 mm—produces over 900 million m^3 of surface runoff each year [17]. This hydrological abundance results in numerous waterfalls, streams, and irrigation channels, offering significant potential for small-scale hydropower development [18].

Fig. 1 illustrates the typical operating ranges for different turbine types, which are generally optimized for one of three conditions: high-head and high-flow, low-head and high-flow, or high-head and low-flow. However, sites characterized by ultra-low head (0.4–0.5m) and low-flow (0.01–0.02m^3/s) are largely underserved by conventional turbine technologies. These conditions are common in many developing regions, including parts of Malaysia, and highlight the need for alternative turbine solutions capable of efficient energy extraction under constrained hydraulic input [15].

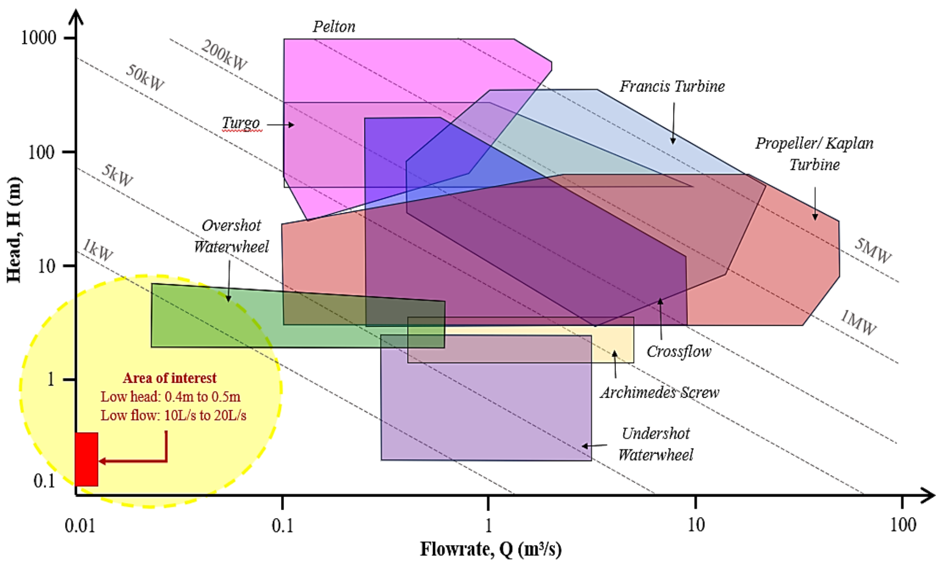

Fig. 1 *Turbine selection range chart*

The turbine selection chart in Fig. 1 provides a comparative overview of various hydro turbines based on water head (H, in meters) and flow rate (Q, in m^3/s), with each turbine type categorized according to its operational range [19]. Impulse turbines such as the Pelton and Turgo turbines are generally employed in high-head, low-flow conditions. Meanwhile, reaction turbines, such as Francis and Crossflow turbines, are typically suited for medium-head, medium-flow conditions and are commonly used in medium scale hydropower applications. Similarly, for low-head, high-flow conditions such as large rivers and canals, Kaplan and Propeller are considered the suitable reaction turbines due to their axial-flow design.

In contrast, gravity turbine including waterwheels and Archimedes screws rely primarily on the gravitational potential energy of falling water, making them conceptually more suited to low-head and low-flow sites. This classification not only reflects the physical principles of operation but also helps engineers and researchers in determining which technology best suits their hydropower site [13].

The red-highlighted region in Fig.1 identifies a specific operational range at low-head (0.4 to 0.5m) and low-flow (0.01 to 0.02m^3/s), which is underrepresented in both design and research. While gravity-based technologies such as overshot and undershot waterwheels are conceptually viable in this range, their performance and efficiency under ultra-low head conditions remain poorly optimized and insufficiently validated. This creates a critical gap in hydropower research and technology, particularly for remote or off-grid sites where minimal water resources are available.

Furthermore, recent interest has emerged in using recycled or repurposed materials for turbine components, including plastic bowls, coconut shells, and PET bottles [22–26]. Although such designs may support circular economy goals, most are informal and lack systematic performance testing. Materials like rust-prone metals or biodegradable wood also pose challenges in terms of durability, highlighting the need for sustainable alternatives that combine environmental benefits with structural reliability.

This study addresses the existing research gap by designing, developing, and experimentally validating a modular overshot waterwheel system that employs recyclable PET plastic bottles as turbine blades. Optimized for low-head (0.4 to 0.5 m) and low-flow (0.01 to 0.02 m^3/s) pico-hydropower conditions, the system's performance was evaluated in real-world settings using two blade configurations: four-blade (B4) and eight-blade (B8). The research is primarily inspired by Stigler's work on overshot waterwheels [27], which demonstrated 59% efficiency at a 1-meter water head. However, performance under sub-1-meter water heads and lower flow rates remains underexplored, which this study aims to investigate.

3. Portable Overshot Waterwheel Design

The proposed overshot waterwheel incorporates recyclable water bottles as the primary blade components, as shown in Fig. 2. The assembly's core consists of a stainless steel, round-shaped surface that serves as the central hub. PVC pipes attached to the fittings function as blade holders, enabling the bottles to efficiently capture and transfer water energy to the rotating system. The blades are secured with stainless steel end caps, enhancing their durability and resistance to water-related wear. Additionally, the system is portable, allowing for easy transportation, assembly, and disassembly, making it ideal for temporary or remote applications. This modular, lightweight design is especially beneficial for small-scale hydropower generation in rural or off-grid areas, where traditional waterwheels may not be feasible. Meanwhile, Fig. 3 shows an exploded view of the turbine, highlighting its structural framework.

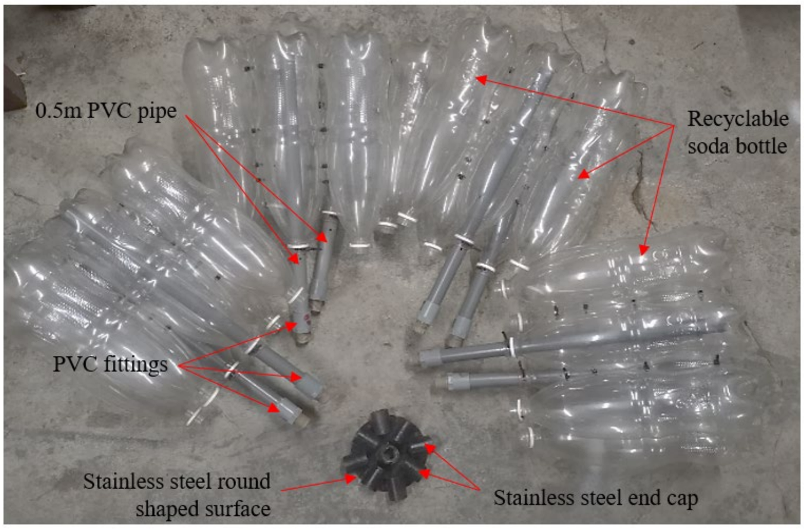

Fig. 2 *Design of bottle blade for portable overshot waterwheel*

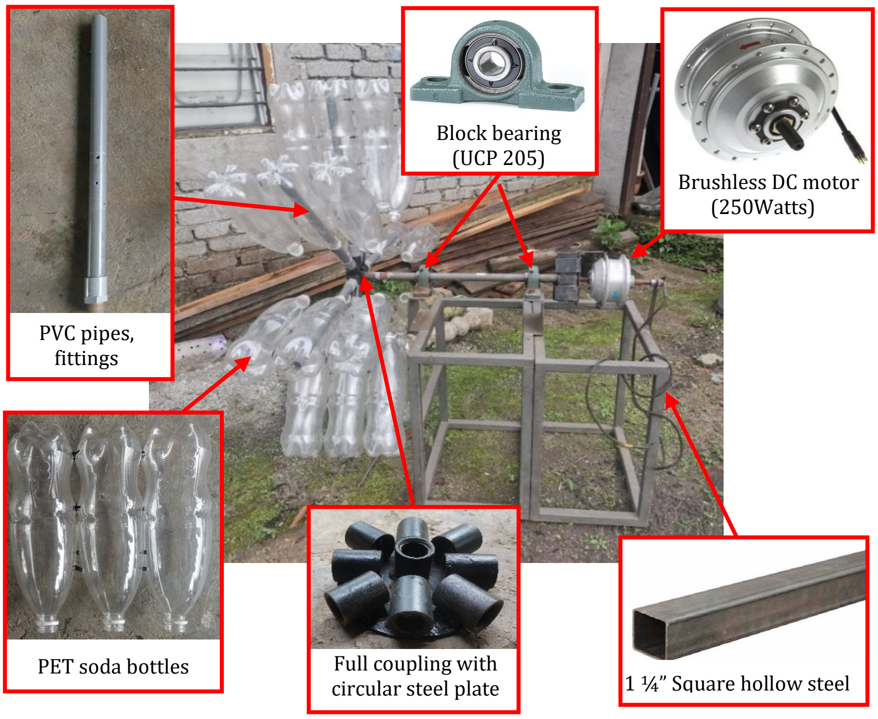

Fig. 3 *Exploded view of the proposed portable overshot waterwheel assembly*

The bottles are attached to 0.5m PVC pipes (1/2 inch), which function as blade holders to secure the bottles. The assembly is reinforced with PVC fittings, ensuring stability and a firm connection to the central rotating hub. The modular design allows flexibility in selecting the number of blades. The choice of blade numbers in this study was determined by hydrodynamic performance, structural feasibility, and experimental stability under ultra-low head (0.4–0.5m) and low-flow (0.015–0.02m^3/s) conditions. Blade numbers 2 and 3 were excluded due to insufficient water capture, unstable rotation, and low torque generation. Intermediate configurations of 5, 6, and 7 blades were also not selected, as they provided no substantial hydrodynamic or structural advantage compared to the 4 and 8 blade designs. Specifically, 5 and 7 blade configurations introduce irregular angular spacing between bottle blades (72° and 51.4°), resulting in asymmetric water impact distribution and potential rotational imbalance. Higher blade counts (more than 8 blades) were excluded due to geometric interference, insufficient inflow exposure, and structural limitations inherent in the modular waterwheel design. Accordingly, the 4 and 8 blade configurations were identified as the most suitable choices for performance testing under the given low-head and low-flow conditions.

Furthermore, the use of lightweight, readily available materials, such as plastic bottles and PVC components, makes this design both cost-effective and environmentally friendly, supporting sustainable energy solutions. The bottle blade turbine consists of four key components: (i) 24 recyclable soda bottles, (ii) eight blade holders made of PVC male threaded adapter fittings with 0.5m PVC pipes, (iii) eight stainless steel end caps, and (iv) one stainless steel round-shaped surface. Table 1 outlines the turbine's specifications, including design criteria, materials, and assembly difficulty. Overall, the assembly of the portable overshot waterwheel takes five hours, including simple welding, soldering, connecting the PVC pipes, and attaching the plastic bottles.

Table 1 *Specification of the proposed portable overshot waterwheel*

Item	Description
Materials	Plastic soda bottle (PET type), Grey PVC pipe, stainless steel.
Assembly difficulty level	• Body part: *Medium, involved welding work.* • Turbine part: *Medium-low, involved in simple welding and soldering works.* • Blade part: *Low, plug-in concept that can disassemble easily when replacing bottles.* • Time taken to assemble: *Approximately 5 hours.*
Preservation	Easy

According to the specifications, the assembly process varies in complexity. The body part requires medium difficulty level welding, while the turbine section involves simple welding and soldering. The blade component is designed with a plug-in concept, allowing easy disassembly and replacement. The estimated assembly time is approximately five hours, and maintenance is straightforward due to the modular nature of the design. Overall, this portable overshot waterwheel offers a practical and efficient solution for harnessing hydropower using easily accessible materials.

3.1 Research Objective

The primary objective of this study is to design, develop, and experimentally validate a novel, low-cost, and portable overshot waterwheel system using recycled PET bottle blades, capable of functioning under low-head (0.4–0.5m) and low-flow (0.015–0.02m^3/s) conditions, where conventional pico-hydropower technologies often experience efficiency limitations. These hydraulic parameters represent a domain where conventional pico-hydropower technologies often exhibit low efficiency or operational infeasibility. The research addresses this gap by demonstrating that efficient energy generation is achievable even under such extreme constraints, using sustainable, low-cost materials and a compact system architecture.

Central to this work is the incorporation of recycled 1.5L PET plastic bottles as turbine blades, integrated into a lightweight, modular, and portable waterwheel structure. This configuration not only reduces production and deployment costs but also reinforces circular economic principles by converting waste materials into functional energy components. The design's modularity allows for easy transportation, assembly, and customization, making it particularly suitable for decentralized applications in off-grid and remote rural areas. The broader significance of the research aligns with Sustainable Development Goals, particularly SDG 7 (Affordable and Clean Energy) and SDG 12 (Responsible Consumption and Production), as the system provides a clean energy solution that is both sustainable and accessible.

To validate the system, a series of controlled laboratory experiments were conducted using a custom-designed water test rig equipped with standard measurement instruments such as a Prony brake system, tachometers, and multimeters. The study tested both four-blade and eight-blade waterwheel configurations under varied hydraulic heads and flow rates to examine mechanical power output, torque, angular velocity, and overall system efficiency. The highest performance was recorded at a 0.5-meter head and 0.02 m^3/s flow rate using the eight-blade configuration, achieving a mechanical efficiency of 49.11% and electrical efficiency of 24.03%. These results represent new empirical benchmarks for energy generation at sub-meter heads and confirm the feasibility of the proposed system under low resource conditions.

3.2 Strengths of the Study

One of the major strengths of this study is its technical innovation in targeting a hydropower range that is largely underexplored. Most existing pico-hydropower systems are designed for higher head and flow conditions, whereas this research demonstrates viable energy generation at significantly lower values. The successful operation of the system under these conditions establishes a new performance domain and contributes original empirical data to the field.

Another key strength lies in the system's use of recycled materials, particularly PET plastic bottles, for turbine blades. This not only reduces manufacturing costs but also aligns the design with environmental sustainability and circular economic practices. Additionally, the modular and portable nature of the system enhances its potential for deployment in remote, off-grid locations where conventional infrastructure may be impractical or too costly.

Moreover, the methodology employed, including the use of a controlled water test rig and precise measurement instruments, ensures data reliability and repeatability. The inclusion of multiple configurations (four blade and eight blade setups) adds robustness to the performance evaluation and provides a baseline for future optimization studies.

3.3 Limitations of the Study

Despite its strengths, this study has several limitations that must be acknowledged. Firstly, the experiments were conducted in a controlled laboratory environment, which may not fully reflect real world conditions such as fluctuating flow rates, debris interference, or seasonal variability. This control setting limits the external validity of the results and necessitates future field testing for comprehensive system validation.

Secondly, the hydraulic range tested in this study is relatively narrow. While it is appropriate for the research objective, testing across a broader range of heads and flow rates would enhance the system's generalizability and applicability to more diverse environments. Similarly, the study focuses primarily on short-term performance, without addressing long-term durability, wear and tear, or maintenance challenges that may arise in prolonged operational conditions.

The study also does not account for total system losses, such as mechanical friction, energy dissipation in transmission, or inefficiencies in power conversion. These factors could influence the net usable energy output in a full-scale deployment. Additionally, although the system is designed to be cost-effective, this research does not include a detailed economic analysis or life-cycle cost assessment, which are essential for determining its feasibility at scale. In summary, while the proposed waterwheel system demonstrates significant innovation and practical promise, further research is needed to test its long-term reliability, expand its operational range, and integrate it into comprehensive rural energy solutions.

4. Experimental Research and Performance Assessment Methodology

To validate the proposed waterwheel system, a systematic experimental investigation was carried out under controlled low-head and low-flow conditions. This section outlines the procedures used to design, construct, and assess the performance of the bottle blade overshot waterwheel using a custom water test rig. The methodology integrates mechanical measurement tools and analytical modelling to accurately capture the system's energy conversion efficiency and operational behavior.

4.1 Experimental Setup and Research Framework

The experimental research focuses on developing and evaluating the performance of an innovative overshot waterwheel designed for low-head, low-flow conditions, with water heads of 0.4m and 0.5m and flow rates of $0.015m^3/s$ and $0.02m^3/s$. The system incorporates simplified modular geometry, portable plug-in design, and recycled plastic bottles (1.5 L) as turbine blades. Two blade configurations were tested: four-blade (B4) and eight-blade (B8), selected based on hydrodynamic and structural considerations (as discussed in Section 3). Fig. 4 presents the framework for the experimental setup of the portable overshot waterwheel.

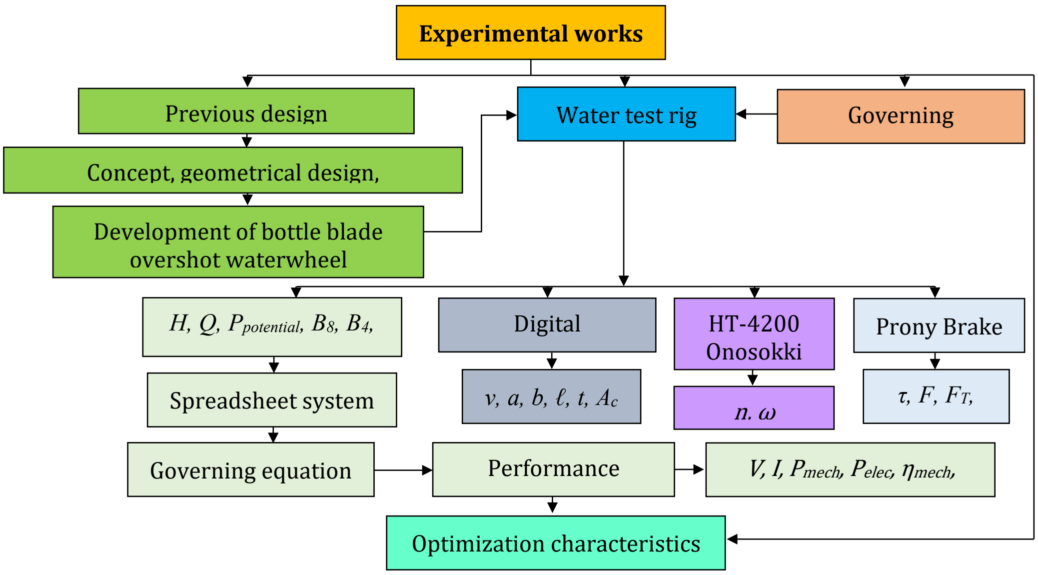

Fig. 4 *Framework of experimental research and performance assessment methodology*

Fig. 4 illustrates the framework of experimental research and performance assessment methodology for investigating a bottle blade overshot. The process starts by reviewing previous design studies and work, including conceptual development, geometrical design, and performance evaluation. These steps lead to the development of the bottle blade overshot waterwheel, which is then tested in a water test rig. In parallel, governing equations are established to support performance analysis. The governing equations are based on the principles of conservation of mass, momentum, and energy. The key parameters such as water head H, flow rate Q, and potential power $P_{potential}$ are considered, along with specific blade and system dimensions like pulley radius r, B8 and B4 configurations. A spreadsheet system is used to organize and compute relevant data, which is then applied to governing equations to analyze system performance.

4.2 Water Test Rig Design

As illustrated in Fig. 5, the water test rig consists of the portable overshot waterwheel turbine, a Prony brake system, water tanks, and a water pump. The red arrow in the figure indicates the water circulation process within the test rig. The system functions by pumping water from tank 2 to tank 1 through an inlet and outlet, ensuring continuous water flow. From tank 1, water enters an adjustable channel, which directs it onto the blades of the turbine. The impact of the falling water generates rotational motion, with the turbine's speed depending on the velocity of the water. A digital scale measures the force exerted by the system, providing valuable data for performance analysis. As the turbine rotates, mechanical energy is produced, which can be converted into electrical power, demonstrating the system's potential as a pico hydropower generator. The water then returns to tank 1, completing the circulation loop and allowing for continuous operation and reuse of water within the system.

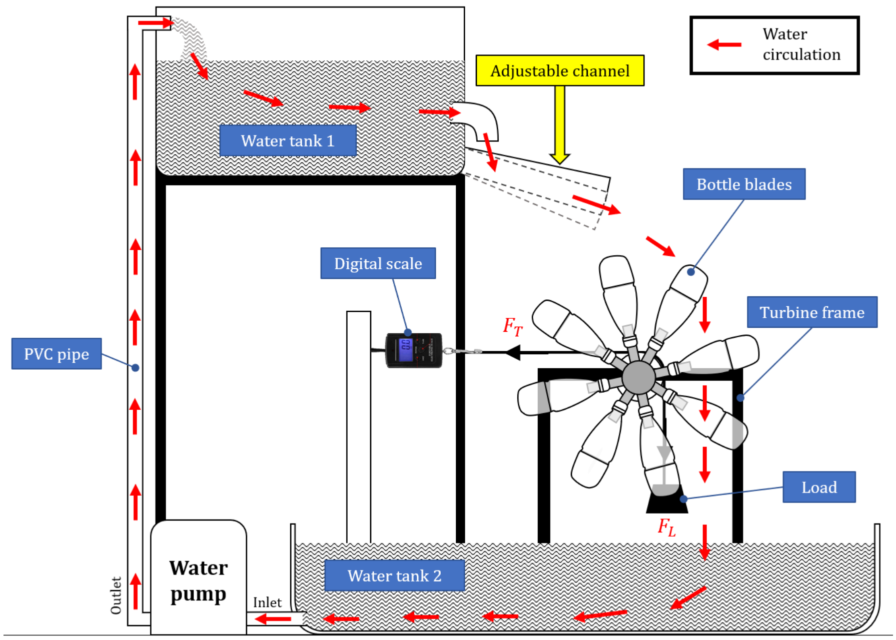

Fig. 5 *Water test rig*

4.3 Measurement Instruments and Data Collection

The water test rig facilitated experimental measurements using different instruments. A digital stopwatch measures time-based parameters, including water velocity v, and parameter L, during the float method approach. Additionally, geometric parameters such as the height a, and width of water b, in the channel, as well as the surface area of water in the channel A_c, must also be determined. Additionally, an HT-4200 Ono Sokki tachometer measures rotational speed n, and angular velocity ω, of the waterwheel. A Prony brake is employed to evaluate mechanical parameters, including torque τ, tension force F_T, and load force F_L. These measurements contribute to the derivation of performance curves, which visualize key performance characteristics such as mechanical efficiency η_{mech} and electrical efficiency η_{elec}, power output P_{mech}, and force variation F. The data collected from these experimental setups help in understanding the waterwheel's energy conversion efficiency and operational behavior under different water flow conditions.

For each test condition, measurements were performed after flow stabilization to ensure steady-state conditions. Each experiment was repeated three times to ensure data accuracy, minimize uncertainty, and verify reproducibility. In total, 25 experimental trials were conducted, covering combinations of flow rates, head levels, and both B4 and B8 blade configurations.

Following data collection, an optimization phase was conducted by analyzing performance curves and applying parametric analysis through the governing equations. Based on this analysis, performance enhancements were identified for energy efficiency, structural design, and operational stability. The results were also compared with previously published studies to evaluate the relative effectiveness of the proposed design, providing valuable insights into the operational feasibility of the bottle blade overshot waterwheel for pico hydropower applications.

4.4 Optimization and Validation

The validation of the proposed bottle blade overshot waterwheel for low-head, low-flow pico hydropower systems was achieved through a comprehensive experimental methodology and performance assessment. The research involved designing and fabricating a novel waterwheel using recycled 1.5L PET plastic bottles as blades. The turbine was tested using a custom water test rig that simulates real-world conditions with controlled water heads of 0.4m and 0.5m, and flow rates of 0.015m^3/s and 0.02m^3/s. These conditions represent low hydropower scenarios, a significant gap in current technology.

Validation began with a rigorous experimental setup, employing precise instrumentation: an HT-4200 Ono Sokki tachometer for rotational speed, a Prony brake system to measure torque and load forces, and digital multimeters for electrical output. Using governing equations based on mass, momentum, and energy conservation principles, parameters such as torque, angular velocity, mechanical and electrical power, and efficiency were calculated.

Two blade configurations, which are B4 and B8, were analyzed to determine optimal performance. Data was systematically collected using a spreadsheet system and plotted to generate performance curves and a nomogram, allowing direct visualization of operational relationships between key parameters. Results demonstrated that the B8 configuration at 0.5m head and 0.02m^3/s flow rate produced the highest mechanical power of 48.58W and achieved peak mechanical and electrical efficiencies of 49.11% and 24.03%, respectively.

The research validated its findings by comparing results with benchmark studies, such as Stigler's overshot waterwheel. Despite operating at half the head height (0.5 m vs. 1 m), the proposed system achieved an efficiency of 49%, close to the benchmark's 59%. This demonstrates the system's robustness under low-head conditions. The experimental setup, parametric analysis, and comparison with established data confirm the system's reliable performance and practical potential in low-resource environments.

5. Parametric Analysis via Governing Equations

Eq. 1 to Eq. 11, adapted from Sari et al. [28] and Ramdhani et al. [29], form the basis of the parametric analysis conducted in this study. The analytical process begins with the calculation of the theoretical hydraulic power available from the incoming flow to the waterwheel, serving as a foundation for subsequent performance evaluation.

$$P_{potential} = \rho g Q H \quad (1)$$

The water flow rate, Q (m^3/s), is measured based on the volume of water passing through an area during a period of time. Meanwhile, the water head, H (m), is obtained by applying the principle of Bernoulli. As for water density, ρ (kg/m^3) and gravity acceleration, g (m/s^2), both are fixed at 1000kg/m^3 and 9.81m/s^2. Hence, Equation 2 was used to obtain the value of Q.

The water density, ρ (kg/m^3), is fixed at 1000 kg/m^3, and the acceleration due to gravity, g (m/s^2), is set at 9.81m/s^2. Meanwhile, Eq. 2 is the water flow rate, Q (m^3/s), which is calculated based on the volume of water passing through an area over a specific period.

$$Q = vA_C \quad (2)$$

where v is water velocity and A_C (m^2) is the surface area of water in the channel. Hence, A_c can be determined based on Eq. 3. Here, v represents the water velocity (m/s), and A_C (m^2) as shown in Eq. 3 is the surface area of the water in the channel.

$$A_C = ab \quad (3)$$

Both a (m) and b (m) represent the height and width of the water in the channel, as shown in Fig. 6. The channel acts as a penstock, carrying water from the tank to the turbines.

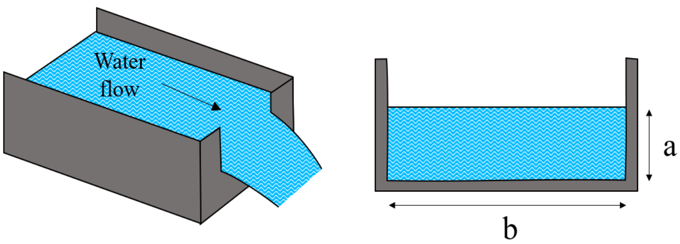

Fig. 6 *Measurement for the area of water in the channel*

At the same time, the parameter H (m) in the system is calculated using Eq. 4, while the water velocity, v, is measured using the float method.

$$H = \frac{v^2}{2g} \quad (4)$$

In the float method, a float object is moved from the first measurement point to the second, a distance denoted as ℓ (m). The time, t (s), taken for the object to travel this distance is recorded using a stopwatch. Consequently, v can be determined using Eq. 5.

$$v = \frac{\ell}{t} \tag{5}$$

Prior to measuring the mechanical power generated, it's essential to determine the force, F, acting on the water wheel. The Prony brake system is used for this purpose, as shown in Fig. 5, which illustrates the system's schematic for force measurement [28, 29].

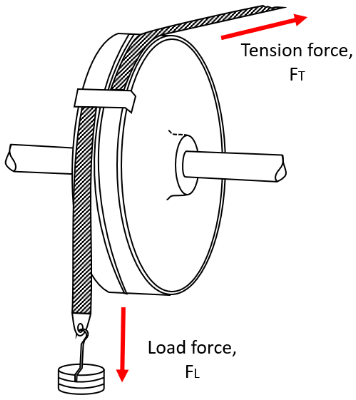

Fig. 7 *General scheme of the prony brake system*

The force, F (N) generated by the wheel is measured using Eq. 6.

$$F = F_T - F_L \tag{6}$$

Here, F_L represents the load force (N) applied by the device until the wheel stops rotating, while F_T is the resulting tension force (N). Once the force, F, is determined, the torque, τ (Nm), is calculated using Eq. 7.

$$\tau = Fr \tag{7}$$

where r represents the pulley radius (m). Therefore, the mechanical power, P_{mech} (W), can be calculated using Eq. 8.

$$P_{mech} = \tau\omega = \tau\,(2\pi n/60) \tag{8}$$

Here, angular velocity is represented by ω (rad/s), and n refers to the rotational speed (rpm) of the turbine wheel, measured using a tachometer. The voltage, V (V), and current, I (A), are then measured using a multimeter. Subsequently, Eq. 9 is applied to calculate the electrical power, $Pelec$ (W), produced by the system.

$$P_{elec} = VI \tag{9}$$

Finally, the mechanical and electrical efficiencies are calculated using Eq. 10 and Eq. 11.

$$\eta_{mech} = \frac{P_{mech}}{P_{potential}} 100\% \tag{10}$$

$$\eta_{elec} = \frac{P_{elec}}{P_{potential}} 100\% \tag{11}$$

6. Experimental Results and Analysis

The proposed overshot water turbine and pico-hydro system were tested under conditions of extremely low water resources. Focusing on the relationship between force F, torque τ, and angular velocity ω, as shown in Fig. 8 and Fig. 9, experiments were conducted by varying the water head H and flow rate Q. These figures also present experimental results for different waterwheel configurations with eight blade, B8 and four blade, B4.

The experimental analysis of the proposed system starts at the highest angular velocity, which is gradually reduced until the turbine comes to a complete stop, as controlled by the Prony brake system. In mechanical systems like turbines, torque τ and speed ω are inversely related, with torque being higher at low speeds and lower at high speeds, as lower speeds require more force to move the system while higher speeds need less force to maintain motion [30]. This trend was observed in the initial experiment, where the force load F_L gradually increased from zero by 0.5N increments until the turbine stopped. The results show that the maximum recorded force F for the B8 setup was 7.2N, with a corresponding maximum torque of 3.42Nm. In contrast, the B4 configuration showed a peak force of 4.64N and a maximum torque of 2.2Nm. Notably, the curve patterns of the results in Fig. 8 and Fig. 9 closely resemble those reported by Sari et al. [28] and Ramdhani et al. [29].

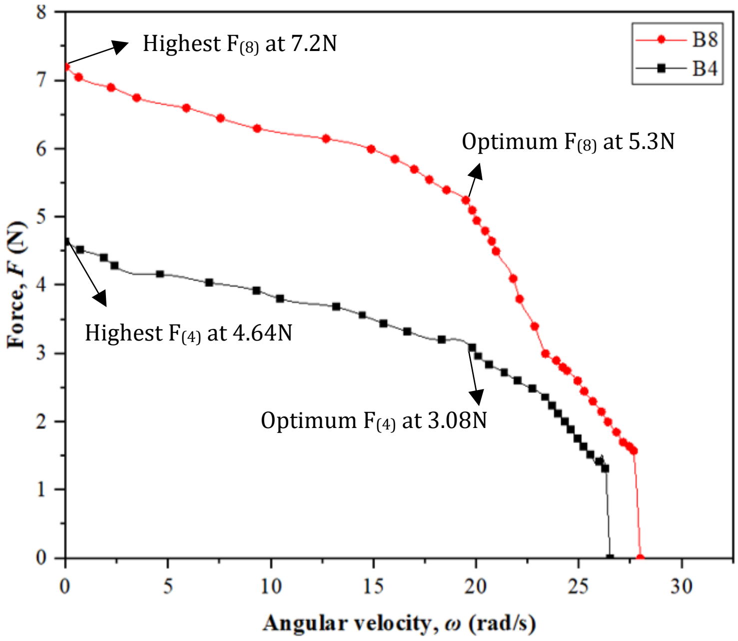

Fig. 8 *Experimental force and angular velocity at 0.5m water head*

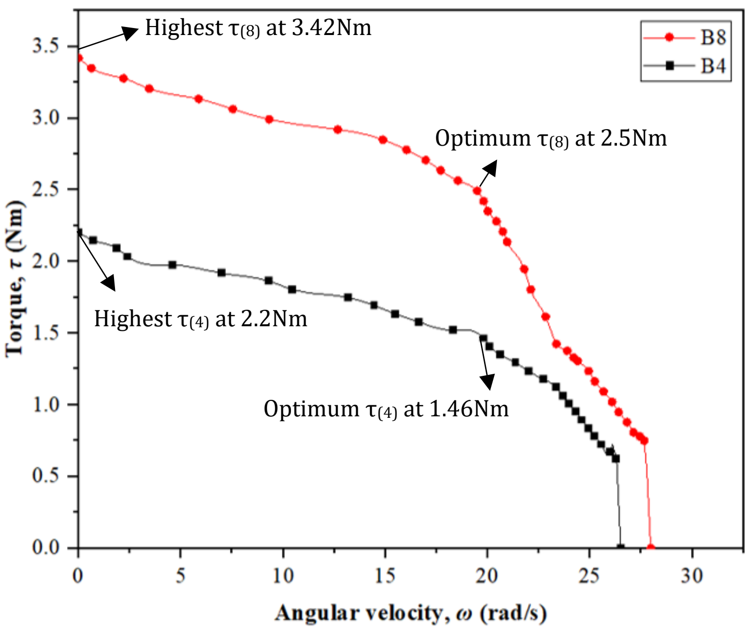

Fig. 9 *Experimental torque at 0.5m water head*

The experimental findings demonstrate that the water head significantly impacts the force and torque output. As the water head increases, both force and torque generated by the system also increase. Furthermore, the results reveal rapid changes in both parameters at high angular velocities, with a gradual decrease in the rate of increase as the system approaches zero angular velocity. Furthermore, since torque is directly proportional to force, as indicated by Eq. 7, any increase in force leads to a corresponding increase in torque. Ultimately, these results confirm that increasing the water head improves the turbine's ability to generate greater force and torque.

Fig. 10 and Fig. 11 illustrate the relationship between mechanical power and efficiency with respect to the parameter U/v for both eight-blade and four-blade configurations. The parameter U/v on the x-axis represents the ratio of the turbine's tangential velocity to the water velocity. The tangential velocity of the turbine U refers to its linear speed during rotation and plays a crucial role in the water wheel's overall performance. However, U is mainly influenced by the rotational speed n, and the turbine's diameter D, as shown in Eq. 12.

$$U = \frac{n}{60} D \quad (12)$$

Referring to Fig. 10 and Fig. 11, the proposed turbine effectively converts potential energy into mechanical power, with performance significantly improving at higher water head levels. The turbine equipped with eight blades demonstrated higher power output, primarily due to the higher force and velocity generated during rotational motion. These parameters are directly influenced by the water head and flow rate, both of which play a crucial role in determining the available potential power, as described in Equation 1.

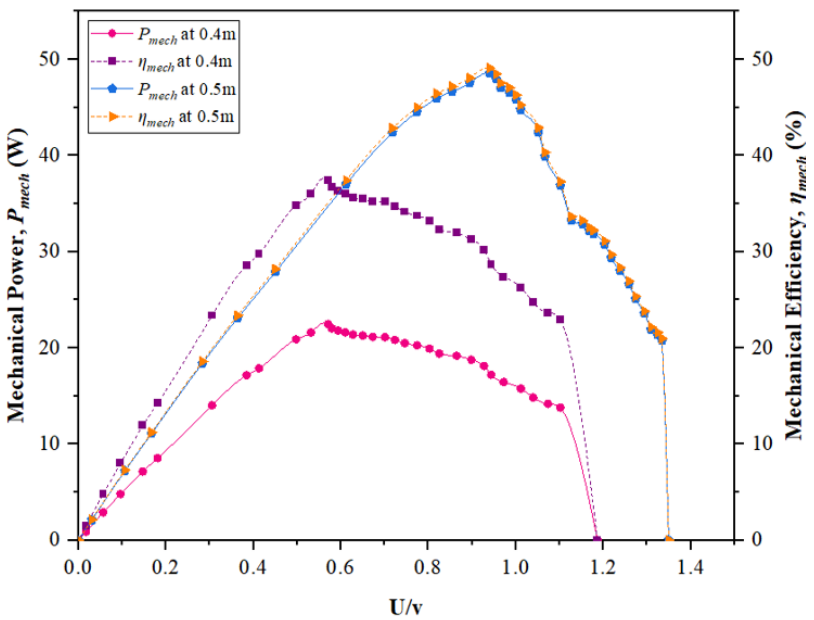

Fig. 10 *Mechanical power and efficiency for 0.4m and 0.5m water head using eight blades waterwheel*

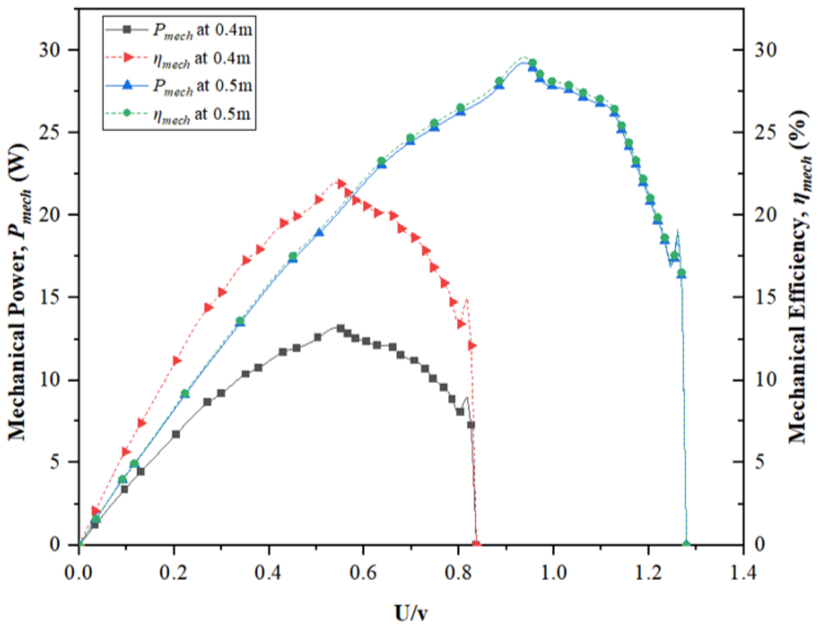

Fig. 11 *Mechanical power and efficiency for 0.4m and 0.5m water head using four blades waterwheel*

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Fig. 10 and Fig. 11 show two graphs depicting the mechanical power and efficiency of a waterwheel system under different conditions. Fig. 10 represents the performance of a waterwheel with eight-blade configuration, while Fig. 11 shows the results for a four-blade configuration. Both graphs compare mechanical power P_{mech}, and mechanical efficiency η_{mech} across varying values of the ratio U/v, which represents the turbine's tangential velocity relative to the water velocity. The data is plotted for two different water heads, 0.4m and 0.5m, with distinct markers used to differentiate between mechanical power and efficiency.

From the graphs, it is evident that the mechanical power increases with U/v until reaching a peak, then it begins to decline until it reaches zero. This trend is observed for both the B4 and B8 blade configurations and under varying water head conditions. This occurs due to changes in torque and rotational speed as the load force applied by the Prony brake increases. While torque continues to increase due to the added resistance, the rotational speed of the waterwheel progressively decreases. Since mechanical power is the product of torque and angular velocity (as shown in Eq. 8), the declining rotational speed eventually outweighs the increase in torque, resulting in a net reduction in power output. At higher load force conditions, the waterwheel slows significantly and approaches a complete stop, thereby disrupting the interaction between the bottle blade and the incoming water flow.

The B8 waterwheel demonstrates a higher mechanical power output and efficiency compared to the B4 setup. The peak efficiency for the eight-blade configuration also occurs at a slightly higher U/v ratio compared to the four-blade design, indicating that having more blades improves energy capture from the water flow. This relationship is governed by Eq. 4, which accounts for water velocity and gravitational acceleration. While gravitational acceleration remained constant at 9.81m/s^2 throughout the experiment, water velocity was adjusted based on its travel time within the open channel, as outlined in Eq. 5. An increase in water head led to a corresponding rise in water velocity and flow rate, ultimately enhancing the turbine's mechanical power output.

Additionally, the difference between the 0.4m and 0.5m water heads is noticeable in both figures, with the higher water head consistently producing greater mechanical power and efficiency. This result aligns with hydrodynamic principles, as an increased water head corresponds to higher potential energy available for conversion. The sharp decline in efficiency after reaching the peak indicates the point at which increasing rotational speed results in diminishing returns due to hydraulic losses and inefficiencies. These findings highlight the importance of optimizing blade design and operating conditions to maximize waterwheel performance.

Furthermore, Table 2 provides a summary of the overall performance of the eight-blade system at a 0.5m water head, including parameters such as load force F_L, tension force F_T, torque τ, angular velocity ω, *U/v* ratio, mechanical power P_{mech}, mechanical efficiency η_{mech}, and electrical efficiency, η_{elec}, as listed in the tables. The experiment involved gradually increasing the load force applied to the Prony brake system in 0.5N increments to evaluate the performance of the turbine at a 0.5m water head. The same experimental procedures were applied to other waterwheel configurations under varying conditions to ensure consistent, accurate results.

The bold text in row No. 23 highlights the highest mechanical and electrical performance achieved by the proposed eight-blade turbine operating at a 0.5m water head. As the load force increased to 11N, mechanical efficiency peaked at 49.11%, while electrical efficiency reached 24.03%. The approximately 51% difference between mechanical and electrical efficiency can be attributed to conversion losses, such as friction and transmission inefficiencies. Although these losses were not explicitly considered in the calculations, they significantly affect the overall energy conversion process. It is noteworthy that beyond the optimal load of 11N, both mechanical and electrical efficiency began to decline. This decrease suggests that with a load force exceeding 11N, the turbine's ability to maintain optimal energy conversion diminishes, likely due to increased resistance and a reduction in angular velocity, which limits power generation.

Table 2 *Overall performance of the eight-blade system at a 0.5m water head*

No.	Load force, F_L (N)	Tension force, F_T (N)	Torque, τ (Nm)	Angular velocity, ω (rad/s)	*U/v* ratio	Mechanical power, P_{mech} (W)	Mechanical efficiency, η_{mech} (%)	Electrical efficiency, η_{elec} (%)
1	0	0	0	27.96	1.59	0	0	0
2	0.5	2.08	0.75	27.65	1.56	20.75	20.98	10.41
3	1	2.64	0.78	27.44	1.53	21.38	21.61	10.74
4	1.5	3.20	0.81	27.13	1.49	21.90	22.14	11.01
5	2	3.85	0.88	26.81	1.46	23.56	23.82	11.77
6	2.5	4.50	0.95	26.39	1.42	25.07	25.34	12.54
7	3	5.15	1.02	26.08	1.36	26.63	26.92	13.28
8	3.5	5.80	1.09	25.66	1.32	28.03	28.34	14.08
9	4	6.45	1.16	25.24	1.29	29.37	29.69	14.86

No.	Load force, F_L (N)	Tension force, F_T (N)	Torque, τ (Nm)	Angular velocity, ω (rad/s)	U/v ratio	Mechanical power, P_{mech} (W)	Mechanical efficiency, η_{mech} (%)	Electrical efficiency, η_{elec} (%)
10	4.5	7.10	1.24	24.93	1.25	30.78	31.12	15.72
11	5	7.75	1.31	24.40	1.22	31.88	32.22	16.42
12	5.5	8.30	1.33	24.19	1.20	32.18	32.53	16.57
13	6	8.90	1.38	23.88	1.16	32.89	33.25	16.89
14	6.5	9.50	1.43	23.36	1.16	33.28	33.64	17.14
15	7	10.40	1.62	22.83	1.14	36.87	37.27	19.10
16	7.5	11.30	1.81	22.10	1.09	39.89	40.32	20.43
17	8	12.10	1.95	21.79	1.01	42.43	42.88	20.83
18	8.5	13.00	2.14	20.95	0.96	44.77	45.26	22.02
19	9	13.65	2.21	20.74	0.85	45.80	46.30	22.41
20	9.5	14.30	2.28	20.42	0.78	46.56	47.07	22.86
21	10	14.95	2.35	20.00	0.75	47.04	47.54	23.30
22	10.5	15.60	2.42	19.80	0.66	47.95	48.47	23.63
23	**11**	**16.25**	**2.49**	**19.48**	**0.64**	**48.58**	**49.11**	**24.03**
24	11.5	16.90	2.57	18.54	0.60	47.55	48.06	23.21
25	12	17.55	2.64	17.70	0.52	46.66	47.17	20.34

** *Row No. 23 highlights the highest mechanical and electrical performance of the eight-blade turbine at 0.5m head.*

Fig. 12 presents a nomogram depicting the performance curves of a portable overshot waterwheel with different configurations. A nomogram is a graphical tool used to represent the relationships between different variables in a system's performance. Its purpose is to simplify complex calculations, allowing users to quickly estimate values or determine relationships between parameters without performing detailed mathematical operations. By using a nomogram, users can visually interpret how changes in one variable affect others, making analysis easier.

The bottom-right graph shows force versus angular velocity, with force decreasing as angular velocity increases. The B8 designs generate greater force than the B4 configurations, further confirming their superior performance in harnessing water energy. Similarly, the top-right graph, which plots torque versus angular velocity, shows that torque decreases as angular velocity increases. The B8 configurations consistently maintain higher torque at all velocities, highlighting their superior power generation compared to the B4 designs.

The top-left graph plots torque against U/v, showing a decline in torque as U/v increases. The red curve represents the B8 at a 0.5m water head, while the black curve represents the B8 at a 0.4m water head. These curves generate higher torque and force than the B4 curves, indicated by the blue and green curves. Finally, the bottom-left graph presents mechanical efficiency as a function of U/v, demonstrating that efficiency rises initially, peaks, and then declines. The red curve for B8 (at 0.5m head) achieves the highest efficiency, exceeding 45%, followed closely by the black curve for B8 (at 0.4m head), while the B4 designs show lower efficiency. This suggests that having more blades enhances the energy conversion process, making the B8 waterwheel more efficient than the B4 waterwheel.

The purple dashed lines highlight a critical operating point (U/v ≈ 0.9, angular velocity ≈ 20rad/s), where torque is approximately 2.5Nm, mechanical efficiency reaches around 50%, and force is about 5.2N. This point represents the optimal operating condition for the waterwheel, balancing efficiency and power output. Initially, an increase in angular velocity leads to a rise in the U/v parameter. As the turbine reaches its optimal angular velocity, both force and torque follow a similar trend, with their rate of increase slowing as they approach peak values. The relationship between torque and mechanical efficiency is also visible in the figure, as the turbine reaches its highest efficiency at the optimal point before gradually decreasing to 0%, at which point the turbine stops. At this stage, the turbine slows down and eventually comes to a complete stop (0rad/s). Overall, the nomogram offers valuable insights into the performance of various waterwheel configurations, aiding in the selection of the most efficient design. The B8 waterwheels consistently outperform the B4 models, making them the preferred choice for higher torque, force, and efficiency.

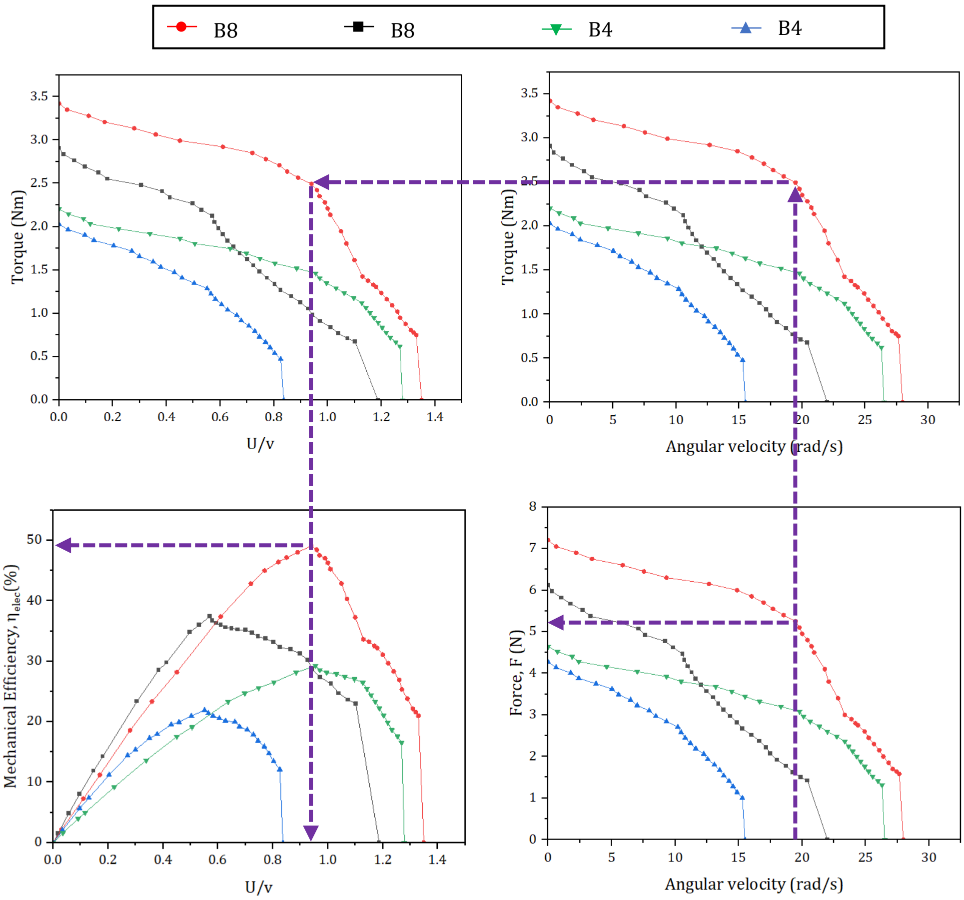

Fig. 12 *Nomogram for the performance curves of the proposed portable overshot waterwheel*

Following this analysis, the research is further examined through a comparison with previous studies on overshot waterwheels. Fig. 13 presents the mechanical efficiency curves for the proposed turbine with eight and four blades, as well as the overshot waterwheel by Stigler et al. [27]. Stigler's waterwheel exhibits the highest mechanical efficiency, reaching 59%, which is 10% higher than the maximum efficiency of the proposed B8 waterwheel, which is 49%. In contrast, the B4 waterwheel achieves a lower mechanical efficiency of approximately 29%. It is important to note that the proposed turbine was tested under significantly different conditions from Stigler's waterwheel. The proposed bottle blade waterwheel operated at a very low water head of just 0.5m with a constant flow rate of 0.0201m^3/s, whereas Stigler's waterwheel operated at a higher water head of 1m and varying flow rates between 0.005m^3/s and 0.013m^3/s. In other words, even though the water head difference is 50% or half the value, the value of efficiency has only a small difference of about 10%.

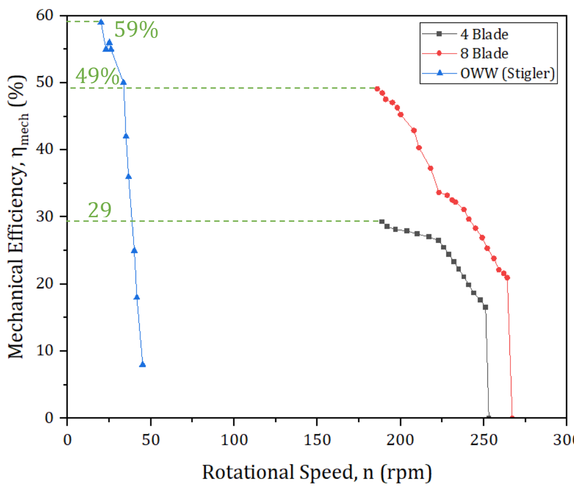

Fig. 13 *Mechanical efficiency curves for eight blades, four blades and an overshot waterwheel by Stigler*

Despite differences in efficiency, all waterwheels displayed a similar trend, with efficiency peaking before gradually declining as rotational speed increased. Additionally, all waterwheels, including the proposed turbine, remained static until water impacted the blades, initiating rotation. As the force applied by the Prony brake system increased, rotational speed gradually decreased, eventually halting when the maximum force was reached. This behaviour was consistent across all tested waterwheels, aligning with the basic principles of energy conversion in overshot systems.

The novelty of this research lies in the development, experimental validation, and performance analysis of a portable, modular overshot waterwheel constructed from recycled PET plastic bottles, which is specifically designed to operate efficiently under low-head (0.4–0.5m) and low-flow (0.015–0.02m^3/s) conditions. Unlike conventional micro and pico hydropower systems, which are typically optimized for higher heads and flow rates, the present study targets a niche yet critical hydrodynamic range that remains underrepresented in the literature.

A comparative assessment with previous studies underscores the novelty and contribution of this work. Stigler et al. [27], for instance, reported a mechanical efficiency of approximately 59% for overshot waterwheels operating at a 1-meter head. In contrast, the waterwheel developed in the present study achieved a peak mechanical efficiency of 49.11% while operating at only a 0.5-meter head, demonstrating strong performance under significantly lower hydraulic conditions. Additionally, prior studies by Sari et al. [28] and Ramdhani et al. [29] investigated breastshot and undershot configurations under variable flow conditions. However, those works did not address key aspects such as modular system design, portability, and the integration of recycled materials, all of which are critical for scalable and decentralized implementation in low-resource settings.

This research distinguishes itself by integrating sustainability through circular economy principles, transforming commonly discarded plastic bottles into functional hydro-mechanical components without compromising performance. In addition, it introduces a performance nomogram for design guidance and provides empirical benchmark data under controlled conditions, both of which are not commonly found in comparable low-head turbine studies. Overall, the research not only addresses a clear technological and environmental gap but also contributes original design methodology, experimental validation, and performance data, advancing the scientific understanding of low head pico hydropower solutions.

7. Conclusion

This study presents the design, development, and experimental validation of a novel overshot waterwheel system specifically engineered for low-head and low-flow pico hydropower applications. The system operates effectively under hydraulic heads ranging from 0.4 to 0.5 meters and flow rates between 0.015 m^3/s and 0.02 m^3/s. These conditions represent a challenging operational regime where conventional turbines typically perform poorly, leaving a significant gap in technological solutions for small-scale energy generation in remote or resource-constrained areas.

A key innovation in this research lies in the use of recyclable 1.5-liter PET plastic bottles as turbine blades. These are mounted on a modular and lightweight frame designed for ease of transport, assembly, and customization. This approach reflects circular economy principles by converting post-consumer plastic waste into functional hydropower components. It enhances accessibility in underserved regions while promoting environmental sustainability. The system design supports global sustainability efforts, particularly those outlined in the United Nations Sustainable Development Goals, including Goal 7 (Affordable and Clean Energy) and Goal 12 (Responsible Consumption and Production).

Experimental evaluation demonstrated consistent system performance under all tested flow and head conditions. Two blade configurations were assessed, comprising a four-blade (B4) and an eight-blade (B8) setup. Results showed that the B8 configuration consistently outperformed the B4 setup. Under optimal operating conditions at a head of 0.5 meter and a flow rate of 0.02m^3/s, the B8 configuration achieved a peak mechanical power output of 48.58 W, a torque of 2.49 Nm, and an angular velocity of 19.48 rad/s. Mechanical efficiency reached 49.11%, while electrical efficiency was recorded at 24.03%. In contrast, the B4 configuration produced a lower mechanical power output of 28.54 W and an efficiency of 29% under the same conditions.

Efficiency trends revealed a strong correlation with hydraulic input. Increases in flow and head directly influenced tangential force, torque, and rotational speed. The eight-blade configuration captured more water momentum than the four-blade configuration, resulting in more effective energy conversion. Mechanical power output followed a typical rise and fall pattern in relation to the ratio of turbine tangential velocity to water velocity, commonly referred to as the U over v ratio. Optimal performance was achieved within a specific range of this ratio, after which efficiency declined due to hydraulic and mechanical losses.

The study established performance curves and a comprehensive nomogram to aid in design optimization, mapping the relationships between efficiency, torque, angular velocity, and the U/v ratio. These visual tools not only validate experimental findings but also serve as practical references for future system development. While comparative analysis with earlier designs, such as Stigler's overshot waterwheel operating at a 1-meter head, shows that the proposed system achieves slightly lower efficiency, it is important to note that this performance was achieved under significantly more constrained conditions. The proposed system operates at only 0.5 meters of head, which is half the head used in the benchmark study, yet it demonstrates strong operational viability and efficiency in ultra-low head environments.

This research addresses a critical void in pico hydropower technology. Existing literature has primarily focused on turbine designs suited to medium or high head systems, with limited data available for ultra-low head applications. The proposed design introduces a new approach by offering a validated, scalable, and low-cost solution that performs reliably under constrained conditions. The use of repurposed plastic materials enhances its practicality and affordability, making it suitable for decentralized energy systems in rural and developing regions.

Future work will extend the system's operational range to cover head values between 0.1 and 1.0 meters, while evaluating various blade counts from two to ten and different PET bottle configurations per blade. Refining blade geometry and exploring multi-stage wheel setups may enhance fluid dynamics and energy conversion. Durability under real-world conditions, including debris impact, UV exposure, and fluctuating flow, will be assessed. Integration with renewable technologies such as photovoltaics and battery storage could enable broader application in decentralized microgrids. Economic evaluations and life cycle assessments will guide scalability, with emphasis on affordability, replicability, and community-level maintenance strategies.

This study confirms the viability of harnessing low-head low-flow hydropower through an innovative and sustainable waterwheel system using recycled materials. Laboratory tests verified its ability to deliver consistent mechanical and electrical output with high efficiency under limited hydraulic conditions. The system offers practical potential for rural electrification, irrigation, and decentralized energy needs. As a low-cost and environmentally responsible solution, it advances the field of pico hydropower and aligns with global sustainability goals. The integration of recycled components without compromising performance highlights its practicality. Continued research will enhance scalability and support wider access to clean energy in underserved regions.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: Mohd Farriz Basar, Izzatie Akmal Zulkarnain, Kamaruzzaman Sopian, Dendy Adanta and Carlos Trenado have equal contributions reviewing and editing the writing, formal analysis, hardware development and conceptualization.

References

[1] M. F. Yaakub, M. F. Basar, F. H. M. Noh, & H. Boejang (2018) Pico-hydro electrification from rainwater's gravitational force for urban area, Telkomnika (Telecommunication Computing Electronics and Control), 16(3), 997-1003, https://doi.org/10.12928/TELKOMNIKA.v16i3.8076

[2] E. Quaranta & R. Revelli (2018) Gravity water wheels as a micro hydropower energy source: A review based on historic data, design methods, efficiencies, and modern optimizations,Renewable Energy and Sustainable Energy Reviews, 97, 414-427, https://doi.org/10.1016/j.rser.2018.08.033

[3] M. Y. Chong, A. A. Rahman, N. A. Aziz, & A. Khamis (2010, June 23-24). Performance comparison of bidirectional converter designs for renewable power generation [Conference session]. Proc. of 4th International Power Engineering and Optimization Conference (PEOCO), Shah Alam, Malaysia. https://doi.org/10.1109/PEOCO.2010.5559213

[4] Pallathadka, H., Askar, S., Kulshreshta, A., Sharma, M. K., Widatalla, S., & Mudae, I. (2024) Economic and environmental energy scheduling of smart hybrid micro grid based on demand response. International Journal of Integrated Engineering, 16(9), 351-365, https://doi.org/10.30880/ijie.2024.16.09.029

[5] Razlan, Z. M., Hasan, H., & Lida, A. (2023). The effect of laying nozzle distance position on operational results Renewable Power Plant Pico-Hydro. International Journal of Integrated Engineering, 15(7), 37-46, https://doi.org/10.30880/ijie.2023.15.07.004

[6] Kamalahasan, M., Raghu, T., Swapna, B., Saravanan, K., & Manjula, D. (2022) Renewable energy powered Autonomous Smart Ocean Surface Vehicles (REASOSE). International Journal of Integrated Engineering, 14(7), https://doi.org/10.30880/ijie.2022.14.07.001

[7] N. A. M. Rais & M. F. Basar (2021) Pico-Hydro Generation System: Empirical Investigation on a Novel Z-Blade Low-Head Low-Flow Water Turbine, International Journal of Renewable Energy Research, 11(1), 108–113, https://doi.org/10.20508/ijrer.v11i1.11387.g8117

[8] Lahimer, A. A., Alghoul, M. A., Sopian, K., Amin, N., Asim, N., & Fadhel, M. I. (2012) Research and development aspects of pico-hydro power. Renewable and Sustainable Energy Reviews, 16(8), 5861–5878.

[9] Basar, M. F. (2021) Investigation on rotor jet interference in a hydraulic reaction turbine for low head low flow water conditions. Energy Harvesting and Systems. 8(1), 29–35, https://doi.org/10.1515/ehs -2021-0019

[10] Basar, M. F., Rais, N. A. M., Rahman, A. A., Mustafa, W. A., Sopian, K. & Wong, K. V. (2022) Optimization of Reaction Typed Water Turbine in Very Low Head Water Resources for Pico Hydro, Journal of Advanced Research in Fluid Mechanics and Thermal Sciences, 90(1), 23-29, https://doi.org/10.37934/arfmts.90.1.2339

[11] I. C. Scotta, W. Maidana & V. Leite (2021) Over-voltage protection for grid-connected pico-hydro generation using photovoltaic inverters, Revista Facultad de Ingenieria, 99(1), 73-72, https://doi.org/10.17533/udea.redin.20200581

[12] M. F. Musthapa, A. Mukhtar, M. F. Mohamed Nasir, & A. F. Tharima (2020) Numerical Simulation of Micro Gravitational Hydro-turbine for Alternative Renewable Energy Resources in Rural Area, INTI JOURNAL, 16(1), 1-7, https://doi.org/10.61453/INTIj.202016

[13] Basar, M. F., Kasimin, A. Z. A., Zulkarnain, I. A., & Ahmad, E. Z. (2024, August 17). Performance of Undershot Water Wheel in Low Head Water Resources for Pico Hydropower [Conference session]. IEEE 15th Control and System Graduate Research Colloquium (ICSGRC), Shah Alam, Malaysia. https://doi.org/10.1109/ICSGRC62081.2024.10691199

[14] M. Zhao, Y. Zheng, C. Yang, Y. Zhang, & Q. Tang (2020) Performance investigation of the immersed depth effects on a water wheel using experimental and numerical analyses, Water (Switzerland), 12(4), 982-999, https://doi.org/10.3390/W12040982

[15] A. Kadier, M. S. Kalil, M. Pudukudy, H. A. Hasan, A. Mohamed, & A. A. Hamid (2018) Pico hydropower (PHP) development in Malaysia: Potential, present status, barriers and future perspectives, Renewable and Sustainable Energy Reviews, 81(2), 2796-2805, https://doi.org/10.1016/j.rser.2017.06.084

[16] M. E. Ya'Acob, M. M. Ideris, N. A. Latiff, & A. N. Iskandar (2018, March 1-3) Conceptual design of an integrated PV catchment storage system for rainwater harvesting [Conference session]. IOP Conference Series: Earth and Environmental Science (IC3E 2018), Xiamen, China. https://doi.org/10.1088/1755-1315/146/1/012055

[17] N. S. Muhammad, J. Abdullah, & P. Y. Julien (2019, November 25-27). Characteristics of Rainfall in Peninsular Malaysia [Conference session]. Journal of Physics: Conference Series (JICETS), Bandung, Indonesia. https://doi.org/10.1088/1742-6596/1529/5/052014

[18] W. Wan Abdullah, M. Osman, Z. Kadir, & R. Verayiah (2019) The Potential and Status of Renewable Energy Development in Malaysia, Energies (Basel), 12(12), 2437-2453, https://doi.org/10.3390/en12122437

[19] International Hydropower Association. (2020). 2020 Hydropower Status Report. https://www.hydropower.org/publications/2020-hydropower-status-report

[20] Pribadyo, H. Hadiyanto, & J. Jamari (2019, October 22). Study of low head turbine propellers axial flow for use of micro-hydropower plant (MHP) in Aceh, Indonesia [Conference session]. The 9th Seminar on New Paradigm and Innovation of Natural Sciences and its Application, Central Java, Indonesia. https://doi.org/10.1088/1742-6596/1524/1/012019

[21] Basar, M. F., Zulkarnain, I. A., Sopian, K., & Rais, N. a. M. (2024) Investigations on the performance of bottle blade overshot water wheel in very low head resources for pico hydropower, Energy Harvesting and Systems, 11(1), 138-148, https://doi.org/10.1515/ehs-2023-0138

[22] Ioakeimidis, C., Fotopoulou, K. N., Karapanagioti, H. K., Geraga, Galgani, F., & Papatheodorou, G. (2016) The degradation potential of PET bottles in the marine environment: An ATR-FTIR based approach. Scientific Reports, 6(1), 23501, https://doi.org/10.1038/srep23501

[23] Chamas, A., Moon, H., Zheng, J., Qiu, Y., Tabassum, T., Jang, J. H., Abu-Omar, M., Scott, S. L., & Suh, S. (2020) Degradation rates of plastics in the environment. ACS Sustainable Chemistry & Engineering, 8(9), 3494–3511, https://doi.org/10.1021 /acssuschemeng.9b06635

[24] Adanta, D., Warjito, W., Febriansyah, D., & Budiarso, B. (2020) Feasibility Analysis of a Pico-Scale Turgo Turbine Bucket using Coconut Shell Spoons for Electricity Generation in Remote Areas in Indonesia, Journal of Advanced Research in Fluid Mechanics and Thermal Sciences, 69(1), 85–97, https://doi.org/10.37934/arfmts.69.1.8597

[25] Sule, L., Mochtar, A. A., & Sutresman, O. (2020). Performance of undershot water wheel with bowl-shaped blades model, International Journal of Technology, 11(2), 278-287, https://doi.org/10.14716/ijtech.v11i2.2465

[26] Sulistyanti, E., Tamado, D. B., Wulandari, F., & Budi, E. (2015) Use of Coconut Shell Activated Carbon as an Alternative Renewable Electricity, KnE Energy, 2(2), 76-81, https://doi.org/10.18502/ken.v2i2.360

[27] J. Štigler (2022) Overshot water wheel efficiency measurements for low heads and low flowrates, EPJ Web Conf, 269(1), 1058-1066, https://doi.org/10.1051/epjconf/202226901058

[28] D. P. Sari, H. Helmizar, I. Syofii, D. Darlius, & D. Adanta (2020) The Effect of the Ratio of Wheel Tangential Velocity and Upstream Water Velocity on the Performance of Undershot Waterwheels, Journal of Advanced Research in Fluid Mechanics and Thermal Sciences, 65(2), 170–177, https://www.akademiabaru.com/submit/index.php/arfmts/article/view/2786

[29] M. Ramdhani, R. Irwansyah, B. Budiarso, W. Warjito, & D. Adanta (2020) Investigation of the 16 Blades Pico Scale Breastshot Waterwheel Performance in Actual River Condition, Journal of Advanced Research in Fluid Mechanics and Thermal Sciences, 75(1), 38–47, https://doi.org/10.37934/arfmts.75.1.3847

[30] H. Zainuddin, A. Khamis, M. S. Yahaya, M. F. M. Basar, J. M. Lazi & Z. Ibrahim (2009). Investigation on the performance of pico-hydro generation system using consuming water distributed to houses. 2009 1st International Conference on the Developements in Renewable Energy Technology (ICDRET), Dhaka, Bangladesh. https://doi.org/10.1109/ICDRET.2009.5454216