International Research Journal of Multidisciplinary Scope (IRJMS), 2025; 6(3):580-599

Original Article | ISSN (O): 2582-631X DOI: 10.47857/irjms.2025.v06i03.05147

A Comprehensive Analysis of Waterwheel Technologies for Pico Hydropower: Evolution, Performance, and Optimization Strategies

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Abstract

Small-scale hydropower systems, particularly pico hydro, are emerging as viable and sustainable renewable energy solutions with significant potential for future power generation. These systems offer economic, social, and environmental benefits, making them ideal for rural electrification, especially in regions with low-head and low-flow water resources. Besides, pico hydro primarily relies on the natural flow of water to generate electricity, requiring minimal or zero water storage, thereby reducing environmental impact and preserving local ecosystems. This paper explores the design and development of an overshot waterwheel turbine specifically designed for pico hydro applications in areas with minimal water resources. A comprehensive review of existing waterwheel technologies, such as undershot, breast shot, pitch back, and overshot, is conducted to understand their historical evolution, fundamental working principles, system designs, and key components. The performance and application of these waterwheel types are analysed, along with the challenges associated with their real-world operation. Additionally, this research addresses critical issues related to waterwheel efficiency and operational limitations, highlighting areas for further improvement and innovation. By comparing different waterwheel designs, the study provides insights into optimizing turbine performance and proposes recommendations for enhancing efficiency, reliability and sustainability in low-resource hydropower applications, particularly in remote or off-grid areas with limited infrastructure access.

Keywords: Low-Flow, Low-Head, Pico Hydropower, Polyethylene Bottle, Waterwheel.

Introduction

Pico hydro systems, including overshot waterwheels, Archimedes screws, breast shot waterwheels, and pitch back waterwheels, are examples of gravity turbines that operate efficiently under low water head conditions (1-3). Unlike impulse and reaction turbines, gravity turbines do not require specialized water jets or rotor blades for operation (4-6). Instead, they utilize gravity and water channelling to drive a rotating runner or wheel (7-9). The functioning of a gravity turbine is based on water entering at the top, descending due to gravity, and exiting at the bottom, thereby converting the potential energy of water into rotational mechanical energy (10). These turbines perform optimally at water heads below 10 meters and low flow rates, operating at lower rotational speeds (11). They are also environmentally friendly, as their design minimizes risks to aquatic life (12-14). One of the key advantages of gravity turbines is their ability to function effectively under varying low flow conditions without complex control systems (3, 12). This makes them particularly suitable for locations where water availability fluctuates daily or seasonally (15-17). Additionally, their low rotational speed reduces wear and tear, prolonging the turbine's lifespan and minimizing maintenance requirements (18). Figure 1 presents an overview of previous studies on pico hydro turbines, highlighting various turbine types such as overshot, undershot, and breast shot waterwheels, as well as Archimedes screws and cross flow turbines (2, 18-20). In low-flow conditions, the Archimedes screw (21), operate at a low water head with a flow rate below 10L/s (21, 22). For higher flow rates, different turbines are utilized. The cross flow turbine (23), functions at a medium water head of 3m with a flow rate of approximately 40L/s (23). Besides that, overshot waterwheels are suitable for high water heads

(Received 23rd April 2025; Accepted 03rd July 2025; Published 24th July 2025)

and larger flow rates (24, 25). Additionally, breast shot waterwheels and undershot waterwheels perform effectively under medium-to-high water heads, handling flow rates exceeding 100L/s (9, 26).

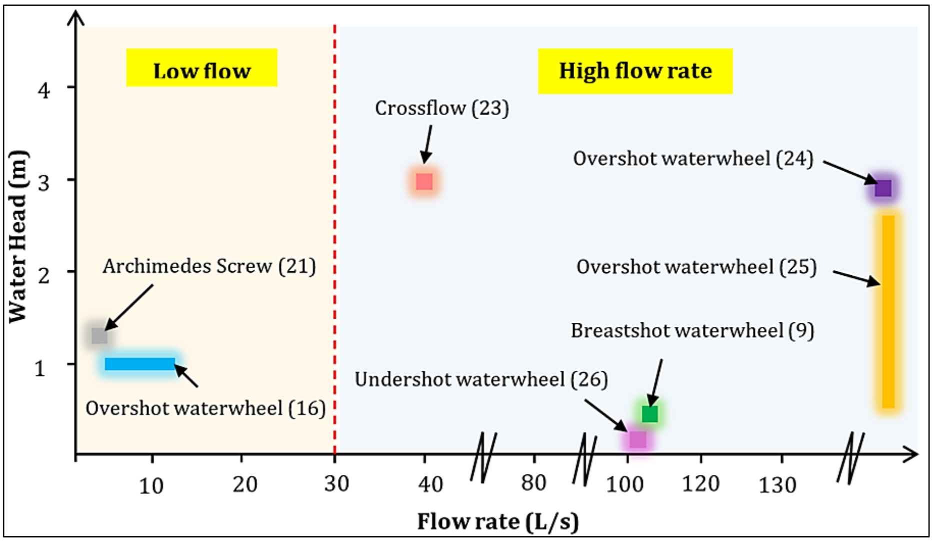

Figure 1: Previous Works on Pico Hydro Turbine

Methodology

This study is primarily conceptual and conducted upon a comprehensive review of existing literature related to waterwheel technologies, with a focus on their application in low-head, low-flow pico hydropower systems. Moreover, the design approach is guided by performance data, empirical results, and design principles documented in previous studies. These sources provided insights into critical design parameters such as water head, flow rate, torque generation, bucket angle, curvature, and material selection.

A comprehensive analysis of waterwheel technologies for pico hydropower necessitates a structured Design of Experiments (DoE) methodology. This approach entails a systematic reassessment of pico hydropower systems to identify their operational characteristics, technological features, and current deployment status. It further involves a detailed review of the historical evolution of waterwheel technologies based on prior research, followed by a performance evaluation under low-head, low-flow conditions typical of pico hydro applications. Optimization strategies are explored by analyzing technical challenges associated with waterwheel efficiency, durability, and adaptability. Special emphasis is placed on the potential application of polyethylene terephthalate (PET) as a material for waterwheel blades, aiming to enhance hydrodynamic performance and structural resilience. The integration of these investigative components within the DoE framework facilitates a robust, data-driven understanding of waterwheel technology development and its future potential in sustainable pico hydropower systems.

Pico Hydropower

Pico hydro, a type of small-scale hydropower with a capacity below 5 kW, is commonly used in rural and mountainous areas for decentralized electricity generation (27-29). Often called "family hydro," it is individually owned and operated, providing an accessible and sustainable energy solution (30-32). The simplicity of its design and ease of operation have made pico hydro a viable option for both experts and non-experts seeking sustainable electricity generation (28, 33).

This technology is particularly advantageous in remote areas where conventional grid-based electrification is impractical (34, 35). Unlike other off-grid energy sources such as wind, photovoltaic, and diesel generators, pico hydro often proves to be the most cost-effective alternative, provided that an adequate water source with consistent flow is available (28). By leveraging the natural flow of water, pico hydro enables reliable and continuous power generation with minimal maintenance, making it a sustainable and economical solution.

Furthermore, when compared to other small-scale renewable options like wind turbines and PV solar home systems, as well as conventional energy sources such as small petrol and diesel generators for remote areas, the pico-hydro scheme stands out as the most cost-effective solution for rural electrification (32). Before considering a pico-hydro site, its cost-effectiveness must be assessed, considering factors such as a shorter payback period (ideally less than six months), cost savings (no fuel required), consistent electricity supply (eliminating the need for batteries), affordability, potential for driving additional mechanical loads for income generation, community sharing, ease of local manufacturing even in basic workshops (13, 30).

Pico-hydro emerges as an optimal solution to address these challenges, offering rural areas access to sustainable and environmentally friendly energy (28). Sustainable energy represents a development paradigm where energy is produced and utilized in a manner that preserves environmental integrity for future generations. The integration of renewable sources such as hydro, wind, solar, and biomass, plays a critical role in decarbonizing and transforming the electricity generation sector, thereby advancing global sustainable development goals (36). Widely regarded as the foremost renewable energy technology in many less developed countries, pico-hydro stands out as the most cost-effective and sustainable electrification option for low-income households residing in remote areas near waterfalls, streams, and irrigation canals (32). Particularly, low head and low flow sites are expected to dominate the hydropower market in the present and near future (11, 27).

Pico hydro is known as a green energy technology that harnesses the power of small streams to generate electricity, typically less than 5kW, as shown in Figure 2. Potential energy in water is initially converted into kinetic energy as it flows, enabling efficient energy transfer. This kinetic energy is then transformed into mechanical energy to drive a generator, resulting in the sustainable production of electricity demonstrating a viable approach for clean energy harvesting from hydraulic system (37). It primarily relies on the natural flow of water to generate electricity, requiring minimal or zero water storage, thereby reducing environmental impact (38). Pico hydro presents a cost-effective, reliable, and efficient alternative energy source among other off-grid solutions (39). With its ability to operate independently of centralized power grids, pico hydro systems offer remote communities access to electricity, promoting socio-economic development and improving quality of life. Additionally, the scalability of pico hydro systems makes them adaptable to various terrains and water flow conditions, further enhancing their suitability for decentralized energy generation in diverse environments.

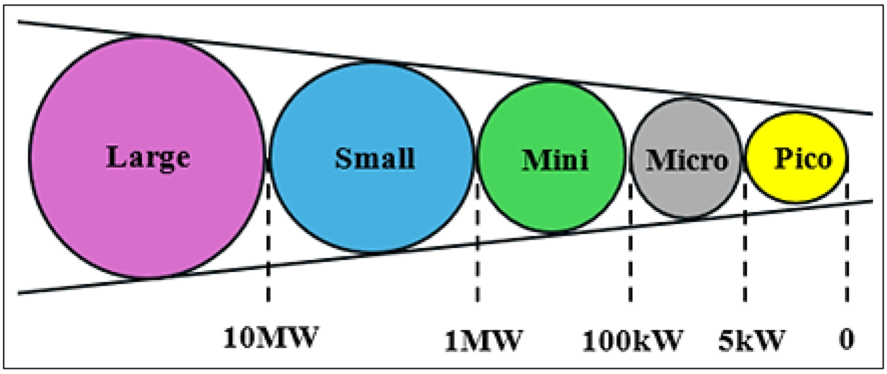

Figure 2: Classification of Hydropower Plants

Pico hydro emerges as the most viable hydropower solution for off-grid regions, particularly remote and hilly areas distant from conventional electrical sources (2, 6). This form of hydropower harnesses the movement of water from small rivers to generate electricity, enabling the power supply to electrical and electronic devices such as televisions, radios, light bulbs, and battery rechargers (39, 40). Pico hydro systems can provide electricity to approximately 30 low-consumption households in rural areas (13, 30).

Pico hydropower is widely recognized for its cost-effectiveness and suitability for decentralized energy generation, making it particularly attractive for rural electrification in underdeveloped regions (30). Countries such as Sri Lanka, Laos, Rwanda, and others across Africa have increasingly integrated pico hydro systems into their national electrification strategies (28). Studies have indicated that the implementation of pico hydro not only provides reliable electricity access but also fosters the development of local technical expertise, supporting the sustainable growth of hydropower infrastructure (32). Southern Asia especially Indonesia, Vietnam, and the Philippines continues to lead the global market in pico hydro deployment (40). Concurrently, regions in Latin America, the Indian subcontinent, and sub-Saharan Africa are progressively utilizing low-head water resources to power off-grid communities (17). This global trend underscores pico hydro's potential as a scalable, community-driven solution to address rural energy poverty while promoting capacity building and localized energy resilience.

In contrast to the construction of large-scale and complex hydropower plants, these initiatives offer numerous advantages, including reasonable capability, low cost, compact size, simplified design and installation, and ease of use (27). Moreover, due to its silent operation, a pico-hydro system causes no disturbance to its surroundings (32). Various approaches exist in designing, operating, assessing, and installing pico hydro systems (34). Many researchers advocate for the construction of modular hydropower systems employing the plug-and-play concept in low-head areas (41). Such features not only offer cost savings but also facilitate easy disassembly, when necessary, such as for broken blade replacement, upgrading systems, or relocating hydro sites.

Evolution Progression of Waterwheel Systems

Waterwheel turbines, also known as slow-running turbines, are a mechanical device that harnesses the kinetic energy of flowing or falling water through blades mounted around their structure (13). The efficiency and power output of a waterwheel, however, are significantly influenced by its design, configuration, and the specific characteristics of the water source (42-49).

Over time, waterwheels have undergone significant transformation. Ancient, traditional, and modern waterwheels differ substantially in terms of manufacturing processes, design specifications, intended applications, efficiency levels, and technological integration. These differences are outlined in Table 1. Since their inception, waterwheels have been recognized as slow-running machines. However, among modern hydropower turbines, waterwheels remain one of the most suitable technologies for low-head sites. Notably, waterwheel systems can operate effectively without requiring advanced irrigation infrastructure.

Waterwheels are classified based on how they interact with water, falling into three main categories:

- Gravity-Driven Waterwheels: Overshot waterwheels operate solely on the gravitational force of falling water, where water is directed onto the blades from above.
- Combined Gravity and Flow-Driven Waterwheels: Breastshot waterwheels utilize both gravity and water flow, as water impacts the blades near the wheel's midpoint, leveraging both weight and velocity.
- Flow-Driven Waterwheels: Undershot waterwheels rely entirely on water flow, with moving water striking the paddles at the bottom, generating rotational motion.

Each type is suited for specific hydropower conditions, influencing performance and efficiency. The waterwheel, developed around 2,000 years ago, was a major technological advancement in harnessing water's kinetic energy (47). During this era, horizontal waterwheels were more common than vertical ones due to their simpler design and adaptability to varying water flows. Ancient Greece and China had distinct waterwheel designs, with the Chinese using water-powered spinning wheels. However, limitations in winding yarn hindered their industrial application. Figure 3 depicts an ancient Greek horizontal waterwheel.

With technological advancements and evolving societal needs, the prominence of horizontal waterwheels declined, particularly during the Industrial Revolution. Vertical waterwheel designs became more popular due to their higher efficiency, greater power output, and adaptability to different site conditions. Despite this transition, horizontal waterwheels played a crucial role in early hydro-mechanical engineering, influencing the development of more advanced water-powered systems, like undershot, overshot, breastshot, and pitchback waterwheels, as illustrated in Figure 4.

Table 1: Differences between Ancient, Traditional, and Modern Waterwheels

Aspects	Waterwheel		
	Ancient	Traditional	Modern
Design	Simple wooden design with paddle blades (47). Relied on the natural flow of water to rotate (47).	Improved efficiency with sturdier construction and streamlined blades (20).	Advanced engineering with metals, composites, and precision components (43, 45).
Purpose	Primarily used for basic tasks such as milling grain, pumping water, and powering small machinery (20, 47).	Same purposes as ancient, used in rural areas (43).	For electricity generation, agriculture, industry, and environmental applications (11, 45).
Efficiency	Relatively low (20% to 25%), heavily relied on water momentum (47).	Moderate efficiency (25% to 40%), with better energy conversion (44).	Highly efficient (more than 40%), with advanced designs and precision manufacturing (45).
Technological integration	Operated as standalone devices, requiring manual intervention for operation and maintenance (10, 47).	Minimal integration of advanced technologies (20).	Integrated with sensors and controls and used in hydroelectric systems (43, 45).

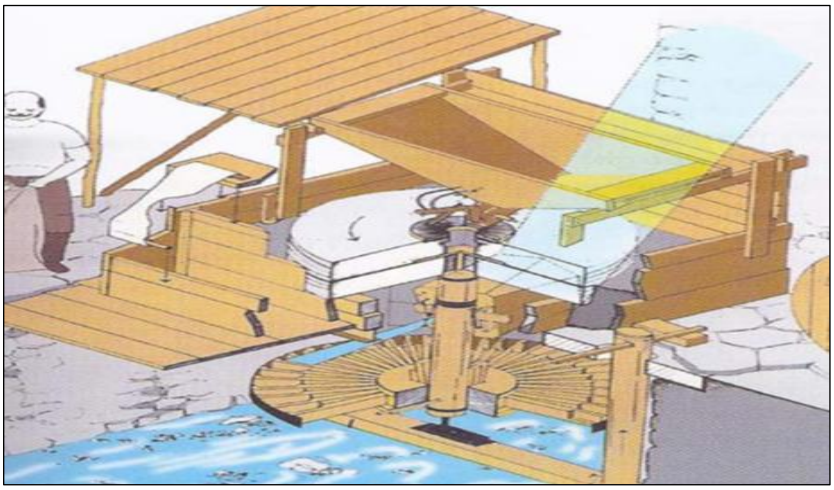

Figure 3: Horizontal Waterwheel in Ancient Greece (47)

The undershot waterwheel operated effectively with a low water head of 0.5m to 2m, making it suitable for small streams in flat areas near populated centers, where it could efficiently utilize available water resources (18). In contrast, the overshot waterwheel, requiring a higher water head of 2m to 10m, was commonly found in hilly or elevated terrains. These locations often necessitated substantial auxiliary constructions due to the significant infrastructure required (15). Modern waterwheel systems involve high manufacturing costs, particularly for water blades (10). To reduce expenses, recyclable materials such as coconut shells, plywood, bowls, cloth, and large spoons are now being used as alternatives for turbine blades and waterwheel buckets (15, 25, 50-52). In addition, many researchers focus primarily on efficiency while overlooking material selection and durability. Hence, this paper advocates for using durable, non-corrosive PET bottles for waterwheel blade construction.

Table 2 summarizes the relevant references on contemporary waterwheel technology. The table also describes the performance results of the waterwheels while operating at certain water head levels and flow rates. All previous waterwheels in Table 2 operated at very low water heads ranging from 0.04m to 3m with a low flow rate of water from 0.1m^3/s to 1m^3/s. The information in the table is suitable for use as a reference for designing the proposed overshot waterwheel.

Table 2: Relevant References on Contemporary Waterwheel Technology

Title of studies	Performance of the system
The effect of the ratio of wheel tangential velocity and upstream water velocity on the performance of undershot waterwheels	Type: Undershot waterwheel The system operated at $0.105m^3/s$ of water discharges. The highest efficiency obtained is 24%, where the power generated is around 11W (26).
Investigation of 16 blades pico scale breastshot waterwheel performance in actual river condition	Type: Breastshot waterwheel The system operated at $0.09708m^3/s$ and 0.26m water resources. The highest mechanical efficiency obtained is 45% (9).
Overshot water wheel efficiency measurements for low heads and low flowrates	Type: Overshot waterwheel The system operated at 1m water head; however, the flow rates varied between $0.005m^3/s$ to $0.013m^3/s$. Hence, the system achieved a good efficiency of 59% and 69.47W of power generated (16).
Bucket design of water wheel for electricity generation	Type: Overshot waterwheel This system operated at 2.74m of water head and a flow rate of $0.55m^3/s$. At the end of the result, it is found that the torque achieved by this system is relatively high, around 3549Nm, which makes it suitable for essential purposes (24).

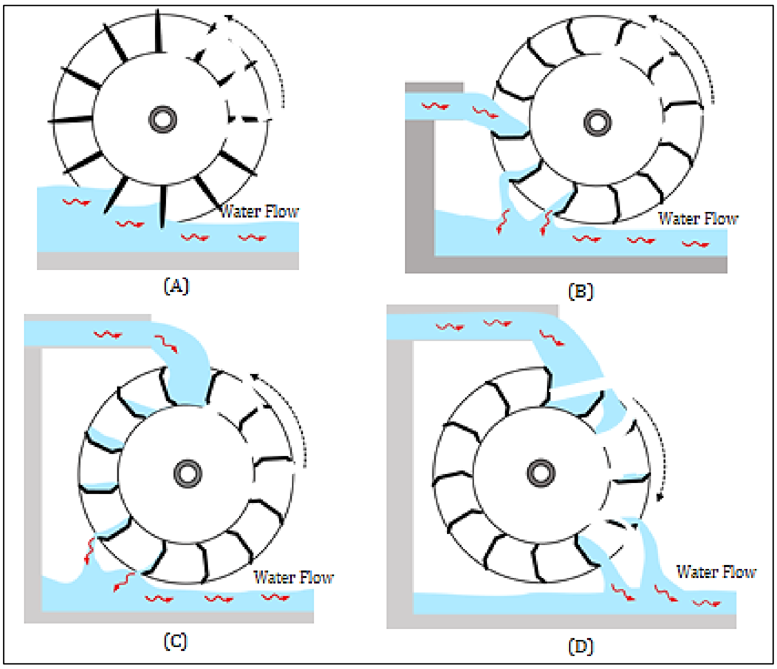

Figure 4: Types of Waterwheels (A) Undershot, (B) Breastshot, (C) Pitchback, (D) Overshot

Results

Performance Assessment of Waterwheel Technologies in Low-Head, Low-Flow Environments

A well-designed overshot waterwheel turbine demonstrates the capability to produce electricity with an efficiency of 85% when subjected to flow rates ranging from less than 0.01 to $0.1m^3/s$ and water heads spanning from a few meters to ten meters of water resources (8, 16). The overshot waterwheel is known as the most prevalent gravity turbine that has been frequently employed in scenarios characterized by low head and low flow conditions (53, 54). This is because it is known for its high efficiency even in low head and low flow conditions. The design of the structure allows it to operate effectively at low head heights.

Moreover, it has a noncomplex design compared to other types of turbines, hence, it is easier to construct and maintain operation, particularly in off-grid locations. Furthermore, when first tested by British engineer John Smeaton in 1759, the overshot waterwheel demonstrated an efficiency exceeding 60%, surpassing the 30% efficiency observed in the undershot waterwheel (55). Since then, substantial advancements in materials, design structure, and operational principles have led to further increases in efficiency levels. Figure 5 shows the examples of a traditional overshot waterwheel.

Figure 5: Traditional Overshot Waterwheel (11)

Primarily, the overshot waterwheel harnesses gravitational potential energy (11). It capitalizes on the potential energy of descending water to generate electrical power through the mechanical energy imparted by its rotational paddles. As water descends from the channel, it strikes the top bucket, initiating rotational movement as it cascades to the wheel's bottom. Consequently, the gravitational energy stored within the buckets or paddles generates torque on the wheel, facilitating its rotation for electricity generation (56). Eventually, the discharged water exits via the tailrace, carrying water away from the waterwheel.

Furthermore, an overshot waterwheel is perceived as being more environmentally sustainable and economically viable compared to Kaplan and Francis turbines (20). This is attributed to their characteristic features, such as low rotational speeds, spacious buckets, and their operation with free-surface flow dynamics. These characteristics enhance its reputation as a more environmentally friendly and economically advantageous choice for hydropower utilization.

In contrast to the pitchback waterwheel, the overshot waterwheel has gained a lot of attention among researchers in the field of small hydropower. It is also renowned as the most efficient waterwheel design for areas with low water head (53, 57). Aside from that, the overshot waterwheel is the most utilised compared to the other types of waterwheels (53, 57).

A previous study (16) focused on the design and measurement of the hydraulic efficiency of an overshot waterwheel for low-head and low-flow conditions (16). Notably, Polyvinyl Chloride (PVC) was used as the primary material for the buckets, which were cut to a quarter of their length and compressed between two circular plastic discs, as shown in Figure 6 and Figure 7. This design allows for precise adjustment of the bucket leading edges relative to the incoming water stream. Additionally, the simplified bucket structure is intended to harness both potential and kinetic energy from the water flow, enhancing overall efficiency. The research also examined how adjusting the leading edge and the position of the channel outflow edge influences waterwheel efficiency, as shown in Figure 8.

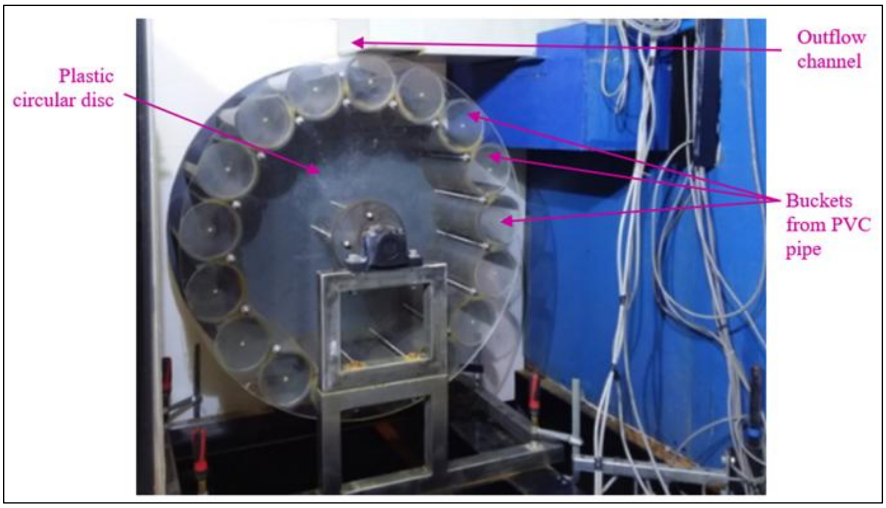

Figure 6: Overshot Waterwheel (16)

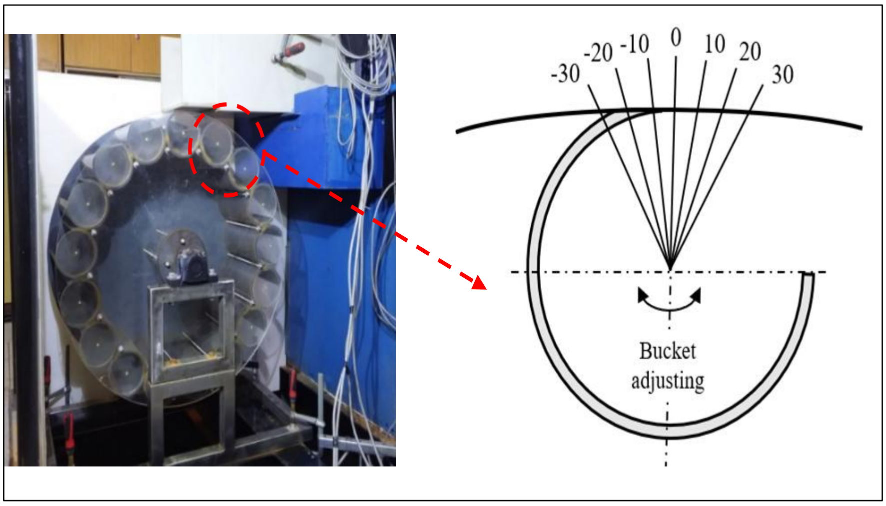

Figure 7: Bucket Angle Adjustment and Bucket Slot Opening (16)

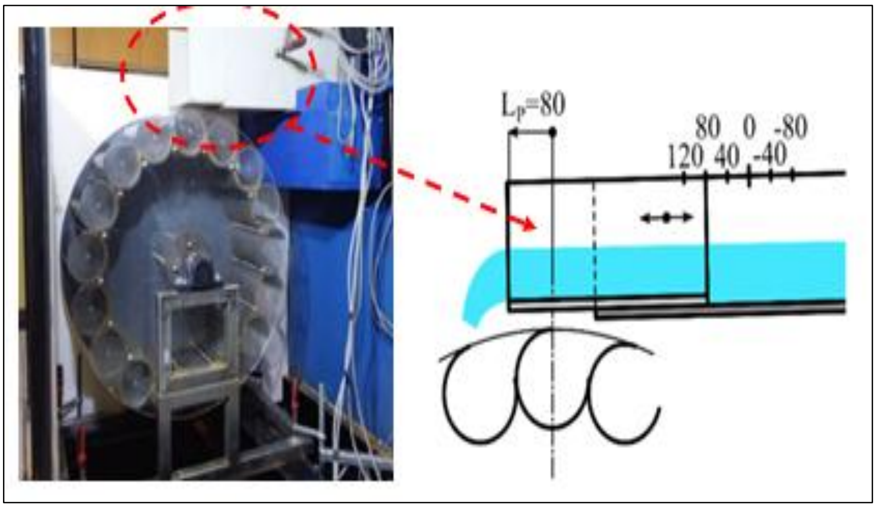

Figure 8: Label of Outflow Channel Edge Position (16)

In terms of operational conditions, the Stigler waterwheel requires a minimum water head of 5m and a high flow rate of at least 30L/s. The research found that the bucket angle significantly influences the performance of the waterwheel.

The correlation between system efficiency and flow rate is greatly influenced by the outflow channel edge position and bucket angle adjustment. Experimental results indicate that these two parameters play a crucial role in overall system performance. At the conclusion of the study (58), it was determined that optimizing the channel outflow edge position and adjusting the bucket angle significantly enhance efficiency, making them key factors in improving waterwheel turbine performance.

Another research emphasized that the waterwheel's performance also depends on the amount of water trapped in the bucket (59). Hence, this curve design helps to maximize water that is trapped within the bucket, thereby enhancing the waterwheel's rotation speed due to increased torque and kinetic energy. Consequently, these two parameters are crucial in enabling the waterwheel to operate effectively under ultra-low water head.

As shown in Figure 9, the highest efficiency was achieved at 59% when operated at channel edge position -80, and bucket angle adjustment -20 with 69.47W of power generated during 0.005m^3/s of water flow rate and at the lowest rotational speed (16). Moreover, this study indicates that the system's efficiency and the water flow rate are inversely proportional. It is good to note that the mechanical efficiency starts to decrease as the rotational speed of the waterwheel increases.

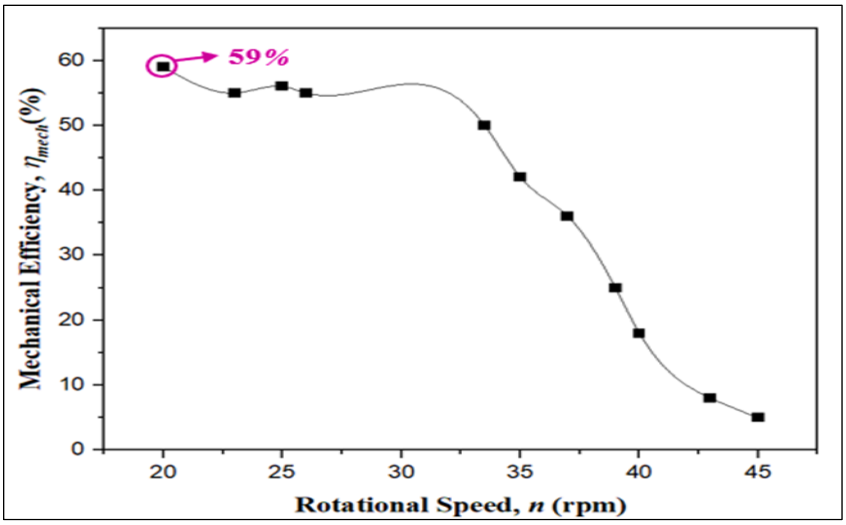

Figure 9: Experimental Result of the Overshot Waterwheel (16)

The other overshot waterwheel project was conducted, which mainly focused on the bucket design of the waterwheel (24). The waterwheel operated at a flow rate of 0.5522m^3/s with a net head of 2.74m. During the experimental process, the authors observed that the experimental torque was relatively high, measuring approximately 3549 Nm, and the system successfully generated 6 kW of mechanical power, even at a low rotational speed of 3.2m/s. On the other hand, the combination of low speed and high torque makes them a suitable choice to operate in other applications. Besides, the power output was found to be highly dependent on the diameter and torque of the waterwheel. Figure 10 illustrates the design of the overshot waterwheel and the angle of water filling in the bucket (24).

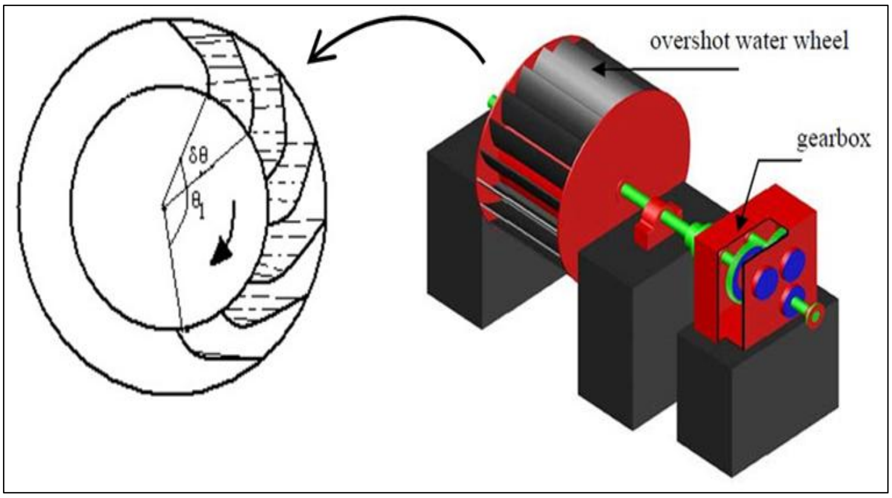

Figure 10: Illustration Design of the Overshot Waterwheel and the Angle of Filled Water in the Bucket, θ_l (24)

It can be seen that, the θ_l is the angle of filled water in the bucket during rotational motion. Therefore, equation [1] is used to determine the mass of water in θ_l. Based on the equation, it can be concluded that torque is directly proportional to the mass of water in the buckets (24). However, theoretically, torque not only depends on the mass of water in buckets but also influences the power output of the waterwheel, as power is the product of torque and angular velocity.

$$Torque, \tau = M_{wt} \cdot g \cdot R \cdot sin\ sin\ \theta_l \qquad [1]$$

Furthermore, the design of the bucket curvature in an overshot waterwheel is a crucial parameter. The curvature and positioning of the buckets significantly influence water transfer efficiency by reducing spillage and maximizing energy capture. Optimizing the bucket design enhances the conversion of water's potential energy into mechanical energy, ultimately improving the overall efficiency of the waterwheel in electricity generation. A well-designed curvature ensures better water retention and smoother rotation, leading to higher performance.

The schematic representation of the bucket curvature is illustrated in Figure 11. The circle center, labelled as O, defines the inner and outer arcs of the blade with radius, $r_1$and r_2, respectively. This curvature is designed to optimize water flow into and through the wheel, minimizing energy losses. As illustrated in Fig. 11, the bucket angle at the point of water entry follows Banki turbine design principles and is maintained below 16° (11, 20). This specific angle is essential for maximizing water capture while reducing splash and turbulence, which significantly affect the waterwheel's efficiency.

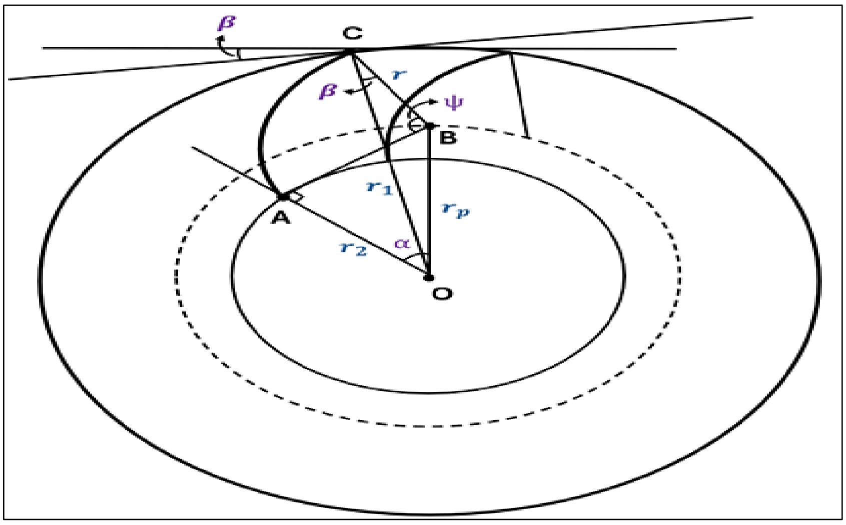

Figure 11: Schematic of Bucket Curvature (24)

The combined effect of blade curvature and bucket angle enhances water retention and ensures a smooth energy transfer process. This results in improved torque generation and higher power output, ultimately contributing to the overall efficiency of the waterwheel. By carefully designing these parameters, the system achieves optimal hydrodynamic performance, making it more effective for low-head and low-flow hydropower applications.

Discussion

Optimization Strategies Derived from the Challenges in Waterwheel System

This paper addresses a significant research gap and technical issues identified through an in-depth literature review. Studies indicate that the limited advancement of pico hydropower technology restricts the utilization of many low-head, low-flow water resources for power generation. Most commercially available turbines are not designed to function efficiently under such conditions. Additionally, the potential of pico hydro systems remains largely underestimated, despite their ability to generate electricity continuously, operating 24/7 throughout the year. As long as water flows in streams, power can be produced. A higher water flow rate through the turbine blades further enhances energy generation, improving overall system efficiency.

For example, Malaysia's topography presents numerous potential sites with head heights below 10 meters, yet these resources remain largely underutilized (60). Many of these locations, characterized by streams, rivers, and irrigation channels, offer ideal conditions for pico hydro turbine installations (61-63). Their reliable and consistent flow rates make them well-suited for small-scale hydropower generation. Table 3 outlines the flow rates of selected rivers in remote regions of Malaysia, offering valuable insights into the hydrological potential for pico hydro development. By leveraging these natural water sources, Malaysia can enhance rural energy access and contribute to broader renewable energy initiatives.

Table 3: Flow Rate of Selected Rivers in Off-Grid Areas in Peninsular Malaysia (30)

River	Min. (m^3/s)	Max. (m^3/s)	Mean (m^3/s)
Sungai Muar	1.22	134.07	26.18
Sungai Triang	6.4	59.76	19.91
Sungai Segamat	3.5	41	8
Sungai Serting	1.81	28.73	6.28
Sungai Sokor	6.36	269.93	12.81
Sungai Pahang	149.1	2,651.5	356.3
Sungai Jelai	150.96	717.28	216.28

Besides that, Figure 12 illustrates that most hydro turbines or waterwheels require precise and sophisticated design parameters, posing a significant challenge for pico hydro researchers. Failure to meet these specifications can result in system damage, reducing efficiency and reliability (30). Additionally, manufacturing such systems often demands high-precision machines by specialized personnel, making production costly and less feasible for widespread implementation. Furthermore, the unique geographical and hydrological conditions of each location necessitate customized designs and equipment to ensure optimal performance. While this tailored approach enhances efficiency, it also increases overall costs and project complexity, making the adoption of pico hydro systems more challenging (18).

Figure 12: Condition of Waterwheel Installed in a Small Stream in Indonesia (26)

Modifying or upgrading the system design after deployment can lead to additional costs and logistical difficulties, further impacting the cost-effectiveness of pico hydro solutions. To improve the feasibility and accessibility of pico hydropower for rural communities, it is essential to develop and adopt more efficient techno-economic strategies (32).

Additionally, variability in natural stream flow is rarely accounted for in traditional waterwheel designs (32). Most systems assume steady flow rates, yet real-world conditions often involve fluctuating volumes due to seasonal or daily changes. Fixed-geometry waterwheels may suffer from reduced performance or even become non-functional during dry periods (15). Therefore, adaptive or self-regulating designs are needed to ensure consistent power generation across a range of flow conditions.

By optimizing system components, reducing material costs, and enhancing performance, pico hydro systems can become more sustainable and practical. Innovative design approaches and locally sourced materials can further lower expenses, making these renewable energy solutions more affordable and adaptable for off-grid areas with limited resources and challenging environmental conditions.

By reducing production costs, streamlining design processes, and fostering innovation in materials and technology, pico hydro systems can become more competitive with other renewable energy options such as solar and wind power. This, in turn, can help to broaden access to clean and sustainable energy sources, particularly in remote and underserved areas, fostering economic development and improving the quality of life for local communities.

Another technical challenge is maintenance complexity and limited access to spare parts in rural settings. Many pico-hydro systems rely on imported or precision components such as sealed bearings, specialized gears, or custom-fabricated parts (32), which are not readily available or serviceable locally. When these parts fail, users often face long downtimes due to the lack of technical expertise or supply chains in remote areas (28). Thus, future designs must prioritize the use of locally available, modular, and easy-to-replace components to ensure long-term operability and reduce system abandonment.

Furthermore, recyclable PET bottles will be repurposed as blades to replace conventional zinc plates or wooden blades (18). This adaptation is anticipated to extend the lifespan of the blades, as materials like metal and wood are susceptible to issues such as rust and damage in humid environments, as shown in Figure 13.

Figure 13: Plastic Bottle Pollution

Plastic bottles are widely available, low-cost, and simple to work with, making them an excellent choice for waterwheel blades (1). Their slow decomposition rate ensures durability, enhancing the longevity of the system. This innovative use of plastic bottles supports recycling efforts and promotes environmental sustainability. By repurposing plastic waste, the approach helps reduce pollution and minimize landfill accumulation. Additionally, integrating recycled materials into waterwheel designs offers a cost-effective and eco-friendly alternative to traditional construction methods. A parametric framework based on Design of Experiments (DoE) principles is essential for guiding design optimization prior to prototype development and testing. This methodology facilitates the identification of key parameter interactions and establishes foundational performance benchmarks. The DoE framework, as outlined in Table 4, serves as a strategic tool for systematic optimization and informed planning in the early stages of waterwheel system design.

Table 4: Design of Experiment (DoE) for Waterwheel System Optimization

Category	**Design Parameter**	**Range/ Type**	**Design Reference**
Independent Variables	Water Head	0.5 m – 2.0 m	Target low-head site conditions (30)
	Flow Rate	0.005 m^3/s – 0.05 m^3/s	General rural stream settings (30)
	Bucket Material	PET bottle	Selected for cost, availability, and durability
	Bucket Angle	0°, 15°, 30° (discrete levels)	Literature review on angle optimization
	Curvature Radius (r_1, r_2)	Variable based on bottle geometry	Geometric fitting of available PET bottles
	Wheel Diameter	0.4 m – 1.0 m	Based on the target torque and RPM design
	Number of Buckets	12 – 24	Derived from prior waterwheel designs
Expected Outcomes	Retention efficiency	Conceptual/maximization	Based on curvature, angle, and spillage data
	Torque	From static water mass and PET geometry	Theoretical equations
	Output Power (theoretical)	$P = \tau\ \omega$	Based on design assumptions
	Ease of Fabrication	Qualitative (High / Medium / Low)	Based on local material constraints

Potential of Polyethylene Terephthalate (PET) in Optimizing Waterwheel Blade Performance

On average, people worldwide purchase approximately 29 billion bottles every year. It is estimated that only one bottle out of every six purchased is recycled (64, 65). Hence, these results in 2 million tonnes of abandoned water bottles due to improper disposal and inadequate recycling infrastructure, which then leads to plastic bottles accumulating in landfills, water bodies, and even remote natural habitats (66). The pollution caused by plastic bottles poses a significant environmental challenge globally. As non-biodegradable items, plastic bottles persist in ecosystems for centuries, releasing toxins and micro plastics into the environment. In marine environments, plastic bottles pose a grave threat to marine life, as animals often mistake them for food or become entangled in them, resulting in injury or death (1). Moreover, plastic bottle pollution contributes to the degradation of water quality, disrupting ecosystems and harming aquatic organisms. Furthermore, each bottle takes at least 70 to 1,000 years to disintegrate (64). Furthermore, numerous countries are recognized as major contributors to plastic pollution, emphasizing the urgent need for effective strategies to manage plastic waste and minimize its environmental impact. Figure 14 depicts an example of a PET water bottle.

Figure 14: PET Bottles

Tackling the pollution stemming from plastic bottles necessitates collaborative efforts aimed at reducing plastic consumption, enhancing waste management practices, and advocating for the adoption of sustainable alternatives. Consequently, repurposing plastic bottles as waterwheel blades emerges as a logical and feasible solution. Utilizing plastic bottles as blade elements not only extends the lifespan of waterwheels but also serves to mitigate plastic waste pollution effectively. This innovative approach embodies a practical step towards addressing environmental concerns while promoting sustainable practices in resource utilization. Nowadays, people have begun to innovate the turbine blade or waterwheel bucket parts by replacing them with recyclable items such as plastic bowls, coconut shells, big spoons, and empty plastic bottles (50, 52). The existence of these varieties of water wheel turbines reflects the interest people have in diversifying water wheel designs. However, many of these projects lack comprehensive scientific research that could serve as valuable references.

Moreover, numerous experts engaged in waterwheel projects often prioritize system efficiency, leading to inadequate material selection and reduced durability. Additionally, existing waterwheel structures typically employ materials susceptible to degradation when exposed to moisture, including rust and rot (20). Metal components with low corrosion resistance are prone to rusting after prolonged exposure to water, particularly in environments with elevated pH levels (10). Similarly, low-quality wooden elements are highly susceptible to deterioration over time when consistently immersed in water and situated in humid regions. In terms of environmental aspects, the PET waterwheel provides a relatively eco-friendly solution for low-head hydroelectric power generation with minimal ecological disturbance, limited sedimentation impacts when properly managed, and low interference with fish migration due to their operational characteristics and design. Table 5 discusses the environmental aspects of the PET waterwheel for low head pico hydropower.

Table 5: Performance of the PET Waterwheel in Ecological Impacts, Sedimentation Consequences, and Interference with Fish Migration

Aspects	Details
Ecological Impact	Gravity turbines, including PET waterwheels, have a relatively low ecological footprint compared to large-scale hydro systems (67). They operate at low heads and low flow rates (11), minimizing disruption to river ecosystems. Their low rotational speeds reduce physical harm to aquatic organisms, and the design allows safe passage for fish, lowering mortality rates (12-14, 36).
Sedimentation Consequences	Water entering from the top can cause localized sediment accumulation near the intake, acting as a minor barrier. However, at low heads and flow rates, sediment transport is mild to none, reducing the risk of significant build-up or downstream erosion. Proper design elements, like intake geometry and flushing mechanisms, help mitigate sedimentation impacts.
Interference with Fish Migration	Waterwheels are considered fish-friendly machines, as they cause minimal disruption to fish migration (68), due to low-speed operation, gentle flow, and open-channel design. These characteristics allow fish to either avoid the structure or pass through it safely (14, 68). However, it has not been scientifically assessed.

Plastic bottles, including water bottles, soft drink bottles, shampoo bottles, and reusable containers, are created through the process of heating and moulding plastic into the desired shape. These bottles are typically made from four primary materials: polyethene terephthalate (PET), polypropylene (PP), and polycarbonate (PC) (61, 68). Each material is chosen for its specific properties, tailored to the intended use of the bottle. For example, PET plastic is commonly used for water and soda bottles due to its lightweight, strength, and ability to act as a barrier against moisture and gases. Similarly, polypropylene (PP) is often employed for pill bottles because of its resistance to chemicals and durability. Polycarbonate (PC) is frequently used for reusable bottles due to its toughness and transparency, while polyethene (PE) is versatile and used for various containers. The careful selection of materials ensures that each type of bottle meets the functional, safety, and durability requirements of its intended application (62). However, there are slight differences in terms of thickness and durability. A soda bottle has a higher level of heat resistance than water bottles since a soda bottle is 2.5 times thicker than water bottles (69). For that reason, the centre of the water bottle tends to bulge outward beyond its edge when exposed to heat, as depicted in Figure 15. The result shows that soda bottles generally exhibit high heat resistance compared to water bottles.

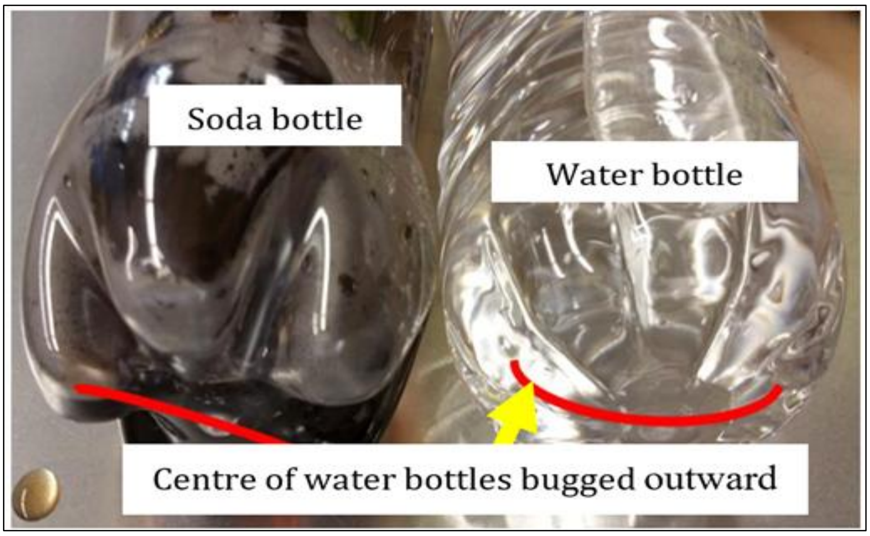

Figure 15: Difference in Bottles Bulge after Exposure to Heat (69)

As previously discussed, soda bottles appear to offer greater potential for use as water wheel blades compared to water bottles. Thus, the concept of innovating soda bottles into water wheel blades is both logical and achievable. Additionally, the size of soda bottles can be adjusted to suit the dimensions of the water wheel turbine. This flexibility arises from the availability of soda bottles in various capacities on the market, ranging from 500ml to 1,500ml. Crucially, employing plastic bottles as blade components can help sustain the lifespan of water wheels while simultaneously mitigating plastic waste pollution.

The durability of soda bottles makes them ideal for waterwheel applications, ensuring structural integrity under operational forces. Repurposing them as blades maintains functionality while reducing plastic waste. This innovative approach highlights the importance of utilizing existing materials to enhance sustainability in renewable energy and waste management.

As part of the assessment, the plastic bottles used as blades can be modified into bucket-like shapes to enhance water-holding capacity. This allows for a performance comparison between uncut and cut bottles. In the future, the project development will be analyzed using methodologies adapted from previous studies to ensure a systematic evaluation of design improvements. The experimental results will then be compared with earlier waterwheel models to assess efficiency. This comparison aims to verify whether the proposed system achieves higher efficiency despite operating with limited water resources, demonstrating its potential as an optimized solution for low-head and low-flow hydropower applications.

Conclusion

Many locations, both in rural and urban areas, have abundant streams and rivers, presenting a significant opportunity for hydropower generation. However, there remains substantial untapped potential for electricity generation using pico hydropower technology, particularly in rural regions. It is recommended to implement pico hydroelectric systems with a maximum capacity of 5kW in isolated areas of developing countries to harness this potential effectively.

Most conventional waterwheels are not specifically designed for extremely low water heads and flow rates. The overshot waterwheel, the most relevant existing technology, operates efficiently at water heads between 1m and 1.5m and flow rates from 10L/s to 20L/s. The absence of suitable waterwheel technology for extremely low flow conditions highlights a significant research gap that this study seeks to address. This study revisits a previous waterwheel project, focusing on optimizing its geometrical design and performance evaluation. The key design and operational parameters from earlier waterwheel models serve as references for developing the proposed system.

Material selection is vital for the efficiency and durability of hydro turbines. This study examines using PET bottles for turbine blades, offering a sustainable solution by repurposing long-lasting PET plastics and minimizing dependence on traditional materials.

From a socio-technical aspect, which interprets between social factors (people, communities, culture) and technical systems (tools, machines, technologies), several factors influence the effectiveness of waterwheel systems. These include community participation, affordability, the use of locally available materials, ease of operation and maintenance, environmental considerations, and institutional support for off-grid energy solutions

The use of recyclable PET bottles not only contributes to environmental sustainability but also enhances economic viability, as they are low-cost, readily available, and easy to replace or maintain locally. Moreover, the simple structure of the overshot waterwheel facilitates fabrication in basic workshops, empowering communities to participate directly in the construction and maintenance of the system.

Furthermore, the adaptability of the design to varied terrains and water availability makes it suitable for decentralized energy access in remote areas. By aligning technical innovation with social and environmental realities, the proposed waterwheel design promotes long-term usability, ownership, and resilience, thereby increasing the likelihood of successful adoption in real-world settings.

A development and policy-oriented approach highlights the potential of integrating pico hydropower systems into national rural electrification programs. National energy agencies and governments are encouraged to support this integration by enabling site mapping, simplifying regulatory procedures for systems under 5kW, and establishing clear, streamlined design standards. These steps can facilitate cost-effective and scalable deployment in off-grid and remote areas.

Public-private partnerships (PPPs) offer an effective pathway to accelerate implementation, especially when local enterprises are involved in manufacturing and maintaining systems using readily available materials such as PET bottles. Combined with community engagement, technical training, and financial support from clean energy funds or rural development programs, these efforts can enhance long-term sustainability. Such strategies contribute to a decentralized, inclusive energy model that aligns with national development goals and empowers local communities through affordable and reliable energy access.

Future studies will incorporate advanced design and simulation tools, including Computational Fluid Dynamics (CFD) and AI-based optimization, to enhance the development and performance evaluation of the proposed waterwheel system. These modern techniques enable detailed geometric modeling, accurate boundary condition application, and integration of real-time data, making them particularly effective during advanced stages of prototype testing and refinement. However, their implementation is most beneficial after initial baseline design validation has been achieved. Therefore, the application of CFD and AI is recommended in subsequent research phases to support precision optimization and performance enhancement of the waterwheel system.

Abbreviations

PC: Polycarbonate, PE: Polyethylene (or Polythene), PET: Polyethylene Terephthalate, PP: Polypropylene (or Polypropene), PVC: Polyvinyl Chloride.

Acknowledgement

The authors also would like to thank Universiti Teknikal Malaysia Melaka (UTeM) for all the supports.

Author Contributions

The authors declare that they have equal rights to this paper.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethics Approval

The conducted research is not related to either human or animal use.

Funding

The authors acknowledge financial support for this study from the Ministry of Higher Education (MOHE) of Malaysia through the Fundamental Research Grant Scheme (FRGS), No: FGRS/1/2024/FTKE/F00578.

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