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Enhancing Efficiency in Small-Scale Hydropower: A Comprehensive Review of Archimedes Screw Turbine Design Innovations

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ABSTRACT

The world's ever-increasing energy needs have necessitated the search for renewable means to satisfy such energy needs. One of those means is small-scale hydropower, and in particular, the Archimedes screw turbine (AST), which has been viewed as one such future option. Initially designed for water lifting, ASTs use incoming water kinetic energy to generate electricity today. This review paper reports on the advances made today in the design of ASTs, emphasizing the geometrical parameters of pitch, diameter, number of blades, and inclination as design parameters affecting efficiency. Improvement was made by either conducting experiments or by optimizing simulation. Flow variation, sediment deposition, material degradation, and other challenges may be overcome. Still, innovations in composite materials, coatings for corrosion protection, and AI design improvements should be considered to enhance their durability and efficiency. Economic and policy barriers discourage collateral investments, such as high upfront capital costs and competition from other renewables. Modern integration with solar and innovative grid systems opens more expansive opportunities for sustainable energy. Future research and development advancements will improve AS output viability for decentralized eco-friendly power generation in remote areas.

1. Introduction

The demand for energy worldwide is rising, making the need for renewable energy sources more urgent than ever. Struggling against climate warming and losing valuable resources requires replacing fossil fuels with sustainable options [1]. Hydropower is still among the most dependable and effective renewable energy sources among these options. While the industry is dominated by large

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hydropower plants, small-scale hydropower systems are becoming more popular due to producing power in rural areas with minimal ecological harm [2].

Small-scale hydropower uses Archimedes screw turbine, which is a new technology that is emerging fast. This ancient device was initially made to pump water, but now it can use currents to turn flowing water into electricity [3]. Compared to standard hydro turbines, Archimedes screw turbines are effective at low-head sites, making them ideal for use in rivers, irrigation ditches, or even the sites of old watermills. Their robust and simple design makes these turbines require minimal maintenance and cause no harm to the fish population, therefore making them a sustainable solution for renewable energy [4].

Although such pumps have their advantages, their efficiency depends also on the design of the screw itself. The screw pitch, diameter, number of blades, and rotation speed are all factors that affect the overall energy conversion process of the whole plant [5]. With such minor changes in the design, the efficiency can be affected; therefore, it is essential to know the optimal configurations [6]. Researchers increasingly use simulations and experimental analyses to improve the performance of these turbines by studying the effects of different screw geometries on the output and efficiency [7].

This review aims to evaluate the current research on Archimedes screw turbines and, more specifically, the impact of screw design on turbine performance [8]. Through the results of computational simulations and real-life applications, this study aims to determine which design parameters are most effective in enhancing efficiency [9]. The findings of this review are expected to be helpful in the improvement of small-scale hydropower technology toward the development of sustainable and decentralized energy solutions [10].

However, despite extensive work optimizing AST performance, many critical research gaps remain. Long-term performance and material degradation resistance have yet to be widely addressed, causing concerns over AST durability and maintenance requirements for real-world use [9]. Furthermore, while some studies have attempted design optimization, there is still a noticeable absence of more robust studies that include environmental and regulatory concerns—concerns that are vital for AST's technological implementation and scaling. Additionally, absent empirical investigations on economic feasibility and sustainability limit the broader acceptability of AST technology in the global energy market [11].

Filling these gaps becomes very important in permitting the pathway for AST to be accepted as a robust and inexpensive hydropower option. With durability studies, regulatory approaches, and economic evaluation in future research, AST can target real-life usefulness beyond theoretical optimization; this will contribute to developing a sustainable and decentralized energy world [12].

2. Methodology

2.1 Background on Archimedes Turbines

2.1.1 Archimedes screw turbine mechanism

An Archimedes screw is a simple yet effective machine initially engineered for the lifting of water. It consists of a helical blade wound on a central axis, enclosed within an open-cylindrical casing or trough. Rotating the screw lifts water from a lower elevation to a higher one [13]. In the opposite sense, that is what happens in hydropower generation- the water turning does the screw as it generates mechanical energy converted to electrical energy through a generator [5].

Archimedes screw turbines operate best at low heads (generally between 1 to 10 m), which is why they are exceptional in locations where conventional hydroelectricity technologies fail to work well [3]. In contrast to their high-pressure counterparts, based on high drops of water, these turbines capture the constant flow of water to create rotation. Because of their low rotational speed, the turbulence is limited, increasing the efficiency in places with varying flow [14]. They have an open design and low impact, allowing aquatic animals to pass through unharmed, unlike conventional turbines, which harm the fish population.

2.1.2 Historical development and global applications

The use of the Archimedes screw can be traced back to ancient Greece, where it was attributed to the famous mathematician and engineer Archimedes of Syracuse (circa 287-212 BCE). Water-lifting was initially conceived for irrigation and water control. Still, from ancient times onward, it was adopted by numerous civilizations, such as the Romans and Egyptians, to move water for agricultural and municipal purposes. For centuries, the Archimedes screw remained mainly a water-lifting device, being applied for drainage systems and flood control [15].

Starting in the late 20th century, as engineers began experimenting to find efficient solutions for small-scale hydropower, the Archimedes screw transitioned from a water-lifting mechanism to a hydroelectric energy generator. In Europe, particularly the Netherlands, Germany, and the United Kingdom, Archimedes screw turbines have been adapted for generating electricity [16]. Nowadays, these turbines are found in all corners of the world, especially in places that emphasize preserving natural ecosystems. Many old water mill sites have been reclaimed with Archimedes screw turbines to show their viability in making best use of hydropower while conserving historical infrastructure. Other countries like Canada, Japan, and the USA have explored decentralized power generation for which Archimedes screws provide sustainable electricity for remote and rural communities [17].

2.1.3 Comparison with other hydropower turbines

Compared to traditional turbines, such as Kaplan, Pelton, and Francis turbines, the Archimedes screw turbine has its own set of advantages with corresponding disadvantages. For example, the Kaplan turbine is one of the most efficient turbines with low heads but requires a complicated infrastructure and excellent maintenance. Pelton turbines are meant to work for places with very high heads and fast-moving streams, becoming inefficient in low gradients where Archimedes screws thrive [18]. Francis turbines are rated to be used in large-scale hydroelectric plants with the same comparative efficiency under medium to high-head circumstances and would not lend themselves well to decentralized small energy projects [18].

Being defined as having an efficiency between 70 and 85%, Archimedes screw turbines are, therefore, indeed in competition with any other turbine type in low-head conditions [19]. Nevertheless, their uniqueness lies in their functioning at sites that conventional turbines consider unsuitable. The minimal civil engineering work required leads to lower installation costs, while their simple machine works towards keeping operational and maintenance costs low. Their eco-friendly attribute is further enhanced: they are considered fish-friendly, and they operate with varying flow rates [20]. Table 1 provides a comparative overview.

Table 1
Comparison of hydropower turbines

Turbine type	Efficiency	Head range	Flow rate	Cost	Application	Reference
Pelton Turbine	90% - 95%	> 300 meters	Low	High (complex installation and infrastructure)	Suitable for high-head, low-flow sites, typically in mountainous regions.	[21]
Francis Turbine	85% - 90%	2 - 800 meters	Medium	High (requires precise manufacturing and maintenance)	The versatile turbine is used in various head and flow conditions and is ideal for large-scale hydroelectric plants.	[22]
Kaplan Turbine	85% - 90%	10 - 70 meters	High	High (custom blades and complex regulation system)	Designed for low-head, high-flow applications, such as large rivers or tidal installations.	[23]
Crossflow (Banki-Michell)	70% - 85%	1 - 10 meters	Variable	Medium (simpler construction but lower efficiency)	Suitable for small-scale installations with variable flow rates, often used in micro-hydro projects.	[24]
Archimedes Screw Turbine	70% - 85%	1-10 meters	High	Low to Medium (simple design, minimal maintenance)	It is ideal for very low-head sites with high flow rates; benefits include simple construction, low maintenance, fish-friendly operation, and suitability for sites unsuitable for traditional turbines.	[25]

Archimedes screw turbines may not make the best option for every hydropower project, but they remain a perfect solution for sustainable small-scale energy generation [26]. Their combination of efficiencies, durability, and compatibility with ecology makes them a growing alternative on the move to renewables. Further research on optimizing their design and improving their efficiency will only enhance their applications on the global energy map, especially in areas that favor low-impact, community-based hydropower approaches [27].

Empirical studies and case analyses provide strong evidence supporting the effectiveness of AST design improvements. For instance, a study conducted in Europe demonstrated that optimizing the inclination angle and blade number led to a 15% increase in efficiency compared to conventional designs [7]. This improvement was achieved through experimental testing and Computational Fluid Dynamics (CFD) simulations, ensuring more precise and reliable results. Such findings reinforce the importance of continuous research and technological advancements in AST, paving the way for broader adoption and integration into global energy systems [7].

3. Importance of Archimedes Screw Turbine Design

The screw design is among the principal determinants of hydraulic performance and efficiency for Archimedes Screw Turbines (ASTs) [28]. Factors such as pitch, diameter, length, and inclination angle greatly influence the efficiency of hydraulic energy conversion into mechanical energy [29]. Figure 1 shows the illustration of Archimedes' screw turbine by [30].

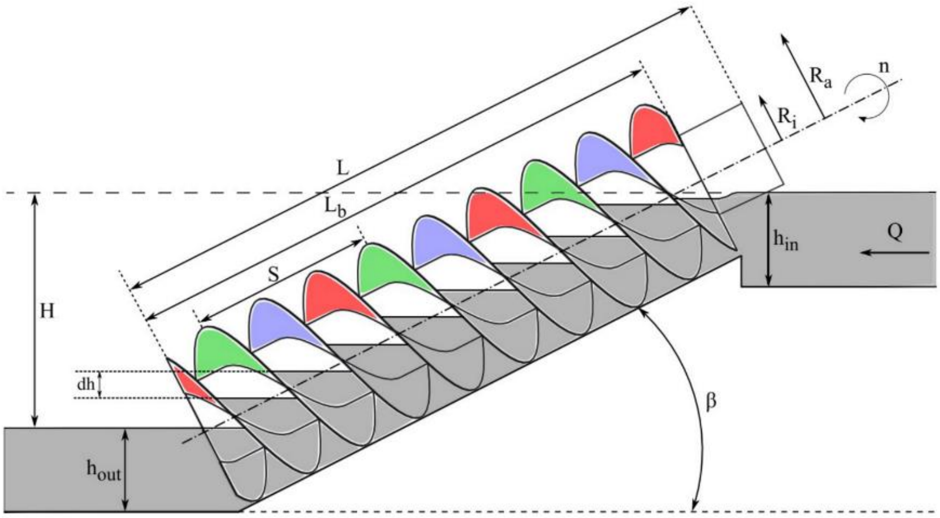


Fig. 2. Illustration of Archimedes turbine [30]

A well-optimized screw design enhances water flow regulation, minimizes energy losses, and reduces leakage between the screw blades and the trough [31]. The pitch affects the volume of water transported per rotation, while the diameter and length determine the turbine's capacity and structural stability. Additionally, the inclination angle influences both efficiency and flow rate, as improper angles can lead to excessive turbulence or inefficient water displacement [32].

The relationship between screw geometry and energy conversion efficiency is essential for maximizing turbine performance. An adequately designed screw ensures optimal interaction between water flow and blade movement, reducing friction losses and maximizing mechanical power output. Engineers can significantly improve AST efficiency by refining these design parameters, making it a more viable solution for sustainable energy generation. Table 2 shows factors influencing the performance of Archimedes screw turbines.

Table 2
Factors influencing the performance of Archimedes screw turbines [30-32]

Factor	Influence on performance
Pitch	Determines the volume of water transported per rotation; affects flow regulation and energy conversion efficiency.
Diameter	Impacts the turbine's capacity and structural stability; larger diameters increase energy capture but may require more substantial support structures.
Length	It affects the overall efficiency and water retention time; longer screws can enhance power generation but increase mechanical losses.
Inclination angle	Controls the balance between efficiency and flow rate; incorrect angles can lead to turbulence or inefficient water displacement.

4. Research Model for Archimedes Screw Turbine Design

The optimization of the Archimedes Wind Turbine (AWT) sophistication of genetic algorithms with ANSYS software was carried out by Omid Salah Samiani and Mehrdad Boroushaki [33]. AWT's unique design requires a different approach than that of conventional wind turbines. Performance evaluation through them was done using Computational Fluid Dynamics (CFD) based on SST k-ω consideration to the extent that the findings showed validation of 5.9% Mean Absolute Error (MAE). After modifications to key parameters of the opening angle, pitches, and rotational speed, an optimal design was decided with an opening angle of 63.49°, Tip Speed Ratio (TSR) of 1.12, pitch1 of 115.03

mm, and pitch2 of 389.54 mm, resulting in increased efficiency by 27.72% and a decrease in thrust force by 7.94% [33]. Figure 3 illustrates the optimized turbine geometry, confirming the effectiveness of GA in improving AWT performance.

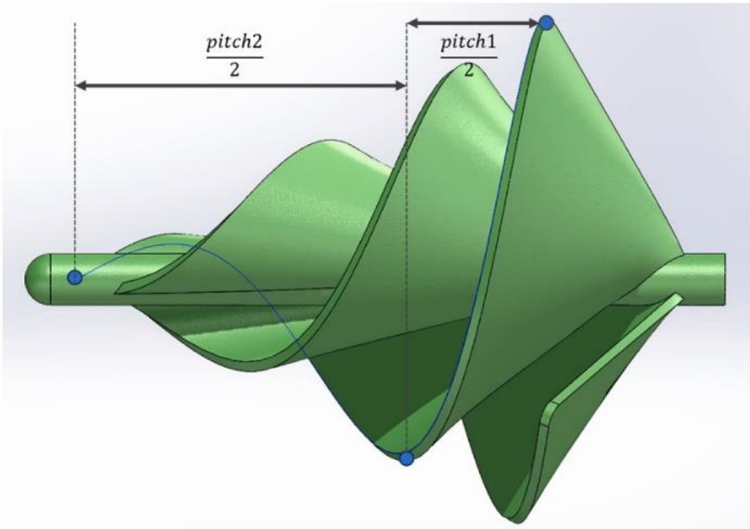


Fig. 3. Geometry of the spiral shape of the blade by [33]

Files related to the experimental and computational analysis of Archimedean screws were delivered after every improvement. Shahverdi [25], thus, developed predictive modeling for the Response Surface Methodology (RSM) based enhancement of the Archimedes Screw Turbine (AST) performance. The various factors, such as the outer diameter of the screw, number of blades, angle of inclination, speed of rotation, available head, and flow rate, were analyzed and found to have a significant influence on efficiency. It was also found that mechanical power and efficiency improved in this region as the rotation speed increased from 5 rad/s to 10 rad/s. However, past this, significant friction losses began, and thereafter, efficiency dropped. At the lower end of rotation speeds, power loss caused by overfilling was predominant. Comparisons between simulated and experimental data showed a high level of agreement, with prediction errors being low from 0.15% to 4.75% [25]. Figure 2 shows the turbine's detailed mechanical efficiency and speed [25].

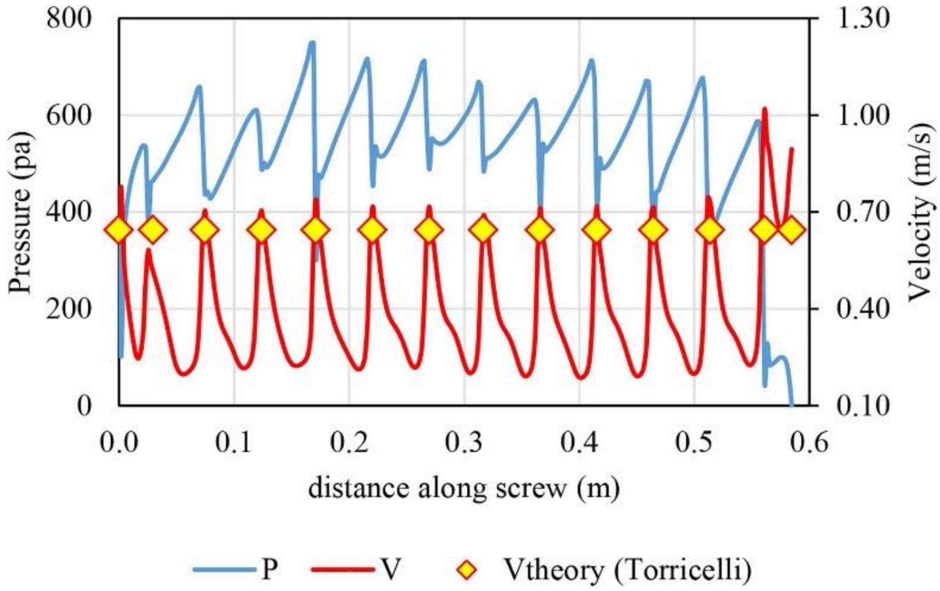
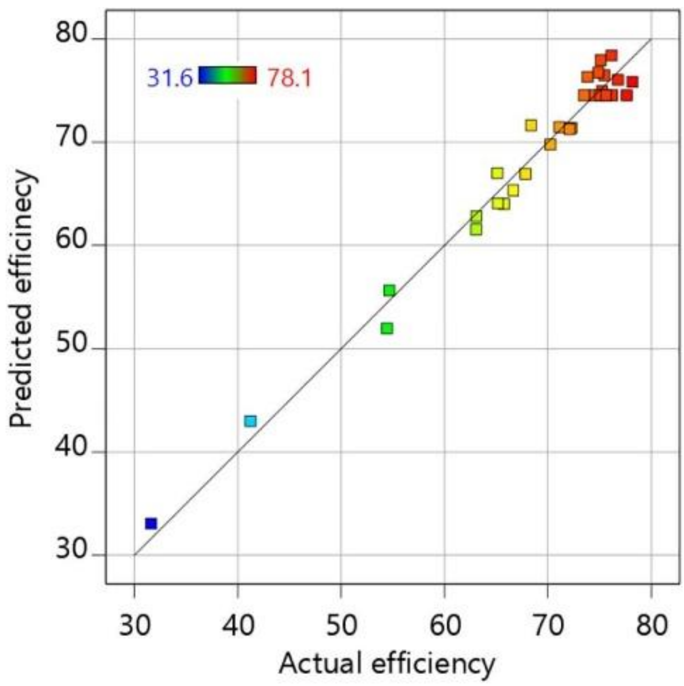
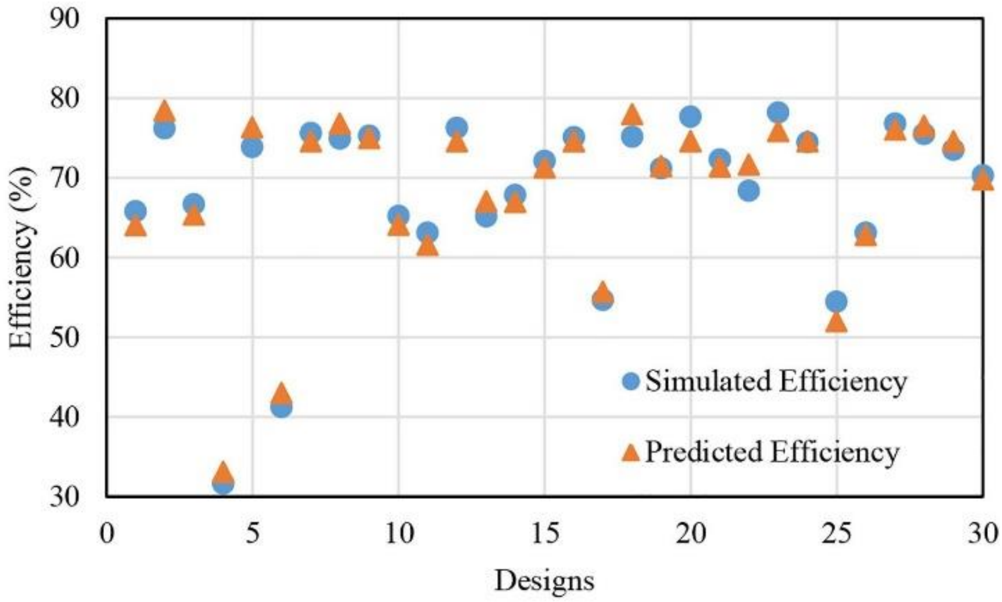


Fig. 4. Graph of mechanical, efficiency, and rotation speed turbine by [25]

According to Shahverdi, the leaky nature of the gap formed between the screw blades and the trough is one of the chief contributors to power loss in ASTs. This region's pressure and fluid velocity distributions were analyzed to understand their effects on performance. Theoretical models often use the Torricelli equation to estimate the gap leakage and determine the velocity of the fluid. Concerning the operational data obtained, an efficiency analysis revealed that practically, the efficiency of an AST lies between 50% and 89%. This shows the significance of optimizing rotation speed and minimizing leakage losses for better turbine performance, which offers perspective on real applications of ASTs. Figure 3 shows the detailed efficiency of the design [25].



(a)



(b)

Fig. 5. (a) Comparison between predicted efficiency and actual efficiency, (b) Predicted efficiency and actual efficiency compared to design quantities by [25]

This research investigated the influence of fluid viscosity on the performance of a labyrinth screw pump through effective numerical simulation corroborated by experimental data by Xin *et al.,* [34]. They found that the interaction between the stator and rotor significantly affects the pump efficiency by optimizing the structural parameters based on the response surface methodology, neural networks, and multi-objective genetic algorithm. The optimization results give an increase in efficiency by 13.55% and head by 19.53% at a viscosity of 133 cp, which indicates a vital design optimization in boosting the performance of an improved labyrinth screw pump [34]. And table 3 is an alternative research design model of the Archimedes screw turbine.

Table 3
Other research models and optimization of Archimedes screw turbine design

Author name	Paper title	Research aspect	Key findings	Result	Reference
Bouvant *et al.,*	Design optimization of an Archimedes screw turbine for hydrokinetic applications using the response surface methodology	Performance evaluation of an Archimedes screw turbine in hydrokinetic applications using the response surface methodology	Design parameters such as inner and outer diameter, shaft length, blade inclination angle, and blade pitch were optimized to maximize the power coefficient (CP)	Optimization led to a significant increase in the turbine's power coefficient	[2]
Vipin Uniyal, Ashish Karn, and Varun Pratap Singh	Parametric Optimization of Archimedes Screw Turbine by Response Surface Methodology and Artificial Neural Networks	The Optimum Performance of an Archimedes Screw Turbine with Response Surface Methodology (RSM) and Artificial Neural Networks (ANN)	Power output was optimized for the flow rate and inclination angle as maximized by an ANN when compared with an RSM in terms of being comparatively more accurate in predicting optimization.	Maximum power output reached 204.16 W (RSM) with a flow rate of 14.58 lps and 36.23º and 187.24 W (ANN) when input at 13.82 lps and 34.15º. ANN had a higher R^2 (0.9842) than RSM with 0.9718	[35]
Shahverdi *et al.,*	Numerical Optimization Study of Archimedes Screw Turbine (AST): A case study	Numerical simulation of AST with variations in turbine length, number of blades, and pitch angle to determine optimal configuration	The study found that a turbine with a single blade, 6-meter length, and 20° inclination angle achieved the highest efficiency	The maximum efficiency achieved was 90.83%	[28]
Kandi *et al.,*	Study and design of Archimedes screw turbine for micro hydro power generation	Archimedes screw turbine design for micro-hydro power generation with different blade configurations	Analysis showed that a three-blade configuration provides an optimal balance between performance and hydrodynamic design	A three-blade turbine is recommended for micro-hydro power generation sites	[36]

5. Recent Innovations in Archimedes Screw Turbine Design

Technology in Archimedes introduces different improvements, as presented in Table 4. These are emerging materials and better and more sustainable manufacturing processes. The high-strength composite and anti-corrosion alloys of nano-coatings are improving the durability and performance of turbines. Moreover, the use of recycled plastics and hybrid structures allows the balance between robust components, flexible components, and sustainability concerning the design of Archimedes screw turbines.

Table 4
Archimedes technology advancements

Aspect	Recent advancements	Reference
Composite Materials	Integrating high-strength composite materials, such as fiberglass-reinforced polymers and carbon fiber, improves durability, reduces weight, and enhances corrosion resistance.	[30]
Sustainable Manufacturing	Development of advanced stainless steel and aluminum alloys with improved anti-corrosion properties for prolonged operational life in harsh water environments.	[37]
Design Optimization	Applying nano-coatings and specialized polymer layers minimizes friction, prevents biofouling, and enhances wear resistance in turbine components.	[38]
Manufacturing Techniques	Utilization of recycled plastics and bio-based composites to create environmentally friendly turbine blades, reducing ecological impact while maintaining structural integrity.	[39]
Hybrid Material Structures	Combination of metal frameworks with composite overlays to achieve an optimal balance between strength, flexibility, and manufacturability in Archimedes screw turbines.	[39]

The Archimedes screw turbine has emerged as a promising technology for utilizing water for electricity generation in rural places. As per Iman *et al.,* [40], in Curug Cibingbin, Sukamandi Village, Subang, West Java; this turbine was put in place to convert the waterfall's flow into electrical energy and generate 37.3 Watts even at the lowest water discharges. The energy generated is used to light the immediate area, thus increasing safety and comfort during the night visit. Meanwhile, Febriani *et al.,* [41] Noted that in Kalisidi Village Central Java, Archimedes screw turbine was adapted into an irrigation channel for a Micro-Hydro Power Plant. The reading maximum voltage stands at 40V, while power output under board records 5 Watts, thus leading up to generating electricity that would be mainly used to provide illumination around the water gate to "lighten" the work environment for the field irrigation personnel, as well as those who live in these villages. Indeed, these now manifest how efficient the Archimedes screw turbine can be with varied flowing water conditions-whether by way of waterfalls, irrigation channels, or so on-as well as hold the feasibility of incorporating this clever innovation into the home-renewable, sustainable energy solution for off-grid areas.

6. Challenges and Opportunities

6.1 Challenges in Optimizing Screw Design for Various Environments

This is quite a fact that Archimedes screw turbine yield performance depends on environmental factors such as water head, flow velocity, sediment characteristics, and aquatic biodiversity found in the installation site [25]. Optimization of screw design becomes inevitable with site-specific conditions. These include inclination angle, number of blades, pitch, and screw diameter, which require careful calibrations between these parameters to maximize energy conversion while minimizing ecological effects [42].

Thus, in addition to other sources of turbulence, leakage losses between screw blades and troughs significantly reduce overall efficiencies [43]. In some environments, coupled with aquatic organisms and suspended sediments, friction worsens and accelerates material deterioration through erosion and corrosion. Hence, the primary challenge in the long-term viability of Archimedes screw turbines becomes the choosing of high-performance materials with superior resistance properties against wear and hydrodynamic forces [44].

6.2 Economic Factors Influencing the Adoption of Archimedes Turbine

The widespread pandemic use of Archimedes screw turbines for sustainable energy, however, is precluded on economic grounds [45]. Initial expenditures in the turbines' design, manufacture, and installation may become an insurmountable barrier, particularly with small rural electrification projects. The infrastructural costs associated with power transmission and storage systems, in this case, would also increase the overall investment needed for deployment [46].

Government policies on renewable energy, incentives, and subsidies weigh highly against the feasibility of these Archimedes screw projects [47]. The economic viability of these turbines in areas with limited financial aid for hydropower may be inhibited by competition from solar photovoltaic and wind technologies, which may frequently benefit from reduced material costs and much larger deployment options [48]. Nonetheless, it is paramount that the actual outlook on financing, which may have a bearing on the adoption of Archimedes screw turbines, is assessed. An overview of the significant economic constraints affecting the viability and implementation of these turbines in rural and small projects is provided in Table 5.

Table 5
Economic factors influencing the adoption of Archimedes turbines [49,50]

Economic factor	Impact on the adoption of Archimedes turbine
High Initial Costs	The initial investment in the design, manufacturing, and installation of Archimedes turbines can be a significant barrier, especially for small-scale rural electrification projects.
Additional Infrastructure Costs	The need for power transmission and storage systems increases the overall investment, further exacerbating financial challenges for implementation.
Government Policies and Incentives	The lack of subsidies or incentives for hydropower may hinder the competitiveness of Archimedes turbines compared to other renewable energy sources such as solar and wind.
Competition with Other Technologies	Archimedes turbines face intense competition from solar photovoltaic and wind energy, which often benefit from lower material costs and broader deployment options.
Access to Funding and Investment	Regions with limited financial support for renewable energy may struggle to fund Archimedes turbine projects compared to other well-established energy solutions.

Although AST holds excellent potential for providing renewable energy in remote areas, economic barriers remain a primary challenge to its adoption. High initial installation costs and the lack of government incentives are major obstacles [49]. AST has a more extended payback period than other technologies like solar panels. However, some countries have begun offering subsidies and tax incentives to enhance AST’s competitiveness in the renewable energy market [49].

6.3 Sosio-environmental Impact

Implementing AST can provide significant social and environmental benefits, particularly in rural communities. AST has proven to be more environmentally friendly than conventional turbines as it does not cause substantial disruptions to aquatic ecosystems [44]. However, some social challenges exist, such as aesthetic impacts and potential conflicts with local water usage. A study in Japan found that community acceptance of AST was higher when the project was combined with education programs and community engagement [44].

6.4 Opportunities for Future Research and Development

Further research and technology enhancement is necessary to improve the efficiency and cost-effective aspect of Archimedes screw turbines. One emerging field is the development of advanced composite materials that promise increased durability, lowered weight, and improved corrosion resistance [51]. Materials like carbon-fiber-reinforced polymers and water-resistant aluminum alloys could significantly extend the operational life of these turbines, with a concurrent decrease in maintenance costs [49,52].

The application of innovative manufacturing methods, such as 3D printing of screw components, would also make it possible to manufacture more complex designs and aerodynamic configurations, aiding energy conversion efficiency [53]. Moreover, the use of intelligent monitoring systems with real-time sensors and AI could serve to improve turbine performance through predictive maintenance and dynamic updates based on changing hydrological conditions [54].

In addition, computational modeling and numerical simulations, in particular Computational Fluid Dynamics (CFD), offer excellent insights into the rather complex interactions between water flow and turbine mechanics [55]. The improvement of these models and the integration of machine-learning algorithms could assist researchers in designing efficient screw geometries that minimize hydraulic losses and maximize power output [56].

7. Conclusion

7.1 Summary of the Key Point

This article has expounded in detail the screw designing in augmenting the efficiency of Archimedes turbines for renewable energy generation. The main variables for this conversion would be diameter, pitch, number of blades, inclination angle, and revolution speed, which substantially impact the hydraulic energy transformation to mechanical energy. Research founded on experimentation and simulation purported to show that the screw designs improve energy efficiency, as well as expand the operational scope of the turbines in low-head sites where conventional hydroelectric technologies fail. Archimedes turbines have, therefore, become an attractive proposition for renewable energy because they are also really easy to install, involve very low running costs, and have the least environmental damage.

7.2 Significance of Screw Design in Realizing the Potential of Archimedes Turbine

The screw design is primarily responsible for exploiting the Archimedes turbines as a green energy solution. Optimization of the screw geometry results in not only improved energy efficiency but also the operation of these turbines in diverse environmental conditions while keeping ecology intact. Water leakage between screw blades and the trough, turbulence, and friction need to be dealt with; an approximation made through a perfect design should convert the energy optimally.

With technology advancing, approaches such as Computational Fluid Dynamics (CFD), artificial intelligence (AI), and newer high-strength composite and anti-corrosion coating have increased turbine performance. So, one of the things that must be continuously innovated in screw designs is making Archimedes Turbines even better and much more affordable with time.

7.3 Future Development Opportunities

To encourage the wider uptake of Archimedes Turbines, further studies are needed to be carried out in areas such as:

- Materials and Manufacturing: Corrosion-resistant materials and optimum production methods like 3D printing.
- Optimization of Screw Geometry: With the help of AI-simulated optimization to achieve best designs that minimize leakage but maximize efficiency.
- Interconnection with Other Renewable Energy Systems: Interconnecting Archimedes Turbines with other renewables like solar energy or energy storage for system reliability enhancement.

In short, any further advancement in the Archimedean Turbine design will vigorously promote adopting such technology as an effective, ecologically friendly, and sustainable renewable energy source, especially for low-head sites and areas with limited infrastructure.

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