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Innovations in Toroidal Propellers and Ultra-Low-Head Turbines: Applications, Performance, and Future Prospects

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Abstract

This study examines recent developments in toroidal propellers and ultra-low-head turbines for sustainable hydropower applications. Traditional turbines often face limitations in low-head environments because of reduced efficiency and the need for large infrastructure. Ultra-low-head turbines, including cross-flow, Archimedes screw, and gravitational vortex models, offer better adaptability and performance under such conditions. At the same time, toroidal propellers, with their continuous ring-like structure, reduce energy loss from tip vortices help prevent cavitation. These propellers were first used in air and marine systems but now show promise for hydropower due to their quiet and efficient operation. By reviewing findings from computer simulations, laboratory experiments, and manufacturer data, this paper explores the combined use of toroidal propellers and ultra-low-head turbines. The evidence suggests that integrating these technologies can increase efficiency and reduce environmental impacts in small-scale and decentralized systems. Future research should focus on real-world testing, improved material strength, and data-based performance monitoring. Together, these innovations may support the expansion of clean and accessible hydropower in both developed and developing regions.

Keywords: toroidal propellers, ultra-low-head turbines, vortex dynamics, computational fluid dynamics, noise reduction

1. Introduction

The global growth of renewable energy over recent decades reflects a major transformation in power generation, emphasizing a shift toward sustainable energy systems. As reported by the International Renewable Energy Agency (2022), renewable energy capacity has more than doubled since 2010, demonstrating its increasing viability and widespread adoption. Hydropower, a seasoned and mature renewable energy form, continues to play a crucial role, especially in geographies blessed with plentiful water resources (Rahman et al., 2022). Advancements in technology, coupled with an enhanced understanding of environmental considerations, have significantly contributed to the evolution of more sustainable practices within the hydropower sector (Hassan et al., 2023). However, conventional hydropower technologies often rely on large-scale infrastructure and substantial hydraulic heads, posing significant challenges in terms of environmental impact, social acceptability, and geographic limitations. To address these issues, the focus has shifted toward innovative solutions that optimize energy capture in distributed and low-energy-density environments, particularly through advancements in turbine and propeller technologies. Among these, ultra-low-head (ULH) turbines and toroidal propellers have emerged as transformative innovations, redefining the potential for efficient, adaptable, and sustainable energy systems.

Turbines are the core of hydropower systems, converting the kinetic and potential energy of water into mechanical and electrical power. Conventional designs such as Kaplan, Francis, and Pelton turbines dominate the hydropower landscape, with Kaplan turbines excelling in low-head conditions due to their adjustable blade geometry. However, when hydraulic heads fall below 3 meters characteristic of ULH scenarios their performance diminishes, necessitating alternative designs tailored for such applications (Zhou & Deng, 2017). ULH turbines address these challenges by leveraging simplicity, adaptability, and enhanced efficiency under low-flow and low-head conditions. Notable advancements include cross-flow turbines, which maintain efficiency across varying loads, and Archimedes screw turbines, celebrated for their fish-friendly operation and minimal environmental footprint (Li et al., 2019; Picone et al., 2023).

ULH turbine technologies are well-suited for distributed energy generation, particularly in settings such as irrigation canals, wastewater treatment facilities, and urban water networks. These systems often integrate modular designs and innovative configurations, such as siphon-based turbines and inline hydroelectric generators, to minimize structural complexity and installation costs (Li et al., 2019). For instance, cross-flow turbines have been adapted for semi-submerged operations, enhancing their utility in tidal streams and wastewater systems where consistent energy recovery is critical (Zhou & Deng, 2017). These innovations demonstrate the growing potential of ULH turbines to unlock underutilized energy resources in both urban and rural contexts.

Despite these advances, ULH turbines face persistent challenges, including reduced efficiency at extremely low heads and vulnerability to sedimentation. To overcome these obstacles, research has increasingly focused on hybrid systems and advanced designs that optimize flow dynamics. In this regard, toroidal propellers have emerged as a complementary technology with the potential to revolutionize turbine applications.

Toroidal propellers, characterized by their continuous, closed-loop geometry, represent a significant departure from traditional blade designs. Unlike conventional propellers, which suffer from tip vortex losses and drag, toroidal designs eliminate blade tips entirely, thereby reducing energy losses and noise emissions. Originally conceptualized for aerial vehicles and drone propulsion, toroidal propellers are now gaining attention for their potential in aquatic and hydropower applications (Hassan et al., 2023; Davis, 2024). Their superior aerodynamic and hydrodynamic properties make them highly efficient in environments with low energy densities, such as ULH hydropower sites (Viollet, 2024).

Computational fluid dynamics (CFD) studies reveal that toroidal propellers achieve higher thrust efficiency and lower turbulence compared to traditional propeller designs (Li et al., 2019; Viollet, 2024). This makes them particularly suited for integration into ULH turbine systems, where optimizing energy conversion efficiency is critical. Their closed-loop structure also mitigates cavitation risks, a common issue in conventional turbines operating under fluctuating flow conditions. Furthermore, their low-noise operation and reduced ecological impact align with the goals of sustainable hydropower development, particularly in ecologically sensitive regions (Zhou & Deng, 2017).

Toroidal propellers' scalability and adaptability further justify their integration into hydropower systems. Their structural simplicity enables cost-effective manufacturing, while their modular nature allows for deployment across diverse scales and settings. From small-scale installations in agricultural canals to larger systems in urban wastewater networks, toroidal propellers offer a versatile solution for energy generation. Moreover, their ability to function effectively in hybrid systems combining hydro-kinetic turbines and ULH setups opens new possibilities for decentralized and distributed energy generation (Li et al., 2019).

The integration of toroidal propellers with advanced turbine systems offers a unique opportunity to redefine the hydropower landscape. These technologies have already demonstrated their potential in diverse applications, ranging from energy recovery in industrial water systems to power generation in tidal streams and wastewater treatment plants. Their ability to operate efficiently in challenging conditions, such as low flow velocities and minimal hydraulic heads, makes them a critical component of future energy strategies aimed at maximizing resource utilization while minimizing environmental impact (Li et al., 2019; Picone et al., 2023).

Despite extensive research on ULH turbines, the application of toroidal turbines in hydraulic systems remains virtually unexplored. While widely studied in drone, marine, and wind applications, their potential in ULH hydropower where efficiency, cavitation control, and modularity are critical has not been systematically assessed. This review addresses that gap by synthesizing cross-sector findings and proposing their integration into sustainable, low-head hydropower systems. Future research must focus on optimizing the performance of toroidal propellers and ULH turbines in integrated systems. Areas of interest include material innovations to enhance durability and corrosion resistance (Khan et al., 2009; Wei et al., 2024), advanced CFD modeling to refine flow dynamics (Viollet, 2024; Wei et al., 2024), and field trials to validate performance under real-world conditions. Additionally, the development of modular and scalable systems will be crucial for expanding their applicability to both developed and developing regions. These efforts will not only advance the state of hydropower technology but also contribute to global efforts toward achieving energy equity and sustainability (Picone et al., 2023; Zhou & Deng, 2017).

2. Literature Review

The reviewed articles highlight significant advancements in toroidal propellers and ultra-low-head turbine designs, showcasing their potential to redefine renewable energy technologies. Future research should focus on scalability, advanced materials, and hybrid systems integration to maximize their applications in both energy and propulsion sectors. These innovations promise to enhance efficiency, reduce environmental impacts, and support the global transition toward sustainable energy solutions.

Table 1: Table of turbine technologies

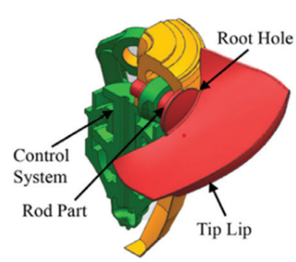
SN	Reference	Focus Area	Key Findings	Future Directions
1	(Sritram & Suntivarakorn, 2017)	Efficiency comparison of Water Free Vortex Turbine (WFVT) and Small Undershot Water Wheel (SUWW) at low hydraulic heads (0–0.5 m).	- WFVT achieved higher efficiency (35.92%) and power output (14.5 W) compared to SUWW (13.96%, 7.51 W). - SUWW provided higher torque but lower rotational speed and power output. - WFVT is more suitable for low-head applications due to its ability to maintain higher cycle speed and energy generation.	- Enhance WFVT designs for broader hydraulic head ranges. - Investigate composite materials to further improve turbine performance and durability. - Explore hybrid setups combining WFVT and SUWW for diverse low-head conditions.
2	(Amini et al., 2025)	Integration of machine learning for turbine health monitoring in hydropower plants.	- Developed a physics-informed ML model to predict turbine performance using high-frequency data (51.2 kHz) and SCADA data (10 Hz). - Proposed a Vibration Content Index (VCI) to quantify machine vibration levels based on real-time sensor data. - Used dimensionality reduction techniques (PCA, Autoencoders) to categorize operating conditions into three distinct clusters. - Introduced "Virtual Sensors"—a method to predict high-frequency turbine behavior using SCADA data, eliminating the need for permanent sensor installations.	- Enhance ML models to predict long-term wear and tear in turbines for predictive maintenance. - Integration of toroidal turbine technologies into data-driven performance optimization. - Application of hybrid monitoring frameworks for small-scale decentralized hydropower plants. - Scaling virtual sensors for broader hydropower applications with minimal hardware requirements.
3	(Quaranta et al., 2022)	Design and performance of Very Low Head Turbines (VLHTs), with a focus on ecological behavior and costs.	- VLHTs are highly efficient (up to 91%) and suitable for heads between 1.5 to 4.5 m and flow rates up to 30 m^3/s. - Ecological efficiency: 90% fish survival rate using blade strike models. - VLHTs reduce civil infrastructure costs by 40-50% compared to Kaplan turbines. - Demonstrated adaptability in irrigation canals, navigation locks, and tidal contexts. - Installation payback times range from 4 to 10 years, with costs typically below €5000/kW.	- Investigate the optimal number of blades and axis inclination for efficiency improvements. - Improve blade design for reduced fish mortality using ecological efficiency models. - Explore the use of superhydrophobic coatings for reduced drag and anti-corrosion properties. - Conduct in-depth studies on free-surface flow interactions and trash rack head losses. - Develop scalable designs for variable hydraulic conditions and flow rates.
4	(Wang, Liu, Xia, Wang, & Ye, 2024)	Evaluation of toroidal propeller hydrodynamic performance through numerical simulation, focusing on geometric parameters such as axis span ratios, lateral angles, roll angles, and vertical angles.	- Toroidal propellers exhibit reduced tip vortex losses and increased thrust compared to traditional designs. - The propeller achieves a peak efficiency of 68.12% at an advance coefficient of 1.2. - Larger axis span ratios improve thrust but may decrease efficiency due to increased torque. - Lateral angles up to 50° enhance thrust, but beyond this, efficiency stabilizes or declines. - The roll angle distribution significantly influences blade thickness and angle of attack, affecting performance. - A small vertical angle ($\leq 10°$) is preferable for optimal thrust and efficiency.	- Optimize toroidal propeller geometry to improve efficiency and minimize torque losses. - Experimental validation of numerical models to refine predictions. - Application of CFD and machine learning techniques for advanced propeller shape optimization. - Integration of toroidal propellers in hybrid marine and hydrokinetic energy systems. - Investigation of noise reduction potential and cavitation control for sustainable propulsion applications.

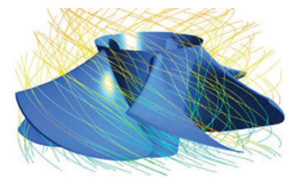
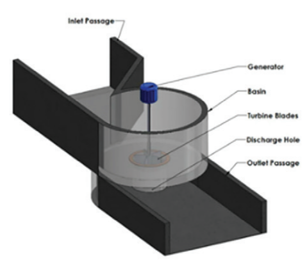
SN	Reference	Focus Area	Key Findings	Future Directions
5	(Xiang & Wang, 2024)	Numerical simulation and analysis of toroidal propeller performance in pump-jet propulsion (PJP) systems for underwater vehicles.	- Toroidal propeller PJP demonstrated a propulsion efficiency of 0.88 at a speed coefficient of 1.2, outperforming conventional propellers. - At 5000 RPM, the toroidal propeller PJP allows submarines to exceed speeds of 60 knots. - Compared to traditional propellers, the toroidal design significantly reduces tip vortex energy loss, leading to better thrust retention. - Hydrodynamic simulations confirm that the toroidal blade design minimizes cavitation, lowering noise emissions and increasing stealth efficiency for underwater applications. - The toroidal propeller exhibits a gradual decay in thrust coefficient, making it suitable for high-speed propulsion at varying advance coefficients.	- Further optimization of toroidal PJP for different operational depths and water conditions. - Experimental validation of cavitation suppression mechanisms in real-world submarine deployments. - Integration of machine learning models to refine blade geometry for optimal performance. - Hybrid applications combining toroidal propeller PJP with renewable energy-driven underwater vehicles. - Development of advanced composite materials to enhance propeller durability and reduce manufacturing costs.
6	(Viollet, 2024)	Historical development of hydroelectricity, including the evolution of turbines, dam technologies, and the role of hydroelectric systems in urban and industrial growth.	- Hydroelectricity emerged in the late 19th century, leveraging advancements in hydraulic technologies and electric generators. - Significant milestones include the development of **Francis turbines** for medium head and **Pelton turbines** for high head applications. - Early adoption linked hydroelectric plants to urban centers (e.g., Niagara Falls) and industries requiring intensive energy, such as aluminum production. - By the 20th century, interconnected hydroelectric systems enabled efficient resource sharing and enhanced reliability. - Hydroelectricity plays a crucial role in energy storage and integration with renewable systems, supporting wind and solar energy.	- Explore the integration of toroidal turbines into modern hydroelectric systems for improved efficiency and noise reduction. - Address challenges related to reservoir management in the context of climate change, including reduced snowmelt and water availability. - Develop smaller, modular hydroelectric solutions tailored for distributed energy systems and low-head sites. - Strengthen governance frameworks to balance hydropower expansion with ecological preservation and community impacts.
7	(Chaulagain, Poudel, & Maharjan, 2023)	Comprehensive review of 38 non-conventional hydropower turbines for ultra-low-head (ULH) applications, emphasizing turbine selection and classification charts.	- Non-conventional turbines are more suitable for hydraulic heads between 0.5 and 3 m. - Developed a turbine selection chart, categorizing turbines based on parameters like flow rate, head, power output, and efficiency. - Identified turbines such as water wheels, Archimedean screws, cross-flow, siphon, and gravitational vortex turbines as optimal for ULH. - Highlighted the environmental benefits of non-conventional turbines, such as fish-friendly designs and minimal civil works.	- Explore advanced material designs for turbine components to enhance performance and durability. - Integrate data-driven optimization techniques for site-specific turbine selection. - Develop modular turbine systems for scalable ULH hydropower solutions. - Establish a global database of ULH turbines with performance benchmarks for better adoption in emerging markets.

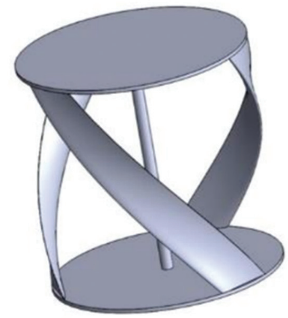
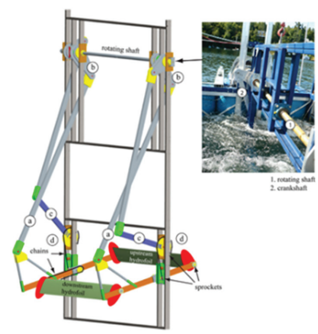
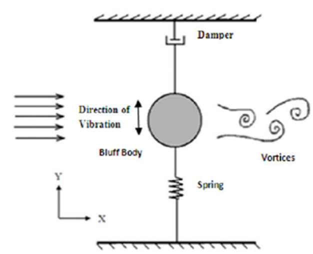
SN	Reference	Focus Area	Key Findings	Future Directions
8	(Alm et al., 2024)	Evaluation of toroidal propeller efficiency and noise reduction in comparison to traditional propeller designs, focusing on drone applications.	- Toroidal propellers reduced tip vortex formation, resulting in quieter operation compared to traditional propellers. - 2-blade toroidal propellers achieved optimal noise reduction (63 dB) but showed slightly lower thrust compared to traditional designs. - 3D-printed toroidal propellers exhibited lower thrust and higher noise than injection-molded counterparts. - CFD simulations confirmed experimental trends, highlighting reduced noise generation due to distributed vortex formation.	- Investigate larger-scale applications of toroidal designs in hydrokinetic energy systems. - Explore advanced manufacturing methods (e.g., metal additive manufacturing) for toroidal propeller production. - Optimize blade geometry for increased thrust without compromising noise reduction. - Extend studies to include diverse fluid environments, such as underwater propulsion systems.
9	(Jansen, 2024)	Evaluation of the aerodynamic and acoustic performance of toroidal propellers compared to traditional UAV propellers through computational fluid dynamics (CFD) and experimental testing.	- Toroidal propellers reduced UAV noise levels by up to 6 dB at 10,000 RPM compared to traditional propellers. - Computational fluid dynamics (CFD) analysis was highly accurate, with less than 5% variation between simulated and experimental thrust values. - Increasing minor axis length improved thrust in two- and three-blade toroidal propellers at 5,000 RPM, but had negligible effects at higher speeds. - Three- and four-blade toroidal propellers matched or exceeded the thrust of conventional propellers at 10,000 RPM. - Resin-based 3D-printed toroidal propellers showed better performance than filament-printed counterparts due to reduced surface roughness.	- Conduct CFD analysis at higher speeds to explore performance scaling for larger UAVs and high-speed applications. - Develop precision-controlled experimental setups with brushless motors and electronic speed controllers for improved accuracy. - Investigate hybrid toroidal propeller designs for enhanced thrust and noise reduction across different UAV applications. - Explore potential integration of toroidal propellers in hydrokinetic turbines for sustainable energy generation.
10	(Fazilati, 2024)	Experimental evaluation of toroidal propellers for UAVs, focusing on thrust performance and noise reduction.	- The toroidal propeller demonstrated superior thrust output compared to conventional three-bladed propellers. - Noise reduction was significant due to the elimination of blade-tip vortices, enhancing UAV stealth capabilities. - Additive manufacturing was successfully used for prototyping, allowing for rapid design iteration and optimization. - Performance measurements indicated that the three-ring toroidal propeller offered the best balance between weight and thrust efficiency. - The toroidal propeller's aerodynamics improved energy efficiency, making it viable for UAV applications requiring extended flight times.	- Explore alternative manufacturing techniques to enhance material strength and aerodynamics. - Investigate the scalability of toroidal propellers for larger UAVs and other aerial applications. - Conduct long-term field testing under real-world conditions to assess durability and reliability. - Optimize blade geometry and weight distribution for further improvements in thrust-to-weight ratio. - Develop hybrid UAV propulsion systems integrating toroidal propellers with electric or hybrid powertrains.

SN	Reference	Focus Area	Key Findings	Future Directions
11	(Xu, Guo, Ye, & Song, 2024)	Evaluation of toroidal propeller hydrodynamic performance through Detached Eddy Simulation (DES) methods, focusing on vortex behavior and pressure distribution.	- Toroidal propellers effectively suppress tip vortex leakage, reducing hydrodynamic noise. - Achieved a peak efficiency of **58.31%** at an advance coefficient of **1.3**. - At high advance coefficients, thrust primarily originates from the back section of the blade. - Transition sections demonstrated susceptibility to erosion due to pressure fluctuations. - Toroidal propellers generate more thrust than tandem propellers but exhibit slightly lower efficiency.	- Optimize blade geometry to improve efficiency while minimizing cavitation risks. - Conduct experimental validations to enhance real-world applicability. - Investigate erosion-resistant materials for transition sections. - Extend numerical studies to marine propulsion and hydrokinetic applications.
12	(Li, Zhao, & Tang, 2019)	Design innovations in composite runner blades for ultra-low-head turbines (ULH).	- Composite materials increased blade durability and efficiency, reducing operational costs. - Optimized blade geometries improved energy capture at low heads. - The use of glass-fiber-reinforced plastics reduced blade weight without compromising strength.	- Develop advanced composite materials for harsher environments. - Apply optimized geometries to other turbine types. - Conduct long-term durability studies in real-world installations.
13	(Khan, Bhuyan, Iqbal, & Quaicoe, 2009)	Review of hydrokinetic energy conversion systems, focusing on horizontal and vertical axis turbines.	- Horizontal axis turbines achieved higher efficiency but required higher flow speeds. - Vertical axis turbines showed better adaptability to low-flow conditions. - Hydrokinetic turbines faced challenges like sedimentation and aquatic life impacts.	- Develop sediment-resistant turbine designs. - Investigate hybrid systems combining horizontal and vertical axis turbines. - Explore modular hydrokinetic systems for off-grid applications.
14	(Wei, Ma, & Guo, 2024)	Noise reduction and aerodynamic performance of toroidal propellers using CFD and experimental validation.	- Noise levels reduced by 19.6 dB(A) compared to traditional designs. - Achieved a 187% increase in lift coefficient due to improved aerodynamics. - Toroidal propellers demonstrated superior performance in higher frequency noise reduction.	- Optimize toroidal designs for scalability in larger UAVs and marine systems. - Investigate advanced materials to improve structural integrity. - Extend research to underwater noise-reduction applications.

Table 2 : Comparative Overview of Conventional and Unconventional Hydropower Turbines

Turbine Type	Flow / Head	Efficiency (%)	Key Feature	Application	Figure	Reference
Pelton Wheel	Impulse / High Head	Up to 95%	Split buckets, high jet deflection	Mountainous high-head sites		(Rai et al., 2019)
Turgo Turbine	Impulse / Med–High Head	Up to 91%	Angled strike, single jet	Medium flow with moderate head		(Benzon et al., 2016)
Francis Turbine	Reaction / Medium Head	Up to 95%	Mixed radial-axial flow, twisted blades	Multipurpose hydropower dams		(Cumbajín et al., 2020)
Kaplan Turbine	Reaction / Low Head	90–93%	Adjustable airfoil blades	Low-head canals, urban rivers		(Zhang et al., 2019)

Turbine Type	Flow / Head	Efficiency (%)	Key Feature	Application	Figure	Reference
Alden Turbine	Reaction / Low Head	Up to 94%	Fish-safe, slow speed blades	Environmentally sensitive zones		(Hogan et al., 2014)
Minimum Gap Runner (MGR)	Reaction / Low Head	Higher than Kaplan	Reduced tip gaps, fish-friendly	Kaplan retrofit, fish passages		(Hogan et al., 2014)
Toroidal Turbine	Reaction / Ultra-Low Head	~58.7% (nascent)	Closed-loop blades, low cavitation	Micro-hydro, new tech testing		(Dhamala et al., 2024)
Gravitational Vortex Turbine	Vortex / Ultra-Low Head	Up to 85%	Swirl basin and central outflow	Rural canals, decentralized hydro		(Maika et al., 2023)
Archimedes Screw Turbine	Gravity / Very Low Head	80–94%	Helical screw, low-speed rotation	Irrigation, fish-friendly applications		(Yoosef Doost & Lubitz, 2020)
Darrieus Hydro Turbine	Hydrokinetic / Very Low Head	≤59.3%	Lift-based rotation, vertical axis	Shallow rivers, estuarine flows		(Vermaak et al., 2014)

Turbine Type	Flow / Head	Efficiency (%)	Key Feature	Application	Figure	Reference
Gorlov Helical Turbine	Hydrokinetic / Very Low Head	~35%	Helical NACA blades, vertical axis	Low-flow sites, easy start-up		(Vijayan & Retnam, 2022)
Oscillating Hydrofoil Turbine	Oscillating / Marine-Tidal	~40%	Lift-based hydrofoil motion to torque	Tidal/marine energy applications		(Kinsey et al., 2011)
VIV Hydro Turbine	Vortex / Low Flow	~52%	Oscillation via vortex shedding around cylinder	Experimental marine, low-velocity flows		(Narendran et al., 2016)

2.1 Operating Range of ULH Turbines from Diverse Manufacturers

Table 3: Table of Turbines from Different Manufacturers

Turbine	Manufacturer/ Supplier	Model	Head (m)	Flow (m^3/s)	Power (kW/ unit)	Efficiency (%)	Reference
ULH Impulse Turbine	Hydrowatt GmbH, Germany	N/A	60–73	N/A	N/A	N/A	(Zhou & Deng, 2017)
Water Wheel	Smith Engineering (GB) Ltd, UK	Kaplan: A, B, R, T, K, S	78–90	2.5–80.0	up to 700.0	64–92	(HydroWatt, 2017)
Screw-based	Jash Engineering Ltd, India	Hydrodynamic Screw	1.0–25.0	2.5–10.0	0.2–60.0	N/A	(Ossberger GmbH & Co. KG, 2012)
Crossflow	Hydro Turbine Technology Energy, Turkey	Through flow	2.0–90.0	1.0–3.0	N/A	N/A	(Voith GmbH, 2021)
Gravitational Water Vortex	ANDRITZ Atro GmbH	2-cell cross flow	0.5–90.0	2.0–6.0	N/A	N/A	(Andritz Hydro, 2019)
Linear	Ossberger GmbH, Germany	Zotloeterer Turbine	3.0–55.0	1.0–10.0	0.5–11.9	N/A	(Clean Power AS, 2013)
ULH Reaction Turbine	Cink Hydro Energy, Czech Republic	Vortex Turbine	1.5–35.0	1.0–10.0	1.0–200.0	N/A	(Mavel, 2015)
Propeller/ Kaplan/Bulb	Zotloeterer Smart Energy Systems, Austria	Hydro Engine: SLH10/ SLH100	1.0–40.0	1.0–10.0	N/A	N/A	(Gugler Water Turbines GmbH, 2019)
Siphon	Turbulent NV, Belgium	Hydro Engine: Linear Pelton	2.0–12.0	2.5–200.0	0.03–3.5	N/A	(Toshiba Energy Systems and Solutions Corporation, 2021)
Very Low-head Open Flume	Natel Energy, Inc., USA	Steff Turbine (Walter Reist)	1.5–6.0	3.0–200.0	0.15–5.0	N/A	(Mavel, 2016)
PAT	Sewaco Limited, UK	Kaplan-Pit, Bulb	1.5–4.5	0.7–3.0	0.5–5.5	N/A	(Lasca Group, 2017)

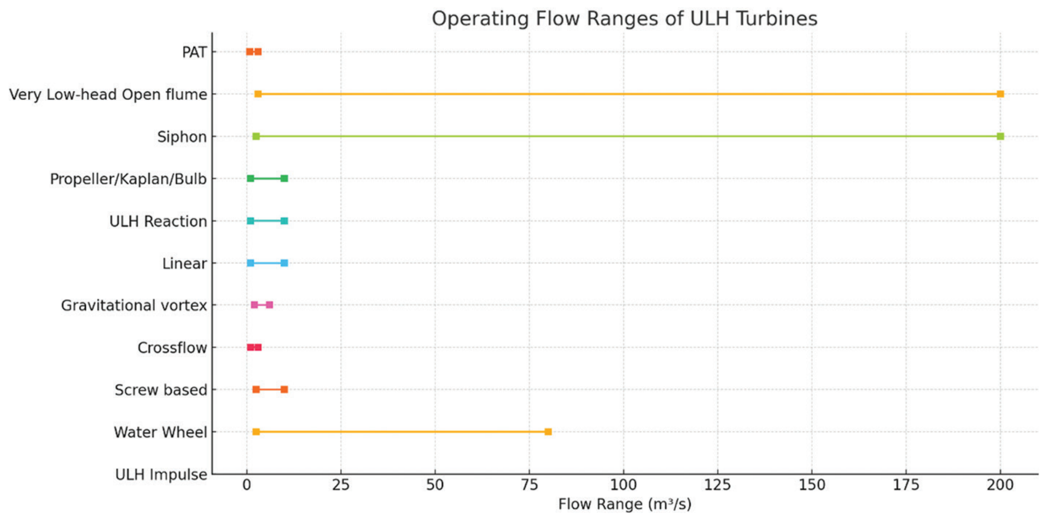


Figure 1: Operating Flow Ranges of ULH Turbines

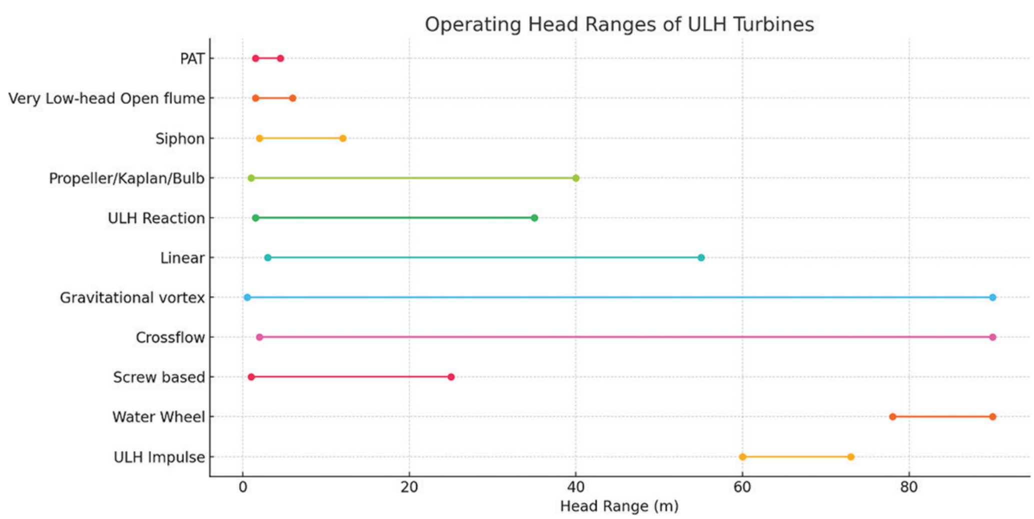


Figure 2: Operating Head Range of ULH Turbines

3. Discussion

This review identifies a notable research gap in the current hydropower literature: although toroidal propellers have demonstrated promising aerodynamic performance in aerial and marine propulsion systems, their application in ultra-low-head (ULH) hydropower contexts has not been systematically examined. Existing studies tend to focus on optimizing conventional turbines such as Kaplan, cross-flow, or Archimedes screw designs for low-head applications, with minimal attention to alternative propeller geometries. As a result, the potential role of toroidal turbines in augmenting the performance and adaptability of ULH hydropower systems remains largely unexplored. This review addresses that gap by synthesizing cross-sectoral findings and proposing a new direction for research and deployment.

Toroidal propellers, characterized by their closed-loop design, are known to suppress tip vortex formation, minimize cavitation, and enhance thrust efficiency, particularly under low energy density conditions. These attributes align closely with the demands of ULH hydropower systems, where low flow velocities and minimal hydraulic heads often constrain performance. When integrated with ULH turbines, toroidal designs could improve energy capture, reduce ecological disturbance, and expand the technical viability of decentralized hydropower, especially in sediment-prone or environmentally sensitive settings. However, the majority of existing performance data on toroidal systems is derived simulations or laboratory experiments conducted in non-hydraulic domains, raising questions about their real-world applicability in hydropower contexts.

To advance this field, further research is required to address critical uncertainties regarding the operational durability, efficiency, and ecological compatibility of toroidal-ULH configurations. This includes the development of erosion-resistant materials, the refinement of fluid-structure interactions through high-resolution numerical modeling, and the implementation of machine learning techniques for real-time performance optimization. Furthermore, pilot-scale field testing across diverse hydrological conditions is essential to establish empirical benchmarks and validate simulation results. The pursuit of scalable, modular designs that are compatible with existing infrastructure and conducive to off-grid deployment will also be crucial for maximizing technological uptake in both developed and developing regions. Overall, these efforts will strengthen the evidence base for incorporating toroidal geometries into future hydropower systems, thereby contributing to broader global goals of sustainable energy access, climate resilience, and technological innovation.

4. Conclusion

This review highlights the promising potential of combining toroidal propellers with ultra-low-head (ULH) turbine technologies to support the next generation of sustainable hydropower systems. Toroidal propellers, characterized by their continuous closed-loop geometry, reduce energy losses associated with tip vortex formation and cavitation, offering quieter and more efficient operation. Their unique hydrodynamic advantages make them well-suited for low-head, low-flow environments where conventional turbines often struggle. ULH turbines, including crossflow, Archimedean screw, and gravitational vortex designs, have already shown significant adaptability in decentralized energy systems across both urban and rural settings. Drawing from computational simulations, experimental research, and industrial case data, this study provides a comprehensive synthesis of their combined potential for distributed hydropower generation.

Despite the encouraging findings, the practical deployment of these innovations remains limited and calls for targeted research. Future work should emphasize real-world testing under variable site conditions, the development of advanced materials to improve resistance to corrosion and erosion, and the application of machine learning techniques to optimize performance and predict operational failures. Addressing these areas will be essential to transform laboratory insights into reliable, scalable technologies. The joint development of toroidal and ULH systems offers a valuable opportunity to expand clean energy access, particularly in underserved regions, and to contribute meaningfully to global efforts in energy equity, ecological protection, and climate resilience.

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