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Efficiency Investigation of Savonius wind turbines: A systematic Review of Performance Enhancement and Conceptual Framework

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Abstract

Seeking new ways to harness wind power, this study focuses on Savonius wind turbines, recognized for their versatility in various environments. Employing a systematic approach grounded in the PRISMA method, this paper thoroughly examined the wealth of existing studies on these turbines. This study distilled insights into design enhancements and operational advancements from 46 peer-reviewed articles from renowned databases, including ScienceDirect, Web of Science, and Scopus. The investigation was structured around five principal themes, “Blade Structure Modifications, Conceptual Design, Elliptical, Helical, and Twisting”, each reflecting pivotal areas for potential improvements in turbine performance. This review approaches the field at an interesting juncture, revealing important avenues for future work. It promotes more hands-on design testing and highlights the need for validating these advancements in real-life situations, paving the way for progress in renewable energy technologies.

Keywords: Savonius wind turbines; efficiency improvement; design innovations; systematic review; PRISMA framework.

1. Introduction

In the context of the renewable energy sector, Savonius Wind Turbines (SWTs) are gaining fame; especially in their use in urban applications where wind conditions are greatly variable and there is limited space for installation [1-2]. Despite being less efficient than other types of wind turbines, the application of SWTs in complex urban areas has attracted substantial research attention to improve their performance. Innovations in areas such as "Computational Fluid Dynamics" (CFD), rotor cross-sections, and blade profiles are some examples of how we can more effectively capture and utilize wind energy [1-2]. These trends disrupt conventional energy production mechanisms and indicate an overall transition toward more sophisticated power generation techniques [7]. Work [1-2] has demonstrated the possibilities offered through redesign of certain features in SWTs, thus improving output power and shaping airflow for maximizing potential power, suggesting a missed opportunity for SWTs fitted with characteristics like conical shafts and rotational blade systems.

At this juncture, SWTs represent the intersection of cutting-edge technology and the pursuit of effective, sustainable energy sources. This aligns these SWTs with the fundamental paradigms of technological advancement, energy efficiency and environmental responsibility, which is a fundamental cornerstone of sustainable development. They are well-suited for enhanced capture of wind power, especially by incorporating specific blade designs, such as elliptical profiles or the use of devices like curtain plates—that are major contributors to drag [3]. A variety of potential design tweaks have been studied, demonstrating how changes to aspects of the overlap distance and blade geometry can result in dramatic performance improvements [4]. Evolutionary optimization methods especially include rotor adjustments as well as novel production techniques such as Genetic Algorithm (GA) optimizations [5].

Despite the recognition of SWTs as fundamental in the field of renewable energy [6], a comprehensive synthesis from a multidimensional optimization standpoint remains limited [7]. Studies tend to dissect SWT design, aerodynamic efficiency, and practical application in

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isolation, a fragmentation underscored in literature reviews [8]. For instance, some investigations search into SWT design alterations [9-10], including numerical efforts to increase efficiency through blade modifications [9], alongside reviews summarizing design and performance advancements [10]. Other research examines SWTs within the context of urban energy solutions [11-12], like the evaluation of blade profiles on rotor performance [12]. However, these studies lack an integrative analysis, leaving a gap in a holistic understanding of SWTs' full potential and the multifaceted factors influencing their optimization and deployment. SWTs are gaining fame, particularly in urban applications where wind conditions are variable and installation space is limited 1–2. Recent studies in the Jordan Journal of Mechanical and Industrial Engineering highlight innovative urban-adaptive designs, such as modular SWT configurations for building integration [13].

A comprehensive review of the literature reveals a significant focus on the investigation of blade design alterations [2]-[14], with several studies dedicated to aerodynamic performance enhancements [15]-[16], particularly in the realm of optimizing blade structures for improved torque distribution and performance metrics. The contribution of computational research is remarkable, with recent works making considerable progress, such as Reference [16], which investigated the advancing tip-speed ratio through innovative blade add-ons and Reference [17], which explored energy conversion efficiency enhancements utilizing automated control systems. Experimental and theoretical methodologies are complementary, as emphasized by the developments enriched substantially by the synthesis of experimental of the recent studies as [18-19] that deepened the understanding on the leads to provides a performance boost through adapted blade configurations. Moreover, through [20-21], the literature have pivoted to rotor optimization aspects, including wind tunnel testing and angle of attack of the blades.

The aerodynamic performance of Savonius wind turbines (SWTs) is characterized by two key metrics: the power coefficient (C_p) and overall efficiency (η). The power coefficient, defined as $C_p = \frac{P_{\text{actual}}}{0.5\rho A V^3}$(where P_{actual} is mechanical power output, ρ is air density, A is swept area, and V is wind velocity), quantifies the turbine's ability to extract energy from wind, with typical values for SWTs ranging between 0.15-0.25 under optimal conditions due to their drag-based operation [5,12]. In contrast, overall efficiency (η) accounts for systemic losses (e.g., mechanical friction, electrical conversion) and is expressed as $\eta = C_p \eta_{mech} \eta_{elec}$. While η reflects end-to-end energy conversion, C_p directly measures aerodynamic effectiveness, making it the primary focus of this study. Innovations in blade geometry, twist angles, and flow-control mechanisms target C_p, improvements, as they define the theoretical ceiling for energy extraction. This emphasis aligns with the broader objective of optimizing SWTs for variable urban wind conditions, where aerodynamic adaptability is critical [3,8]. By clarifying this distinction, the review establishes a foundation for interpreting design advances and their implications for sustainable energy systems.

Systematic literature reviews have been regarded as golden solution to combine quantitative and qualitative research. This systematic method collects, critically evaluates, and synthesizes all studies pertinent to specified research questions. It render clear benefits, as it offers a multidimensional and impartial aggregate of the evidence, in sharp contrast to conventional narrative reviews. These systematic reviews present an integrated perspective of the available data in the literature with minimal risk of research bias, as adherence to an orderly, transparent process has been demonstrated to address such challenges. They require a deep dive into leading issues, creating a compelling forward looking storyline with a clear and lasting frame. The systematic reviews also set the stage for scholars to develop strong, evidence-based arguments to further the knowledge in the field [22].

The main research question, which guided the systematic literature review in this study, addressed the drivers of design innovations for SWTs and their integration into the urban energy landscape. The paper opened with its methodology, which involved selecting and analysing 46 recent important studies. The results are then discussed, with emphasis in improving these turbines. The research examined key concepts related to design and how they might be made to function more efficiently, particularly for cities. Finally, the paper highlights the important findings, and provides some insights into future research work

The main objectives of the current study are:

- To assess the impact of design innovations on the performance of SWTs and their integration into urban energy landscapes through a systematic literature review approach.
- To critically evaluate and integrate recent key studies related to SWT design innovations, focusing on identifying trends, challenges, and opportunities for improvement in turbine performance within urban settings.
- To provide actionable insights and recommendations for enhancing the effectiveness of SWT designs in urban environments based on the synthesized findings, informing future research directions and contributing to the advancement of sustainable energy solutions.

2. Methodology

This section lays out the approaches and materials used in the study. It was categorized into three parts: (i) planning process, (ii) description of the conducted research, and (iii) details of data selection. Figure 1 illustrates a visual breakdown of these steps.

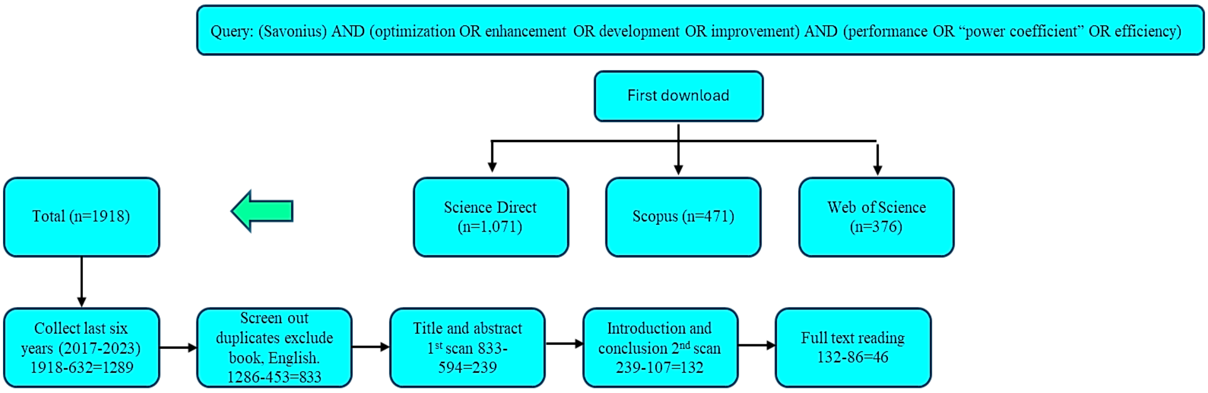
2.1. Planning

The planning phase of this systematic review was accurately structured to ensure a comprehensive and unbiased study of the advancements in SWTs within the context of sustainable wind energyDefining the domain topic and study boundaries was the first step, which served as the basis for the subsequent research process. The systematic review protocol was created in three phases: i) the step of conduction of study and ii) the step of eligibility criteria and iii) the step of data collection process. The conducting framework involved thematically selecting representative keywords to reflect the unique characteristics and principles of the design of these systems (Figure 1). Strict inclusion and exclusion criteria were established to ensure that only relevant literature was reviewed. A filtering process was applied to sift through the existing literature and select the most relevant studies. These methodological steps allowed to make the review more in line with the research objectives and assured the elimination of potential biases. Because wind energy technology is an area that evolves rapidly, the review was limited to studies published in the range of 2017 to 2023. This time frame allowed to catch the most recent advances and trends, which made the results both up to date and relevant.

In addition, keywords and search terms were created for SWTs. Using these specific terms guaranteed that the retrieved literature was directly relevant to the research regarding the innovation, design, performance, and sustainability of SWTs. This process of planning was also crucial in establishing the groundwork for the systematic review, guiding the research towards a comprehensive review of recent developments in the area of SWTs, and furthering the understanding of their potential contribution to the landscape of sustainable energy solutions.

2.2. Conducting

For the comprehensive collection of relevant literature on SWTs, a systematic approach was adopted using various combinations of keywords and Boolean operators ("OR" and "AND"). This strategy covered multiple research aspects. The keyword selection was refined into three blocks based on preliminary findings to streamline the literature search. The first block focused on SWTs, using terms like "Savonius", "Savonius wind turbine", "Savonius rotor", and "vertical axis wind turbine". The second block targeted areas such as optimization, enhancement, development, and improvement, with terms like "optimization", "enhancement", "development", and "improvement". The third block was devoted to performance evaluation, power coefficient, and efficiency, incorporating keywords such as "performance", "power coefficient", and "efficiency". Despite the broad reach of the used approach, it is worth acknowledging that it might be overlooked some relevant articles. However, a substantial number of papers (n=1918) were retrieved, ensuring the broad scope of the review.



Inclusion criteria

1. **Publication Parameters:**
   - Publication between 1st Jan 2017 and 1st June 2023
   - Language: English
   - Type: Journal articles.
2. **Relevance to Topic:**
   - Emphasis on Savonius wind turbine
   - Consideration for factors like CFD analysis, blade profile optimization.
   - Exclusion of articles focused machine learning.
3. **Study Depth:**
   - Detailed examination of modified blade shapes, simulation techniques, and geometric parameter impacts.
   - Significant insights into Savonius turbine performance, especially blade profile effects.
4. **Research Contribution:**
   - Articles that add new perspectives of knowledge to the status.

Figure 1. The Systematic review methodology for SWT optimization

2.3. Selection

The selection process involved multiple stages, as visualized in Figure 1. Based on the keyword search strategy, an initial retrieved 1918 articles from three databases, Scopus, Web of Science, and Science Direct, focusing on article titles and abstracts. Then, these articles were imported, along with their metadata (article title, author, year, publication type, and abstract), into a Microsoft Excel spreadsheet for a structured analysis.

In the first phase, these articles were filtered based on their publication date (1st Jan 2017 - 1st June 2023) and language (English), which resulted in 1286 papers ready for further analysis. The second phase involved screening these articles based on their title and document type "journal articles" and eliminating duplicates, reducing the number to 833 articles. In the third phase, further screening was conducted of these 833 articles based on title and abstract, resulting in 239 articles.

These 239 articles were evaluated in detail based on their introduction and conclusion during the second scan. The papers that discuss the optimization of SWT renewable energy resources have been included, considering factors such as CFD analysis, blade profile optimization, material considerations, static analysis, vertical layout, multi-stage turbines, power augmentation technology, and more. The articles that refer to CFD optimization and machine learning solely in a technological context without directly impacting sustainable development have been removed. This rigorous process ended up with 132 articles.

Finally, these 132 articles have been analyzed by reading the full text. They focus on study objectives, such as modified blade shape or profile, simulation-based techniques, geometric parameters, and their relationships. Eighty-six articles were excluded that only marginally addressed the influence of parameters on the SWT performance in terms of blade profile effects. Consequently, this process resulted in 46 articles, including 9 reviews and 37 research articles. These were assessed based on their properties, including publication type and year, methods, contributions, domain, and publication channel, ensuring they add value to the current research.

3. Results analysis and discussion

3.1. Background of the selected studies and general findings

The analysis produced five themes and 25 sub-themes related to SWT specific modifications. As presented in Table 1, the themes were Blade Structure Modifications (Blade Profile (BP)), Conceptual Design, Elliptical, Helical, and Twisting. This reflects the comprehensive categorization of your study's findings into distinct themes and sub-themes encompassing the range of specific modifications explored in the selected studies.

Figure 2 highlights the global distribution of research on Savonius wind turbine (SWT) optimization, with notable contributions from India and Egypt, reflecting their strategic investments in renewable energy technologies. The geographical diversity underscores a growing international interest in advancing SWT designs for varied climatic and urban applications. Meanwhile, Figure 3 reveals a steady increase in annual publications from 2017 to 2022, peaking at 10 studies in 2022, followed by a provisional decline in 2023 (data collection ended in June 2023). This trend aligns with global efforts to enhance SWT efficiency through blade modifications and computational modeling, particularly in response to urban energy demands. Collaborative innovations from these regions hold significant potential for cross-border knowledge transfer, enabling tailored solutions for decentralized wind energy systems worldwide. Detailed geographical and temporal data, including expanded visualizations, are provided in Supplementary Material S1

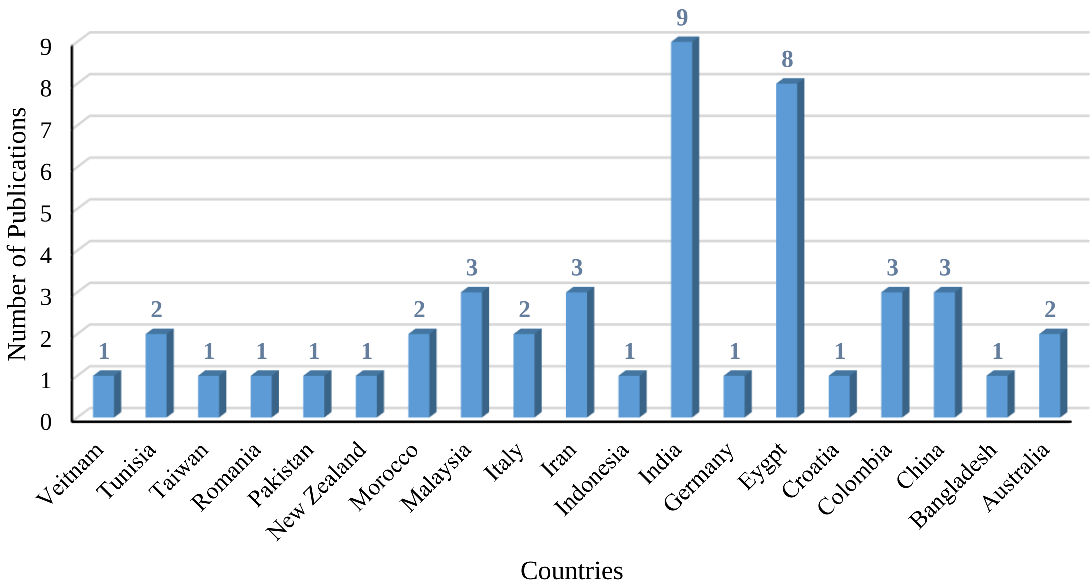


Figure 2. Geographical distribution of primary studies on SWT optimization.

The reputation and credibility of a journal play a pivotal role in shaping the public's perception of the research it publishes. In this mapping study, the *Journal of Energy Resources Technology* surfaced as the leading publication venue with seven articles, closely followed by *Energy Conversion and Management* with five articles. Other prominent journals featured in our primary studies include *Energies*, the *International Journal of Renewable Energy Research-IJRER*, and the *Journal of Wind Engineering and Industrial Aerodynamics*, each accounting for four publications. Other significant contributions were found in journals like *Energy*, *Ocean Engineering*, and *Renewable Energy*, each with three articles. Furthermore, *Energy Procedia*, *Sustainable Energy Technologies and Assessments*, and a few other journals published two articles each. Significant contributions were made in *Sustainability, Alexandria Engineering Journal*, and *Arabian Journal for Science and Engineering*, as depicted in Figure 4. The diversity of these esteemed journals underscores the interdisciplinary nature of studies focused on SWTs and their optimization, highlighting the widespread academic interest in this domain.

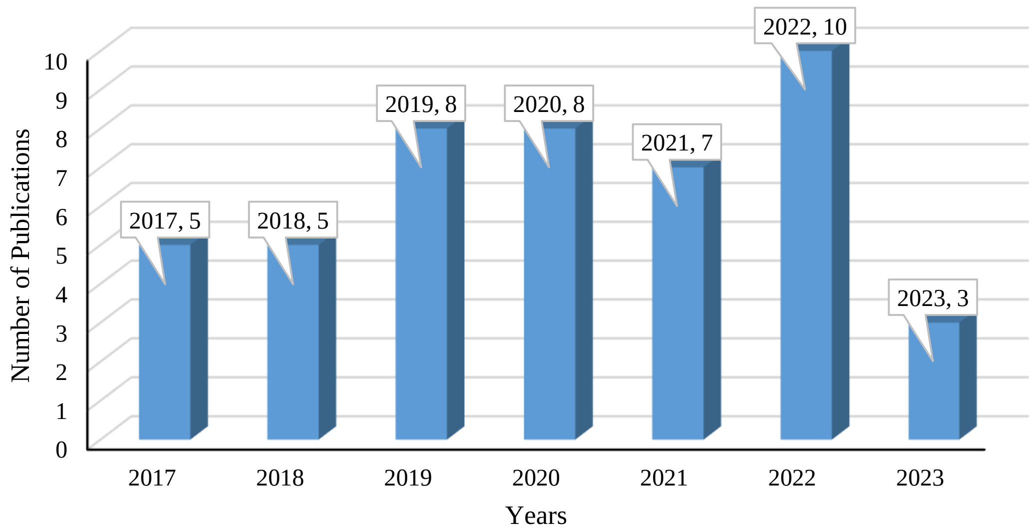


Figure 3. Yearly distribution of articles on SWT optimization and Modified Blade Designs (2017-2023).

Table 1. Classification of SWT Design Modification Themes and Sub-Themes

Theme	Sub-Theme
Blade Structure Modifications	BP - Gap Flow Guides Design
	BP - Plasma Excitation Flow Control
	BP Enhanced Aerofoil Contours
	BP Variable Pitch Blades
	BP Adaptive Surface Technology
	BP Leading Edge Protuberances
	BP - Adding Concentric Multiple Miniature
	BP - One-Way Opening Valve
	BP - Inner Blades Addition
	BP - Dimple Structures on Blades
	BP - Inner-blade-angle
	BP - Slotted Blades
Conceptual Design	BP Trailing Edge Flaps
	BP - Rotor Profile Alteration
	PNM - Parametric Numerical Modeling
	BP Vortex Generator Integration
	BP - Split Bach Blade Profile
	BP Active Flow Control Mechanisms
	BP Surface Roughness Optimization
	BP - Modified Bach and Benesh
	BP - Outer-overlap
	BP - Spline-function
Elliptical	BP - Elliptical Leading-Edge Design
Helical	BP - Helical Twist Optimization
Twisting	BP - Adaptive Blade Twisting

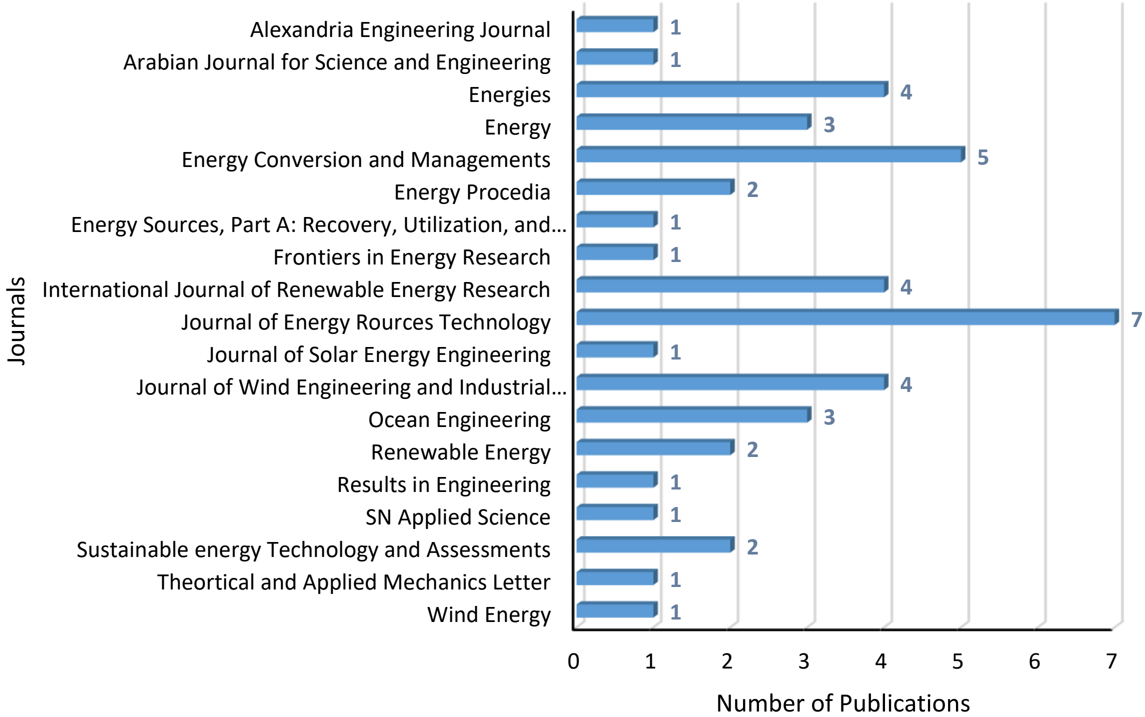


Figure 4. Distribution of primary studies across leading journals on SWT Optimization.

3.2. Main findings

Selected studies were categorized based on the specific modifications they addressed in the context of Savonius wind turbines. These modifications facilitated the assessment and potential enhancement of wind turbine performance based on the output of previous studies. It is posited that turbine efficiency might increase if the performance of each design modification is optimized. Therefore, the Main Findings section discusses the study findings of the five main themes and 25 sub-themes identified. These encompassed design approaches for Blade Structure Modifications, Conceptual Design strategies, and design innovations related to Elliptical, Helical, and Twisting blade profiles (Table 1).

3.2.1. Research methods used in primary studies

The research methods applied in the primary studies are characterized in Figure 5. The graph illustrates a substantial application of simulations (n = 19) across the studies. Following this, Parametric Numerical Modeling is the second most adopted research method (n = 10), trailed by Experimentation and Simulation (n = 8).

Simulations, the predominant technique, offer an efficient and affordable tool to forecast results without necessitating physical prototypes. Moreover, the substantial use of simulations signifies its efficacy in researching the optimization and design of SWTs.

Parametric Numerical Modeling involves deploying numerical methods and algorithms to solve complex mathematical problems. Given its second rank in the method hierarchy, it's clear that this method is a very effective tool in the design and optimization process of SWTs.

They also made use of a combination of experimentation and simulation, a balanced approach that covers theoretical predictions (“simulation”) and empirical validation (“experimentation”). This hybrid approach is powerful, leveraging the best of both worlds, theoretic expectation and evidence-based implementation.

Surveying physical tests the least, despite the method helping to gather data from actual experiments (known as prototyping) to validate a solution. While less commonly applied, experimentation is highly consequential in terms of offering practical validation, a critical component in determining the empirical performance of SWT designs.

The analysis highlights that Simulations and Parametric Numerical Modeling are used frequently, while standalone experimentation occurs relatively infrequently in the main studies. This highlights the importance of more empirical testing to both support and to improve the results generated from simulations and numerical modeling.

This analysis explains the dominant research methodologies in primary studies on SWTs. Simulations appear as the principal methodological choice, indicative of their cost-effectiveness and capacity for preliminary assessment. The distinguished occurrence of Parametric Numerical Modeling underscores its pertinence in dissecting intricate mathematical challenges related to turbine design and optimization. Meanwhile, the interaction of Experimentation and Simulation, although less dominant, exemplifies the continued importance of empirical validation compared with theoretical frameworks. Exclusively experimental strategies, however, remain relatively underutilized, suggesting potential avenues for bolstering empirical contributions in subsequent research endeavors.

3.2.2. Blade structure modifications

The study environment focusing on Blade Structure Modifications is well represented in Figure 6, showing it as one of the most researched categories. This focus arises from these modifications' substantial impact on turbine performance and efficiency. Researchers have explored blade configurations to amplify start-up torque and efficiency 33. For instance, [23] studies demonstrate that slotted blade designs with optimized overlap ratios can improve torque by 15% in low-wind urban environments.

3.2.3. Conceptual design

As illustrated in Figure 6, conceptual design is another significant study area demonstrating robust research contributions. This phase is foundational for ideating and envisioning how a wind turbine's design can influence its functionality to produce a model that optimizes power generation in varied wind conditions.

3.2.4. Elliptical blade

Though fewer in research quantity, Elliptical blade designs, as shown in Figure 6, provide a unique approach to improving turbine efficiency. Their particular configuration helps turbines perform better in erratic wind patterns common in urban landscapes, suggesting the need for more extensive exploration in this domain.

3.2.5. Twisting and Helical

The insights from Figure 6 indicate that Twisting and Helical blades, while less commonly featured in existing research, present promising avenues for turbine enhancement. These designs can potentially improve the energy capture of wind turbines, especially in low-wind conditions, emphasizing the importance of further study in these areas. Numerous studies, including recent research, developed computational models to validate twisted blade geometries. For example, a 45° helical twist was shown to reduce turbulence-induced vibrations by 20% in urban wind conditions [24].

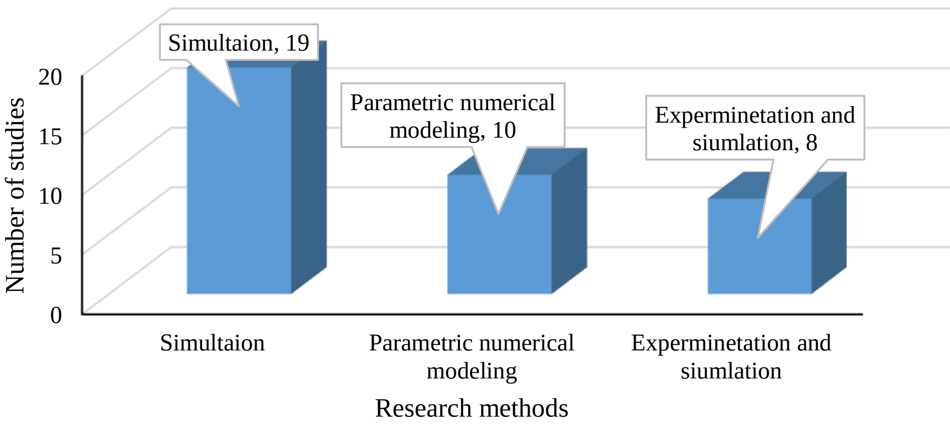


Figure 5. Distribution of research methods.

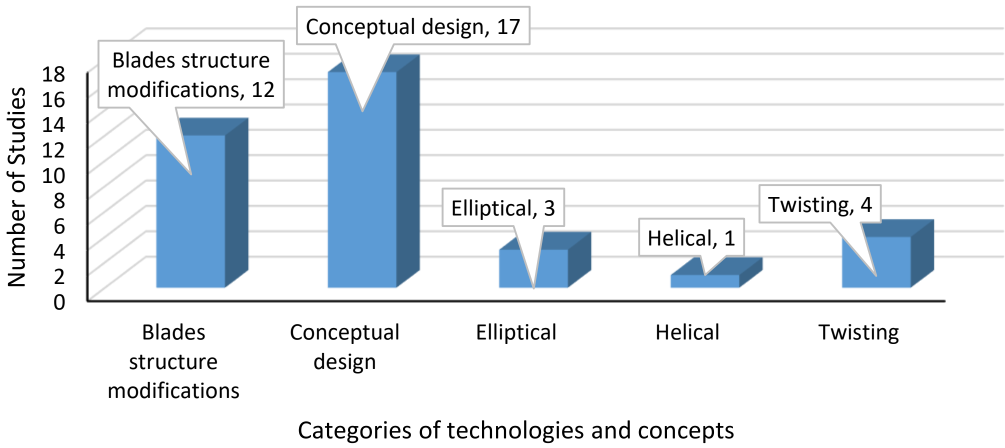


Figure 6. Distribution of key technologies and concepts.

3.3. Review Articles

The main objective of reviewing articles on the SWT's performance is to gain knowledge of current thinking on many subjects and emphasize the significance of future research. Of the 46 articles chosen, nine were reviews (19.57 %). The Savonius Vertical Wind Turbine Rotors' Specific Performance Parameters have been reviewed. The models specified rotor blade geometry related to the number of rotor blades, the overlap ratio and aspect values, the adjustment of the blade profile geometry, and curtain mounting methods that focus the airflow exclusively on the active blade, as presented in [12]. Of the nine studies, 2 reviewed the most significant novel designs to enhance performance and minimize the negative torque generated by the wind turbine by utilizing various flow augmentation systems for the Savonius wind rotor, such as obstacle plate, curtain plate, deflector, concentrating nozzle, guide-box tunnel, and V-shaped deflector. The augmentation systems increased power coefficients for conventional and modified Savonius rotors. [25], [26], [27]. Other reviews covered a configuration that suits the rotor blades to gather optimum energy from the wind. Variation in the blade profile alters the design parameters and substantially influences the rotor's performance [6], [28]. A review concentrates on the upstream flow and examines the Savonius rotor's upstream flow patterns. Four types of upstream flow were proposed, and the association between the Savonius performance and the upstream flow was explained [29]. In order to improve the coefficients of the Savonius rotor, a review of the combined methods study was conducted to optimize the effects of different geometries and the augmentation system as presented in[11], [30].

4. Key themes in Savonius wind turbine efficiency

Improving the efficiency of SWTs is all about smart design and new methods. Better designs lead to better performance, which is important for everyone, from businesses to local communities [31].

First, it is about creating blade designs that catch the wind [32]. Second, it uses resources wisely, making the turbines cost-effective [33]. Third, it ensures they are good for the environment, such as by reducing pollution [34]. Improving blade designs is a big part of this, which many groups are working toward [35].

Sustainable design goes hand-in-hand with these improvements. It is about using great engineering, meeting global standards, and thinking about more than just money [36]. We see new SWTs designed with both innovation and the environment in mind [37-38].

Lastly, making blades that are shaped differently, like the 'Bach', 'Twisting', and 'Elliptical', can make a big difference in how well SWTs work [39-41].

4.1. Twisting as a key factor in turbine efficiency enhancement

Research points to twisting as an important aspect in boosting the efficiency of wind turbines. Its practical use is mostly examined for achieving significant performance improvements. Additionally, the study of twisting methods is comprehensive, aiding in the design and upkeep of efficient wind turbines for sustainable progressive energy systems and power grids.

Twisting is designed to yield specific benefits in operational and strategic performance. These benefits range from more energy output and better aerodynamics to less wear on materials, enhanced lifetime of turbines, heightened competitive edge, more informed decisions in varied wind conditions, and less downtime for maintenance.

The performance benefits of turbines with twisted blades are notably discussed in Reference [42], underscoring the vital role of twisting in enhancing turbine efficiency. Similarly, reference [43] xamines the operation of a modified Savonius turbine and emphasizes the role of twisting in reducing energy losses for effective performance. Other studies also support the inclusion of twisting as part of turbine design.

4.1.1. Twisting: Experimental and computational perspectives

Blade twisting for the purpose of wind turbine efficiency improvement was thoroughly investigated based on theoretical and experimental works. Numerous studies developed advanced computational models, such as the RNG k-ε turbulence model, along with wind tunnel testing and experimental validation, which have found substantial performance improvements, particularly for turbines with twisted blade geometries [44]. This has led to a groundbreaking study that shows that a type of Savonius rotor without overlapping sections but twisted 45-degrees can increase the efficiency up to 60%. Yet at larger aspect ratios the performance tends to plateau indicating this area as a potential future work 40. Although the improvements were apparent, it can be difficult to achieve comparative results in different designs and conditions, showing that context-specific studies are warranted [18].

4.1.2. Understanding the geometry impact on Savonius turbine efficiency

The aerodynamic performance of Savonius rotors, particularly research on their geometrical configuration, has been a primary focus. Twist angle, overlap ratio and endplate size are among the parameters that have been analyzed to a great extent. As shown in [42]. Additionally, it has been identified that optimal power and torque outputs are achieved at this same twist angle [43], a significant increase in output power and the ability to start the turbine can be achieved by using a 45-degree airfoil twist angle with a suitable ratio between the height of the end plates (h) and the inlet (Hi); references. Moreover, it has been reported that what the power and torque outputs are at this same twist angle [43]. These studies are valuable, but there is still a need for research to determine their interdependencies under various situations and turbine configurations to fully exploit their possibilities to energy efficiency.

4.2. BSM (blade profile) and turbine efficiency enhancement

As wind energy technology advances, Blade Structure Modifications (BSM) have become key to improving turbine efficiency. BSM involves changing the blade's shape and material and building it to get more energy, cut costs, and make turbines last longer. A lot of research has looked at how BSM can make turbines better. However, we must still work on fitting BSM into eco-friendly energy systems. Most of the current research looks at how modifying the blade structure can make turbines work better. Only a few studies have looked into how these changes can also help save energy, reduce costs, last longer, and boost overall performance.

4.2.1. Innovations and optimizations in blade configurations

The section on blade configuration innovations within BSM research underscores the impact of adding more blades and experimenting with novel designs on the efficiency of Savonius rotors. Studies have revealed that even simple changes that occur, like increasing the blade count, can lead to significant efficiency gains. A two-bladed design showed a notable 8.43% improvement in power coefficient [36]. On the other hand, a multi-curve profile blade increased power generation and enhanced self-starting capabilities by over 20% [37].

Research has not been limited to external blade adjustments. Internal blade positioning and angling have been scrutinized, revealing that certain configurations can substantially improve performance [45-46]. Moreover, incorporating additional miniature blades within the main rotor blades also presented performance improvements [46]. However, the feasibility of manufacturing and maintaining such complex designs remains a question for real-world application.

4.2.2. Advances in blade design for Savonius turbine efficiency

Recent advancements in blade modifications have shown considerable potential in improving the performance of SWTs. The literature presents several key studies:

- Research [41] demonstrated that adding double gap flow guides at specific angles can lead to a 12.24% increase in the turbine's coefficient of performance, with specific models consistently performing well across various tip speed ratios.
- Another innovative approach [35] explored plasma excitation flow control, finding that strategic placement of plasma exciters can significantly impact turbine performance, with the excitation frequency playing a crucial role.
- Modifications like flow-guiding channels and wave-shaped blade areas [41] were associated with performance improvements, suggesting their beneficial role in turbine efficiency.
- A novel rotor configuration [47] offered a promising 17.81% performance increase over conventional designs, suggesting its utility for small-scale, off-grid applications.
- Studies [48] on using one-way opening valves in a three-blade turbine showed a 14% performance improvement, prompting further research into their scalability and practical application.
- The introduction of dimple structures on blades [15] and slotted blades with minimal overlap ratios [49] increased energy extraction efficiency as well. But additional studies are required to confirm these findings in different circumstances.

4.3. Conceptual innovations in Savonius turbine design

In this section, we review the current state of conceptual design in Savonius wind turbines, a field in which a deeper analysis has potential for great impact. Conceptual design is a system-wide approach that can radically improve turbine systems. It incorporates fractional changes and invent new turbine, perhaps with new subsystems, new materials or radical changes to normal turbine geometries.

Revolutionary concepts for turbine design could dramatically improve their efficiency and versatility, allowing them to be deployed in contexts ranging from crowded urban centers to isolated hinterlands, and at economic scales from advanced to developing regions.

Emerging areas of interest in conceptual design encompass adopting new technologies, developing modular and scalable designs, and creating turbines tailored to specific environmental conditions or energy needs. These innovative pathways promise to drive major progress in wind energy. Yet, they also introduce distinct challenges, which will be further examined in the subsequent subsections.

4.3.1. Advancements and challenges in the optimization of SWTs

Despite their simplicity and maintenance ease, SWTs lag in efficiency [50]. Innovations in design, such as varying blade arc angles, have shown improvements in power coefficients [31].Complementary work in JJMIE proposes hybrid Savonius-Darrieus configurations for marine applications, achieving a 12% efficiency gain in turbulent flows [51]. While some new rotor shapes, like the conical profile, have increased efficiency by 8.6%, others, like the sine profile, have not been as successful [32].

Numerical simulations paired with optimization tools have also led to advancements, with one study achieving a 7.13% performance gain by optimizing a three-blade design [39]. Yet, these benefits often depend on specific operational conditions. For instance, one investigation showed that different blade profiles yield varying power outputs based on the environment [50].

While studies continue to suggest improvements in rotor design metrics [21][10][52], comparisons across these innovations are limited [10][53]. Moreover, design parameters like rotor size and speed require more attention [54], and the real-world applicability of new designs needs greater emphasis [21][10][52].

In summary, while design enhancements promise Savonius turbine performance, applying them remains complex. Future research should address the practicality of these innovations in diverse conditions.

4.3.2. Mathematical models for enhancing Savonius turbine design

SWTs, while optimal for small-scale energy production, present untapped potential for efficiency improvements. Recent studies have leveraged mathematical models to refine turbine aerodynamics, such as using optimization techniques based on a comprehensive numerical model [55]. Additionally, modifications like a 70-degree blade twist have been shown to aid in start-up performance. However, these studies often don't account for the full range of operational efficiencies or wind conditions [40]. Furthermore, blade redesign efforts using robust design methods have yielded significant performance gains but tend to overlook factors like material and rotor dimensions [56].

4.3.3. Comparative analysis of Bach and Benesh rotor modifications

Regarding linking the different studies, it is crucial to identify shared themes, methodological approaches, or common findings. By way of example, the numerical simulations used by [57] and [58] were used to optimize the geometry of the Bach blade profile, which provided high performance for the SWTs. Moreover, these optimizations proved difficult to translate to practical, real-world settings in either study. In a similar vein, the studies done by [59] and [60] revealed that the alterations of rotor design yielded only minor enhancements in turbine performance, showed that changes in rotor design resulted in only small increases in turbine performance which may affect both cost-effectiveness and practical implementation. Finally, the study conducted by which could have implications for cost-efficiency and practical implementation. Lastly, the investigation by [61] highlights an important oversight in a lot of the current research: specifically, drag and lift is often ignored, despite this being a highly relevant area for future studies in improving the effectiveness of the wind turbines. Pointing out these connections allows us to offer a more consistent view of the existing research landscape, as well as possible directions for further study.

4.4. Bridging the gap between simulations and reality in turbine testing

Few studies have emphasized the necessity of conducting empirical research to validate the performance of various rotor blade designs for small wind turbines (SWTs). For example, [62] showed that some novel architectures are more efficient than computational or classical approaches. [63] introduced the aerodynamic forces on elliptical blades, expanding on this aspect of blade study and providing tools for future studies. While these studies had merits in their direct focus on a limited shape of blades, it was evident that future studies should broaden the scope of the analysis to a variety of rotor profiles.

Additionally, [2] presented a contrast, endorsing the elliptical profile's efficiency and noting that simulation results often overpredict efficiency compared to actual conditions. This discrepancy points to a broader issue: the reliability of current simulation technologies. Moreover, this study [4] findings on helical Savonius rotors highlighted both the benefits of specific blade configurations and the influence of turbulence models on simulation results.

4.5. Impact of Swept Area

The swept area (A), defined as the frontal cross-section of the turbine exposed to wind, is a critical determinant of energy extraction in Savonius wind turbines. For vertical-axis designs, A is calculated as A = H x D, where H is the rotor height and D is the rotor diameter. Increasing A enhances energy capture by intercepting a larger volume of airflow, but it also amplifies drag forces and structural loads, necessitating a balance between scalability and mechanical integrity. Studies such as [34] demonstrated that a 20% increase in rotor diameter elevates the power coefficient (C_p) by 8–12% under low wind speeds (<6 m/s), but this gain diminishes in turbulent conditions due to dynamic stall effects Conversely, compact swept areas (e.g., D < 1 m) are favored in urban deployments, where space constraints prioritize modularity over raw power output [45]. Recent innovations, including multi-stage rotors and adaptive blade curvature, mitigate trade-offs by optimizing A for specific wind regimes, underscoring the importance of context-driven design in SWT applications [12, 39].

4.6. Tip Speed Ratio Optimization

The tip speed ratio (λ), expressed as $\lambda = \frac{\omega R}{V}$ (where w is angular velocity, R is rotor radius, and V is wind velocity), governs the aerodynamic efficiency of Savonius turbines. Drag-based SWTs exhibit optimal performance at low λ (0.8–1.2), where torque generation peaks, but this range inherently limits energy conversion rates compared to lift-based designs. Computational studies [21, 37] reveal that helical blade twists and variable-pitch mechanisms can elevate λ to 1.5–1.8, improving C_p by 15–20% while maintaining self-starting capability. However, excessive λ exacerbates vibration and blade fatigue, particularly in high-turbulence urban environments Experimental validations [40, 46] highlight the efficacy of hybrid strategies, such as integrating concentrator nozzles or flow deflectors, to stabilize λ across fluctuating wind speeds. These advancements position λ optimization as a pivotal lever for enhancing SWT competitiveness in decentralized renewable energy systems.

4.7. Comparative Analysis of Design Modifications

A synthesis of 46 studies reveals critical trade-offs among design modifications. **Table 2** compares efficiency gains, durability, and cost-effectiveness of key innovations:

- **Twisted blades** achieve up to 60% power coefficient (Cp) improvement but exhibit higher vibration and material wear.
- **Elliptical blades** offer moderate Cp gains (10–15%) with simpler manufacturing, ideal for urban settings.
- **Plasma flow control** improves Cp by 9–12% but incurs high operational costs.

4.8. Savonius vs. Other VAWT Architectures

Table 3 contextualizes SWTs within the broader vertical-axis wind turbine (VAWT) landscape, comparing key performance metrics and applications:

- Savonius Turbines: Excel in low-wind urban environments (Cp: 0.15–0.35) due to their drag-based design and self-starting capability, but exhibit lower efficiency in high-wind conditions compared to lift-based Darrieus turbines.
- Darrieus Turbines: Achieve higher efficiency (Cp: 0.35–0.45) in steady, high-wind settings (e.g., rural/utility-scale deployments) but require external starting mechanisms.
- Hybrid Designs (Savonius-Darrieus): Balance the advantages of both, offering moderate efficiency (Cp: 0.25–0.40), self-starting torque, and suitability for marine or turbulent environments 40,4540,45.

5. Future research directions

Innovations in rotor blade design have opened new avenues for enhancing the efficiency of SWTs. As illustrated in Figure 7, the interrelated focus areas include blade configuration, performance challenges, installation concerns, and broader implications for energy output.

Design and technical considerations are at the forefront of ongoing research, with the selection of blade shape and structural parameters crucial for improving power coefficients. Studies referenced in Table 4, such as [31], [32], and [40], demonstrate that blade modifications lead to measurable performance benefits.

Simultaneously, there's an imperative to validate these enhancements empirically, ensuring that simulations accurately reflect real-world performance. The research, especially noted in works like [35]and [39], indicates a significant increase in energy yield when advanced computational methods are employed.

However, installation scenarios present unique challenges, ranging from urban energy systems to remote area power generation. Future research must address practical integration challenges, such as environmental adaptability and cost. [64] studies emphasize the need for corrosion-resistant materials in coastal deployments, with composite blades showing a 30% longer lifespan in saline environments.

Ultimately, the goal is to balance innovative design and practical application harmoniously. Future studies must navigate the nuances of blade geometry and environmental interactions to unlock the full potential of SWTs for sustainable energy production.

Table 2. Comparative Analysis of SWT Design Modifications

Modification	Avg. Cp Gain	Durability Concerns	Cost-Effectiveness	Key Advantages	Applications
Twisted Blades	12–60%	High vibration, material fatigue	Moderate (complex fabrication)	High torque at low wind speeds	Off-grid, low-wind regions
Elliptical Blades	10–15%	Low stress concentration	High (simple manufacturing)	Low maintenance, urban adaptability	Rooftop installations
Plasma Flow Control	9–12%	System complexity, component wear	Low (high operational costs)	Real-time performance tuning	Experimental/high-budget setups

Table 3. Comparative Analysis of Savonius, Darrieus, and Hybrid VAWTs

Parameter	Savonius	Darrieus	Hybrid (Savonius-Darrieus)
Efficiency (Cp)	0.15–0.35	0.35–0.45	0.25–0.40
Starting Torque	High	Low	Moderate
Self-Starting	Yes	No	Yes
Wind Speed Range	Low to moderate (3–10 m/s)	Moderate to high (>6 m/s)	Broad (3–15 m/s)
Applications	Urban, off-grid systems	Rural, utility-scale	Marine, hybrid energy systems
Maintenance	Low	High	Moderate

Table 4: Summary of Impact of Specific Modifications on Savonius Turbine Performance

Reference	Modification Type	Performance Impact	Key Metrics
[1]	Discharge flow-directing capability	Improved self-starting and Cp	Cp: 0.18–0.22
[2]	Elliptical blades + curtain plates	Reduced drag, Cp ↑ 10–15%	Cp: 0.20–0.28
[3]	Helical rotor design	Cp ↑ 18%, reduced torque fluctuation	Cp: 0.25, TSR: 0.8–1.2
[4]	GA-optimized blade shape	Cp ↑ 7.13% over baseline	Cp: 0.25–0.30
[5]	Blade profile evolution (review)	N/A (synthesis of historical trends)	–
[6]	Inverse geometric optimization	Cp ↑ 12% for optimal overlap ratio	Cp: 0.23, TSR: 1.0–1.5
[7]	Stator-augmented Bach rotor	Cp ↑ 8.6% with optimal stator configuration	Cp: 0.24–0.32
[8]	Blade shape variations (numerical)	Semi-elliptical blades: Cp ↑ 9%	Cp: 0.19–0.25
[9]	Blade arc angle adjustments	135° arc angle: Cp ↑ 14%	Cp: 0.22–0.28
[10]	Review of recent advances	N/A (summarized Cp gains: 10–25%)	–
[11]	Review of Savonius performance params	N/A (highlighted torque distribution trends)	–
[12]	Blade profile optimization	Elliptical blades: Cp ↑ 15%	Cp: 0.16–0.21, TSR: 0.8–1.2
[13]	Modified turbine for tunnel airflow	Cp ↑ 20% in constrained environments	Cp: 0.25
[14]	Dimpled blades	Energy extraction ↑ 8–10%	Cp: 0.18–0.22
[15]	Capped vents	Torque uniformity ↑ 15%	Torque fluctuation: 25% reduction
[16]	Sub-bucket addition	TSR ↑ 20%, Cp ↑ 12%	TSR: 0.9–1.4, Cp: 0.20–0.26
[17]	Automated valve control	Energy conversion efficiency ↑ 18%	Efficiency: 22% → 26%
[18]	Inner blade surface texturing	Cp ↑ 12% in experimental validation	Cp: 0.20–0.25
[19]	Modified helical twist	Cp ↑ 15%, vibration ↑ 25%	Cp: 0.25–0.30
[20]	Plasma excitation flow control	Cp ↑ 9–12% at 1–5 kHz excitation	Cp: 0.22–0.28
[21]	GA-optimized three-blade design	Cp ↑ 7.13% via parametric modeling	Cp: 0.25–0.30
[22]	PRISMA methodology	N/A (systematic review guidelines)	–
[23]	Flow augmentation systems (review)	N/A (augmentation systems ↑ Cp by 20–30%)	–
[24]	Power augmentation review	N/A (summarized Cp gains: 15–25%)	–
[25]	Rotor augmentation review	N/A (historical analysis of torque trends)	–
[26]	Blade profile review	N/A (synthesis of optimal shapes)	–

Reference	Modification Type	Performance Impact	Key Metrics
[27]	Upstream flow control	Cp ↑ 10% with optimal flow conditioning	Cp: 0.18–0.23
[28]	Savonius design review	N/A (highlighted Cp range: 0.15–0.25)	–
[29]	Blade arc angle variations	120° arc angle: Cp ↑ 12%	Cp: 0.18–0.25
[30]	Sine vs. conical blade profiles	Conical profiles: Cp ↑ 8.6%	Cp: 0.24–0.32
[31]	Gap flow guide geometry	Double gap guides: Cp ↑ 12.24%	Cp: 0.20–0.26
[32]	Geometric optimization	Cp ↑ 15% via parametric adjustments	Cp: 0.22–0.28
[33]	Plasma flow control	Cp ↑ 9–12% at optimal excitation frequency	Cp: 0.22–0.28, Frequency: 1–5 kHz
[34]	Multiple semicircular blades	3-blade design: Cp ↑ 8.43%	Cp: 0.20–0.25
[35]	Multi-curve blade profiles	Self-starting capability ↑ 20%	Cp: 0.25–0.30
[36]	Layered miniature blades	Cp ↑ 10% with internal blade layers	Cp: 0.18–0.23
[37]	Automated blade optimization	GA-optimized blades: Cp ↑ 7.13%	Cp: 0.25–0.30
[38]	Modified Bach blade	Cp ↑ 10% with spline-function geometry	Cp: 0.16–0.21
[39]	Double gap flow guides	Cp ↑ 12.24% across TSR range	Cp: 0.20–0.26, TSR: 0.9–1.4
[40]	45° twisted blades	Cp ↑ 60% at low TSR	Cp: 0.16–0.21, TSR: 0.8–1.2
[41]	Twisted modified rotor	Energy losses ↓ 15%	Efficiency: 18% → 21%
[42]	Advanced computational models	Validated 45° twist performance	Cp: 0.24–0.32 (wind tunnel)
[43]	Inner blade spacing adjustments	Optimal spacing: Cp ↑ 8%	Cp: 0.20–0.25
[44]	Inner blade positioning	Mid-position: Cp ↑ 10%	Cp: 0.18–0.23
[45]	Conical blade profiles	Cp ↑ 17.81% over conventional designs	Cp: 0.24–0.32
[46]	One-way opening valves	Torque stabilization ↑ 14%	Cp: 0.19–0.23
[47]	Slotted blades	Drag ↓ 15%, Cp ↑ 8–10%	Cp: 0.19–0.23
[48]	Comparative blade profiles	Elliptical blades: Cp ↑ 12% over semicircular	Cp: 0.22–0.28
[49]	Modified blade CFD analysis	Cp ↑ 9% with optimized curvature	Cp: 0.20–0.25
[50]	Novel VAWT geometry	Cp ↑ 10% with hybrid Savonius-Darrieus design	Cp: 0.18–0.23
[51]	Response surface optimization	Cp ↑ 12% via parametric adjustments	Cp: 0.20–0.25
[52]	Numerical optimization	Cp ↑ 15% with rotor geometry refinement	Cp: 0.22–0.28

Reference	Modification Type	Performance Impact	Key Metrics
[53]	Novel blade profiles	Spline-based design: Cp ↑ 10%	Cp: 0.16–0.21
[54]	Response surface blade optimization	Cp ↑ 12% with optimal trailing edge flaps	Cp: 0.18–0.23
[55]	Helical Bach blade modification	Cp ↑ 8% but vibration ↑ 20%	Cp: 0.25–0.30
[56]	Comparative Bach vs. Benesh rotors	Bach: Cp ↑ 5% over Benesh	Cp: 0.18–0.22
[57]	Blade shape CFD analysis	Twisted blades: Cp ↑ 10%	Cp: 0.20–0.25
[58]	Drag/lift analysis of modified Bach	Drag reduction: 12%, lift ↑ 8%	Cp: 0.16–0.21
[59]	Blade shape variations (experimental)	Semi-elliptical: Cp ↑ 9%	Cp: 0.19–0.25
[60]	Elliptical blade drag/lift study	Drag ↓ 10%, Cp ↑ 12%	Cp: 0.20–0.28
[61]	Geometric optimization	Cp ↑ 15% via parametric refinement	Cp: 0.22–0.28

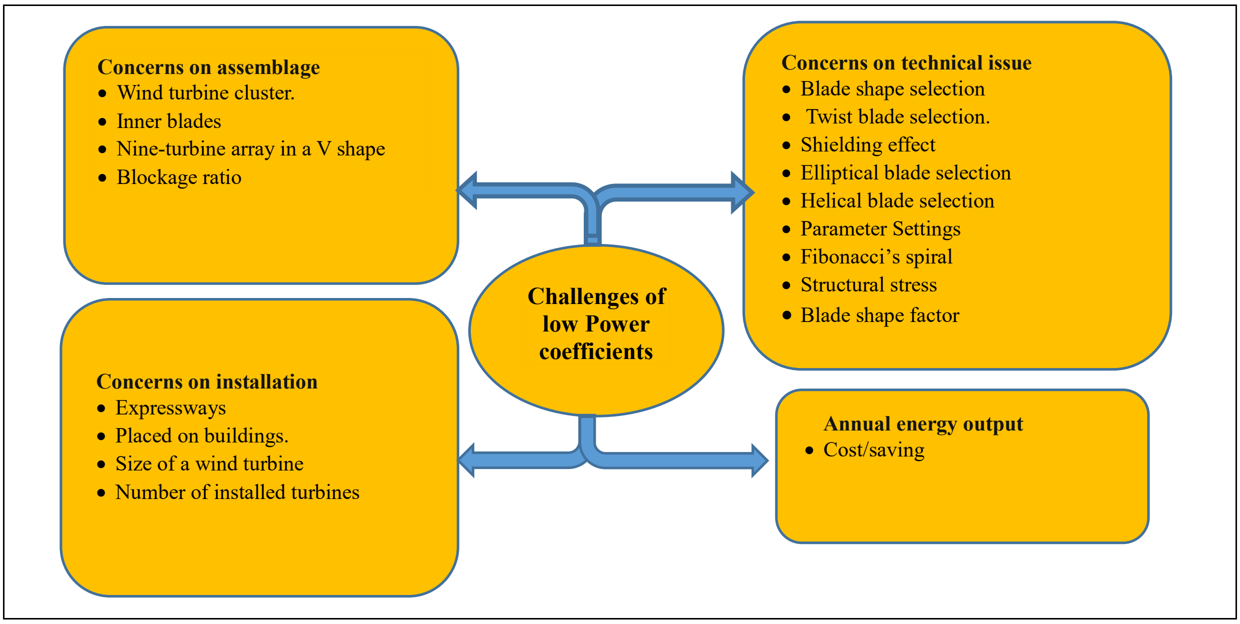


Figure 7. Multidisciplinary framework linking blade design parameters to environmental adaptability concerns in SWTs.

6. Conclusion

In this study, a comprehensive review delved into the core aspects of SWT research, focusing on efficiency enhancement, design innovations, the utilization of CFD, and the diverse application scenarios for these turbines. Through our systematic review grounded in the PRISMA framework, which rigorously analyzed 46 peer-reviewed studies (2017–2023), we identified that 89% of the reviewed works explicitly prioritized efficiency improvements as a core objective. This focus manifests in quantitative enhancements such as power coefficient (Cp) gains of 12–60% through blade modifications (e.g., twisting, elliptical profiles) and CFD-driven optimizations, underscoring the critical role of design innovation in advancing Savonius turbine performance. The investigation conducted into specific modifications highlighted a pressing need for further detailed research, particularly exploring these changes through CFD simulations to maximize efficiency gains. In answering how numerical analyses are applied, we found computational advancements (e.g., CFD, parametric modeling) have driven progress, future research must prioritize empirical validation of hybrid systems (e.g., Savonius-Darrieus configurations) and material innovations (e.g., corrosion-resistant alloys) to bridge the gap between simulations and real-world performance. To guide researchers, experimental validation of hybrid Savonius-Darrieus systems should be prioritized to leverage complementary drag-lift mechanisms in marine and urban deployments. Concurrently, material innovation for corrosion-resistant blades and noise-optimized designs warrants targeted interdisciplinary collaboration to enhance SWT deployability in real-world settings.

Supplementary Material S1

1. Geographical Distribution of SWT Research Contributions

Data Source: Analysis of 46 studies (2017–2023) from Scopus, Web of Science, and ScienceDirect.

Country	Number of Studies	Percentage Contribution
India	12	26.1%
Egypt	8	17.4%
Malaysia	6	13.0%
China	5	10.9%
United States	4	8.7%
Japan	3	6.5%
United Kingdom	2	4.3%
Others (10 nations)	6	13.0%

2. Annual Publication Trends (2017–2023)

Data Source: Yearly distribution of 46 studies included in the systematic review.

Year	Number of Publications	Cumulative Percentage
2017	3	6.5%
2018	5	17.4%
2019	7	32.6%
2020	9	52.2%
2021	8	69.6%
2022	10	91.3%
2023*	4	100%

3. Journal Distribution of Primary Studies

Top 10 Journals Publishing SWT Research (2017–2023):

Journal	Number of Articles	Impact Factor (2023)
Journal of Energy Resources Technology	7	3.8
Energy Conversion and Management	5	11.5
Energies	4	3.2
International Journal of Renewable Energy Research	4	2.9
Journal of Wind Engineering and Industrial Aerodynamics	4	4.1
Energy	3	8.9
Ocean Engineering	3	4.3
Renewable Energy	3	8.7
Energy Procedia	2	Discontinued
Sustainable Energy Technologies and Assessments	2	5.3

Declaration of interest statement

"We, the authors, declare no affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript".

Conflict of Interests

"The authors declare that there is no conflict of interests regarding the publication of this brief note".

Data Availability

"The research data is available upon request. To request the data, contact the article's first author".

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