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## Multi-objective and Multi-disciplinary Optimization of Vertical Axis Wind Turbine Blades

Chockalingam Palanisamy\*, Siva Kathirvelsamy, Ras Mathew Yanose and Gangadharan Tharumar

**Abstract – Abstract –** The demand for renewable energy is increasing, leading to more research on Vertical Axis Wind Turbines (VAWTs) because they can be used in cities and rural areas. This review looks at the latest methods for improving the design of VAWT blades, to summarize the advancements in multi-objective optimization and to highlight the interdisciplinary nature of the research, encompassing aerodynamics, materials science, and structural mechanics. It examines important factors like how air flows around the blades, their strength, and the materials used. The review also identifies gaps in current research and suggests future study directions. The goal is to enhance VAWT performance for better energy capture and use in various environments, especially where wind speeds are low. This research is crucial for advancing VAWT technology and making renewable energy more accessible and efficient. Aerodynamic performance remains a key focus, with computational fluid dynamic being the dominant method used for analysis. A few of the literature review findings are AI and machine learning are valuable tools for optimization but require validation. The structural and material innovations are advancing but need to be integrated with aerodynamic studies. Sustainable materials and manufacturing techniques are underexplored in the context of multi-objective optimization.

**Keywords—** Vertical Axis Wind Turbine, Multi-objective Optimization, Multi-disciplinary Design Optimization, Computational Fluid Dynamics, Urban Wind Energy Systems, Sustainable Materials.

### I. INTRODUCTION

Recent advancements in computational methods, such as Computational Fluid Dynamics (CFD) and Finite Element Analysis (FEA), have enabled detailed studies on the aerodynamic and structural performance of VAWT blades [1]. Vertical Axis Wind Turbines (VAWTs) emerge as a promising alternative to Horizontal Axis Wind Turbines (HAWTs), particularly in urban and rural environments where wind conditions are often variable and turbulent [2]. Unlike HAWTs, VAWTs can operate efficiently at low wind speeds and do not require alignment with wind direction, making them suitable for diverse applications. Despite these advantages, the performance of VAWTs remains suboptimal compared to their horizontal counterparts, necessitating further research into blade design and optimization. Integrating Vertical Axis Wind Turbines (VAWTs) into urban energy systems presents several challenges, including low wind speeds that hinder energy generation, high manufacturing and installation costs, and increased

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maintenance needs due to urban pollution [3]. Environmental impacts on wildlife and noise concerns also pose issues, alongside public apprehension regarding aesthetics and safety. Additionally, the integration of Artificial Intelligence (AI) techniques, such as machine learning and genetic algorithms, has significantly enhanced the efficiency of optimization processes [4].

However, VAWTs offer economic benefits in low-wind areas. They are cost-effective to produce and maintain, can generate electricity at lower wind speeds, and require less maintenance [5]. Their compact design allows for easy integration into urban settings, leading to shorter payback periods and making them a viable option for renewable energy adoption. These methodologies facilitate multi-objective optimization, addressing critical factors such as aerodynamic efficiency, structural integrity, and material sustainability [6].

However, significant challenges persist. For instance, while composite materials have improved blade durability and reduced weight, their aerodynamic implications remain underexplored [7]. Similarly, the high computational cost of coupled simulations and the limited real-world validation of optimization frameworks hinder the practical application of research findings [8]. This review aims to: Summarize recent advancements in the multi-objective optimization of VAWT blades. Highlight the interdisciplinary nature of the research, encompassing aerodynamics, materials science, and structural mechanics. Identify existing research gaps and propose future directions for sustainable and efficient VAWT blade design.

## II. METHODOLOGY

The methodology for this review article includes the following steps: Literature Collection, Screening and Selection, Data Extraction, Analysis and Synthesis, Presentation. The methodology followed in this review is depicted in Figure 1.

The optimization of Vertical Axis Wind Turbine (VAWT) blades is a multi-disciplinary challenge involving aerodynamics, material science, and computational techniques. Recent studies have emphasized importance of aerodynamic modeling using Computational Fluid Dynamics (CFD) to enhance blade performance under low wind speeds. Structural optimization using Finite Element Analysis (FEA) has demonstrated improved load distribution and stability, but limited integration with aerodynamic factors persists. Multi-objective frameworks combining genetic algorithms with CFD/FEA have successfully balanced performance and structural integrity, though computational costs remain a challenge.

### A. Vertical Axis Wind Turbine (VAWT)

Vertical Axis Wind Turbines (VAWTs) have gained attention due to their ability to harness wind from all directions, making them ideal for urban and decentralized applications. Studies highlight their advantages in low wind speed conditions and turbulent urban environments [1], [2]. Research on VAWTs has

primarily focused on optimizing blade designs to improve efficiency and reduce noise [3]. However, challenges such as lower efficiency compared to Horizontal Axis Wind Turbines (HAWTs) and complex wake interactions remain [4]. Advancements in computational modeling and material science are paving the way for more efficient, cost-effective, and durable VAWT designs [5].

### B. Multi-objective Optimization

Multi-objective optimization techniques have been widely applied to balance conflicting objectives in VAWT blade design, such as maximizing aerodynamic performance while minimizing structural stress [6]. Artificial intelligence (AI) has emerged as a transformative tool in blade optimization, with machine learning models reducing computational time and enabling data-driven design [7]. Genetic algorithms and machine learning models have shown promise in achieving optimal solutions [8]. These methods enable simultaneous consideration of multiple variables, including blade shape, material properties, and environmental factors. However, these approaches often overlook material considerations. Advances in composite materials and bio-based alternatives have shown promise for enhancing sustainability and durability, yet their aerodynamic implications require further exploration [9]. Despite their success, high computational costs and the complexity of integrating diverse objectives pose challenges [10]. Future research must focus on refining algorithms and incorporating real-world constraints to improve the practical applicability of multi-objective optimization frameworks [11].

### C. Multi-disciplinary Design Optimization (MDO)

MDO frameworks integrate aerodynamics, structural mechanics, and material science to achieve holistic optimization of VAWT blades [12]. These approaches allow for simultaneous consideration of multiple disciplines, enhancing the overall performance and durability of turbine blades [13]. Recent studies have employed coupled CFD-FEA simulations and genetic algorithms to address complex design challenges [14]. However, the integration of sustainability and manufacturing constraints into MDO frameworks remains underexplored [15]. By addressing these gaps, MDO approaches can significantly contribute to the development of advanced VAWT designs that align with economic and environmental goals [16].

### D. Computational Fluid Dynamics (CFD)

CFD has revolutionized the study of VAWT aerodynamics by enabling detailed analysis of flow patterns and wake interactions [17]. It has been instrumental in identifying optimal blade shapes and configurations for improved efficiency [18]. Coupled with machine learning, CFD has reduced computational time while maintaining accuracy [19]. However, limitations such as high computational costs and challenges in

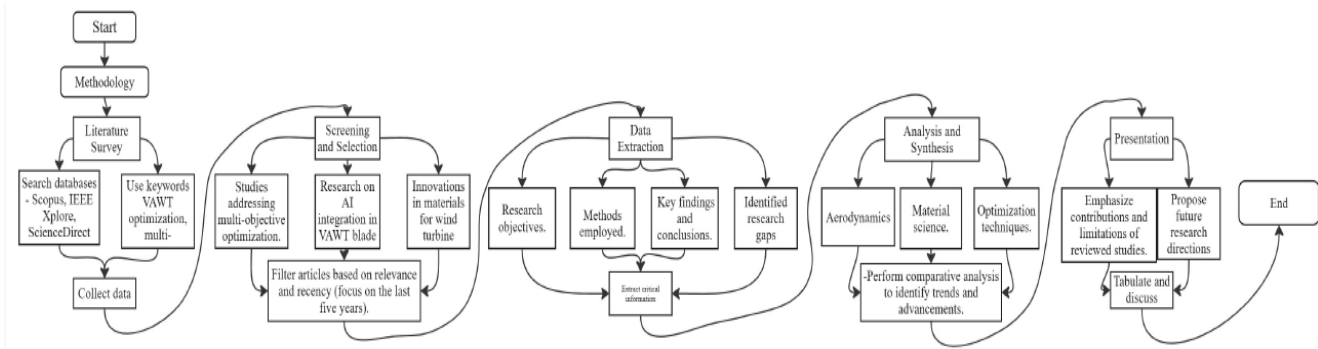


FIGURE 1. REVIEW METHODOLOG

TABLE 1 SUMMARY OF THE LITERATURE REVIEWED

Author(s)	Methods Used	Findings	Research Gap	Applications	Contributions	Practical Implications
Fazlizan et al. (2025)	CFD review (RANS, LES, DES)	CFD significantly improves aerodynamic prediction accuracy.	Lack of standardized CFD validation frameworks.	VAWT aerodynamic design	Comprehensive CFD methodology comparison	Helps researchers select appropriate CFD models
Kumar et al. (2018)	Critical review	VAWTs suitable for urban low-wind conditions	Limited real-world urban deployment data	Urban wind energy systems	Early identification of urban VAWT potential	Supports rooftop and distributed energy planning
Bello et al. (2024)	Optimization + design analysis	Improved efficiency via blade and configuration tuning	Limited experimental validation	Urban VAWTs	Focus on low-wind optimization strategies	Enhances feasibility in cities
Farrar et al. (2023)	AI/ML review (ANN, RL)	AI improves turbine control and grid integration	Lack of real-time implementation studies	Smart wind energy systems	Integration of AI in wind turbine control	Enables adaptive and intelligent turbine systems
Bošnjaković et al. (2025)	Sustainability review	VAWTs have strong potential in decentralized energy	Economic feasibility not fully explored	Sustainable energy systems	Holistic view (technical + sustainability)	Supports policy and green energy planning
Posteljnik et al. (2016)	Multi-objective optimization	Trade-offs between efficiency, cost, and structure	Outdated optimization techniques	Small-scale VAWTs	Early optimization framework	Guides design balancing multiple objectives
Firoozi et al. (2024)	Systematic review (aerodynamics)	Blade design critical for efficiency	Lack of unified optimization framework	Blade design	Consolidates aerodynamic strategies	Improves blade design practices
Sanaye et al. (2025)	CFD + ANN + GA	Hybrid AI optimization improves turbine performance	Limited scalability studies	Smart VAWT optimization	Integration of AI + CFD optimization	Enables high-efficiency turbine design
Lagos et al. (2025)	Materials review (polymer composites)	Advanced composites enhance durability and efficiency	Limited long-term performance data	Wind turbine materials	Focus on polymer composite innovation	Improves lifespan and reduces maintenance
Abdolahifar & Zanj (2024)	Aerodynamic analysis	Aerodynamic inefficiencies remain key limitation	Lack of experimental validation	VAWT aerodynamics	Identifies critical aerodynamic challenges	Guides performance improvement strategies
Hosseini et al. (2024)	Experimental + NSGA-II optimization	Improved Savonius turbine efficiency	Limited generalization to other VAWTs	Small-scale turbines	Experimental validation with optimization	Practical design improvements for prototypes
He et al. (2025)	Collaborative optimization (multi-disciplinary)	Integrated aero-structural optimization improves performance	High computational cost	Wind turbine blade systems	Multi-disciplinary optimization approach	Leads to better-performing turbine designs
Davari et al. (2025)	Comprehensive review	Significant advancements in VAWT technology	Lack of commercialization studies	VAWT technology development	Broad synthesis of advancements	Identifies future research directions
Luo et al. (2024)	CFD + FEA (FSI modeling)	FSI improves floating VAWT performance prediction	Limited real-sea validation	Offshore floating VAWTs	Coupled aero-structural modeling	Enhances offshore turbine reliability

validating results against real-world data persist [20]. Future work should focus on integrating CFD with experimental studies to improve reliability and exploring its application in adaptive blade designs for variable wind conditions [21].

### E. Urban Wind Energy Systems

Urban wind energy systems utilizing VAWTs offer a promising solution for decentralized renewable energy generation [22]. Their compact size and ability to

operate efficiently in turbulent wind conditions make them suitable for urban environments [23]. Research has explored the integration of VAWTs into building designs and their potential for hybrid renewable energy systems [24]. However, challenges such as noise, visual impact, and lower efficiency compared to large-scale turbines need to be addressed [25]. Advances in adaptive blade designs and noise-reducing materials can further enhance the feasibility of VAWTs in urban applications [26].

#### F. Sustainable Materials

The use of sustainable materials in VAWT blades is a growing area of research, driven by the need to reduce environmental impact [27]. Bio-based composites and recyclable materials have demonstrated potential for enhancing durability and reducing the carbon footprint of wind turbines [28]. Studies have highlighted the need to balance sustainability with performance, as some eco-friendly materials may compromise aerodynamic efficiency [29]. Integrating AI tools for material selection and optimization has shown promise in addressing these trade-offs [30]. Future research should focus on scalable manufacturing processes and lifecycle analysis to promote the adoption of sustainable materials in VAWTs [31].

### III. KEY FINDINGS AND INSIGHTS

**Aerodynamic Design:** Advanced CFD simulations have enabled detailed studies of the flow dynamics around 3D VAWT blades. However, the computational expense remains a barrier to widespread adoption. Recent studies have explored bio-inspired designs and adaptive geometries to enhance aerodynamic performance under variable wind conditions.

**Structural Optimization:** Structural integrity is critical for VAWT blades to withstand dynamic loads and fatigue. FEA has been widely used to analyze stress distribution and deformation. Hybrid materials and advanced composites have shown promise in improving the strength-to-weight ratio.

**Material Innovations:** The integration of lightweight and sustainable materials, such as bio-composites, is gaining traction. However, their aerodynamic and structural implications need further investigation.

**Artificial Intelligence in Optimization:** Machine learning (ML) and genetic algorithms have emerged as powerful tools for multi-objective optimization. These methods can reduce computational time while maintaining accuracy.

**Multi-disciplinary Approaches:** Combining aerodynamics, structural mechanics, and material science in a single optimization framework remains a challenge due to the complexity and computational demands.

### IV. SUMMARY OF FINDINGS

Aerodynamic performance remains a key focus, with CFD being the dominant method used for analysis.

AI and machine learning are emerging as valuable tools for optimization but require extensive datasets and validation.

Structural and material innovations are advancing but often lack integration with aerodynamic studies.

Sustainable materials and manufacturing techniques are underexplored in the context of multi-objective optimization.

### V. RESEARCH GAPS

Limited integration of sustainable materials into aerodynamic and structural designs.

Insufficient validation of computational models under real-world conditions.

Lack of exploration into hybrid manufacturing techniques for blade production.

Underutilization of adaptive and bio-inspired designs for fluctuating wind conditions.

### VI. POTENTIAL FUTURE DIRECTIONS

**Integrated Frameworks:** Develop holistic optimization frameworks that combine aerodynamics, structural mechanics, and material science.

**Sustainability:** Investigate the use of bio-based and recyclable materials for blade fabrication.

**Advanced Computational Methods:** Leverage AI-driven methods to reduce computational costs and improve design efficiency.

**Validation and Real-world Applications:** Conduct large-scale field studies to validate computational models and optimization frameworks.

**Adaptive Designs:** Explore cost-effective solutions for adaptive blade geometries to optimize performance in variable wind conditions.

### VII. CONCLUSION

The optimization of 3D VAWT blades is a multi-disciplinary challenge requiring collaboration across aerodynamics, materials science, and structural mechanics. Future research should focus on integrating sustainability into design and manufacturing processes, addressing real-world variability, and enhancing computational efficiency.

The optimization of 3D VAWT blades is a multi-disciplinary challenge requiring collaboration across various fields. While significant advancements have been made in computational modeling and material science, practical implementation and sustainability considerations are still in their infancy. Future research should focus on integrating these disciplines into comprehensive optimization frameworks and addressing real-world variability to make VAWTs a viable and sustainable alternative in renewable energy systems.

The optimization of 3D VAWT blades is a multi-disciplinary challenge requiring collaboration across

aerodynamics, materials science, and structural mechanics. Future research should focus on integrating sustainability into design and manufacturing processes, addressing real-world variability, and enhancing computational efficiency.

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#### AUTHOR CONTRIBUTIONS

Chockalingam Palanisamy: Conceptualization, Supervision, Methodology, Validation, Writing – Review & Editing.

Ras Mathew Yanose: Conceptualization, Draft Writing –Review & Editing.

Siva Kathirvelsamy: Draft Writing – Original Preparation.

Gangadharan Tharmar: Review & Editing.

#### CONFLICT OF INTERESTS

No conflict of interests was disclosed.

#### ETHICS STATEMENTS

There are no ethical considerations to declare. This work does not involve human subjects, animals, or data from any social media platforms.

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