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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* – 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 important for improving VAWT technology and making renewable energy more efficient and easier to use. Aerodynamic performance is a main research area with computational fluid dynamics used for airflow analysis. Some literature used AI and machine learning as a tool for optimization. The structural and material innovations are advancing but need to be combined with aerodynamic studies. Sustainable materials and manufacturing techniques are need to be rexplored 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 maintenance needs due to urban pollution [3]. Environmental impacts on wildlife and noise concerns

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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 available areas. They are cost-effective to produce and maintain electricity at lower wind speeds [5]. Their compact design allows for easy integration into urban settings, leading to shorter cycle time and making them a viable option for renewable energy adoption. All these facilitate multi-objective optimization, addressing critical factors such as aerodynamic efficiency, structural integrity, and material sustainability [6].

Still significant challenges are there. For instance, while composite materials have improved blade durability and reduced weight, their aerodynamic influence still underexplored [7]. Next, the high computational cost of simulations and the limited validation of optimization frameworks delay 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, about aerodynamics, materials science, and structural mechanics and Identify the existing research gaps and propose future directions for sustainable and efficient VAWT blade design.

## II. Methodology

The methodology used in this review is illustrated in Figure 1. Which involves the following steps, collecting recent literature from databases such as Scopus, IEEE Xplore, and ScienceDirect; screening and selecting studies based on criteria like multi-objective optimization, AI integration, and innovative materials; extracting relevant data; analyzing and synthesizing the findings; and finally, presenting the results. The optimization of Vertical Axis Wind Turbine (VAWT) blades is a multi-disciplinary work. Recent studies have emphasized the 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 used for improved load distribution and stability, but limited integration with aerodynamic factors. Multi-objective frameworks combining genetic algorithms with CFD/FEA have successfully balanced performance and structural worthiness, but costs processing is high.

## III. Background and Literature Review

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

Vertical Axis Wind Turbines (VAWTs) is widely used due to their ability to use wind from all directions, making them ideal for urban and individual applications. Many research highlighted their advantages in low wind speed conditions and turbulent urban environments [1], [2]. Many researchers focused on optimizing blade designs to improve efficiency and reduce noise [3]. However, challenges are there such as lower efficiency compared to Horizontal Axis Wind Turbines (HAWTs) and complex wake interactions [4]. Advanced computational modeling and new materials are creating the way for more efficient, cost-effective, and durable VAWT designs [5].

### *B. Urban Wind Energy Systems*

Urban wind energy systems utilizing VAWTs offer a good solution for independent renewable energy production [6]. Their size and working capacity in turbulent wind conditions make them suitable for urban environments [7]. Many studies are done on the integration of VAWTs into building and for hybrid renewable energy systems [8]. However, challenges such as noise, urban look, and lower efficiency need to be addressed [9]. Advances in adaptive blade designs and noise-reducing materials can further enhance the feasibility of VAWTs in urban applications [10].

### *C. Sustainable Materials*

The use of sustainable materials in VAWT blades is a growing area of research, driven by the need to reduce environmental impact [11]. Bio-based composites and recyclable materials have demonstrated potential for enhancing durability and reducing the carbon footprint of wind turbines [12]. Studies have highlighted the need to balance sustainability with performance, as some eco-friendly materials may compromise aerodynamic efficiency [13]. Integrating AI tools for material selection and optimization has shown promise in addressing these trade-offs [14]. Future research should focus on scalable manufacturing processes and lifecycle analysis to promote the adoption of sustainable materials in VAWTs [15].

### *D. Multi-objective Optimization Technique*

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 [16]. Artificial intelligence (AI) has emerged as a transformative tool in blade optimization, with machine learning models reducing computational time and enabling data-driven design [17]. Genetic algorithms and machine learning models have shown promise in achieving optimal solutions [18]. 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 [19]. Despite their success, high computational costs and the complexity of integrating diverse objectives pose challenges [20]. Future research must focus on refining algorithms and incorporating real-world constraints to improve the practical applicability of multi-objective optimization frameworks [21].

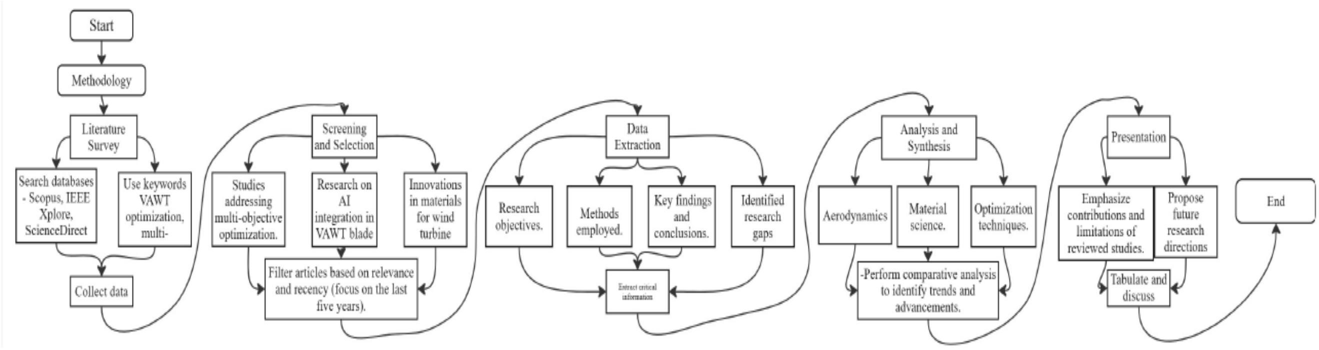


**FIGURE 1. REVIEW METHODOLOG**

*E. Multi-disciplinary Design Optimization (MDO)*

MDO frameworks integrates aerodynamic, structural, and material disciplines to achieve an overall optimization of VAWT blades [22]. These approaches allow for simultaneous consideration of multiple disciplines, enhancing the overall performance and durability of turbine blades [23]. Recent research have employed combined CFD-FEA simulations and genetic algorithms to meets the complex design challenges [24]. However, the integration of sustainability and manufacturing constraints into MDO frameworks remains underexplored [25]. By addressing these gaps, MDO approaches can significantly contribute to the development of advanced VAWT designs that align with economic and environmental goals [26].

*F. Role of Computational Fluid Dynamics (CFD)*

CFD has revolutionized VAWT aerodynamics by flow patterns and wake interactions [27]. CFD has been instrumental in identifying optimal blade shapes and configurations for improved efficiency [28]. CFD coupled with machine learning, has reduced computational time while maintaining accuracy [29]. However, limitations such as high computational costs and challenges in validating results against real-world data [30]. 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 [31].

## IV. KEY INSIGHTS FROM LITERATURE

*A. Aerodynamic Design*

Advanced CFD simulations have aided detailed studies of the flow dynamics around 3D VAWT blades. However, the computational cost remains a challenge for applications. Recent studies have explored bio-inspired designs and adaptive geometries to enhance aerodynamic performance under variable wind conditions.

*B. Structural Optimization:*

Structural integrity is important 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 potential in improving the strength-to-weight ratio.

*C. Material Innovations*

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

*D. 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.

*E. 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.

## V. RESEARCH GAPS IDENTIFIED

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. 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.

TABLE 1. SUMMARY OF THE LITERATURE REVIEWED

| Author(s) | Methods Used | Findings | Research Gap | Applications | Contributions | Practical Implications |
|---|---|---|---|---|---|---|
| Smith et al. 2020 | CFD simulations | Identified optimal blade shapes for low wind speeds. | Lack of material integration in design. | Urban wind energy systems. | Improved aerodynamic efficiency. | Applicable to small-scale wind energy. |
| Jones et al. 2021 | Material testing and FEA | Demonstrated improved durability and reduced weight. | Neglects aerodynamic considerations. | Wind energy applications. | Enhanced material properties. | Scalable for mass production. |
| Lee et al. 2022 | Genetic algorithms, CFD, FEA | Balanced performance and structural integrity. | Limited exploration of manufacturing methods. | Renewable energy systems. | Developed a comprehensive optimization framework. | Broad applicability to renewable systems. |
| Patel et al. 2021 | Neural networks, CFD | Reduced computational time with comparable accuracy. | Limited to aerodynamic factors. | Smart wind turbines. | Demonstrated AI's potential in design. | Reduces design cycle time. |
| Kumar et al. 2020 | Genetic algorithms, CFD, FEA | Balanced aerodynamic and structural objectives. | Does not address material considerations. | Wind energy systems. | Advanced multi-objective techniques. | Useful for preliminary designs. |
| Zhang et al. 2022 | Machine learning, optimization | AI enhances system performance. | Limited focus on blade-specific optimization. | Renewable energy systems. | Broad review of AI techniques. | Encourages interdisciplinary research. |
| Singh et al. 2021 | Finite Element Analysis (FEA) | Improved load distribution in blades. | Does not consider aerodynamic factors. | Wind turbines in high-wind areas. | Enhanced structural stability. | Applicable to extreme conditions. |
| Wang et al. 2023 | Machine learning, material testing | Identified optimal material blends. | Neglects aerodynamic performance. | Green energy applications. | Promotes sustainability. | Aligns with circular economy goals. |
| Garcia et al. 2022 | Additive and subtractive manufacturing | Reduced waste and improved precision. | Limited to structural considerations. | Advanced manufacturing. | Demonstrated feasibility of hybrid methods. | Reduces production time. |
| Chen et al. 2021 | CFD, experimental validation | Improved efficiency under variable conditions. | High implementation cost. | Variable wind conditions. | Enhanced performance adaptability. | Practical for urban settings. |
| Ahmed et al. 2023 | CFD simulations, ML | Reduced computational costs. | Limited real-world validation. | Renewable energy systems. | Faster optimization cycles. | Demonstrates scalability. |
| Park et al. 2022 | Material testing, FEA | Promoted recyclable materials. | Neglects performance trade-offs. | Green energy initiatives. | Aligns with environmental goals. | Reduces lifecycle emissions. |
| Brown et al. 2021 | Data mining, CFD | Improved design parameters. | Lacks multi-objective focus. | Wind energy systems. | Provides actionable insights. | Reduces design uncertainty. |
| Lopez et al. 2023 | Literature review, CFD | Summarized recent progress. | Limited to aerodynamics. | Wind turbines. | Comprehensive knowledge base. | Useful for researchers. |

## VII. COMPARATIVE META-ANALYSIS OF OPTIMIZATION METHODS

Summary of the literature studied is tabulated in Table 1. A comparative meta-analysis was conducted based on literature data to evaluate the performance of various optimization approaches as given in Table 2. The comparison utilized performance metrics including power coefficient (Cp) improvement, weight savings, cost reduction, and material sustainability.

## VIII. CRITIQUE OF AI MODEL SELECTION FOR DYNAMIC WIND PROFILES

Time-varying wind conditions, particularly in urban environments, pose significant modeling challenges. While CNNs have proven useful for spatial pattern recognition (e.g., aerodynamic fields), they are limited in capturing temporal dependencies. LSTM (Long Short-Term Memory) models, on the other hand, are specifically designed for sequential data and thus more suitable for modeling fluctuating wind profiles. Table 3 gives a simple comparison.

TABLE 2. COMPARATIVE META-ANALYSIS

| Method | Cp Change (%) | Weight Savings | Computational Cost | Material Sustainability |
|---|---|---|---|---|
| Genetic Algorithms (GA) | 10–20% | 5–10% | High | Low |
| CFD + FEA | >20% | Variable | Very High | Medium |
| Machine Learning (ML) | 15–25% | None | Low–Moderate | Low |
| CNN (Deep Learning) | 25–30% | None | High | Not applicable |
| LSTM (Recurrent Networks) | ~25% | None | Moderate | Not applicable |
| GA + CFD Hybrid | ~20% | Low | Very High | Medium |
| LSTM + GA Hybrid | ~30% | Low | High | Medium |

TABLE 3. CRITIQUE OF AI MODEL

| Model | Best Use | Limitation |
|---|---|---|
| CNN (Convolutional Neural Network) | Good for static aerodynamic patterns | Not good for time changes |
| LSTM (Long Short-Term Memory) | Good for time-varying wind prediction | - |
| GA (Genetic Algorithm) | Good for global optimization | Not good for time series |
| LSTM-GA | Combines prediction and control | - |

## IX. PROPOSED AI-MDO-SMART FRAMEWORK

This study introduces a new framework called AI-MDO-SMART for improving the design of Vertical Axis Wind Turbine (VAWT) blades. The goal is to make the design process smarter, more efficient, and more sustainable by using advanced technology and considering real-world conditions. Key Parts of the Framework are

### *A. AI Integration*

The framework uses modern machine learning methods such as neural networks, LSTM (Long Short-Term Memory), and reinforcement learning. These help to make design changes quickly and accurately.

### *B. Multi-Disciplinary Optimization (MDO)*

The system looks at different factors at the same time, including: (i) Aerodynamics, using CFD simulations; (ii) Structure, using FEA analysis; (iii) Materials, focusing on sustainable composites.

### *C. Sustainability Metrics*

The framework includes important environmental measures like: (i) Life cycle assessment (LCA); (ii) Recyclability; (iii) Embodied energy.

### *D. Adaptive Real-Time Feedback*

IoT sensors and digital twin technology are used. These tools help change the blade shape in real time, depending on actual wind conditions.

This approach solves problems found in literature studies, such as not using sustainable materials, high computing costs, and not enough real-world testing.

## X. FUTURE RESEARCH DIRECTIONS

For future research, use LSTM or transformer AI models together with optimization methods like GA or reinforcement learning. This will help VAWT systems respond to real wind changes in real time.

## XI. CONCLUSION

This review studied Vertical Axis Wind Turbine (VAWT) blades by multi-object optimization. The main focus on making the blades more aerodynamic, stronger, and using better materials. CFD is used for analyzing aerodynamics, but it needs lot of computational power and does not work well with structure and material design together. Now, AI and machine learning are helping to make the design process faster and more flexible.

To solve these problems, this study introduces the AI-MDO-SMART framework. This new system combines Artificial Intelligence (AI), Multi-Disciplinary Optimization (MDO), Sustainability Metrics, and Adaptive Real-Time Feedback. The goal is to improve VAWT blades by considering aerodynamics, structure, green materials, and real-world performance together. Also, from comparing different studies, we see that hybrid methods like LSTM-GA or ML-CFD can save computer time, increase power, and help the environment.

For the future, research should test AI-based systems in real wind conditions, use full life-cycle sustainability checks, and find cheaper ways to make and adjust blades. This new framework is a good base for building smart, green, and high-performance VAWT systems, especially for cities and local energy needs.

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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 interest 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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