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Indonesian Journal of Science & Technology

Journal homepage: http://ejournal.upi.edu/index.php/ijost/

IJoST Indonesian Journal of Science & Technology

# Towards Sustainable Wind Energy: A Systematic Review of Airfoil and Blade Technologies Over the Past 25 Years for Supporting Sustainable Development Goals (SDGs)

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## ABSTRACT

Wind energy is vital for transitioning to renewable sources, reducing reliance on fossil fuels, and mitigating climate change. Harnessing wind power provides sustainable solutions to meet global energy demands. The systematic review provides valuable insights into recent advancements in blade design for wind turbines, crucial for optimizing efficiency, and sustainability in wind energy systems. The study emphasized advancements in Horizontal Axis Wind Turbines, concentrating on efficiency enhancements with numerical simulations and optimization strategies. Additionally, it explored developments in Vertical Axis Wind Turbine technology, notably hybrid rotor systems, and primarily utilized wind turbine airfoils over the past 25 years. Many researchers focused on optimizing aerodynamic systems using advanced numerical simulations, experiments, and optimization techniques, stressing the significance of achieving optimal lift-to-drag ratios. Furthermore, factors like bend-twist coupling and stall characteristics to prolong turbine lifespan and maximize power extraction were investigated. The interdisciplinary nature of wind energy research emphasizes collaborative efforts to address challenges and foster innovation, driving progress toward sustainable development goals. This review also supports current issues in the sustainable development goals (SDGs).



## ARTICLE INFO

***Article History:***
*Submitted/Received 04 Jan 2024*
*First Revised 19 Feb 2024*
*Accepted 1 Mar 2024*
*First available online 14 Jun 2024*
*Publication Date 01 Dec 2024*

***Keyword:***
*Bibliometric analysis,*
*Horizontal and vertical axis wind turbine,*
*Lift-to-drag ratio,*
*Stall characteristics,*
*Sustainable development goals,*
*Systematic review.*

## 1. INTRODUCTION

Renewable energy sources (RESs) are crucial for tackling climate change and ensuring energy security. Solar, wind, hydro, geothermal, and biomass power offer various advantages, including emission reduction, pollution mitigation, job creation, and economic growth. A diverse of renewables is vital for establishing a resilient and sustainable energy landscape. This makes many reports regarding RES being well-documented (see **Table 1**). Many countries across the globe are increasingly harnessing wind energy, both onshore and offshore, as they transition towards cleaner energy sources. As the world strives to attain net-zero carbon energy generation, wind power emerges as a promising avenue, offering abundant potential. This inquiry delves into the realm of wind turbines, exploring the diverse array of research dedicated to improving their efficiency.

Addressing the imperative of reducing fossil fuel dependency and mitigating environmental degradation in electricity generation requires a comprehensive analysis of alternative sources (Pebrianti & Salamah, 2021). By examining the current landscape and prospects of RES-based power plants across leading nations, insights into their global potential, installed capacity, and emission rates are gleaned. This scrutiny extends to a comparative evaluation of renewable energy practices and associated environmental impacts, while also shedding light on the capacity installation required to achieve net-zero emissions goals.

Furthermore, an exploration of the strengths, weaknesses, opportunities, and threats inherent in different RESs, informs strategic planning for sustainable energy solutions. Leveraging these insights, forecasts of installed capacity facilitate informed decision-making to meet burgeoning electricity demands sustainably, thus heralding a transition towards a greener energy paradigm. Transitioning to wind energy, specifically, exemplifies a pivotal step in this trajectory, given its significant capacity and contribution to net-zero emission goals globally. Several nations, like the USA, Brazil, Sweden, China, and Australia, have significant wind energy capacity contributing towards RES for net-zero emission goals. Growth rates of wind power plants differ among countries; some need to boost their rates to meet future needs, while others can maintain current rates. Wind energy is praised for its simplicity, recyclability, and high capacity, but it also faces challenges like power variability and storm-related risks (Molla *et al.,* 2024). Bosnia and Herzegovina has big potential for RES like hydropower, solar, wind, geothermal, and biomass. Hydropower is the most promising, with many plants already built, under construction, or planned. Solar power is also good, especially in Herzegovina. Biomass, including wood and farm waste, is another option, along with biodiesel, although it's not as popular due to cost and government focus on other renewables. In the future, there is a plan to develop more hydropower, wind, solar, and geothermal energy, explore biomass potential, and invest in biodiesel (Sher *et al*., 2024).

Much of the wind turbine research at present has leaned towards analyzing wake models for the rotors. Various approaches for modeling wind turbine wakes include computer simulations, physical tests, and simpler analytical techniques. The studies explained how each method works, the assumptions it makes, and its limitations. The two common models used are the Actuator Disk and Actuator Line models. The Actuator Disk with a Rotation model is better at predicting wakes because it considers the real thickness of turbine blades, unlike the Actuator Disk with No Rotation model. The Actuator Line model treats rotor blades as rotating lines. This method is good at showing how many blades there are and how tip vortices form. Future research should focus on improving how to model loads on airfoils, handling uneven loads, and including tower and nacelle effects (Amiri *et al*., 2024).

DOI: https://doi.org/10.17509/ijost.v9i3.72369
p- ISSN 2528-1410 e- ISSN 2527-8045

**Table 1.** Top cited articles relating to RES published in the Journal of Engineering, Science, and Technology. Data was obtained from the Scopus database using the keywords "renewable energy source".

| No | Title | Ref |
|---|---|---|
| 1 | Wind energy conversion systems-a technical review. | Babu & Arulmozhivarman (2013) |
| 2 | Microwave-assisted pretreatment of lignocellulosic biomass: A review. | Saleem *et al.* (2015) |
| 3 | Design and flow velocity simulation of diffuser augmented wind turbine using CFD. | Kannan *et al.* (2013) |
| 4 | Experimental study of palm oil mill effluent and oil palm frond waste mixture as an alternative biomass fuel. | Hassan *et al.* (2013) |
| 5 | A new energy management system of on-grid/off-grid using adaptive neuro-fuzzy inference system. | Alhasnawi & Jasim (2020) |
| 6 | Trends in research related to photonic crystal (PHC) from 2009 to 2019: A bibliometric and knowledge mapping analysis. | Wiendartun *et al.* (2022) |
| 7 | Effects of particle size and composition of sawdust/carbon from rice husk on the briquette performance. | Anggraeni *et al.* (2021) |
| 8 | Review of thermoelectric cooling devices recent applications. | Salah & Abuhelwa (2020) |
| 9 | Liquid air as an energy storage: A review. | Lim *et al.* (2016) |
| 10 | Design and development of a large size non-tracking solar cooker. | Nahar (2009) |
| 11 | Effects of microwave absorbers on the products of microwave pyrolysis of oily sludge. | Mokhtar *et al.* (2018) |
| 12 | Experimental investigations on the effect of hydrogen induction on performance and emission behaviour of a single cylinder diesel engine fuelled with palm oil methyl ester and its blend with diesel. | Boopathi *et al.* (2017) |
| 13 | Topological review and analysis of DC-DC boost converters. | Indragandhi *et al.* (2017) |
| 14 | Teaching on the concept of energy to students with hearing impairment: changes of electrical energy to light and heat. | Rusyani *et al.* (2021) |
| 15 | Biodiesel production from waste animal fat using a novel catalyst HCA immobilized AuNPS amine grafted SBA-15. | Srinivasan *et al.* (2018) |
| 16 | A fractional model predictive control design for 2-d gantry crane system. | Singh & Agrawal (2018) |
| 17 | Experimental and numerical investigation of combustion behaviour in diesel engine fuelled with waste polyethylene oil. | Naima *et al.* (2018) |
| 18 | Decentralized optimal LFC for a real hybrid power system considering renewable energy sources. | Magdy *et al.* (2019) |
| 19 | Potential thermo-responsive ionic liquid as draw solution in forward osmosis application. | Abdullah *et al.* (2019) |
| 20 | Effect of channel length variation on analog and RF performance of junctionless double gate vertical MOSFET. | Kaharudin *et al.* (2019) |
| 21 | An overview of gas-upgrading technologies for biohydrogen produced from treatment of palm oil mill effluent. | Mohamad *et al.* (2017) |
| 22 | Optimization of economic environmental and social benefits for integrated energy systems. | Huynh *et al.* (2021) |
| 23 | Ammonia-based pretreatment for ligno-cellulosic biomass conversion – an overview. | Latif *et al.* (2018) |

Wake models are essential for designing wind farms effectively and in showing how wind turbines interact with each other, helping to place individual rotors in the best spots to produce the most energy and make the farm more efficient. The models also help predict

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p- ISSN 2528-1410 e- ISSN 2527-8045

power losses from wake interactions, guiding decisions on how far apart turbines should be placed. Overall, using wake models leads to better wind farm designs, improving performance, and saving costs for renewable energy projects.

Lamnatou *et al*. (2024) investigated the relationship between energy transition and factors associated with RESs, buildings, and other sectors, primarily focusing on France. The study analyzed various scenarios and factors related to energy transition, including energy coordination in urban environments, carbon neutrality, energy demand, and achieving net-zero emissions. The article underscored the challenges inherent in energy transition and emphasized the connection between emerging technologies and this transition. Additionally, the significance of factors such as biological agriculture, agroecology, integrated production, and biomass in energy transition were discussed. Prospects in energy transition may involve enhancements in efficiency, while further exploration of potential research areas and innovative ideas in RESs and small-island economies is suggested. Further studies could delve into the development of eco-friendly storage materials, end-of-life management, and recycling in RESs.

Identified as a promising solution for utilizing extensive wind resources in deeper waters, floating offshore wind turbines (FOWTs) were deemed suitable for various floater platform designs in Indonesia, including spar, semi-submersible, and Tension Leg Platforms, within a depth range of 50-80 m. Considerations regarding logistics and installation, such as port and wind farm locations, along with manufacturing facilities, were highlighted. Projections suggested that global FOWT capacity would increase to 18.9 GW by 2030 and 264 GW by 2050, with China leading in construction rates. Future endeavors encompassed optimizing floater motion and control mechanisms, exploring passive control strategies, enhancing Tension Leg Platform performance, and evaluating stress distribution and hydrodynamic response for Tension Leg Platform structural design (Kusuma *et al*., 2024).

As of 2018, Africa had a lot of wind energy potential, estimated at 100 GW, but only about 5.7 GW of capacity was installed, mostly in Northern and South Africa. The wind energy industry faced challenges like policy, competition, technical, and economic issues. Investing in wind energy could lead to benefits like cheaper electricity, more jobs, and eco-friendly energy. Globally, wind power was growing fast, with plans to add 469 GW of capacity in the next five years. To help Africa catch up, needed clear policies and more local businesses involved. Future research should focus on making better policies, growing the market, and developing new technologies (Boadu & Otoo, 2024).

Exploring the enhancement of wind turbine efficiency reveals the possibility of a wide array of innovations and challenges across different regions. From continents spanning the globe to remote island nations, the potential for wind energy is vast, providing a pathway toward a cleaner and more sustainable future. Despite facing turbulence in policy, technology, and markets, wind power remains a promising solution. Here, based on our previous studies (Eftekhari *et al*., 2022; Alawad *et al*., 2022; Husain *et al*., 2023; Namasivayam *et al*., 2023; Khaleel *et al*., 2024; Shafiq *et al*., 2024) this systematic literature review conducted using the Scopus database, meticulously curated relevant studies on improvements in wind turbine efficiency. By employing specific search terms and criteria, pertinent studies were selected and evaluated to extract essential insights and methodologies. Through this methodical approach, the review provides a comprehensive overview of current research in wind turbine efficiency, aiding decision-makers in the field. This review also adds suggestions and supports current issues in the sustainable development goals (SDGs), as reported elsewhere (see **Table 2**).

DOI: https://doi.org/10.17509/ijost.v9i3.72369
p- ISSN 2528-1410 e- ISSN 2527-8045

**Table 2.** Previous studies in SDGs.

| No | Title | Ref |
|---|---|---|
| 1 | What Phenomena Happen During Pyrolysis of Plastic? FTIR AND GC-MS Analysis of Pyrolyzed Low Linear Density Polyethylene (LLDPE) Polymer Particles Completed with Bibliometric Research Trend and Pyrolysis Chemical Reaction Mechanism | Nandiyanto *et al.* (2025) |
| 2 | Utilization of Bamboo Powder in The Production of Non-Asbestos Brake Pads: Computational Bibliometric Literature Review Analysis and Experiments to Support Sustainable Development Goals (SDGs) | Nandiyanto *et al.* (2024a) |
| 3 | Green Innovation in Brake Pad Production: Harnessing Teak Powder and Clam Shells as Sustainable Alternatives for Subtractive Residual Waste. | Nandiyanto *et al.* (2024b) |
| 4 | Sustainable biochar carbon microparticles based on mangosteen peel as biosorbent for dye removal: Theoretical review, modelling, and adsorption isotherm characteristics. | Nandiyanto *et al.* (2023a) |
| 5 | Adsorption isotherm characteristics of calcium carbon microparticles prepared from chicken bone waste to support sustainable development goals (SDGs). | Nandiyanto *et al.* (2023b) |
| 6 | Computational calculation of adsorption isotherm characteristics of carbon microparticles prepared from mango seed waste to support sustainable development goals (SDGs). | Nandiyanto *et al.* (2023c) |
| 7 | A comprehensive study on biochar production, bibliometric analysis, and collaborative teaching practicum for sustainable development goals (SDGs) in Islamic schools. | Ramdhani *et al.* (2023) |
| 8 | Project effectivity of adsorbent from food waste for handling wastewater as a learning strategy to learning achievement of education for sustainable development and inquiry abilities. | Anggraeni *et al.* (2023) |
| 9 | Biomass Composition (Cassava Starch And Banana (Musa Sp.) Peels) On Mechanical And Biodegradability Properties Of Bioplastics For Supporting Sustainable Development Goals (SGDs). | Ragadhita *et al.* (2023) |
| 10 | Low-carbon food consumption for solving climate change mitigation: Literature review with bibliometric and simple calculation application for cultivating sustainability consciousness in facing sustainable development goals (SDGs) | Nurramadhani *et al.* (2024) |
| 11 | Smart learning as transformative impact of technology: A paradigm for accomplishing sustainable development goals (SDGs) in education. | Makinde *et al.* (2024) |
| 12 | Analysis of student’s awareness of sustainable diet in reducing carbon footprint to support sustainable development goals (SDGs) 2030. | Keisyafa *et al.* (2024) |
| 13 | Safe food treatment technology: The key to realizing the sustainable development goals (SDGs) zero hunger and optimal health | Rahmah *et al.* (2024) |
| 14 | Implementation of sustainable development goals (SDGs) no. 12: Responsible production and consumption by optimizing lemon commodities and community empowerment to reduce household waste | Maulana *et al.* (2023) |
| 15 | Sustainable packaging: Bioplastics as a low-carbon future step for the sustainable development goals (SDGs). | Basnur *et al.* (2024) |
| 16 | The relationship of vocational education skills in agribusiness processing agricultural products in achieving sustainable development goals (SDGs) | Gemil *et al.* (2024) |

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p- ISSN 2528-1410 e- ISSN 2527-8045

## 2. METHODS

The methodology section elucidates the systematic approach adopted for analyzing recent developments in modifying wind turbine airfoils and blades. This section outlines the step-by-step process, encompassing database selection, search strategy formulation, criteria for inclusion, and analytical methodologies employed to discern prevalent themes and trends across the literature. Referencing **Figure 1**, a visual understanding of the comprehensive methodology is presented. To support this analysis, several nomenclatures are presented in **Table 3**.

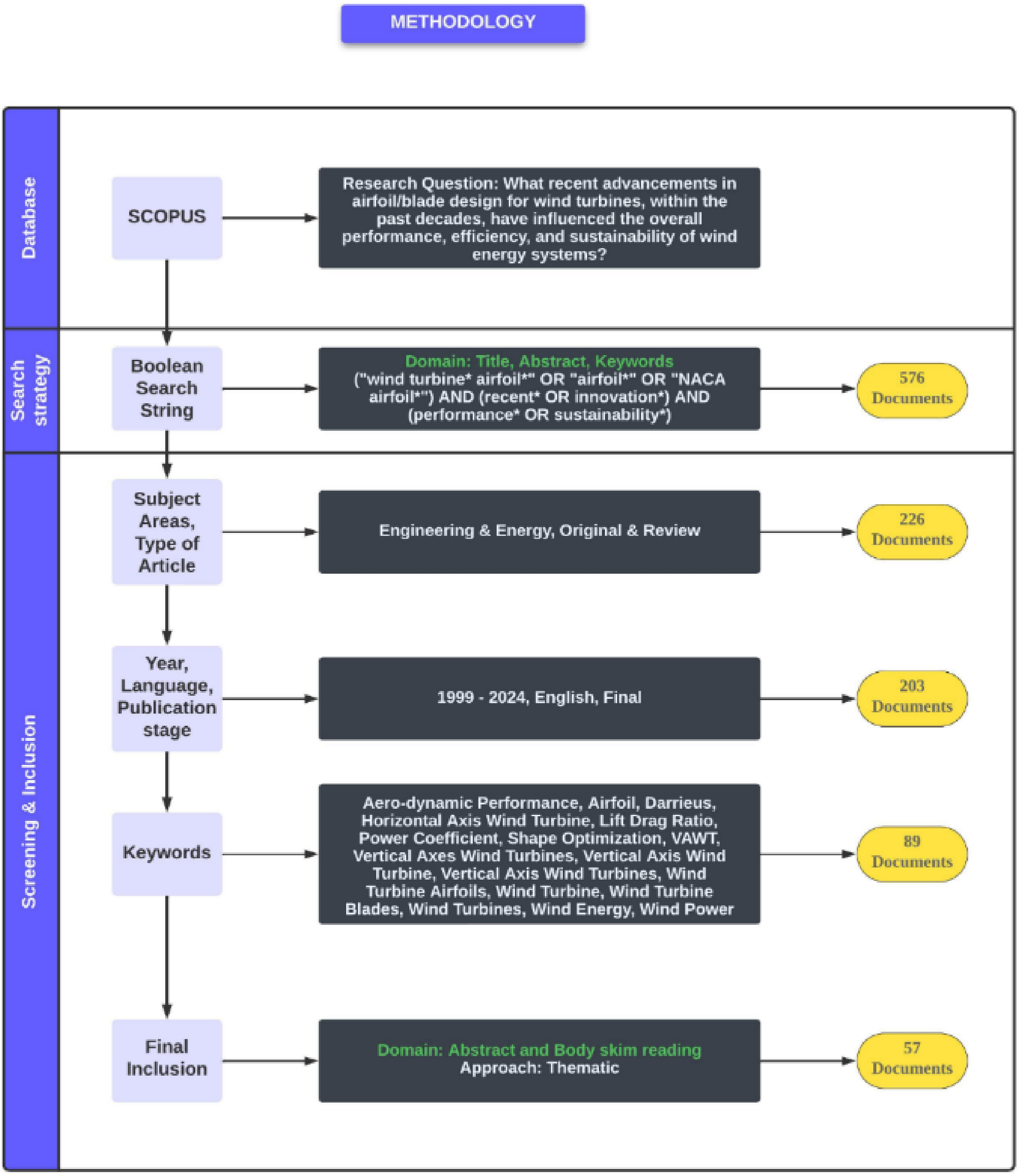


**Figure 1**. Methodology overview: Systematic review of wind turbine airfoil studies.

DOI: https://doi.org/10.17509/ijost.v9i3.72369
p- ISSN 2528-1410 e- ISSN 2527-8045

**Table 3.** Nomenclature.

| Symbol | Note |
|---|---|
| 2D | 2-Dimensional |
| 3D | 3-Dimensional |
| AEP | Annual Energy Production |
| ALM | Actuator Line Method |
| BEM | Blade Element Momentum |
| $C_d$ | Drag Coefficient |
| CFD | Computational Fluid Dynamics |
| $C_l$ | Lift Coefficient |
| $C_l/C_d$ | Lift-to-Drag Ratio |
| $C_M$ | Pitching Moment Coefficient |
| $Cp$ | Power Coefficient |
| DNS | Direct Numerical Simulation |
| FEH | Flutter-Based Energy Harvesters |
| FEM | Finite Element Method |
| FOWT | Floating Offshore Wind Turbine |
| GRP | Glass Fiber Reinforced Plastics |
| HAWT | Horizontal Axis Wind Turbine |
| LEFS | Leading Edge Flow Sensing |
| LER | Leading Edge Roughness |
| LES | Large Eddy Simulation |
| MAV | Micro Air Vehicle |
| MOGA | Multi-Objective Genetic Algorithm |
| MT | Micro Tab |
| RCC | Ratio of Airfoil Chord Length to Rotor Circumference |
| Re | Reynolds Number |
| RES | Renewable Energy Source |
| TKE | Turbulent Kinetic Energy |
| TSR | Tip Speed Ratio |
| VAWT | Vertical Axis Wind Turbine |
| VG | Vortex Generator |

### 2.1. Database

In our investigation, the selection of the appropriate database was crucial for accessing relevant documents. Scopus was chosen as the preferred database due to its extensive collection across the scientific field, surpassing alternatives like Web of Science. Its intuitive interface enables straightforward data export, streamlining subsequent analyses. Offering both basic and advanced search functionalities, Scopus accommodates complex queries, ensuring the validity of the research objectives. Its versatile search criteria, spanning titles, abstracts, journal names, authors, and affiliations, rendered it well-suited for our literature review on wind energy.

### 2.2. Search Strategy

The next step in this systematic review involved crafting the Boolean search strategy. This literature search utilized specific search terms to target relevant articles spanning the title, abstract, and keywords sections. These terms included ("wind turbine* airfoil*" OR "airfoil*" OR "NACA airfoil*") AND (recent* OR innovation*) AND (performance* OR sustainability*). Original and review articles published between 1999 and 2024, written in English, and in the final publication stage were selected in the survey. The search was confined to the subject areas of Engineering and Energy.

The specific keywords selected to match the research objective encompassed terms like "Aero-dynamic Performance," "Airfoil", "Darrieus", "Horizontal Axis Wind Turbine", "Lift Drag Ratio", "Power Coefficient", "Shape Optimization", "VAWT", "Vertical Axes Wind Turbines", "Vertical Axis Wind Turbine", "Vertical Axis Wind Turbines", "Wind Turbine Airfoils", "Wind Turbine", "Wind Turbine Blades", "Wind Turbines", "Wind Energy", and "Wind Power". This comprehensive search strategy ensured a thorough exploration of relevant literature on wind turbine efficiency and innovation over the past two decades.

### 2.3. Result

The initial search yielded 88 documents in total. After filtering out articles unrelated to our research question regarding recent developments in airfoil/blade design for wind turbines over the past decade, which have impacted the overall performance, efficiency, and sustainability of wind energy systems, the final list was narrowed down to 57 documents. This process involved scrutiny to ensure that only the most relevant and influential studies were included for analysis, thereby refining the scope of our investigation, and enhancing the quality of our findings.

### 2.4. Bibliometric Indicators

VOSviewer is a sophisticated software application tailored for constructing and illustrating bibliometric networks, which serve to map relationships among diverse entities within the scholarly literature. These entities encompass journals, researchers, or specific publications, with networks formed based on citation patterns, bibliographic coupling, co-citation, or co-authorship associations. Moreover, VOSviewer offers robust text mining functionalities, enabling users to extract and visualize networks representing the co-occurrence of significant terms within the scientific literature corpus. Detailed information on how to use VOSviewer is explained elsewhere (Al Husaeni & Nandiyanto, 2022b). Examples of reported papers on the use of bibliometric analysis are presented in **Table 4**.

The network visualization as shown in **Figure 2** showcases the evolution of wind turbine research using the most repeated keywords, offering insights into the major changes occurring in the field, based on the initial 576 documents identified through the Boolean search. After conducting the literature search and selecting relevant documents, network visualization and overlay visualization techniques were employed as shown in **Figure 3** and **Figure 4** to analyze and interpret the relationships and patterns within the chosen articles.

Overlay visualization in bibliometric analysis involves adding extra details like keywords onto a bibliometric network, helping researchers see connections and patterns. It helps uncover trends and clusters in the literature related to specific variables. The subsequent structuring of this article was based on the most frequently occurring keywords extracted from these documents. This method ensures that the content is organized around the prevalent themes and topics identified in the literature, enabling a thorough examination of recent advancements in airfoil/blade design for wind turbines and their influence on the performance, efficiency, and sustainability of wind energy systems.

DOI: https://doi.org/10.17509/ijost.v9i3.72369
p- ISSN 2528-1410 e- ISSN 2527-8045

**Table 4.** Previous studies on bibliometric analysis.

| No | Title | Ref |
|---|---|---|
| 1 | A computational bibliometric analysis of science education research using VosViewer. | Maryanti *et al.* (2023) |
| 2 | Sustainable development goals (SDGs) in science education: definition, literature review, and bibliometric analysis | Maryanti *et al.* (2022) |
| 3 | Particle size and pore size of rice husk ash on the resin-based brake pads performance: experiments and bibliometric literature review | Nandiyanto *et al.* (2022) |
| 4 | Bibliometric computational mapping analysis of publications on mechanical engineering education using VosViewer | Al Husaeni & Nandiyanto (2022a) |
| 5 | Bibliometric analysis of engineering research using VosViewer indexed by Google Scholar | Nandiyanto & Al Husaeni (2022) |
| 6 | A bibliometric analysis of chemical engineering research using vosviewer and its correlation with Covid-19 pandemic condition | Nandiyanto *et al.* (2021) |
| 7 | Evaluation on research effectiveness in a subject area among top class universities: A case of Indonesia's academic publication dataset on chemical and material sciences. | Nandiyanto *et al.* (2020) |
| 8 | Digital content contribution of earth and space phenomena to science during 2003-2023: Bibliometric Analysis | Saminan *et al.* (2023) |
| 9 | The future of beauty innovations in face reconstruction and airbrush makeup technology completed with bibliometric analysis | Sakti *et al.* (2024) |
| 10 | Research trends of mental models and opportunity in science education: A Bibliometric Analysis | Ashel *et al.* (2023) |
| 11 | Trends on augmented reality in education: Bibliometric analysis and visualization using r studio | Supriyadi *et al.* (2023) |
| 12 | Research trends about STEM of internet of things for science teachers: A bibliometric analysis | Susilawati *et al.* (2023) |
| 13 | Research trends of control accounting systems in the industry: A bibliometric analysis | Anwar *et al.* (2023) |
| 14 | Bibliometric analysis of the legal issues relating to artificial intelligence technology in tourism | Roestamy *et al.* (2023) |
| 15 | Bibliometric analysis of near field communication technology using VosViewer application with Publish or Perish | Saputra *et al.* (2023) |
| 16 | Using VosViewer for a bibliometric computational mapping analysis of publications on communication technology | Febrianto *et al.* (2023) |

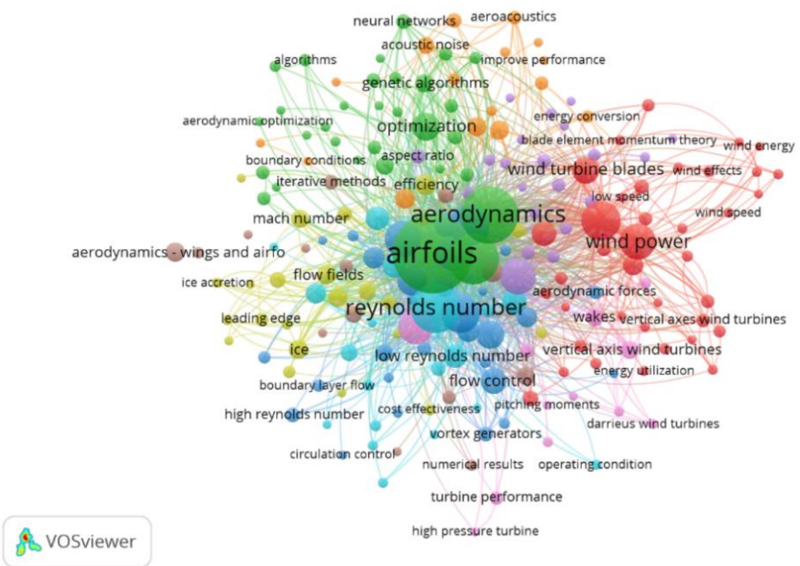


**Figure 2.** Network visualization map: Literature after initial boolean search (576 articles).

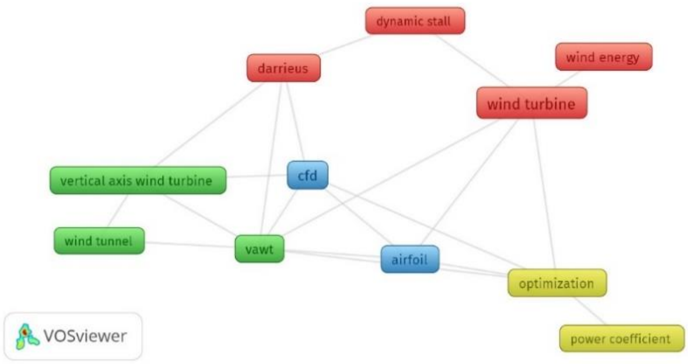


**Figure 3.** Network visualization map: Selected literature over the past 25 years.

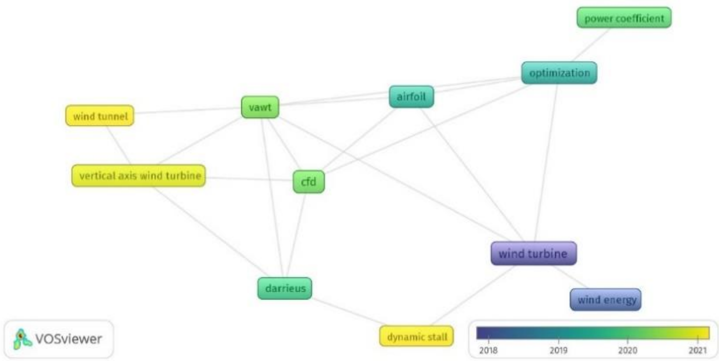


**Figure 4.** Overlay visualization map: Selected literature over the past 25 years.

## 3. RESULTS AND DISCUSSION

### 3.1. Exploring Review Articles: Unveiling Insights

Examining review articles is significant because they offer an in-depth understanding of the field by condensing existing knowledge and highlighting recent trends. These articles offer insightful analyses, pinpointing areas for further investigation and guiding future research endeavors. Moreover, review articles serve as valuable assets for literature searches, streamlining the process for researchers.

In a review conducted by Balat (2009), the focus underscored the pivotal role played by expansive, contemporary wind turbines engineered to optimize wind interaction, thereby maximizing overall efficiency. The narrative emphasized the incorporation of cutting-edge developments in materials, engineering, electronics, and aerodynamics within the realm of modern wind technology. A noteworthy finding was that a standard wind turbine possessed the capability to generate an annual output ranging from 1.5 to 4.0 million kWh of electricity. The operational range was between wind speeds of 3 to 4 m/s, gradually escalating to 25 to 30 m/s, contingent upon the specific manufacturer and model. Furthermore, according to the study, the widely favored design featured a three-bladed rotor with actively yawed upwind rotors, a low-speed shaft intricately linked to a gearbox, and an estimated operational lifespan of 20 years. The operational wind speed from the above review provides only a broad understanding of wind turbine performance across varying conditions, though specific site and turbine characteristics could further contextualize these findings. For the applicability of wind turbines for low-speed conditions, a much deeper understanding of the flow phenomena needs to be obtained.

A review conducted by Ponta *et al.* (2014) explored the evolution, recent advancements, and prospects of the adaptive-blade concept for wind turbines. The focus was on rotors

DOI: https://doi.org/10.17509/ijost.v9i3.72369
p- ISSN 2528-1410 e- ISSN 2527-8045

capable of automatically adjusting to weather and operational conditions, reducing the need for an active control system. The concept involves inducing coupling among deformation modes like bending and twisting to manage power production, minimize vibration and loads, and enhance fatigue performance. Two approaches were presented: structural adaptiveness, involving changes to internal layout and material distribution, and geometrical adaptiveness, which redesigns the blade's curved shape. The study highlighted the potential of passive pitch control, utilizing inherent rotor forces for bend-twist coupling, and optimizing the advantages of structural adaptiveness. This review article thoroughly explored the concept, covering its evolution, contemporary advancements, and future trajectories. The study emphasized the integration of structural and geometrical adaptiveness, highlighting the role of passive pitch control in optimizing structural adaptiveness.

Another review by Martini *et al.* (2022), extensively examined the application of the Quasi-3D simulation method in assessing power loss caused by icing in wind turbines. It synthesized findings from diverse studies, enhancing the understanding of estimating annual power production loss in iced wind turbines. The research highlighted the limitations of fully 3D simulations for rotating turbines in icing conditions, emphasizing the practicality of the Quasi-3D steady-state simulation with lower computational costs. Numerical simulation is vital in wind turbine research for several reasons. It enables the modeling and analysis of complex aerodynamic phenomena, predicting parameters like power output and structural loads where unfavorable conditions like low wind speed, icing, and erosion exist. By reducing the need for extensive physical testing, it accelerates development and aids in optimizing turbine designs, ultimately improving performance and reliability.

In the context of recent research on flutter-based energy harvesters (FEHs), three categories based on flat plate, airfoil, and flexible body. The exploration encompassed the presentation of relevant concepts and theoretical models for each category. The study then categorized advancements in improving FEH performance, highlighting structural enhancements, optimization strategies, the incorporation of nonlinearity, and the integration of hybrid structures and mechanisms. The review succinctly summarized the primary challenges encountered by FEHs and provided insights into potential future research directions. A notable emphasis was placed on acknowledging the importance of considering unstable airflow in the development and application of FEHs. This consideration arises from the recognition that harvester outputs may exhibit instability in such environments, presenting challenges for electrical energy storage.

A comprehensive literature review conducted a thorough examination of wind turbine blade aerodynamics, aero-acoustics, and structural properties under diverse operational scenarios. It explored methods to enhance turbine efficiency through active and passive flow control devices and biomimetic adaptations. Various experimental and numerical techniques for optimizing wind turbine performance were thoroughly discussed. Recommendations were made for further research, including a design guideline for low-speed wind turbine blade applications (Krishnan *et al.*, 2023). Shi *et al.* (2023) conducted a systematic review of the historical evolution, present state, and emerging trends in floating wind energy technology and model testing methodologies. The researchers outlined advancements in real-time calculations of numerical substructures, loading of physical substructures, and signal acquisition and transmission. Future research directions, encompassing numerical simulations, physical modeling, communication protocols, and error handling in real-time hybrid model tests, were summarized.

Sharma and Goyal (2023) provided a critical assessment of flow control methods for improving wind turbine efficiency and addressed the dynamic stall formation mechanism and its impact on VAWT performance. Recent advancements in mitigation techniques, which boosted the power coefficient by 50-60%, were emphasized. It outlined key factors influencing performance and stability enhancement in VAWTs, covering objective functions, design constraints, airfoil dynamics, models, flow control, and optimization techniques. Various mitigation approaches were analyzed to determine their effectiveness. Overall, the review offered a comprehensive understanding of the challenges and strategies involved in VAWTs, laying the groundwork for further research to optimize aerodynamic performance.

In conclusion, the review articles surveyed in this section offer a rich tapestry of insights into various facets of wind energy research. They delve into topics such as blade aerodynamics, flutter-based energy harvesters, and flow control methods for wind turbines. These reviews provide a comprehensive overview of recent advancements, challenges, and future directions in the field. By synthesizing findings from multiple studies, they contribute to a deeper understanding of wind energy technology, paving the way for further innovation and optimization in the quest for sustainable energy solutions. Furthermore, the need to make wind energy feasible in adverse climates underscores the importance of employing innovative methods, as highlighted by these reviews.

### 3.2. Exploring Review Articles: Unveiling Insights

#### 3.2.1. Horizontal axis wind turbine (HAWT)

A horizontal axis wind turbine (HAWT) is one where the main rotor shaft and electrical generator are oriented horizontally. In HAWTs, the turbine blades rotate around an axis parallel to the base. These turbines are commonly used in large-scale wind farms and are designed to capture wind energy efficiently for electricity generation. This section will comprehensively explore the advancements and innovations shaping the landscape of HAWTs.

A study concentrated on the localized design of wind rotor blades using Glass fiber Reinforced Plastics (GRP) in Jordan. The authors detailed the selection method for airfoil sections tailored for small turbines, specifically those measuring up to 5 m in length. A unique approach was proposed, advocating the use of two different airfoils for the entire span. While the use of GRP was highlighted for rotor blade manufacturing, a critical perspective arose from the limitations of the study. Firstly, the concentration solely on Jordan might have limited the generalizability of the findings to a broader context. Additionally, the research utilized methods that might not be considered contemporary in the present scenario, raising questions about the applicability of the study in the rapidly advancing field of wind energy technology. Despite this, the paper underscored the importance of fostering a connection between local scientific endeavors and industries to bolster the production of viable wind energy technology and increase Jordan's participation in the emerging wind energy industry (Habali & Saleh, 2000b). In continuation to the study producing and testing a rotor blade made from GRP, for a wind rotor, 15 kW capacity connected to the grid, was done. The blade effectively cleared the necessary assessments achieving a favorable power coefficient (Cp) of 41.2% when incorporated into an operational wind turbine (Habali & Saleh, 2000b). Investigating the performance of a smaller-capacity HAWT, a study assessed four airfoils (NACA 4412, SG6043, SD7062, and S833) using QBlade. Results demonstrated superior overall Cp of the NACA 4412 airfoil compared to the other airfoils (Said *et al.*, 2019).

The icing of wind turbine blades arises when water droplets freeze upon contact with the blades, leading to the formation of ice deposits. This accumulation results in a modification of the aerodynamic profile, thereby perturbing airflow and inducing drag. Exploring the effects of atmospheric icing on wind turbine aerodynamics and structural integrity, a study by

DOI: https://doi.org/10.17509/ijost.v9i3.72369
p- ISSN 2528-1410 e- ISSN 2527-8045

Lagdani *et al.* (2021) utilized the QBlade software for the aerodynamic analysis of the NACA 4412 airfoil. Comparative evaluations were conducted between clean and iced airfoil profiles. The structural behavior of a wind turbine blade, featuring 100 mm of ice thickness, was simulated using ABAQUS software. A detailed comparative study considered two composite materials (Carbon and Glass fibers) and two blade positions to assess their impact on the blade's performance. The study identified failure modes and pinpointed the most sensitive areas within the structure. Results indicated a notable degradation in both aerodynamic and structural performance when ice accumulated on the blade leading edge, altering its shape. Employing a low-speed subsonic wind tunnel, Prasad investigated how different ice shapes influenced aerodynamic coefficients across various angles of attack and wind speeds. The methodology included the creation of prototypes based on ice shapes observed through Infrared Thermography, with results validated through numerical simulations. The study utilized a tracing method to document the geometric and aerodynamic characteristics of ice accretion. By computing friction coefficients for various ice shapes and geometries, the authors assessed their effects on lift and drag coefficients under freezing-drizzle exposure conditions.

An investigation was conducted to assess the impact of blade rotor diameter and airfoil section on the output of small wind turbines. Utilizing CFD, four distinct airfoils (NACA 0012, NACA 0015, NACA 4412, and NACA 4415) and three rotor diameters (50,75, and 100 cm) were analyzed for their influence on aerodynamic performance. The study provided a detailed examination of aerodynamic characteristics, highlighting the superior lift-to-drag ratio of the NACA 4412 airfoil. Power output for each airfoil and rotor diameter size combination was determined, with the NACA 4412 airfoil demonstrating the highest power output at 1.947 W under specific tapered geometry at a rated speed of 4 m/s (Yossri *et al.*, 2021).

Nakhchi *et al.* (2021) aimed to develop direct numerical simulations (DNS) for a detailed examination of wind turbine blade aerodynamics. Utilizing the spectral/hp element method, the simulations were designed to capture intricate flow separation details over NACA 4412 airfoil wind turbine blades, considering a diverse range of design parameters. The research addressed the inherent challenges in experimental methods to accurately capture flow instabilities and pressure fluctuations in the separated shear layer of wind turbines. High-resolution DNS results successfully portrayed vortex structures, the evolution into fully turbulent flow downstream of the trailing edge, and the correlation of increased pressure fluctuation with the angle of attack.

In a more recent investigation, an innovative approach to designing turbine models for wind tunnels was introduced, employing a genetic algorithm. The main objective was to optimize the thrust performance of blades, ensuring equivalent thrust at various wind velocities. The study utilized the DTU 10 MW and NREL 5 MW wind turbines as case studies to validate the applicability of the methodology. Three distinct methods for shape control were implemented to adjust chords and twist angles during the design process, and their effects were differentiated. The aerodynamic performance analysis demonstrated consistent agreement with the prototypes throughout the wind speeds tested (Ma *et al.*, 2022).

To conclude, this section delved into various aspects of HAWT research, spanning design, testing, and performance assessment through diverse methodologies. Numerical techniques emerge as pivotal in supplementing real-time experiments, offering profound insights into intricate phenomena and advancing our comprehension of wind turbine dynamics and efficiency. Investigations on blade design underscore the importance of Indigenous innovation in advancing wind energy technology, while studies on icing impacts and blade aerodynamics offer critical solutions for navigating challenges in unfavorable weather

DOI: https://doi.org/10.17509/ijost.v9i3.72369
p- ISSN 2528-1410 e- ISSN 2527-8045

conditions. Collectively, these endeavors propel the enhancement of HAWT efficiency and dependability, bolstering its viability for integration into sustainable energy systems.

#### 3.2.2. Vertical axis wind turbine (VAWT)

A vertical-axis wind turbine (VAWT) contrasts with the horizontal model as its main rotor shaft and electrical generator are vertically aligned. VAWTs harness wind energy from all directions by rotating around a vertical axis, making them ideal for regions with modest wind speeds and minimal starting torque. Despite horizontal axis turbines dominating large-scale wind farms, VAWTs demonstrate practical benefits in low-wind settings and display versatility. This segment will delve into recent progress and innovations propelling the development of VAWTs, emphasizing their distinct attributes and uses.

In a recent investigation, a three-bladed H-rotor was designed using an unsymmetrical cambered S818 airfoil to achieve self-starting capabilities at various azimuthal angles. Integrated into a hybrid system with a Savonius rotor as a starter, the H-rotor demonstrated full self-starting capability. Rigorous wind tunnel experiments were conducted to optimize power performance at different Re and overlap conditions in the Savonius rotor part. Comparative analysis revealed that the hybrid rotor outperformed the simple H-rotor, achieving a maximum Cp of 0.34 at the optimal 0.15 overlap, compared to 0.28 for the simple H-rotor (Bhuyan & Biswas, 2014).

Bianchini *et al.* (2016) focused on the behavior of symmetric airfoils in Darrieus wind turbine blades, revealing virtually cambered characteristics due to orthogonal axis rotation. Symmetric airfoils exhibited a counterintuitive nonsymmetric starting torque, contrasting conventional theories relying on single-dimensional aerodynamic coefficients. The often-neglected pitching moment in lumped parameters models played a substantial role in torque output, emphasizing the need to consider it across the entire power curve and optimize the blade-spoke connection point for performance and stress reduction. The findings also suggested implications for low-order simulation models, necessitating different temporal and spatial discretization for various tip-speed ratios (TSR) in the power curve. Exploring the phenomenon of virtual incidence generated by the curved streamline approaching Darrieus wind turbine blades, another investigation introduced a unique computational method for determining the incidence angle. The authors compared effective angles of attack with theoretical expectations, quantifying virtual incidence across different airfoils, chord-to-radius ratios, and TSRs. The study provided a comparative analysis of the predictive capabilities of Blade Element Momentum (BEM) codes concerning virtual incidence (Bianchini *et al.*, 2016).

Continuing with the above researchers aimed to enhance Darrieus VAWTs' efficiency through CFD simulations and wind tunnel experiments, providing a detailed understanding of the aerodynamics around a rotating Darrieus turbine. Utilizing a validated 2D Unsteady numerical model for an H Darrieus VAWT of small scale, this study systematically compared simulations with wind tunnel experimental data. Emphasis was placed on analyzing the wake structure and correlating flow macro-structures, revealing good agreement between simulated and experimental turbine performance estimation. Furthermore, the investigation incorporated numerical results from a prior 3D study to address tip losses in the analysis (Bianchini *et al.*, 2018).

Exploring the aerodynamic behaviors of Darrieus VAWTs in turbulent flows has been a subject of significant interest. Balduzzi *et al.* (2020), utilizing both numerical simulations and wind tunnel experiments, delved into the complex dynamics associated with the operation of a two-blade Darrieus VAWT under varying turbulence conditions. The study also introduced

DOI: https://doi.org/10.17509/ijost.v9i3.72369
p- ISSN 2528-1410 e- ISSN 2527-8045

an engineering simulation tool capable of predicting VAWT rotor performance amid turbulent conditions. Specifically targeting medium-small machines characterized by low Re and airfoil transitions, the research identified key phenomena, transition, and turbulence intensity increase, as pivotal factors shaping the aerodynamics and energy conversion capabilities of small Darrieus VAWTs in turbulent environments. Another study (Mohamed *et al.*, 2021), through a 2D CFD investigation, has gained potential interest in the research of VAWTs. Utilizing the ANSYS FLUENT solver with sliding mesh and Six Degrees of Freedom (6DOF) to simulate fluid-structure interaction to understand the substantial impact of drag force on Darrieus turbine start-up, emphasizing the necessity of reliable lift and drag coefficient data. The study deepened insights into Darrieus turbine start-up aerodynamics, with potential implications for optimization.

Examining the numerical simulation and experimental characterization of VAWTs, Rahromostaqim *et al.* (2016) investigated the flow dynamics around a pitching airfoil (Eppler 387). Utilizing Large Eddy Simulation (LES) modeling, the study delved into the analysis of force coefficients, vortex behavior, and the impact of pitching frequency and amplitude on force generation. Notably, the findings indicated a correlation between higher pitching frequencies and amplitudes with increased forces (Rahromostaqim *et al.*, 2016). In another research, the primary focus was on addressing torque ripple, a notable operational challenge observed in VAWTs, potentially leading to fatigue-related failures. The study introduced a pioneering blade design, optimized through genetic algorithms and CFD simulations, to alleviate torque fluctuations. The inventive surface distortion approach exhibited superior performance compared to conventional pitching solutions, achieving a remarkable 25% decrease in torque ripple with only a 17% decrease in CP. A practical and efficient solution for enhancing the life cycle without compromising the efficiency of VAWTs was provided in the study (Erfort *et al.*, 2021).

In a recent investigation the validation of a custom three-component external strain gauge balance, specifically designed for airfoil testing, was undertaken. The investigation delved into physical factors causing disparities with literature data, exploring lift and drag coefficients, pitching moments, and instantaneous forces for various configurations, including the DU06-W-200 airfoil. Critical factors influencing measurements were identified, and recommendations for future enhancements were made. The new balance design was thoroughly assessed, emphasizing its significant potential for VAWT applications (Santamaría *et al.*, 2022). Tong *et al.* (2023) examined how airfoil chord length and rotor diameter affect the performance of straight-bladed VAWTs using numerical simulation. It introduced a dimensionless parameter, RCC (ratio of airfoil chord length to rotor circumference), to assess this influence. Recommended RCC values were suggested for different scenarios: approximately 8% with constant airfoil chord length and changing rotor diameter, and between 9.5% and 13.4% with constant rotor diameter and changing airfoil chord length.

To summarize, this section encapsulated a breadth of research endeavors aimed at advancing VAWT technology. Studies have delved into various aspects, from blade design and aerodynamics to the optimization of performance under different conditions. The findings revealed innovative approaches to enhance VAWT efficiency, such as the integration of hybrid rotor systems and the utilization of advanced CFD simulations. Additionally, investigations into aerodynamic behaviors in turbulent flows and the mitigation of operational challenges like torque ripple underscore ongoing efforts to refine VAWT design and operation. Collectively, these studies contributed to a deeper understanding of VAWT dynamics and offer valuable insights for further advancements in this field.

DOI: https://doi.org/10.17509/ijost.v9i3.72369
p- ISSN 2528-1410 e- ISSN 2527-8045

### 3.3. Understanding Operational Factors: Research Insights
#### 3.3.1. Force parameters

The upcoming section explores a range of research articles that investigate lift, drag, and lift-to-drag coefficients. Studies employ numerical simulations and experiments to improve the efficiency of aerodynamic systems like wind turbine blades and airfoils. Topics include optimizing airfoil shapes, using flow control devices, and exploring bio-inspired designs. Through detailed analysis and innovative methods, these studies help advance our understanding and promote the development of sustainable solutions.

An investigation was undertaken to perform numerical simulations on a symmetrical NACA 0005 airfoil subjected to combined pitching-plunging motions at low Re. The simulations confirmed the generation of regular vortices on both upper and lower surfaces during airfoil flapping. Additionally, a preliminary study of flows around an insect-like wing revealed persistent 3D flow separation on the wing surfaces, challenging computational convergence. The research also noted that 2D computations of a representative wing cross-section tended to over-predict forces compared to a real low aspect-ratio 3D wing. This understanding of complex aerodynamic behaviors at low Re could offer valuable insights for enhancing the efficiency of wind turbines operating under low-speed conditions (Yuan *et al.*, 2010).

Chen and Agarwal (2013) focused on optimizing flatback airfoils for large turbine blades using a multi-objective genetic algorithm (MOGA) to maximize both CL and CL/CD ratio. The study demonstrated that MOGA outperformed single-objective genetic algorithms, yielding globally optimal flatback airfoils with superior aerodynamic properties. The findings suggested the potential application of MOGA for optimizing other types of wind turbine blades. The conclusion highlighted two significant contributions: the efficiency and accuracy of MOGA in producing globally optimal airfoils and its potential for enhancing the performance of 3D rotor blades.

Another exploration focused on enhancing the aerodynamic performance of wind turbine blades using a flow control device. The S809 airfoil model, simulated using Ansys Fluent, exhibited good agreement between steady-state computational and previously published experimental results. The flow control effectiveness was explored by adjusting parameters like jet slot position, jet angle, and jet magnitude. Optimal performance was observed when the start position of flow separation matched the slot position, showcasing significant flow control effects. The study concluded that the flow control device demonstrated the best performance with specific jet parameters and slot positions, contributing valuable insights to enhance wind turbine efficiency (Kang & Park, 2013).

Conducting numerical computations, Hirata et al. (2016) explored the aerodynamic traits of high-performance airfoils at extremely low Re (Re = 1×102). Three high-performance airfoils, iNACA0015 (inverted NACA0015), FPBi (iNACA0015 airfoil with flat plate blended as its lower half), and FPBN (NACA0015 airfoil blended with flat plate blended as lower half) were compared with base airfoils (flat plate and NACA0015). The results highlighted the superior performance of the FPBi airfoil among the five tested. The study provided a summary of the aerodynamic characteristics and observed that the aerodynamic features of all five airfoils exhibited qualitative similarity.

Investigating the aerodynamic effects of innovative denticle-inspired patterns on the suction side of an airfoil, Domel *et al.* (2018) combined both experimental and simulation-based approaches. The study revealed a range of denticle-inspired surface configurations that achieved a simultaneous reduction in drag and increase in lift on an airfoil, showing improvements in lift-to-drag ratios comparable to the best-performing traditional low-profile

DOI: https://doi.org/10.17509/ijost.v9i3.72369
p- ISSN 2528-1410 e- ISSN 2527-8045

vortex generators. Particularly noteworthy was the superior performance of these new designs at low angles of attack, demonstrating enhancements of up to 323%. The research identified two simultaneous mechanisms contributing to this enhanced aerodynamic performance: a separation bubble in the wake of the denticle altering the pressure distribution of the flow, and streamwise vortices replenishing momentum loss in the boundary layer caused by skin friction. In another research (Jo & Majid, 2022), the application of bio-inspired morphing wings in MAVs was investigated, focusing on the potential benefits of mimicking avian wing morphologies. The study employed a combination of experimental testing and computational simulations to explore the aerodynamic advantages and improved performance associated with morphing wing designs. The research aimed to enhance the understanding of how bio-inspired morphing wings could contribute to the efficiency and agility of MAVs, offering valuable insights for the development of more effective aerial vehicles.

Exploring the performance enhancement of leading-edge slotted cambered airfoils through both computational simulations and practical experiments, a recent investigation conducted optimization studies and design of experiments on five crucial design factors including slot width or thickness, length, exit angle, inlet angle, and vertical position, to evaluate their impact on lift and lift-to-drag ratio. The study highlighted the significant influence of three design variables, length, inlet angle, and vertical position, on lift and lift-to-drag ratio, while the remaining two variables showed comparatively lesser impact (Beyhaghi & Amano, 2019). Examining the interface between fluid flow and a plasma actuator within wind turbine blades, Omidi *et. al.* (2020) introduced a numerical model with a specific focus on enhancing the aerodynamics of DU21 wind turbine blade airfoils. The authors investigated the influence of various geometric parameters and dielectric materials on the plasma actuator's performance, considering factors such as embedded electrode length and electrode thickness, material, and dielectric thickness. The study revealed distinct limits of each parameter, indicating that further increases beyond these limits did not significantly impact the actuator's performance. For example, there were upper limits for both the length of the embedded electrode and the dielectric permittivity. The results underscore the effectiveness of the improved electrostatic model in modeling various parameters and guiding the optimization of wind turbine blade designs. A novel approach was presented by Uranai *et al.* (2020) to simulate icing on a 2D airfoil with a heated surface by adapting the extended Messinger model. Experiments were conducted to validate the wall temperature distribution. The study computed aerodynamic performance and ice shape for leading-edge heater-equipped NACA 0012 airfoil. Examining the effect of heating area on lift and drag coefficients revealed significant lift improvement (up to 15%) once the heating area represented 1.0% chord length.

Introducing a novel multipoint infill criterion for adaptive Kriging-based optimization in computationally expensive multi-objective problems, another method, based on Expected Angle-Penalized Length Improvement, demonstrated increased efficiency. With the ability to increase the number of infill points tenfold in each iteration, the new method employed multiple reference vectors for improved optimization speed and performance. The approach balanced diversity and convergence in obtaining non-dominated solutions and accommodated designer preferences for preference-driven optimization. Applied to the NACA 0012 airfoil, the method showcased significant improvements in lift-to-drag ratio, demonstrating its high capacity for practical preference-driven aerodynamic design problems (He *et al.*, 2020).

DOI: https://doi.org/10.17509/ijost.v9i3.72369
p- ISSN 2528-1410 e- ISSN 2527-8045

Exploring the aerodynamic behaviors of distinct airfoil variations, including an actively deformable design and a fluid-solid coupling passive counterpart, through numerical simulations was the focus of a recent investigation. The study scrutinized lift coefficients and the control of vortex generation across these airfoils, considering varying maximum deformation amplitudes and angles of attack. It showcased the achievement of an improved lift-to-drag ratio and the inhibition of surface vortex generation, attributing these enhancements to the incorporation of fluid-solid coupling effects (Hou *et al.*, 2021).

Ballesteros-Coll *et al.* (2021) proposed a pioneering approach for optimizing wind turbines through the introduction of the cell-set model in CFD. This approach enabled the integration of a rotating microtab (MT) onto the trailing edge of the DU91W250 airfoil. The investigation explored the impact of different MT lengths and orientations on airfoil aerodynamic performance, presenting numerical results and performance curves. The findings indicated that increased MT length (h) and rotating angle (β) corresponded to higher performance aerodynamically. The use of a Local Flexible Membrane (LFM) as a passive flow control mechanism for enhancing wind turbine blade aerodynamics and stability was explored recently by Koca *et al*. (2022). An experimental investigation was done in a wind tunnel facility, employing the WASP airfoil in assessing LFM's impact on aerodynamic characteristics and flow-induced vibrations. Results indicated favorable outcomes, including the improvement of the lift coefficient and the reduction of vibrations, particularly at lower angles of attack. However, the LFM did not yield a significant enhancement in power efficiency compared to the uncontrolled airfoil.

In the realm of aerodynamic research, another interesting study introduced the leading-edge flow sensing (LEFS) technique, employing a limited number of pressure points in the leading edge to deduce the state of aerodynamics during periods of unsteady motion. The method presented facilitated the computation of the suction parameter, a measure of the suction force around the leading edge, utilizing specific pressures located at the airfoil's leading edge. The research outlined criteria for identifying vortex shedding-related occurrences, encompassing initiation, pinch-off, and termination events, relying on the variations observed in LEFS outputs and the calculated LESP. Computational and experimental outcomes convincingly affirmed the efficacy of LEFS as a method for instances linked to the shedding of vortices in unsteady airfoils (Saini *et al.*, 2021). Zhao *et al.* (2022) delved into the creation of a convolutional neural network designed for both visual interpretability and precise prediction of aerodynamic forces. The investigation justified the preference for circular padding mode over zero padding mode through a kinetic analysis, providing a more reasonable explanation. An input-output explainability module, incorporating class activation mapping, was introduced to offer direct insights into local mapping relationships and facilitate the optimization of the airfoil shape. The study validated the efficiency and effectiveness of the proposed method through extensive experiments on varied datasets. Furthermore, a saliency map of the predicted aerodynamic force was presented as a more intuitive means to analyze the impact of different airfoil components on the ultimate aerodynamic force.

In brief, the section showcased a range of approaches to enhance aerodynamic performance, in wind turbine blades and airfoils. Employing both active and passive flow control methods alongside sophisticated optimization techniques, scientists have made notable strides in improving lift and lift-to-drag ratios. By emphasizing the importance of optimizing lift-to-drag ratios, these investigations seek to maximize lift while minimizing drag, ultimately driving the development of more effective and sustainable aerodynamic solutions. These advancements hold the potential to transform wind turbine aerodynamics across diverse sectors.

DOI: https://doi.org/10.17509/ijost.v9i3.72369
p- ISSN 2528-1410 e- ISSN 2527-8045

### 3.3.2. Performance metrics

This section provides a thorough examination of essential performance indicators concerning wind turbine blades and airfoils. Ranging from innovative approaches inspired by biomimetics to sophisticated optimization methods, each study endeavors to improve overall turbine functionality. Through computational modeling, experimental validation, and creative designs, researchers strive to optimize vital factors, thereby pushing the boundaries of wind energy generation systems. Addressing variable loads in wind turbines, novel research proposed a strategy inspired by fish locomotion and similar to spoilers and ailerons, involving the variation of blade geometry. A fully integrated method utilized both CFD and Finite Element Method (FEM) techniques, with particular emphasis on analyzing the extensively utilized NACA 4412 blade design. The study aimed to introduce continuous morphing to the blade, evaluating its aerodynamic behavior in a 2D computation, considering factors like material elasticity, wind speed, and trailing edge deflection. Computational results indicated morphing blade outperformed the rigid blade in part-load efficiency, showcasing the potential of this approach for enhancing wind turbine performance (Krawczyk *et al.,* 2013).

Vesel and McNamara (2014) focused on optimizing a turbine rotor blade to minimize the cost of energy by concurrently considering bend-twist coupling and aerodynamics. Several design parameters, including, chord and twist distributions, variations in airfoil shapes, and the extent of bend-twist coupling, were thoroughly examined. A computationally efficient method was employed to predict the bend-twist coupling behavior, utilizing XFOIL for airfoil performance computation and the NREL FAST code for wind turbine loads and performance. The optimization process aimed to minimize the annual cost of energy, assuming that reductions in flap-wise bending loads would lead to decreased turbine costs.

Introducing a discrete optimization method tailored to low wind speed sites, a recent investigation considered aerodynamic and structural parameters as design variables for wind rotor blades. The optimization process included airfoil design using the airfoil integrated theory to enhance both aerodynamic and structural performance. BEM theory assessed the blade's aerodynamic performance, while Classical Laminate Theory estimated stiffness and mass per unit of each blade section. Verification of the optimized blade's strength under extreme loading conditions employed FEM structural analysis. In a case study featuring a commercial 2.1 MW HAWT blade, the results demonstrated improved aerodynamic and structural performance compared to the original blade (Yang *et al.*, 2019).

Investigating the buoyant airborne turbine shell with a NACA airfoil (9415) and variable tip clearance for the blade, a group of researchers examined mass flow rate, aerodynamic coefficients, and generation of the wake turbulence. A diminishing trend in the CP was observed with increased tip clearance at wind velocities from 10 to 20 m/s, while at wind speeds higher than this range, a direct correlation between CP and tip clearance emerged for tip gaps (1-3%) and a decline at wider tip clearances (Saleem & Kim, 2019). Another study explored passive leading-edge slots on airfoil pressure sides to potentially enhance peak and overall lift-to-drag ratio. Employing experimentally validated CFD simulations, the DU12W262 airfoil was analyzed with various slot concepts, including suction side and trailing edge slots. The findings were applied to HAWTs and VAWTs through CFD simulations. It revealed a 3.2% increase in peak power coefficient for HAWTs and a 3.5-9.6% increase for VAWTs (Acarer, 2020). In the exploration of rain-induced erosion's impact on a multi-MW wind turbine, another study quantified associated uncertainties affecting AEP and turbine performance. Sobol indices were employed to identify the most influential uncertainty parameters, aiding in prioritizing accurate uncertainty estimation. The paper presented a probability density function for AEP, elucidating potential values across varying conditions. The analysis extended

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p- ISSN 2528-1410 e- ISSN 2527-8045

to scrutinizing relative differences in main controller parameters, including torque and rotor speed, revealing their respective impacts on wind turbine performance (Papi *et al.*, 2021). De Fezza and Barber (2022) examined the application of multi-element airfoils in airborne wind energy using CFD simulations. The investigation identified the optimal angle of attack, which, at 17°, demonstrated a maximum performance of approximately seven times larger compared to typical airfoils of a single element. A parametric study, involving adjustments to the sizes and angles of separate airfoil elements, revealed a potential performance increase of up to 46.6%.

A new wind turbine structure was proposed by Gao *et al*. (2022), incorporating both drag and lift features, utilizing the NACA 0018 symmetrical airfoil. The study employed a combination of CFD numerical simulation and physical experiments to comprehensively analyze the performance of the innovative design. The research explored the influence of the drag-lift hybrid blade's opening angle factor on self-starting performance, identifying an optimal angle of 80°. Additionally, the study examined the blade morphology switching mechanism and implemented adaptive control using springs. Wind tunnel testing of a physical model confirmed the enhanced wind energy exploitation of the drag-lift design highlighting its promising potential. In the context of wind tunnel model tests for FOWTs, a recent study introduced a unique criterion centered on mapping the optimal TSR and the changing rate of relative TSR. This criterion aimed to enhance the representation of expected dynamic aerodynamics resulting from platform motions. Utilizing the National Renewable Energy Laboratory 5-MW offshore wind turbine as a reference, the authors applied a genetic algorithm to optimize the chord and twist of the model wind turbine. This optimization aimed to maintain consistency in thrust and power coefficients with the reference turbine. Through simulations with the BEM method considering the unsteadiness involved, the study verified the effectiveness of the new similarity criterion across various surge frequencies. The results showcased an enhanced agreement between the new model wind turbine, designed with the new criterion, and the reference turbine in terms of thrust and power coefficients. Furthermore, the new model successfully captured hysteresis effects and demonstrated closer loops to the reference turbine (Wang *et al.*, 2023).

Innovative approaches were explored by Eltayesh *et al.*, (2023) to improve the performance of a Darrieus VAWT using numerical and engineering methods. Rotor hybridization, incorporating an inner Savonius section for start-up assistance, and the potential benefits of adding dimples to enhance NACA 0021 airfoil performance were investigated. These interventions proved effective in maintaining stable performance across various wind conditions. CFD simulations analyzed different hybrid rotor configurations, confirming the model's validity with standard isolated geometries. Results showed that the hybrid turbine with inboard dimples performed better than other configurations, evident from velocity streamlines. Moreover, utilizing inboard and outboard dimples reduced vortex size around airfoils, leading to increased power generation. Another recent study (Wu *et al.*, 2023) introduced a novel turbine design with swept-back flat blades utilizing a NACA0012 airfoil cross-section, enabling effortless pitch adjustment and flow direction adaptation via hydrodynamic forces. Additionally, it proposed a magnetic coupling system for torque transmission in the turbine prototype, enhancing reliability compared to conventional models. The researchers extensively examined the performance of a self-pitching double turbine's front and rear components, comparing them with a single turbine. The design's innovation and feasibility were confirmed through theoretical analysis, simulation, and experimental validation.

DOI: https://doi.org/10.17509/ijost.v9i3.72369
p- ISSN 2528-1410 e- ISSN 2527-8045

Gupta *et al.* (2024) conducted a flow analysis and sensitivity investigation of a VAWT under varying pitching conditions. CFD modeling was applied to examine the flow patterns around the VAWT. The research examined how altering blade pitching influenced the self-starting performance of the VAWT across different TSR types. The study proposed integrating a blade pitching mechanism with any VAWT type to enhance self-starting capabilities at varying TSRs. Furthermore, the authors recommended future investigations using 3D LES to address the 3D impacts of variable blade pitching. In essence, the studies in this section extensively explored the optimization of wind turbine blades and airfoils, extending beyond standard metrics like CL, CD, and CL/CD ratio, which are crucial considerations for real-world application wind turbine design. Apart from AEP, the section discussed other important factors. These include how well turbines work at different loads, the yearly cost of energy, blade strength in tough conditions, power coefficient, hysteresis effect on turbine performance, vortex size around airfoils, and starting ability. Researchers investigated blade features like bend-twist coupling to improve how turbines work at various loads and cut energy costs. Past research also delved into how erosion from rain affects turbine performance and ways to boost overall efficiency by focusing on thrust and power coefficients. Additionally, they worked on reducing hysteresis effects and making turbines easier to start by designing new types and using better methods. These efforts aim to make wind energy systems perform better, last longer, and be more eco-friendly, guiding future developments in the field.

#### 3.3.3. Stall characteristics

Understanding stall is vital as it directly affects wind turbine blade performance, efficiency, and structural integrity. Stall occurs when airflow over an airfoil separates, reducing lift and increasing drag, impacting turbine efficiency and longevity. Methods like CFD simulation and wind tunnel tests help study stall behavior, revealing how factors like surface roughness and passive control methods like vortex generators influence aerodynamics. Analysing stall aids in optimizing turbine design, such as blade shape and airfoil profile, to enhance efficiency across different wind conditions, crucial for advancing wind energy technology and maximizing power extraction.

The aerodynamic performance of airfoils, both without and with leading-edge protuberances, was examined in the presence of surface roughness. Zhang *et al.* (2019) employed a combination of CFD and wind tunnel tests to analyze the impact of surface roughness on airfoil lift and drag coefficients. Results indicated that the airfoil with leading-edge protuberances displayed a more subdued stall behavior, leading to a reduction in fatigue load variation and improved structural stability. In another recent study by Mohamed *et al.* (2022), the implementation of the Actuator Line Method (ALM) for Darrieus VAWTs was explored. Introducing the frozen ALM method, the findings revealed that, for high and medium TSRs, ALM yielded highly accurate solutions for the flow field, nearly equivalent to those obtained through blade-resolved CFD, provided correct aerodynamic forces were utilized. An investigation delved into the combined impact of vortex generators (VG) and leading edge roughness (LER) on dynamic stalls for NREL S809 airfoil. Through CFD simulations, Zhu *et al.* (2022) aimed to discern unsteady flow characteristics and evaluate how VGs and LER influenced the airfoil's aerodynamic performance. Results revealed that LER heightened turbulent kinetic energy (TKE) and suction loss at the leading edge, hastening the onset of separated flow and dynamic stall. Increasing roughness height was associated with a reduced linear lift-curve slope, heightened aerodynamic hysteresis, and hindered reattachment of separated flow. Furthermore, the study demonstrated that VGs elevated near-wall TKE, suppressed separated flow, delayed dynamic stall, and diminished

DOI: https://doi.org/10.17509/ijost.v9i3.72369
p- ISSN 2528-1410 e- ISSN 2527-8045

aerodynamic hysteresis. Emphasis was placed on the superior effectiveness of double-row VGs compared to single-row VGs in enhancing the aerodynamic performance of roughened airfoils.

In pursuit of enhancing Darrieus VAWT performance, another study utilized CFD analysis and optimization with the Kriging model. The research identified specific design parameters, such as a three-bladed turbine with a solidity ratio of 1.2, a symmetrical airfoil with 21% thickness-to-chord ratio, and a high aspect ratio of 0.8, to improve turbine efficiency. Implementing toe-out blades upstream successfully delayed stall conditions at low TSRs, resulting in a 22.4% power increase. Furthermore, the addition of auxiliary blades enhanced turbine starting power by 75.8% and extended its operational range across various TSRs. The study also projected an optimal power coefficient of 0.457 for the optimized turbine design (Asadbeigi *et al.*, 2023). Hao *et al.* (2023) experimentally assessed how varying the height distribution of ramp VGs affected wing aerodynamic properties. Different VG layouts, such as equal height, triangular, and trapezoidal distributions, underwent testing across the wingspan. Optimal VG configurations (Trapezoidal translation 2 and Triangular translation 3) were identified, delaying stall, improving maximum CL, and enhancing CL/CD ratio at high angles of attack. Rough set theory analysis investigated VG height and position effects on wing stalls, providing valuable insights for VG arrangement. Exploring stall characteristics is paramount in advancing wind turbine technology, as it directly influences the efficiency and reliability of turbine operation. Understanding these dynamics enables the optimization of turbine design parameters and the implementation of innovative solutions to enhance aerodynamic efficiency and extend turbine lifespan. In summary, an in-depth examination of stall phenomena is crucial for driving advancements in wind energy technology and securing a sustainable future powered by wind resources. The timeline as shown in **Figure 5** displays the range of airfoils examined by researchers from 2019 to 2024.

This thorough review encompasses diverse airfoil designs explored during this period, providing valuable insights into the changing trends of aerodynamic research in wind turbine technology. The summary presented in **Table 5** outlines significant studies in wind turbine aerodynamics discussed in the article, detailing modifications to airfoils, turbine types, Reynolds numbers, methodologies, parameters analyzed, and improvements identified. These studies offer diverse strategies for enhancing wind turbine performance and efficiency under varied conditions. The accompanying data in **Table 5** provides a concise reference, summarizing the multifaceted aspects of aerodynamic research in wind turbine design and will act as a guide for further studies related to optimizing wind turbines for various operating conditions.

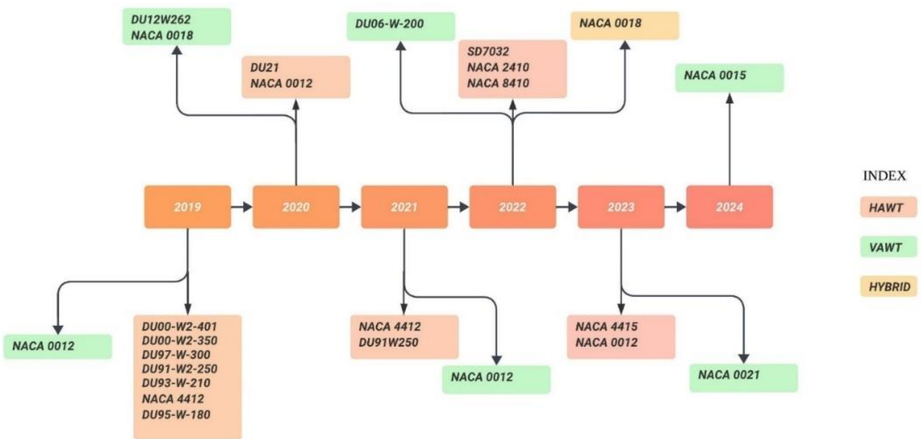


**Figure 5.** A timeline (2019-2024): Airfoil design evolution in wind turbine research.

DOI: https://doi.org/10.17509/ijost.v9i3.72369
p- ISSN 2528-1410 e- ISSN 2527-8045

**Table 5.** Key findings: Recent studies on wind turbine airfoil modifications.

| Study | Type of Airfoil | Reynolds number* | Application | Methodology | Parameters studied | Improvement |
|---|---|---|---|---|---|---|
| Habali & Saleh (2000a) | NACA 63-621, FX 66-S-196 | ≈ $1.8\times10^5$ | HAWT | Aerodynamic theory, Computational analysis, FEM | $C_{P,}$ structural load | Average $C_p$ of 41.2% |
| Yuan *et al.* (2010) | NACA 0005 | ≈ $10^4$ | MAV | CFD Simulation, Experiment | Aerodynamic coefficients, Vorticity | - |
| Chen & Agarwal (2013) | FB-0050, 0875,1750 | = $6.6\times10^5$ | HAWT | CFD Simulation, GA | $C_l$, $C_d$, $C_l/C_d$ | 43.63% increase in $C_l/C_d$ *for* FB-0050 airfoil |
| Kang & Park (2013) | S809 | = $2\times10^6$ | HAWT | CFD Simulation, Experiment | $C_l$, $C_d$, $C_l/C_d$ | $C_l/C_d$ of approx. 30 |
| Krawczyk *et al.* (2013) | NACA 4412 | ≈ $5\times10^5$ (for rated power) | HAWT | CFD+FEM | $C_l$, $C_d$, *Force, Power* | Approx. 27% increase in power for the flexible blade* |
| Vesel & McNamara (2014) | DU 21, 25, 30, 35, 40 and NACA 64 series | ≈ $1.9\times10^6$ (average) | HAWT | XFOIL, NREL FAST | Cost of Energy (COE) | Max. COE decrease of 6% |
| Bhuyan & Biswas (2014) | S818 | $1.44\times10^5$ to $2.31\times10^5$ | VAWT | Wind tunnel testing | $C_p$ | Max. $C_p$ of 0.34 |
| Bianchini *et al.* (2016) | NACA 0021 | $1.5\times10^5$ | VAWT | CFD Simulation | $C_p$, $C_T$ | - |
| Hirata *et al.* (2016) | NACA 0015 | $1\times10^2$ | MAV | CFD Simulation | $C_l$, $C_d$, $C_l/C_d$ | 34% improvement in $C_l/C_d$ |
| Rahromostaqim *et al.* (2016) | E387 | $3\times10^4$ | VAWT | CFD Simulation | Forces and coefficient of pressure | - |
| Bianchini *et al.* (2018) | NACA 0018 | ≈ $1\times10^5$ | VAWT | CFD Simulation | Virtual incidence, power | - |
| Domel *et al.* (2018) | NACA 0012 | $1\times10^4$ to $1\times10^6$ | HAWT | CFD Simulation, water tunnel testing | $C_l$, $C_d$, $C_l/C_d$ | 323% improvement in $C_l/C_d$ |
| Yang *et al.* (2019) | DU00-W2-401, DU00-W2-350, DU97-W-300, DU91-W2-250, DU93-W-210 | ≈ $4\times10^5$ to $3\times10^6$ | HAWT | BEM, FEM | $C_l/C_d$, stiffness, deflection, AEP | 7.96% increase in AEP |
| Said *et al.* (2019) | NACA 4412 | $1\times10^5$ to $5\times10^5$ | HAWT | Numerical Analysis | $C_p$ | - |

DOI: https://doi.org/10.17509/ijost.v9i3.72369
p- ISSN 2528-1410 e- ISSN 2527-8045

**Table 5 (Continue).** Key findings: Recent studies on wind turbine airfoil modifications.

| Study | Type of Airfoil | Reynolds number* | Application | Methodology | Parameters studied | Improvement |
|---|---|---|---|---|---|---|
| Beyhaghi & Amano (2019) | NACA 4412 | $1.6\times10^6$ | HAWT | CFD Simulation, SHERPA Optimization | $C_l$, $C_l/C_d$ | 11% increase in $C_l/C_d$ |
| Erfort *et al.* (2021) | NACA 0012 | $3.6\times10^5$ & $7\times10^5$ | VAWT | Numerical methods, Genetic Algorithm | *Torque coefficient, $C_P$* | 25% reduction in torque ripple |
| Zhang *et al.* (2019) | DU95-W-180 | $2\times10^5$ | HAWT | CFD Simulation, Wind Tunnel | $C_l$, $C_d$, $C_M$ | Subdued stall behaviour |
| Omidi & Mazaheri (2020) | DU21 | $10^6$ | HAWT | Numerical method | $C_l$, $C_d$ | 40% increase in $C_l$ |
| Uranai *et al.* (2020) | NACA 0012 | $2.8\times10^6$ | HAWT | CFD Simulation, Experiment | $C_l$, $C_d$ | 15% increase in $C_l$ |
| Saleem & Kim (2019) | DU12W262 | $10^6$ | HAWT, VAWT | CFD Simulation | $C_P$ | 3.2% increase in $C_P$ for HAWTs and 3.5% to 9.6% for VAWTs |
| Balduzzi *et al.* (2020) | NACA0018 | $8\times10^4$ | VAWT | CFD Simulation, Wind Tunnel testing | $C_l$, $C_d$, $C_p$ | - |
| Yossri *et al.* (2021) | NACA 4412 | $0.6\times10^4$ | HAWT | CFD Simulation | $C_l$, $C_d$, Power | - |
| Ballesteros-Coll *et al.* (2021) | DU91W250 | $2\times10^6$ | HAWT | CFD Simulation | $C_l/C_d$, Pressure distribution | Max. $C_l/C_d$ of 164.10 |
| Gao *et al.* (2022) | NACA 0018 | $\approx 3\times10^4$ to $7\times10^4$ | HYBRID | CFD Simulation | $C_M$, $C_p$ | Reduced starting speed by 34.7% |
| Ma *et al.* (2022) | SD7032 | $\approx 3\times10^5$ | HAWT | GA Optimisation | Thrust | Thrust deviation less than 5% |
| Jo & Majid (2022) | NACA 2410, NACA 8410 | $1\times10^6$ | HAWT | CFD Simulation | $C_l$, $C_d$ | - |
| Santamaría *et al.* (2022) | DU06-W-200 | $2\times10^5$ | VAWT | CFD Simulation, Wind Tunnel testing | $C_l$, $C_d$, $C_M$ | - |
| Eltayesh *et al.* (2023) | NACA 0021 | $4.3\times10^5$ and $6.4\times10^5$ | VAWT | CFD Simulation | $C_P$, $C_T$ | 47.5% increase in $C_P$ |
| Asadbeigi *et al.* (2023) | NACA 0021 | $5.3\times10^4$ to $1.23\times10^5$ | VAWT | CFD Simulation | $C_P$, *Torque* | 22.4% increase in $C_P$ |
| Hao *et al.* (2023) | NACA 4415 | $\approx 5\times10^5$ | HAWT | Wind Tunnel testing | $C_l$, $C_d$ | 2.5% increase in $C_L$ , 2-degree increase in stall angle |
| Wu *et al.* (2023) | NACA 0012 | $\approx 0.3\times10^5$ | HAWT | CFD Simulation, Wind Tunnel testing | Power, Efficiency | Approx. system efficiency of 22% at 0.8 m/s |
| Gupta *et al.* (2024) | NACA 0015 | $2\times10^5$ | VAWT | CFD Simulation | Avg. torque, $C_P$ | 81.3% increase in $C_P$ |

DOI: https://doi.org/10.17509/ijost.v9i3.72369
p- ISSN 2528-1410 e- ISSN 2527-8045

## 4. CONCLUSION

In conclusion, this systematic review employed a thorough database and precise search tactics to uncover 57 relevant articles from the past 25 years on the Scopus database, concerning recent progress in airfoil and blade design for wind turbines. By utilizing bibliometric analysis, connections and trends among the chosen documents were identified, guiding the structure of our review based on prevalent themes and keywords derived from the literature. This methodological framework facilitated a comprehensive examination of contemporary advancements in wind turbine technology and their broader impact on performance, efficiency, and sustainability across the wind energy domain as stated in the following: (i) The extensive research on Horizontal Axis Wind Turbines provided insights into improving efficiency and reliability. Recent innovations, from blade designs to addressing icing effects, use numerical simulations and optimization methods like genetic algorithms; (ii) Efforts to advance Vertical Axis Wind Turbine technology have also been noteworthy, with research exploring hybrid rotor systems to improve efficiency and address operational challenges; (iii) Utilizing advanced numerical simulations, experimental approaches, and optimization techniques, researchers aimed to enhance lift, minimize drag, and optimize lift-to-drag ratios. Achieving an optimal lift-to-drag ratio is critical for boosting the efficiency and performance of various aerodynamic systems; (iv) Beyond traditional metrics like lift and drag, the research explored factors essential for real-world performance, such as bend-twist coupling, torque ripple, and hybrid rotor designs, and (v) Researchers employed diverse methods to investigate factors like surface roughness and passive control methods like vortex generators and their impact on stall characteristics. By delving into stall characteristics, researchers contributed to innovative solutions that extend turbine lifespan and maximize power extraction.

This systematic review revealed the interdisciplinary essence of wind energy research, integrating fields like aerodynamics, materials science, and engineering, emphasizing collaborative efforts to tackle complex challenges and foster innovation. By consolidating findings and proposing future research directions, the study serves as an invaluable guide, driving ongoing advancements in wind energy technology and aiding the quest for sustainable energy solutions worldwide.

## 5. ACKNOWLEDGMENT

This work was supported by Taylor's University through its Taylor's research scholarship Programme.

## 6. AUTHORS' NOTE

The authors declare that there is no conflict of interest regarding the publication of this article. The authors confirmed that the data and the paper are free of plagiarism.

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