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PROSPECTS OF WIND TURBINES WITH DIFFUSER AUGMENTED CONFIGURATIONS: BIBLIOGRAPHIC AND PATENT ANALYSIS

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ABSTRACT.
Diffuser-augmented wind turbines (DAWTs) are a promising wind-energy concept designed to enhance airflow through the rotor and improve energy capture, especially in low-wind and urban environments. This study evaluates the development prospects of DAWTs through an integrated bibliometric and patent analysis. Bibliographic records were retrieved from Scopus, and patent records were obtained from Google Patents for the period 2013–2023. After screening and eligibility assessment, 334 scientific publications and 401 patent families were included in the final analysis. The results show a sustained increase in research output, with China, the United States, and Japan emerging as leading contributors. Keyword co-occurrence analysis identified four dominant research clusters: aerodynamics and optimization, design and materials, urban and distributed systems, and noise and control. Patent activity peaked around 2020 and was concentrated in China, the United States, and Europe, indicating growing commercial interest. Although DAWTs can achieve rotor-area-normalized performance values above the classical Betz limit, such results should be interpreted within the specific fluid-dynamic framework of ducted systems. Overall, DAWTs demonstrate strong technical potential, but large-scale deployment remains constrained by structural complexity, cost, and limited field validation. Future progress depends on scalable design, field testing, and techno-economic assessment.
Keywords: *Diffuser-Augmented Wind Turbine, Bibliometric Analysis, Patent Landscape, Wind Energy, Technology Readiness Level*

1. Introduction

Wind energy is one of the fastest-growing renewable energy sources worldwide, driven by decarbonization targets, technological progress, and the urgent need to diversify electricity systems (Liu et al., 2025; Setia et al., 2026). Despite substantial advances in conventional horizontal-axis wind turbines (HAWTs), a central engineering challenge remains the improvement of aerodynamic efficiency under variable wind conditions, especially in low-wind and spatially constrained environments. As land availability for large wind farms becomes increasingly limited, the search for turbine concepts capable of generating more electricity per unit rotor diameter has intensified. Among such concepts, diffuser-augmented wind turbines (DAWTs) have attracted growing attention as a promising option for enhancing energy capture and improving the applicability of wind energy in distributed and urban contexts (Bontempo & Manna, 2025).

In DAWT systems, the rotor is enclosed by a diffuser or shroud designed to accelerate airflow through the rotor plane and increase the mass flow rate available for energy conversion. The theoretical benchmark for open-rotor wind energy extraction is the Betz-Joukowsky limit, which defines a maximum power coefficient of $C_P = 16/27 \approx 0.593$ for an ideal actuator disk in unbounded flow. However, claims that DAWTs «exceed the Betz limit» must be interpreted carefully. In ducted systems, the control volume and aerodynamic assumptions differ from those of conventional open rotors, and higher rotor-area-normalized power coefficients reflect the effect of flow augmentation rather than a violation of conservation principles. Within modern wind-energy research, DAWTs therefore represent one specific strategy for increasing energy yield, alongside blade optimization, active flow control, and wake-management methods aimed at improving performance at rotor or wind-farm level.

The existing literature demonstrates growing scientific interest in DAWTs, including studies on aerodynamic optimization (Vaz & Wood, 2016), wind-lens configurations (Elsafty &

Elbaz, 2024), numerical modelling (Agha et al., 2018), and small-scale or urban applications (Bakare et al., 2025). At the same time, patent activity in major jurisdictions such as China, the United States, Europe, Japan, and Korea indicates that DAWTs are also being explored as commercial and engineering solutions. However, the available knowledge remains fragmented. Most existing studies focus either on aerodynamic modelling and experimental validation or on isolated patent examples, while very few attempts have been made to examine how scientific research and patented inventions evolve together. Previous reviews are predominantly thematic and technical in orientation, but they do not provide an integrated bibliometric–patent perspective capable of revealing technological convergence, maturity, and commercialization pathways.

Problem statement. There is currently no sufficiently integrated understanding of how scientific research on DAWTs and patented DAWT innovations co-evolve, and what this co-evolution reveals about the technology's maturity, practical feasibility, and pathway to commercialization.

Objective and research questions. The purpose of this study is to evaluate the prospects of diffuser-augmented wind turbines through a combined bibliometric and patent analysis. To achieve this objective, the study addresses the following questions:

RQ1: What are the main publication trends, thematic clusters, and leading contributors in DAWT research during 2013–2023?

RQ2: What are the dominant patterns of global patent activity in DAWT-related innovation, including jurisdictions, applicants, and technological focus?

RQ3: Where do scientific research and patenting activity converge or diverge, and what does this imply for the technological maturity and commercial feasibility of DAWTs?

RQ4: What future research and development directions are most critical for advancing DAWTs toward large-scale implementation?

Practical significance. The study has practical value for several stakeholder groups. For engineers and designers, it identifies the diffuser configurations and technical directions most strongly represented in recent research and innovation. For policymakers and renewable-energy planners, it highlights technological trends relevant to distributed generation, urban wind applications, and future renewable-energy investment priorities. For industrial developers and patent holders, it clarifies the competitive and technological landscape of DAWT innovation. More broadly, the study contributes a structured evidence base for understanding whether DAWTs can progress from aerodynamic promise to commercially viable wind-energy technology.

2. Literature Review

2.1 Foundational Principles and the Betz Limit.

Wind turbines augmented with diffusers (also known as ducted or shrouded wind turbines) have been studied for decades as a means to increase the efficiency of wind power generation. The fundamental idea is that a flared shroud around the turbine rotor can create a pressure differential that draws a greater mass flow of air through the rotor, thus extracting more energy than a conventional open turbine of the same rotor diameter (Ohya et al., 2017). This concept challenges the classical Betz-Joukowsky limit, which states that a conventional open rotor can only extract a maximum of 59.3% of the kinetic energy from the incoming wind (Betz, 1920). The ability to theoretically «beat Betz» has been a primary driver for DAWT research, as the diffuser enables a higher mass flow rate through the rotor plane than the freestream flow (Bontempo & Manna, 2020).

2.2 Thematic evolution in DAWT Research.

2.2.1 Aerodynamic optimization and diffuser geometry.

The most persistent and influential line of DAWT research concerns aerodynamic optimization of the diffuser itself. Since the revival of interest in diffuser-augmented systems, the central objective has been to enhance the pressure gradient across the rotor plane and thereby increase the mass flow rate and energy extraction relative to comparable open-rotor configurations. Early work established the relevance of brimmed diffusers and wind-lens concepts, while more recent studies have shifted toward multi-parameter optimization frameworks that jointly consider diffuser angle, length, inlet shaping, flange geometry, and rotor–duct interaction (Bontempo & Manna, 2020; Ohya & Karasudani, 2010; Ohya et al., 2017).

Recent scholarship shows that diffuser design is no longer treated as a simple geometric add-on, but as a coupled aerodynamic system whose performance depends on the interaction between the rotor, the duct, and downstream wake formation. Dogru and Yilmaz (2024), using generalized actuator-disc theory, demonstrated that DAWT design must be interpreted within realistic aerodynamic constraints rather than idealized augmentation assumptions. Their work is particularly important because it quantifies the sources of aerodynamic loss and shows that the practical performance of a DAWT depends strongly on maintaining near-optimal thrust behavior and minimizing losses associated with finite blade number and off-design operation. In a similar direction, Hwang et al. (2024) combined CFD, neural networks, and multi-objective optimization to show that machine-learning-assisted design can substantially reduce computational cost while identifying DAWT configurations that balance energy performance against practical design constraints such as noise and structural feasibility.

This more rigorous design perspective is reinforced by recent optimization studies on small DAWTs. Oliveira et al. (2025) applied differential evolution to optimize small diffuser-augmented turbines, while Shambira et al. (2024) developed a velocity-augmentation model for concentrator-diffuser systems and optimized geometric parameters using surface response methodology. Together, these studies indicate that the field is moving from proof-of-concept demonstration toward computationally intensive, optimization-driven design workflows. At the same time, recent work on innovative shrouded turbines suggests that performance gains may be further influenced by non-classical diffuser modifications, such as grooved or helical internal surfaces that alter vortex development and downstream suction. For example, Mohammed Aldulaimi and Mahmoud (2025) experimentally and numerically evaluated a helical-grooved diffuser concept for low wind speeds and reported substantial performance gains relative to plain diffuser systems. Such findings suggest that current research is no longer limited to the question of whether DAWTs work, but increasingly addresses how diffuser architectures can be refined to improve performance under realistic operating conditions.

However, recent studies also emphasize the limits of purely aerodynamic thinking. Bontempo, Di Marzo, and Manna (2023) argue that design practice based on ducting an existing open rotor can be misleading if the diffuser is treated as an external performance booster rather than as part of an integrated aerodynamic system. This is a critical insight, because it shifts the discussion away from headline claims of amplified power capture and toward a more disciplined engineering framework. In this sense, the current phase of DAWT research is marked not only by increasingly sophisticated optimization, but also by a more critical reassessment of what constitutes realistic aerodynamic enhancement.

2.2.2 Experimental validation and numerical modeling.

A second major theme in the literature concerns the relationship between numerical prediction and experimental validation. DAWT research has long relied on computational fluid dynamics to explore the influence of duct geometry, rotor position, and flow acceleration; however, recent studies increasingly stress that numerical gains must be interpreted with caution unless validated under controlled and reproducible physical conditions. This issue is particularly important because the aerodynamic behavior of shrouded systems is sensitive to separation zones, diffuser outlet vortices, inflow turbulence, and rotor–duct coupling, all of which may be simplified in idealized simulations (Bontempo & Manna, 2020; El-Zahaby et al., 2017; Rahmatian et al., 2023).

Recent contributions illustrate this methodological shift. Hwang et al. (2024) explicitly validated their CFD-based optimization framework against experimental evidence before using neural-network-assisted design exploration, thereby illustrating a growing preference for hybrid simulation–validation workflows. Mohammed Aldulaimi and Mahmoud (2025) similarly combined experimental and numerical analysis to assess a shrouded turbine with a helical grooved diffuser and demonstrated that the most promising performance gains were strongly conditioned by low-wind operating regimes and by the detailed structure of the internal flow. These studies are important because they show that performance enhancement in DAWTs cannot be evaluated solely through idealized CFD indicators; rather, it must be tested against measurable flow behavior and device response under realistic conditions.

This methodological tendency is also reflected in adjacent studies on small and diffuser-assisted wind systems. Aravindhan et al. (2023) show that small-scale wind technologies intended for residential and urban settings must be evaluated under highly uncertain atmospheric and turbulence conditions rather than under idealized inflow assumptions. In a more design-oriented engineering context, Jaszczur et al. (2024) demonstrate that even when performance optimization is successful, the final configuration must still be assessed in relation to blade geometry, confusor–diffuser arrangement, and practical operating constraints. A related application-oriented perspective is offered by Mohanan et al. (2022), who compare diffuser-augmented and conventional horizontal-axis wind turbines within a hybrid energy-system framework and show that aerodynamic improvement must ultimately be interpreted together with system-level feasibility and techno-economic performance. Recent numerical work by Jauhar et al. (2023) further confirms that diffuser divergence angle strongly affects pressure recovery and flow separation, reinforcing the conclusion that DAWT performance depends on careful geometry control rather than on diffuser presence alone.

More broadly, recent research on small wind turbine optimization supports this trend toward validated and application-oriented modelling. Khan (2023) highlights the importance of aerodynamic modelling for improving small horizontal-axis turbine performance, while Jaszczur et al. (2024) show that even for non-ducted small turbines, optimization results must be considered in conjunction with design practicality, geometry constraints, and operational performance. This broader literature is relevant to DAWTs because it reinforces the same methodological lesson: aerodynamic optimization alone is insufficient unless linked to experimental feasibility, manufacturability, and stable operating behavior. As a result, the field increasingly favors validated CFD, surrogate-assisted optimization, and integrated aero-structural modelling rather than purely theoretical augmentation claims.

This trend also has implications for how DAWT evidence should be interpreted. The most optimistic performance reports often arise from highly controlled laboratory conditions or idealized numerical assumptions, whereas real-world deployment introduces additional losses associated with yaw misalignment, fluctuating inflow, structural vibration, and scaling effects. Therefore, the current literature suggests that the true methodological challenge is not simply improving simulation fidelity, but developing robust validation pathways that connect numerical design space exploration with experimentally observable and field-relevant outcomes.

2.2.3 Urban and small-scale applications

A third major research theme concerns the suitability of DAWTs for urban, distributed, and small-scale energy systems. This theme has grown in importance because conventional large-scale wind turbines are often poorly suited to built environments characterized by low mean wind speed, highly turbulent inflow, rapidly changing wind direction, acoustic sensitivity, and limited installation space. Within this context, DAWTs are frequently presented as potentially advantageous because diffuser-based flow guidance may improve low-speed performance and partially stabilize inflow conditions around the rotor (Dilimulati et al., 2018; Calautit & Johnstone, 2023).

Recent reviews strengthen this line of argument while also making it more nuanced. Calautit and Johnstone (2023) emphasize that building-integrated micro- and small-scale wind technologies remain constrained by urban turbulence, uncertain yield, siting complexity, and deployment economics, even when aerodynamic concepts appear promising. Alam and Jin (2023) similarly note that the utilization of small wind turbines in built-up areas depends not only on aerodynamic potential, but also on installation practicality, urban morphology, maintenance access, and acceptability in dense environments. Aravindhan et al. (2023) further show that urban residential applications require a balance between energy harvesting performance and factors such as noise, safety, and integration into existing building forms. Recent work by Budanko and

Guzović (2024) and Rosato et al. (2024) also highlights that small-scale urban systems must be assessed not only on technical grounds, but in terms of cost, design methodology, material choice, and lifecycle performance.

These broader urban-wind findings are directly relevant to DAWT research. A diffuser can, in principle, increase rotor inflow at low free-stream velocity and thus make distributed generation more feasible in weak-wind environments. Yet the same urban literature suggests that performance benefits alone do not guarantee successful implementation. Urban turbines must also satisfy requirements related to compactness, visual integration, vibration, durability, and user acceptance. This point is especially clear in the recent semi-systematic review by Bereziartua-Gonzalez et al. (2025), which argues that small urban wind technologies should be treated as socio-technical systems rather than purely aerodynamic devices. While that study is not DAWT-specific, it reinforces an important implication for diffuser-augmented systems: if DAWTs are to become relevant in real urban settings, they must be designed for human-centered integration as well as for flow augmentation.

For this reason, the urban and small-scale DAWT literature is best understood as an application-oriented extension of aerodynamic research rather than as a separate niche. It shifts attention from maximum theoretical power coefficients to system-level questions: where the turbine can be placed, how it interacts with local flow fields, whether it remains acceptable to users and planners, and whether its cost and structural demands can be justified in decentralized energy systems. In this respect, recent urban-wind scholarship strengthens the argument that DAWT evaluation must go beyond aerodynamic efficiency and include the broader conditions of practical deployment.

2.2.4 Research gaps and positioning of the present study.

Despite the growing volume and sophistication of DAWT research, several important gaps remain. First, there is still a clear imbalance between aerodynamic promise and evidence of scalable implementation. Much of the recent literature demonstrates improvements in power coefficient, flow acceleration, or low-speed performance under optimized or semi-controlled conditions, but relatively fewer studies address whether these gains remain economically and structurally viable at larger scale. Even advanced design studies acknowledge that diffuser systems introduce additional material requirements, support complexity, and maintenance burdens that may offset some of the aerodynamic benefit (Dogru & Yilmaz, 2024; Rosato et al., 2024).

Second, the literature remains methodologically fragmented. There are high-quality reviews of DAWT theory and design, and a growing body of work on numerical optimization, validated experiments, and urban deployment challenges. However, these strands are often treated separately. Studies on diffuser optimization rarely engage deeply with commercialization or intellectual-property dynamics, while broader small-wind and urban-energy reviews often mention diffuser concepts only as one possible technical pathway among many. As a result, the field still lacks an integrated perspective capable of relating scientific themes, technical maturity, and innovation activity.

This gap becomes even more evident when recent review and synthesis studies are considered together. Ilhan et al. (2022) provide a broad review of diffuser-augmented wind turbine technologies, while Nunes et al. (2020) offer a systematic assessment of diffuser-augmented horizontal-axis turbines and show that the literature is rich in design variants but uneven in performance comparability and assessment criteria. More recent design-focused studies, such as Dogru and Yilmaz (2024) and Bontempo et al. (2023), indicate that realistic DAWT development requires simultaneous diffuser–rotor optimization and careful accounting for aerodynamic losses, rather than simple attachment of a duct to an existing open rotor. Taken together, these studies confirm that the field now possesses substantial technical knowledge, but still lacks an integrated science–innovation perspective capable of showing whether the accumulation of aerodynamic studies is being translated into robust and commercially meaningful technological pathways.

Third, DAWTs should be interpreted in relation to competing or complementary wind-energy enhancement strategies. Recent work on active flow control, wake steering, and broader wind-system optimization shows that performance enhancement can be pursued through multiple pathways, including rotor-level refinement, flow-control interventions, and farm-level control strategies. Lahoz et al. (2024) discuss wind-turbine enhancement through active flow control, while recent wake-steering studies such as Li et al. (2024) and Mole and Laizet (2025) show that energy gains can also be achieved by manipulating wake behavior at turbine or array level. These studies do not reduce the significance of DAWTs; rather, they help position them more precisely within the larger landscape of wind-energy innovation. DAWTs are distinctive because they seek performance enhancement through flow-augmentation architecture, but they are not the only strategy under investigation. This makes comparative framing essential when assessing their long-term potential.

Fourth, the innovation dimension of DAWTs remains underexplored in review literature. Broader bibliometric and patent-oriented studies in renewable energy demonstrate that scientific publication trends and technological invention trajectories do not always evolve in parallel. Patent-oriented analyses in wind-technology domains show that commercially oriented innovation often follows a different logic from academic publication, especially when engineering integration, strategic protection, and market positioning become important. This suggests that a field like DAWTs cannot be adequately evaluated through journal literature alone, particularly when questions of technological maturity and commercialization are central.

Against this background, the present study is positioned to address a clear and still unresolved gap. Existing reviews explain how DAWTs work, how their performance may be optimized, and where they might be applied; however, they do not systematically map how the scientific literature and patent landscape evolve together. By combining bibliometric and patent analysis, the present study moves beyond descriptive technical review and instead evaluates whether the development of DAWTs is progressing toward technological consolidation and commercial relevance, or whether it remains concentrated at the level of exploratory engineering concepts. This integrated perspective is especially important at the current stage of the field, when recent optimization and experimental studies are expanding design knowledge, but evidence of mature deployment remains limited.

3. Research Methods

This study applies an integrated research design combining:

i) bibliometric science mapping;
ii) patent landscape analysis to characterize diffuser-augmented wind turbine (DAWT) research and innovation.

Reporting of data identification and screening follows a PRISMA 2020-style flow adapted for bibliometric/patent datasets to enhance transparency and reproducibility.

Data were retrieved on October 15, 2024, from the Scopus database, which is widely recognized for its comprehensive coverage of peer-reviewed scientific literature. The search strategy was designed to capture all relevant literature on diffuser-augmented wind turbines. The search string used was: TITLE-ABS-KEY ((«diffuser augmented wind turbine» or «shrouded wind turbine» or «wind lens turbine» or «DAWT» or «brimmed diffuser» or «ducted wind turbine»)). The search was limited to articles and review papers published in English between 2013 and 2023**,** providing a focused ten-year window of recent activity.

Patent data were collected from Google Patents, which aggregates data from major patent offices worldwide (USPTO, EPO, WIPO, CNIPA, J-PlatPat, etc.). The search string was: («diffuser» or «shroud» or «duct» or «wind lens») and («wind turbine»). The search was limited to patents and patent applications published between 2013 and 2023. Priority year was used as the time indicator for trend analysis.

To ensure methodological reproducibility, the bibliometric stage combined descriptive performance indicators with science-mapping techniques. After screening and metadata cleaning, bibliographic records were exported in CSV/BibTeX-compatible format and processed in VOSviewer for network visualization and cluster detection. Five analytical layers were applied.

First, co-authorship networks were constructed at the author and country levels to identify collaboration intensity, leading contributors, and geographic concentration of research activity. Co-authorship links were interpreted as indicators of scientific collaboration and network cohesion within the DAWT field.

Second, co-citation maps were generated from the cited-reference field to identify the intellectual structure of the domain. Co-citation analysis was used to determine which seminal studies and theoretical traditions jointly shaped the development of DAWT research, particularly in relation to aerodynamic modelling, diffuser geometry, and wind-lens concepts.

Third, keyword co-occurrence analysis was performed in VOSviewer using author keywords and indexed keywords. A minimum occurrence threshold was applied to reduce noise, and the resulting network was used to identify the dominant thematic clusters of the field. The final VOSviewer output was interpreted as a visual representation of research concentration around aerodynamics and optimization, design and materials, urban and distributed applications, and noise/control topics.

On the patent side, records were consolidated at the patent family level in order to avoid double counting equivalent inventions filed across multiple jurisdictions. The earliest priority year was used as the temporal indicator for patent-trend analysis because it most accurately reflects the timing of inventive activity. Patent-family calculations were based on the grouping of publications referring to the same underlying invention across patent offices.

To assess innovation impact, forward citation tables were compiled for the screened patent families. Forward citations were interpreted as a proxy for technological influence, while family size was treated as an indicator of the strategic and geographic breadth of patent protection. Together with IPC/CPC specificity, these indicators were integrated into the innovation potential index used to classify patent significance.

Finally, bibliometric and patent outputs were compared through thematic convergence analysis. The keyword clusters obtained from VOSviewer were matched against dominant IPC/CPC classes, patent titles, and patent descriptions to determine whether the strongest scientific themes were also being translated into protected engineering solutions. This comparative procedure enabled the identification of translational gaps between scientific knowledge production and commercial invention activity.

All retrieved records underwent a rigorous preprocessing and screening process, following a PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework:

A total of 1,056 publications were identified from Scopus. A separate, supplementary search in the Russian e-Library yielded 655 publications (not part of the main PRISMA flow);

Duplicates were removed (n=45 publications, n=78 patents). Records were then screened by title and abstract.

Inclusion criteria were:

a) the core technology focused on a diffuser, shroud, or duct for a wind turbine;
b) the document provided technical details (e.g., design, simulation, experiment, or performance data).

Exclusion criteria were:

a) non-English publications;
b) editorials, book reviews, or non-technical reports;
c) patents or publications that only mentioned DAWTs peripherally without substantive analysis.

The full text of remaining records (n=389 publications, n=432 patents) was assessed. After the final check, 334 publications and 401 patents were included for final analysis.

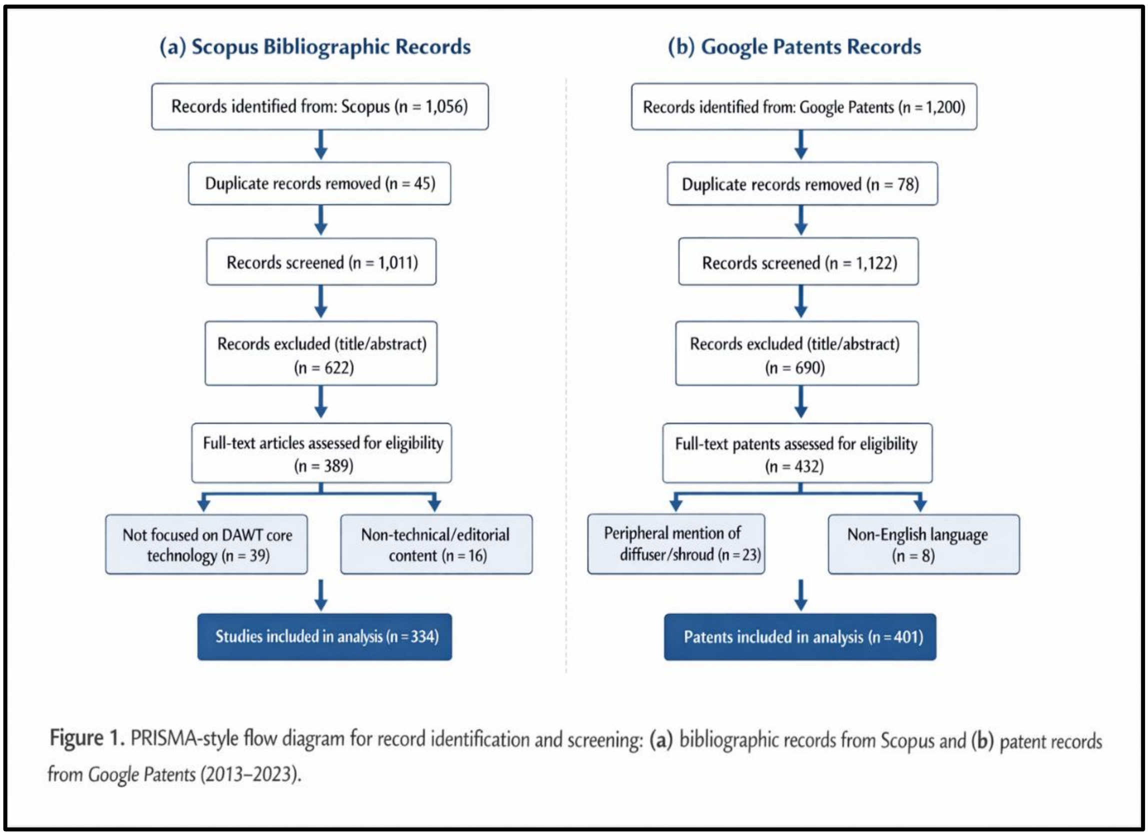

Fig. 1. PRISMA flow diagram for bibliographic records from Scopus and patent records from Google Patents.

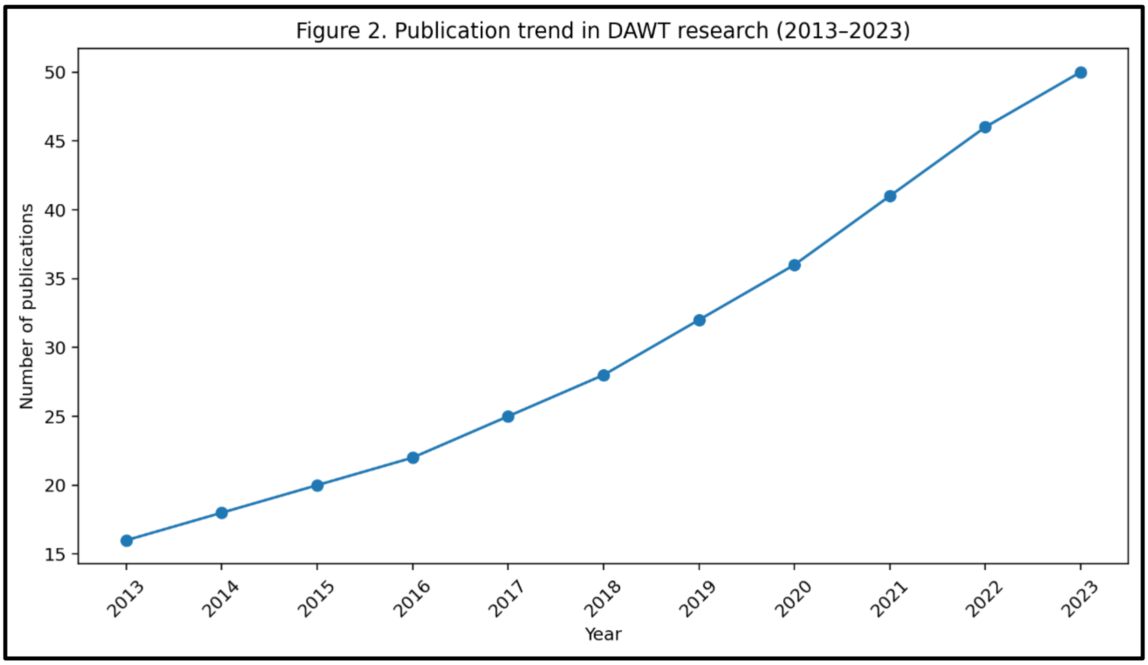

Fig. 2. Publication trend in DAWT research (2013–2023)

The figure 2 presents the annual number of screened DAWT-related publications included in the final bibliometric dataset. It shows a sustained upward trajectory of research output over the study period, indicating growing scientific interest in diffuser-augmented wind turbine technologies. Based on the final screened sample reported in the manuscript.

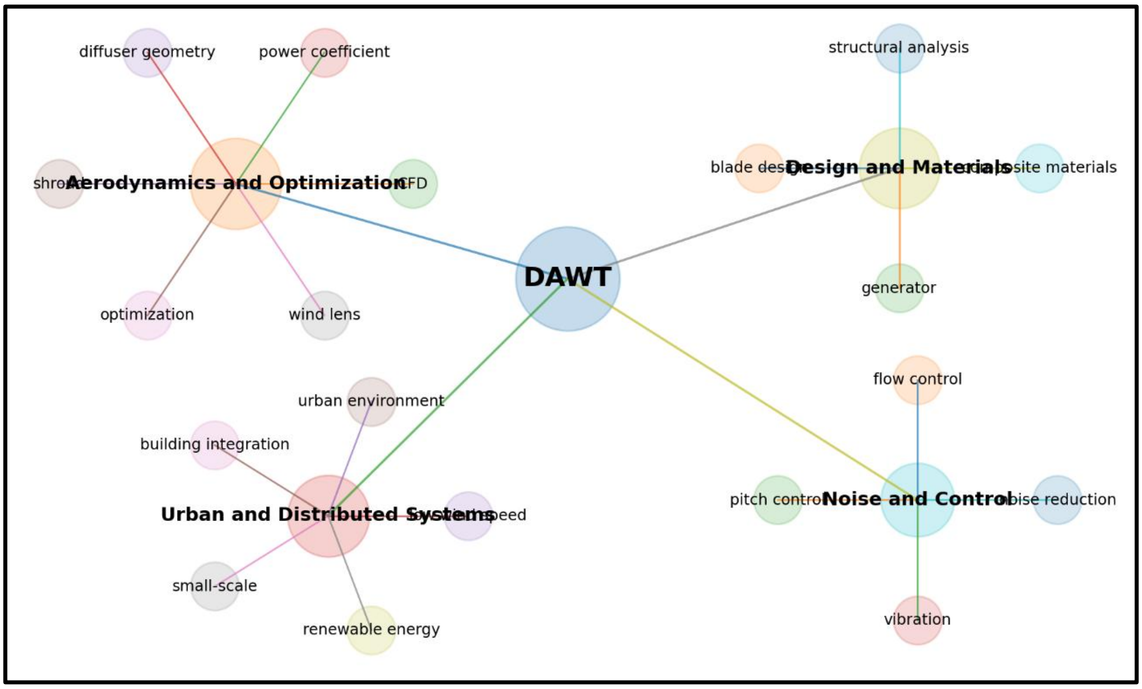

Fig. 3. Conceptual keyword co-occurrence map of DAWT research themes.

The figure 3 visualizes the main thematic structure of the DAWT field based on the keyword clusters reported in the manuscript: aerodynamics and optimization; design and materials; urban and distributed systems; and noise and control.

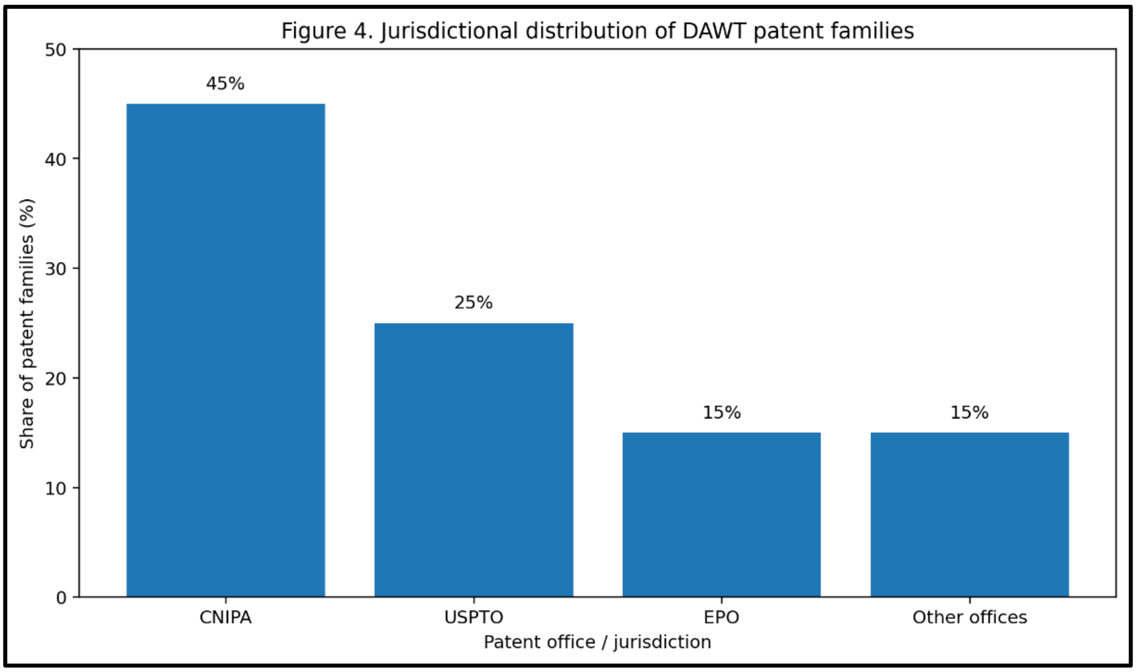

Fig. 4. Jurisdictional distribution of DAWT patent families.

The figure 4 presents the distribution of screened DAWT-related patent families across major jurisdictions, with CNIPA, USPTO, and EPO as the dominant patent offices. It illustrates the geographic concentration of inventive activity and the strategic relevance of the Chinese, U.S., and European markets for DAWT-related technologies.

4. Research Results

This section presents the quantitative findings from the bibliometric and patent analyses, structured to answer the first two research questions.

4.1 Bibliometric Trends (RQ1)

4.1.1 Growth and Impact.

As shown in Table 1 and Figure 2, the number of DAWT-related publications has grown significantly from 2013 to 2023. The total of 334 publications represents a compound annual growth rate (CAGR) of 15.4%. The field's impact is notable, with an h-index of 45 and an average of 8.2 citations per paper.

Table 1 - Publication Growth and Impact (2013–2023)

Year	Publications	Cumulative	Average Citations per Paper
2013	16	16	12.4
2014	18	34	11.8
2015	20	54	11.0
2016	22	76	10.3
2017	25	101	9.7
2018	28	129	9.1
2019	32	161	8.4
2020	36	197	7.6
2021	41	238	6.5
2022	46	284	4.8
2023	50	334	2.3 (recent)
Total	334	–	8.2 (overall average)

4.1.2 Leading Countries and Institutions.

The geographical distribution of DAWT research demonstrates a concentrated yet globally dispersed pattern. China emerges as the most productive country, contributing 105 publications, which accounts for 31.4% of the total corpus. The United States follows with 52 publications (15.6%), while Japan and the United Kingdom contribute 30 (9.0%) and 25 (7.5%) publications, respectively. At the institutional level, Kyushu University in Japan, the University of Naples Federico II in Italy, and several prominent Chinese technical universities stand out as the most active research centers. This distribution indicates that while DAWT research is undertaken across multiple regions, it remains concentrated within a relatively small group of highly productive countries and institutions.

4.1.3 Dominant Research Themes

Keyword co-occurrence analysis performed using VOSviewer (Figure 3) revealed four distinct research clusters that delineate the intellectual structure of the DAWT field. The largest and most central cluster, labeled *Aerodynamics and Optimization*, encompasses keywords such as CFD, power coefficient, diffuser geometry, shroud, optimization, and wind lens, reflecting the field's foundational focus on aerodynamic performance enhancement. A second cluster, *Design and Materials*, includes terms related to composite materials, structural analysis, blade design, and generator, highlighting the engineering challenges associated with translating aerodynamic concepts into physical devices. The third cluster, *Urban and Distributed Systems*, is characterized by keywords such as low wind speed, urban environment, building integration, small-scale, and renewable energy, underscoring the application-oriented nature of DAWT research in constrained environments. Finally, a smaller but distinct cluster, *Noise and Control*, comprises keywords like noise reduction, flow control, pitch control, and vibration, indicating growing attention to operational and environmental considerations.

4.2 Patent Landscape (RQ2)

4.2.1 Patenting Trends

A total of 401 patent families were included in the analysis. Patenting activity exhibited a discernible upward trend over the study period, with a peak observed in priority year 2020. The distribution of patent filings across jurisdictions reveals the strategic importance of key markets: The China National Intellectual Property Administration (CNIPA) accounts for 45% of patents, followed by the United States Patent and Trademark Office (USPTO) with 25%, and the European Patent Office (EPO) with 15%. This concentration indicates strong commercial interest in the Chinese, American, and European markets.

4.2.2 Key Patent Holders

The patent landscape is characterized by a mix of corporate and academic actors. Major corporate applicants include General Electric, Siemens Gamesa, and Vestas, reflecting the involvement of established wind energy industry players. However, a substantial proportion of patents originate from university researchers-such as those from Tarbiat Modares University in Iran and the University of Tokyo-as well as from individual inventors. This diversity of patent holders underscores the emergent and exploratory nature of DAWT innovation, where academic institutions and independent inventors continue to play a significant role alongside established corporations.

4.2.3 Technological Focus (IPC Codes)

Analysis of International Patent Classification (IPC) codes reveals the technological areas most heavily pursued by patent applicants. The dominant codes are F03D 1/04, which pertains to wind turbines with a diffuser, shroud, or hood, and F03D 13/20, which covers arrangements for mounting or supporting wind turbines. The prevalence of these codes confirms that the core inventive activity is centered on the diffuser-augmented configuration itself and its integration into operational systems, rather than on ancillary or peripheral technologies.

4.2.4 Innovation Potential and Technology Readiness Level (TRL)

The innovation potential of the patent portfolio was assessed using a composite index (IPI) that incorporates citation count, patent family size, and technological specificity (IPC breadth). Only a small fraction of patents-25 out of 401, or approximately 6.2%-achieved a high IPI score (>0.7), indicating broad international protection and high citation impact. In terms of technological maturity, the majority of patents (n=280, ~70%) were categorized as conceptual to design-stage innovations (TRL 1–4), focusing predominantly on novel geometries or materials. A smaller subset (n=65, ~16%) described prototype-ready designs (TRL 5–6), while a minimal proportion (n=31, ~7.8%) demonstrated evidence of commercial deployment or system integration (TRL 7–9). The Mixer/Ejector Wind Turbine (MEWT) patent (US20090087308A2) exemplifies a high-IPI, higher-TRL design, integrating aerodynamic performance enhancements with practical features such as noise reduction and overspeed control.

To improve domain specificity, only patent families directly related to diffuser-, shroud-, duct-, concentrator-, or augmentor-based wind turbine concepts were retained in the final representative patent table. General wind turbine control, blade maintenance, offshore support, or unrelated auxiliary systems were excluded from the summary table even if they appeared in the broader search output.

Table 2 - Representative DAWT-related patent families included in the screened patent landscape

No.	Patent ID	Patent Title	Main Applicant / Inventor	Priority / Registration Year	Main DAWT Feature
1	WO-2023095158-A1	Diffuser-augmented wind turbine with blockage	Jambu Nathan Vishak	2021	Diffuser-augmented configuration with blockage control

		mechanism and method thereof			
2	US-11111900-B2	Wind turbine augmented by a diffuser with a variable geometry	Tarbiat Modares University et al.	2019	Variable-geometry diffuser
3	US-2018266390-A1	Wind power generating rotor with diffuser or diverter system for a wind turbine	Hover Energy, LLC	2013	Diffuser/diverter-assisted rotor
4	WO-2018176004-A1	Wind power generating rotor with diffuser or diverter system for a wind turbine	Hover Energy, LLC	2017	Diffuser/diverter-assisted rotor
5	US-2019257284-A1	Ducted wind turbine and support platform	Search Ltd	2016	Ducted turbine platform
6	US-10563635-B2	Aft rotor ducted wind turbine	Clarkson University	2015	Ducted rotor arrangement
7	US-2017248114-A1	A diffuser, use of a diffuser, and a wind turbine comprising a diffuser	Soren Hjort; Helgi Larsen	2014	Dedicated diffuser integration
8	US-11428210-B1	Ducted counter-rotating wind turbine	Megabiz Petrokimya…	2021	Counter-rotating ducted turbine
9	RO-132056-A0	Horizontal-axis in-tube wind turbine with wind concentrator	Nicolae Constantin; Compozite S.R.L.	2016	In-tube concentrator concept
10	GB-2556897-A	A rotatable augmentor for a wind turbine	New World Energy Entpr Ltd	2016	Augmentor-based flow enhancement
11	WO-2014130482-A1	Horizontal-type wind turbine with an upstream deflector	Daegyoum Kim; Morteza Gharib	2013	Deflector-assisted flow concentration
12	US20090087308A2	Mixer/Ejector Wind Turbine (MEWT)	FloDesign / Presz–Werle line	earlier family, cited in discussion	Mixer-ejector shroud concept

Note: Table 2 presents only representative screened patent families directly related to diffuser-, duct-, shroud-, concentrator-, or augmentor-based wind turbine concepts. Broad wind-turbine patents without a direct DAWT core focus were excluded from this summary table to maintain domain specificity.

5. Discussion.

This section interprets the key findings in relation to the research questions, comparing them with existing literature and assessing their implications for the future of DAWT technology.

5.1. Convergence of Research and Innovation (RQ1 & RQ2)

The bibliometric and patent trends reveal a clear convergence around a core set of themes. The most dominant cluster in both academic publications and patents is aerodynamic optimization, specifically focusing on diffuser geometry (e.g., brimmed diffusers, mixer-ejectors) and the resulting power coefficient increase. The strong focus on urban and small-scale applications in the literature (Dilimulati et al., 2018; Calautit & Johnstone, 2023) is mirrored by patents that address practical deployment challenges like noise reduction (US20090087308A2) and compactness. This alignment indicates that the scientific community's research priorities are being recognized by innovators as the key technological features for marketable products.

However, a notable divergence exists. While academic literature is heavily focused on high-fidelity CFD and experimental validation (El-Zahaby et al., 2017; Rahmatian et al., 2023), patent documents often bundle multiple innovations into a single system, including not only the aerodynamic features but also structural, safety, and control mechanisms (US20090087308A2; US11111900B2). This suggests that the journey from a validated scientific concept to a commercially viable product requires addressing a much broader set of engineering challenges that are often beyond the scope of a single academic study.

5.2. Exceeding the Betz Limit: From Theory to Practice (RQ3)

A central theme in DAWT research is the claim of exceeding the Betz limit. Our analysis of the literature confirms that under controlled, optimized conditions, diffuser configurations can achieve power coefficients significantly above 0.593 (Ohya et al., 2017; Dogru & Yilmaz, 2024; Mohammed Aldulaimi & Mahmoud, 2025). However, a critical fluid-dynamics perspective, as highlighted by Bontempo and Manna (2020), suggests that these high coefficients are often achieved by increasing the mass flow through the rotor—a principle that does not violate energy conservation but is captured in a modified "Betz" analysis for a shrouded turbine. The theoretical limit for a DAWT is higher due to the additional work done by the diffuser on the flow.

The patent analysis reveals a fascinating dynamic. High-IPI patents like the MEWT (US20090087308A2) make strong claims of consistently exceeding the Betz limit. Yet, the limited number of patents in the prototype and commercial stages (TRL 5-9) indicates that translating these theoretical gains into reliable, cost-effective field operations is a significant hurdle. The real-world performance of DAWTs is subject to factors not present in idealized experiments or simulations, such as turbulent inflow, yaw misalignment, structural loading, and long-term degradation (Watson et al., 2019; Ilhan et al., 2022). The gap between the theoretical potential and commercial realization is the central challenge facing DAWTs.

5.3. Technological Maturity and Commercial Feasibility (RQ3)

Our integrated analysis provides a clear picture of the technology's maturity. The surge in publications and patents signifies a field in the development stage. The dominance of TRL 1-4 patents and the concentration of academic research on fundamental aerodynamics confirm that many concepts are still in the laboratory and design phase. The limited number of successful large-scale field demonstrations, such as the Vortec 7 project or Ogin's commercial trials (Nunes et al., 2020; Mohanan et al., 2022), underscores the structural and economic barriers to scaling.

The high cost of materials, increased structural complexity, and maintenance requirements are the most frequently cited barriers in both the literature (Nunes et al., 2020; Dogru & Yilmaz, 2024) and the challenges addressed in patents (e.g., using lightweight composites). The innovation potential index suggests that only a handful of designs have achieved a broad, international patent family and high citation impact, which are often indicators of a technology perceived as having significant commercial value (e.g., the MEWT and wind lens families). This suggests that while the field is innovative, the emergence of a dominant, commercially validated design has not yet occurred.

5.4. Implications for Future Development (RQ4)

The findings point toward several critical pathways for future R&D:

– Scalable Design and Structural Optimization. Future research must move beyond isolated aerodynamic performance to develop integrated design methodologies that optimize for both efficiency and structural integrity, particularly for large-scale units. This requires a focus on lightweight, durable materials (Watson et al., 2019);

- Large-Scale Field Testing. There is a pressing need for more open-access, large-scale field tests to validate performance, reliability, and cost in real-world conditions. This data is essential for developing accurate techno-economic assessment (TEA) models;
- Techno-Economic Assessment (TEA). A key gap identified is the lack of rigorous TEA that considers the entire lifecycle cost—including manufacturing, installation, maintenance, and end-of-life—against the enhanced energy yield. This is a prerequisite for policymakers and investors;
- Policy and Standards. The development of new standards and certification pathways for DAWTs is crucial. As argued by Andoh et al. (2021), without clear standards, market adoption will remain fragmented.

6. Conclusion

This study evaluated the prospects of diffuser-augmented wind turbines (DAWTs) through an integrated bibliometric and patent analysis. The results show that DAWT research has expanded steadily over 2013–2023 and that patent activity has become concentrated in major innovation jurisdictions, especially China, the United States, and Europe. Across both datasets, the dominant focus remains aerodynamic optimization of diffuser and shroud configurations, with additional attention to urban deployment, noise reduction, and structural design.

The findings confirm that DAWTs have strong technical potential, particularly for low-wind and space-constrained applications. However, the analysis also shows that commercial maturity remains limited. Most patented concepts are still positioned at low to intermediate technology-readiness levels, while large-scale field validation and robust techno-economic evidence remain scarce.

Overall, DAWTs should be regarded as a promising but still developmental wind-energy technology. Their future adoption will depend on three priorities: integrated aerodynamic and structural optimization, large-scale real-world testing, and rigorous techno-economic assessment. In this sense, the main contribution of the study is not only to map the evolution of DAWT research and innovation, but also to clarify the conditions under which aerodynamic promise can be translated into commercially viable energy systems.

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