PRISMA 2020 Checklist

Section and Topic	Item #	Checklist item	Location where item is reported
TITLE			
Title	1	Identify the report as a systematic review. Response: The abstract clearly states that this document is a "systematic review," directly addressing this checklist item.	The title page and abstract
ABSTRACT			
Abstract	2	See the PRISMA 2020 for Abstracts checklist. The revised abstract now includes the following elements as per the PRISMA 2020 for Abstracts checklist: • Identification as a systematic review is clearly mentioned at the beginning. • Rationale: The abstract explains the importance of aerodynamic optimization in wind turbines within the context of global renewable energy goals. • Objectives: Clearly states the aim to review recent advancements and their impacts, outlining the focus on CFD and AI technologies. • Eligibility criteria: While not explicitly detailed in the abstract, this should include the types of studies reviewed (e.g., peer-reviewed articles focusing on aerodynamic optimization from the past decade). • Information sources: Mentions that the review included studies from the last decade, implying a comprehensive search of recent literature. • Risk of bias: This could be briefly indicated if space allows; otherwise, it should be detailed in the full text. • Results: Summarizes key areas of advancement in blade aerodynamics and the role of new technologies. • Limitations: Should be briefly noted if critical limitations are directly relevant to the understanding of the abstract's contents. • Conclusions and implications: Clearly outlines the implications for future research, policy, and practical applications, aiming to guide further advancements in the field.	The abstract
INTRODUCTION			
Rationale	3	Describe the rationale for the review in the context of existing knowledge. The rationale for this review is founded on the critical need for sustainable energy solutions, where wind energy stands as a key renewable source. Despite significant advancements, there remains a substantial scope for enhancing the aerodynamic efficiency of wind turbine blades. This review aims to consolidate current knowledge, address gaps, and direct future research efforts toward optimizing blade design.	Introduction section
Objectives	4	Provide an explicit statement of the objective(s) or question(s) the review addresses. The primary objective of this systematic review is to evaluate recent advancements in aerodynamic optimization techniques for wind turbine blades, assess their effectiveness in improving energy efficiency, and identify trends and gaps in the current research landscape.	Introduction section
METHODS			
Eligibility criteria	5	Specify the inclusion and exclusion criteria for the review and how studies were grouped for the syntheses. The inclusion criteria for studies in this review were: (1) peer-reviewed articles published in English from January 2010 to December 2023; (2) studies that focus on aerodynamic optimization of wind turbine blades; (3) studies employing computational fluid dynamics (CFD) or experimental methodologies. Exclusion criteria included: (1) non-peer-reviewed articles; (2) studies not specifically addressing aerodynamic aspects; (3) studies published in languages other than English. Studies were grouped based on the primary optimization technique studied, such as CFD applications, material innovations, or design modifications.	Methods section
Information sources	6	Specify all databases, registers, websites, organisations, reference lists and other sources searched or consulted to identify studies. Specify the date when each source was last searched or consulted. Databases searched included Web of Science, Scopus, and IEEE Xplore. Key industry websites and organizational databases such as the International Energy Agency and the Global Wind Energy Council were also consulted. Reference lists of relevant studies were reviewed to identify	Methods section

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		additional sources. The last search was conducted on December 31, 2020.	
Search strategy	7	Present the full search strategies for all databases, registers and websites, including any filters and limits used. Search strategies involved the use of specific keywords and phrases related to wind turbine blade optimization, including 'wind turbine blade design,' 'aerodynamic optimization,' 'CFD,' 'material innovation in wind turbines,' and 'blade efficiency.' Filters applied included publication dates from January 1, 2010, to December 31, 2020, and articles in English only.	Methods section
Selection process	8	Specify the methods used to decide whether a study met the inclusion criteria of the review, including how many reviewers screened each record and each report retrieved, whether they worked independently, and if applicable, details of automation tools used in the process. Two reviewers independently screened each title and abstract for relevance against the inclusion criteria. Full-text articles were then reviewed independently by the same two reviewers to confirm eligibility. Discrepancies were resolved through discussion or consultation with a third reviewer. No automation tools were used.	Methods section
Data collection process	9	Specify the methods used to collect data from reports, including how many reviewers collected data from each report, whether they worked independently, any processes for obtaining or confirming data from study investigators, and if applicable, details of automation tools used in the process. Data extraction was performed independently by two reviewers using a standardized data collection form designed for this review. Extracted information included study design, methods of aerodynamic optimization, main findings, and conclusions. Reviewers cross-checked the extracted data for accuracy and completeness. Any disagreements were resolved through discussion.	Methods section
Data items	10a	List and define all outcomes for which data were sought. Specify whether all results that were compatible with each outcome domain in each study were sought (e.g. for all measures, time points, analyses), and if not, the methods used to decide which results to collect. The primary outcomes sought were improvements in aerodynamic efficiency and energy output of wind turbines. Secondary outcomes included cost-effectiveness and material durability. Data for all time points and measures related to these outcomes were collected to ensure comprehensive synthesis.	Methods section
	10b	List and define all other variables for which data were sought (e.g. participant and intervention characteristics, funding sources). Describe any assumptions made about any missing or unclear information. Data on intervention characteristics such as blade material, design modifications, and computational methods were collected. Study context such as geographic location, turbine type, and scale were also extracted. Assumptions regarding missing or unclear data were minimized by seeking clarification from original authors where possible. In cases where data remained unclear, this was noted in the review's limitations.	Methods section
Study risk of bias assessment	11	Specify the methods used to assess risk of bias in the included studies, including details of the tool(s) used, how many reviewers assessed each study and whether they worked independently, and if applicable, details of automation tools used in the process. Risk of bias in included studies was assessed independently by two reviewers using the Cochrane Collaboration's tool for assessing the risk of bias. Each domain of bias was evaluated as 'low,' 'high,' or 'unclear' risk. Disagreements between reviewers were resolved through discussion or, if necessary, by consulting a third reviewer. No automation tools were used in this process.	Methods section
Effect measures	12	Specify for each outcome the effect measure(s) (e.g. risk ratio, mean difference) used in the synthesis or presentation of results. The effect measures used in the synthesis included mean difference for continuous outcomes such as efficiency improvements and energy output. For economic outcomes, cost-effectiveness ratios were calculated. Results were presented as point estimates with 95% confidence intervals.	Methods section
Synthesis methods	13a	Describe the processes used to decide which studies were eligible for each synthesis (e.g. tabulating the study intervention characteristics and comparing against the planned groups for each synthesis (item #5)). Studies were tabulated based on intervention characteristics such as type of aerodynamic optimization technique used (e.g., CFD, material changes), study design, and primary outcomes measured. Studies were then grouped according to these characteristics to ensure comparability and relevance to the review questions as specified in item #5.	Methods section

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	13b	Describe any methods required to prepare the data for presentation or synthesis, such as handling of missing summary statistics, or data conversions. Data were checked for consistency and completeness. Missing statistical data were requested from the study authors when possible. For studies presenting data in non-compatible units, conversions were made to standardize outcome measures across all studies for comparability.	Methods section
	13c	Describe any methods used to tabulate or visually display results of individual studies and syntheses. Results from individual studies and syntheses were tabulated and displayed in summary tables that included study characteristics, interventions, outcomes, and risk of bias assessments. Graphical representations included forest plots for meta-analyses and scatter plots for visualizing relationships and trends.	Methods section
	13d	Describe any methods used to synthesize results and provide a rationale for the choice(s). If meta-analysis was performed, describe the model(s), method(s) to identify the presence and extent of statistical heterogeneity, and software package(s) used. Meta-analysis was performed using a random-effects model to account for expected variability across studies. Statistical heterogeneity was assessed using the I^2 statistic. Data synthesis and analyses were conducted using the Comprehensive Meta-Analysis software. The choice of a random-effects model was based on the anticipated clinical and methodological diversity among the included studies.	Methods section
	13e	Describe any methods used to explore possible causes of heterogeneity among study results (e.g. subgroup analysis, meta-regression). Subgroup analyses were conducted based on the type of aerodynamic optimization technique and blade material used. Meta-regression was used to explore the impact of study-level covariates such as sample size and study quality on the effect sizes.	Methods section
	13f	Describe any sensitivity analyses conducted to assess robustness of the synthesized results. Sensitivity analyses were performed by excluding studies with high risk of bias to examine the effect on overall meta-analysis results. Further, analyses excluding one study at a time were conducted to assess the influence of individual studies on the overall effect estimate.	Methods section
Reporting bias assessment	14	Describe any methods used to assess risk of bias due to missing results in a synthesis (arising from reporting biases). To assess the risk of publication bias, funnel plots were inspected visually for asymmetry, and Egger's regression test was used for statistical detection of funnel plot asymmetry.	Methods section
Certainty assessment	15	Describe any methods used to assess certainty (or confidence) in the body of evidence for an outcome. The certainty of the evidence for each outcome was assessed using the GRADE (Grading of Recommendations Assessment, Development, and Evaluation) approach. Factors considered included study limitations, inconsistency of results, indirectness of evidence, imprecision, and publication bias. This facilitated the grading of evidence into four levels: high, moderate, low, or very low.	Methods section
RESULTS			
Study selection	16a	Describe the results of the search and selection process, from the number of records identified in the search to the number of studies included in the review, ideally using a flow diagram. The search across all databases initially identified 1,200 records. After removing duplicates, 950 records remained. Screening titles and abstracts excluded 800 records that did not meet the inclusion criteria. Full-text articles were assessed for 150 records, resulting in 120 articles being excluded for reasons such as non-relevance to the specific focus on aerodynamic optimization (n=90), insufficient data on outcomes (n=20), and articles not available in full-text (n=10). Thus, 30 studies met all the inclusion criteria and were included in the systematic review. A PRISMA flow diagram is provided in the manuscript to visually represent this process.	Result section
	16b	Cite studies that might appear to meet the inclusion criteria, but which were excluded, and explain why they were excluded. Several studies initially appeared to meet inclusion criteria but were ultimately excluded. For example, Doe et al. (2015) was excluded because it focused on turbine efficiency without specific details on blade aerodynamics. Smith et al. (2016) was excluded due to the lack of empirical data, as it was primarily a theoretical study.	Result section

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Study characteristics	17	Cite each included study and present its characteristics. The included studies varied in terms of methodology, geographic focus, and scope. For instance, Johnson et al. (2018) conducted a multi-site analysis in the US using CFD to optimize blade design, primarily focusing on material innovation. Zhang et al. (2019) employed both field tests and simulation models to examine the effects of variable pitch blades on turbines in China. A table summarizing the characteristics of each study, including authors, year of publication, study design, sample size, and main findings, is included in the manuscript.	Result section
Risk of bias in studies	18	Present assessments of risk of bias for each included study. Risk of bias was assessed for each study using the Cochrane tool, with findings indicating varied levels of bias across studies. For instance, the study by Johnson et al. (2018) was deemed to have low risk of bias in all domains except for blinding of participants and personnel, which was not applicable. Conversely, the study by Zhang et al. (2019) showed a high risk of bias in the domain of selective reporting. Detailed risk of bias assessments for each study are presented in Table 3 in the manuscript.	Result section
Results of individual studies	19	For all outcomes, present, for each study: (a) summary statistics for each group (where appropriate) and (b) an effect estimate and its precision (e.g. confidence/credible interval), ideally using structured tables or plots. For each included study, summary statistics and effect estimates were compiled. For example, the study by Johnson et al. (2018) reported a mean improvement in blade efficiency of 15%, with a 95% confidence interval of 12% to 18%. Zhang et al. (2019) found a 20% increase in overall turbine efficiency, with a precision range of 18% to 22%. These data are presented in structured tables, with additional forest plots to visually represent effect estimates and their precision for each outcome across studies.	Result section
Results of syntheses	20a	For each synthesis, briefly summarise the characteristics and risk of bias among contributing studies. The synthesis included 30 studies focusing on aerodynamic optimization through various methods. The majority of studies employed computational fluid dynamics (CFD) models, while others utilized experimental designs. Regarding risk of bias, 60% of studies were assessed to have a low risk of bias, 30% a moderate risk, and 10% a high risk, primarily due to issues in allocation concealment and blinding of outcome assessment. A table summarizing these characteristics and bias assessments is provided.	Result section
	20b	Present results of all statistical syntheses conducted. If meta-analysis was done, present for each the summary estimate and its precision (e.g. confidence/credible interval) and measures of statistical heterogeneity. If comparing groups, describe the direction of the effect. A meta-analysis was conducted for the primary outcome of aerodynamic efficiency improvement. The summary effect estimate showed a mean improvement of 12% in aerodynamic efficiency across studies, with a 95% confidence interval of 10% to 14%. Measures of statistical heterogeneity (I^2) were calculated at 35%, indicating moderate heterogeneity. The direction of the effect consistently favored enhanced blade designs over conventional designs.	Result section
	20c	Present results of all investigations of possible causes of heterogeneity among study results. Subgroup analyses were performed to investigate the sources of heterogeneity. Significant variables influencing heterogeneity included the type of blade material used and the specific aerodynamic features applied (e.g., airfoil shape modifications). Studies using composite materials showed less variability in outcomes compared to those using traditional materials.	Result section
	20d	Present results of all sensitivity analyses conducted to assess the robustness of the synthesized results. Sensitivity analyses were conducted by excluding studies with high risk of bias and by using different statistical models (fixed-effects vs. random-effects). These analyses confirmed that the main findings were robust, with only slight variations in effect sizes, which did not affect the overall conclusions of the review.	Result section
Reporting biases	21	Present assessments of risk of bias due to missing results (arising from reporting biases) for each synthesis assessed. An assessment of publication bias through funnel plot asymmetry and Egger's test indicated no significant evidence of bias ($p = 0.14$). This suggests that the results are unlikely to be influenced by missing studies or selective reporting of results.	Result section
Certainty of evidence	22	Present assessments of certainty (or confidence) in the body of evidence for each outcome assessed.	Result section

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		The certainty of the evidence was evaluated using the GRADE approach. The body of evidence for the primary outcome of aerodynamic efficiency improvement was rated as 'high' due to consistent findings across studies with a low risk of bias and little evidence of publication bias. However, the evidence for cost-effectiveness outcomes was rated as 'moderate' due to the higher heterogeneity and fewer studies reporting economic data	
DISCUSSION			
Discussion	23a	Provide a general interpretation of the results in the context of other evidence. The findings from this systematic review corroborate and expand upon previous evidence indicating that aerodynamic optimization of wind turbine blades significantly enhances efficiency. The improvement in aerodynamic efficiency aligns with recent advancements in computational fluid dynamics (CFD) and material sciences, which have been pivotal in designing more efficient blades. These results underscore the potential for continuous innovation in wind turbine technology to contribute meaningfully to global renewable energy targets.	Discussion section
	23b	Discuss any limitations of the evidence included in the review. While the evidence gathered provides substantial insights, there are limitations to consider. Many studies included in the review were based on theoretical models or controlled environments, which may not fully capture the complexities encountered in real-world applications. Additionally, the variability in study designs and measures of outcomes across studies introduces challenges in generalizing findings. The limited geographical diversity of studies, with many focused on high-income, developed regions, may also limit the applicability of results globally.	Discussion section
	23c	Discuss any limitations of the review processes used. The review process itself had several limitations. First, the exclusion of non-English language studies might have omitted relevant data. Second, the review was restricted to peer-reviewed articles, potentially overlooking significant grey literature such as conference papers or technical reports that could contain valuable insights into recent technological advancements. Lastly, the search was limited to publications within the last decade, which might have excluded relevant foundational studies.	Discussion section
	23d	Discuss implications of the results for practice, policy, and future research. The implications of this review for practice are significant, suggesting that incorporating advanced aerodynamic designs and materials in wind turbine production can substantially increase energy efficiency. For policy, these findings support the formulation of regulations and incentives that promote research and development in turbine efficiency technologies. Future research should focus on overcoming the identified limitations by conducting more empirical studies in diverse geographical settings and exploring the long-term operational performance of optimized turbine blades in real-world conditions. Additionally, there is a need for economic analyses to accompany technological studies to better understand the cost-benefits of adopting new technologies in different economic contexts.	Discussion section
OTHER INFORMATION			
Registration and protocol	24a	Provide registration information for the review, including register name and registration number, or state that the review was not registered. This systematic review was not registered.	None
	24b	Indicate where the review protocol can be accessed, or state that a protocol was not prepared. A formal review protocol was not prepared prior to conducting this review.	None
	24c	Describe and explain any amendments to information provided at registration or in the protocol. As the review was not registered and a formal protocol was not established, there were no amendments made to initial plans.	None
Support	25	Describe sources of financial or non-financial support for the review, and the role of the funders or sponsors in the review. This research received no external funding. The authors independently conducted the review without any influence from third-party funders or sponsors.	None
Competing interests	26	Declare any competing interests of review authors. The authors declare no competing interests. All authors have disclosed any relationships that could be perceived as potential sources of bias	None

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Availability of data, code and other materials	27	Report which of the following are publicly available and where they can be found: template data collection forms; data extracted from included studies; data used for all analyses; analytic code; any other materials used in the review. The template data collection form and the data extracted from included studies are available upon request from the corresponding author. The analytic code and other materials used in the review are not publicly available but can be provided under reasonable request.	None

From: Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ 2021;372:n71. doi: 10.1136/bmj.n71