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A Comprehensive Review of Multi-criteria Decision-making (MCDM) Toward Sustainable Renewable Energy Development

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ABSTRACT

The transition to sustainable renewable energy necessitates robust decision-making frameworks that integrate economic, environmental, and social considerations. Multi-Criteria Decision-Making (MCDM) methods have become vital for optimizing energy planning and policy formulation. This review systematically examines MCDM applications in sustainable renewable energy from 2015 to 2025 using bibliometric analysis. Data were sourced from 4,101 UGC CARE List II research papers indexed in Scopus and Web of Science via the Dimensions.ai database, applying predefined inclusion and exclusion criteria. The study identifies key trends, methodological advancements, and research gaps, highlighting the increasing adoption of hybrid MCDM approaches. Despite progress, challenges such as subjective weight assignment and model uncertainties remain. The review underscores influential contributions, assesses methodological limitations, and explores MCDM models. Future research should focus on model transparency, standardized criteria selection, and real-world applications, offering insights for policymakers, researchers, and industry stakeholders to enhance sustainable energy decision-making.

1. Introduction

The global shift towards sustainable energy solutions has necessitated robust decision-making frameworks to balance economic, environmental, and social factors. MCDM methods have emerged as powerful tools for evaluating renewable energy alternatives, optimizing resource allocation, and enhancing sustainability in energy policies [1]. Given the complex and conflicting nature of energy-related decisions, MCDM approaches provide structured methodologies for selecting the most suitable renewable energy solutions [2, 3]. This review aims to comprehensively analyze the role of MCDM in sustainable renewable energy development, highlighting key trends, methodologies, and future research directions.

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1.1 The Importance of MCDM in Renewable Energy Decision-Making

The integration of renewable energy sources into national and global energy systems presents multiple challenges, including resource variability, technological feasibility, economic viability, and environmental impact [4, 5]. MCDM methods address these challenges by:

i. Systematically evaluating multiple conflicting criteria.
ii. Enhancing decision transparency for policymakers, investors, and stakeholders.
iii. Providing adaptable frameworks for different energy systems and geographical contexts.
iv. Facilitating a structured comparison between various renewable energy alternatives such as solar, wind, hydro, and biomass. By considering diverse criteria simultaneously, MCDM enables decision-makers to develop more balanced and effective energy strategies, ensuring long-term sustainability.

1.2 Common MCDM Methods Used in Renewable Energy Studies

Several MCDM techniques have been extensively applied in renewable energy decision-making, each with distinct characteristics:

i. Analytic Hierarchy Process (AHP): Used for ranking energy alternatives based on expert opinions and pairwise comparisons [6, 7].
v. Technique for Order Preference by Similarity to Ideal Solution (TOPSIS): Helps in selecting the most efficient renewable energy system by comparing alternatives to an ideal solution [8, 9].
vi. Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE): A preference-based ranking method suitable for complex energy scenarios [10, 11].
vii. Weighted Aggregated Sum Product Assessment (WASPAS): A hybrid method combining additive and multiplicative approaches for energy evaluation [12, 13].
viii. Multi-Objective Optimization (MOORA, VIKOR): Used for optimizing multiple conflicting criteria simultaneously [14, 15].

Each method has specific strengths and limitations, influencing their applicability in different energy planning scenarios.

1.3 The Need for a Comprehensive Review and Research Objectives

Despite the extensive use of MCDM in energy planning, several research gaps persist, necessitating a systematic review to:

i. Identify major trends in MCDM applications for sustainable energy.
ii. Analyze research patterns using bibliometric analysis from 2015-2025.
iii. Highlight challenges and future directions in integrating MCDM with emerging technologies (e.g., AI, IoT, blockchain).

This review will provide valuable insights for policymakers, researchers, and industry experts, ensuring more informed decision-making in the transition towards sustainable renewable energy systems.

2. Literature Review

The growing global demand for sustainable energy has driven extensive research into decision-making methodologies for optimizing renewable energy solutions. Multi-Criteria Decision-Making (MCDM) methods have emerged as essential tools for evaluating and selecting the most suitable energy alternatives, balancing economic, environmental, and social factors [16, 17]. This section provides a comprehensive analysis of existing literature on MCDM applications in renewable energy development, highlighting key trends, methodologies, and challenges.

2.1 Evolution of MCDM in Renewable Energy Decision-Making

MCDM methods have evolved over the years, adapting to the increasing complexity of energy systems and sustainability concerns. Early studies focused on cost-effectiveness and technical feasibility, while recent research incorporates environmental impact assessments, policy frameworks, and stakeholder preferences [18, 19, 20]. Key developments in MCDM for renewable energy:

i. Pre-2000 Era: Dominance of cost-benefit analysis and simple decision-making models.
ii. 2000–2015: Emergence of advanced MCDM methods like AHP, TOPSIS, and PROMETHEE for energy planning.
iii. 2015–Present: Integration of artificial intelligence, fuzzy logic, and hybrid MCDM approaches for better decision accuracy.

2.2 Application Areas of MCDM for Sustainable Renewable Energy

Multi-Criteria Decision-Making (MCDM) has been widely applied in various domains of sustainable renewable energy development. It plays a crucial role in optimizing energy planning, evaluating energy policies, selecting suitable energy sources, and ensuring long-term sustainability. Below are the major application areas of MCDM in renewable energy.

2.2.1 Renewable Energy Source Selection and Evaluation

MCDM methods help in choosing the most suitable renewable energy source based on multiple criteria such as economic feasibility, environmental impact, social acceptance, and technical performance. Key Applications:

i. Solar vs. Wind vs. Biomass Selection: MCDM techniques like AHP, TOPSIS, and PROMETHEE are used to compare energy alternatives based on cost, efficiency, and sustainability [21, 22].
ii. Hybrid Energy System Design: Evaluating the optimal combination of renewable energy sources for decentralized power generation [23, 24].
iii. Geographical Suitability Analysis: Identifying the best locations for wind farms, solar power plants, and hydroelectric stations using GIS-based MCDM approaches [25, 26].

2.2.2 Energy Policy and Strategic Decision-Making

Governments and policymakers utilize MCDM methods to develop and evaluate renewable energy policies, ensuring alignment with sustainability goals. Key Applications:

i. Policy Framework Assessment: Evaluating the effectiveness of energy transition policies such as feed-in tariffs, subsidies, and carbon taxes [27, 28].
ii. Sustainability Impact Assessment: Assessing long-term environmental and socio-economic impacts of renewable energy policies [29, 30].
iii. Stakeholder Preference Analysis: Incorporating the views of policymakers, industries, and communities in energy decision-making [31, 32].

2.2.3 Smart Grid and Renewable Energy Integration

The integration of renewable energy into smart grids requires advanced decision-making techniques to ensure efficiency, reliability, and stability. Key Applications:

i. Grid Stability and Energy Storage Optimization: Selecting optimal battery storage solutions for intermittent renewable sources [33, 34].

ii. Demand Response Management: Using MCDM to design flexible energy pricing strategies for better load balancing [35, 36].
iii. Microgrid Planning: Evaluating distributed renewable energy generation for off-grid and rural electrification projects [37, 38].

3. Methodology

This study follows a structured methodology to conduct a comprehensive review of multi-criteria decision-making (MCDM) methods applied to sustainable renewable energy development. The research aims to analyze existing literature, identify key trends, and provide insights into the effectiveness and limitations of MCDM techniques in this domain. A systematic review approach is employed, integrating bibliometric analysis and content-based evaluation to ensure an in-depth understanding of the subject matter [39]. The methodology consists of three key components: literature search strategy, inclusion and exclusion criteria, and bibliometric analysis.

3.1 Literature Search Strategy

A rigorous literature search was conducted to identify relevant research articles, conference papers, and review studies on the application of MCDM in sustainable renewable energy development [40]. The following steps were taken:

i. Databases Used: The search was performed across dimension.ai database, including UGC CARE LIST II group (Scopus, Web of Science), ensuring a wide coverage of published research.
ii. Keywords and Search Strings: The search was conducted using combinations of keywords such as:
"Multi-Criteria Decision-Making (MCDM)"
"Sustainable Renewable Energy"
"Optimization in Renewable Energy"
"Decision Analysis for Energy Management"
"AHP, TOPSIS, VIKOR, and other MCDM methods in energy"
iii. Time Frame Consideration: The review covers studies published between 2015 and 2025, as this period witnessed significant advancements in renewable energy technologies and decision-making methodologies.
iv. Types of Sources Considered: Peer-reviewed journal articles were prioritized to ensure credibility.

3.2 Inclusion and Exclusion Criteria

To maintain the relevance and quality of the review, strict inclusion and exclusion criteria were applied to the selection of research papers [41].

Inclusion Criteria:

i. Studies that explicitly focus on MCDM applications in renewable energy decision-making.
ii. Papers that compare or evaluate multiple MCDM techniques (e.g., AHP, TOPSIS, VIKOR, PROMETHEE, etc.).
iii. Research that integrates sustainability principles in energy project selection, site suitability analysis, or resource allocation.
iv. Studies published in high-quality journals and indexed in Scopus or Web of Science.

Exclusion Criteria:

i. Papers that discuss MCDM in non-energy sectors, such as healthcare or manufacturing, without a clear connection to renewable energy.
ii. Studies that focus solely on single-objective optimization techniques rather than multi-criteria decision-making.
iii. Articles with limited methodological clarity or lacking sufficient data for meaningful comparison.
iv. Duplicate studies or conference papers that have been later expanded into journal publications.

Applying these criteria helped refine the dataset, ensuring that only the most relevant and high-quality research contributions were included in the final analysis.

3.3 Bibliometric Analysis

A bibliometric analysis was conducted with 4101 research paper to quantitatively assess the publication trends, influential authors, key journals, and collaborative networks in MCDM-based renewable energy research [42]. The following key aspects were analyzed:

i. Publication Trends: The number of research papers published annually was examined to identify growth patterns and emerging trends in MCDM applications for renewable energy [43].
ii. Top-Contributing Authors and Institutions: Citation analysis was used to identify the most influential researchers and institutions contributing to this field [44].
iii. High-Impact Journals: The most frequently cited and high-impact journals were identified to determine where significant research is being published [45].
iv. Country-wise Collaboration: Global research collaboration trends were mapped to understand which countries and institutions are leading in this area [46].

The bibliometric analysis provided a comprehensive overview of the research landscape, offering valuable insights into the evolution and impact of MCDM methodologies in sustainable renewable energy decision-making.

4. Current State of MCDM in Energy Management

4.1. Trends in research and publication

The publication trend on multi-criteria decision-making (MCDM) for sustainable renewable energy development from 2015 to 2025 demonstrates a steady rise in research interest as shown in Figure 1. The number of publications increased from 115 in 2015 to 760 in 2024, reflecting growing global attention toward MCDM applications in energy sustainability. A notable surge occurred between 2018 and 2024, indicating advancements in computational methods and policy-driven research. The peak in 2024 (760 papers) suggests mature research expansion, emphasizing the relevance of MCDM in optimizing energy strategies. The 2025 count (104) appears low due to early-year data collection and is expected to rise. This trend highlights the increasing reliance on MCDM methodologies to address complex decision-making in renewable energy planning and management.

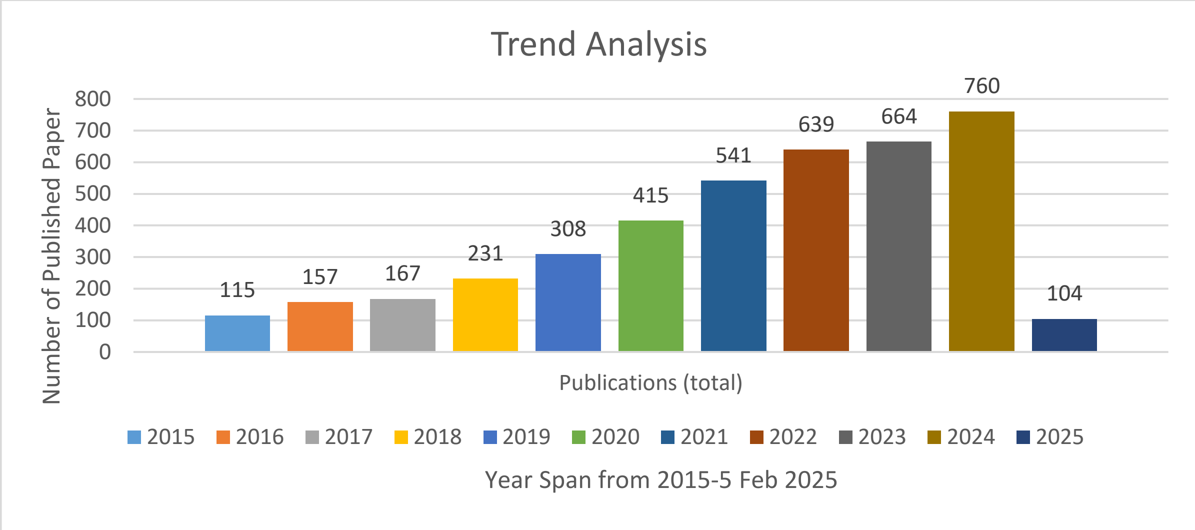

Fig. 1. Trend analysis of research paper publication

4.2 Trends in Research category

The field-wise distribution of research on multi-criteria decision-making (MCDM) in sustainable renewable energy development highlights its multidisciplinary nature as shown in Figure 2.

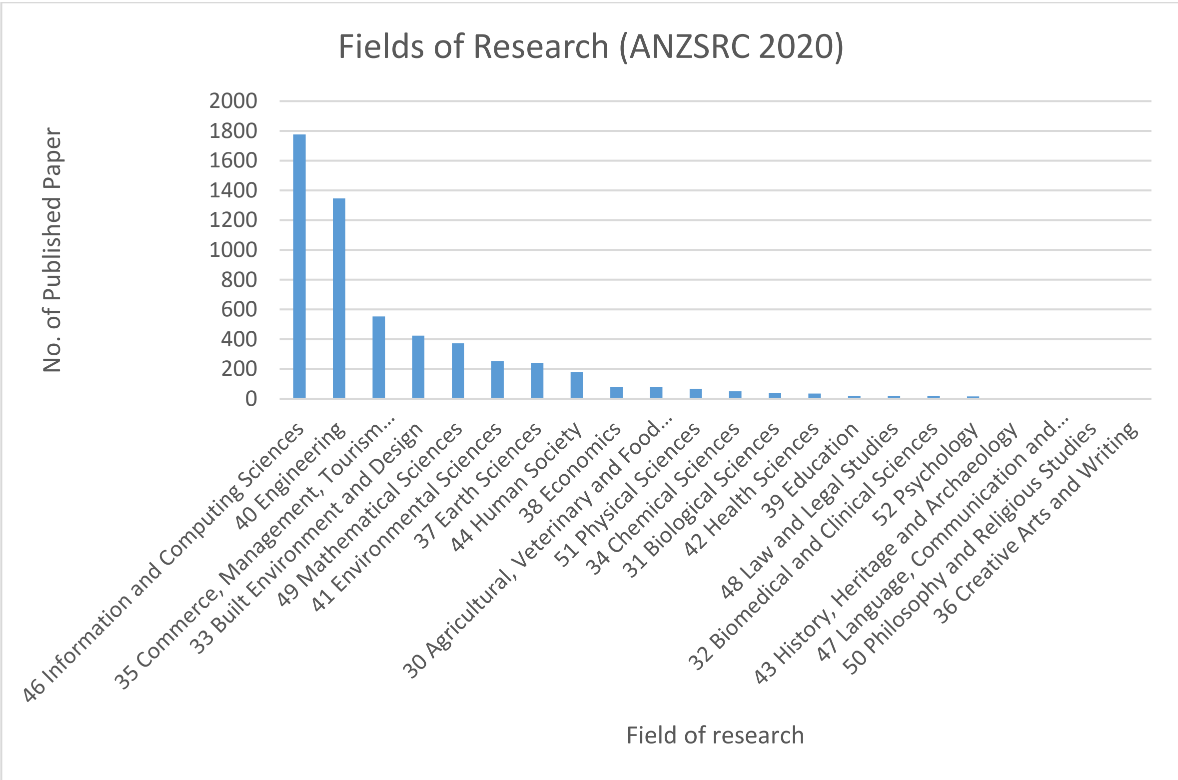

Fig. 2. Trend in Research Category (ANZSRC 2020)

The highest contributions come from Information and Computing Sciences (1777 papers) and Engineering (1346 papers), indicating the integration of computational techniques, AI, and optimization models in MCDM applications. Commerce and Management (553) and Built Environment and Design (425) reflect the role of MCDM in business decision-making and urban energy planning. Mathematical Sciences (373) contribute to the development of quantitative decision models, while Environmental Sciences (252) and Earth Sciences (242) focus on sustainability aspects. Lower contributions from Health (34), Psychology (16), and Philosophy (3) suggest limited exploration of human-centric and ethical considerations in MCDM. These trends emphasize growing interdisciplinary collaboration in energy sustainability research.

The research distribution across Sustainable Development Goals (SDGs) in multi-criteria decision-making (MCDM) for sustainable renewable energy development highlights a strong focus on SDG 7 (Affordable and Clean Energy) with 715 papers, emphasizing MCDM's role in optimizing energy solutions as shown in Figure 3. SDG 13 (Climate Action) and SDG 12 (Responsible Consumption and Production), with 336 and 302 publications, respectively, reflect MCDM's application in mitigating climate change and improving resource efficiency. Urban sustainability (SDG 11 - 218 papers) and land conservation (SDG 15 - 149 papers) further illustrate the integration of MCDM in infrastructure and ecological planning. However, lower contributions to SDG 5 (Gender Equality - 1 paper) and SDG 10 (Reduced Inequalities - 2 papers) suggest gaps in social and equity-focused applications of MCDM. This trend highlights the need for broader interdisciplinary research.

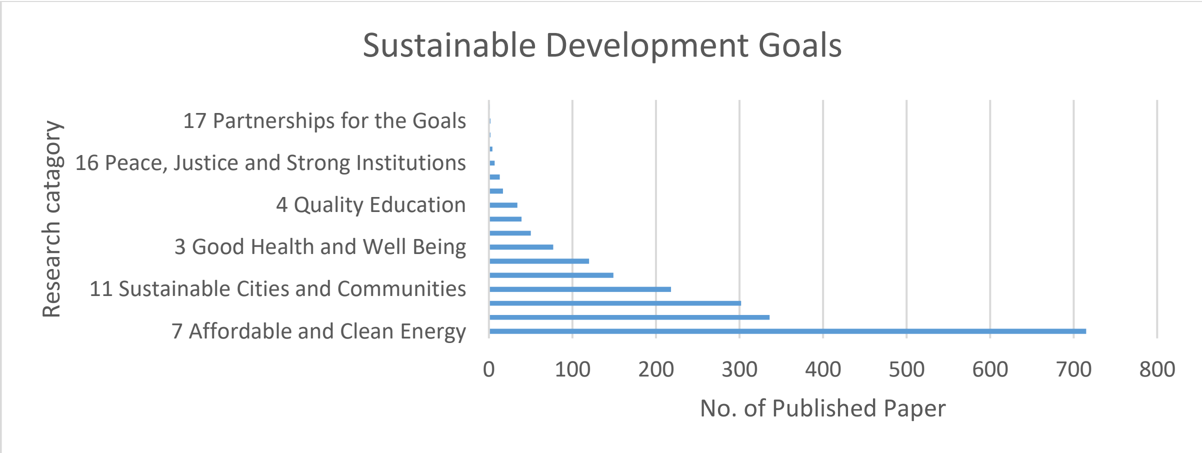

Fig. 3. Trend in Research Category (SDG)

4.3 Publication Citation analysis

The citation data reveals a significant upward trend in the number of citations from 2015 to 2024, reflecting the growing academic interest in multi-criteria decision-making (MCDM) for sustainable renewable energy development as shown in Figure 4.

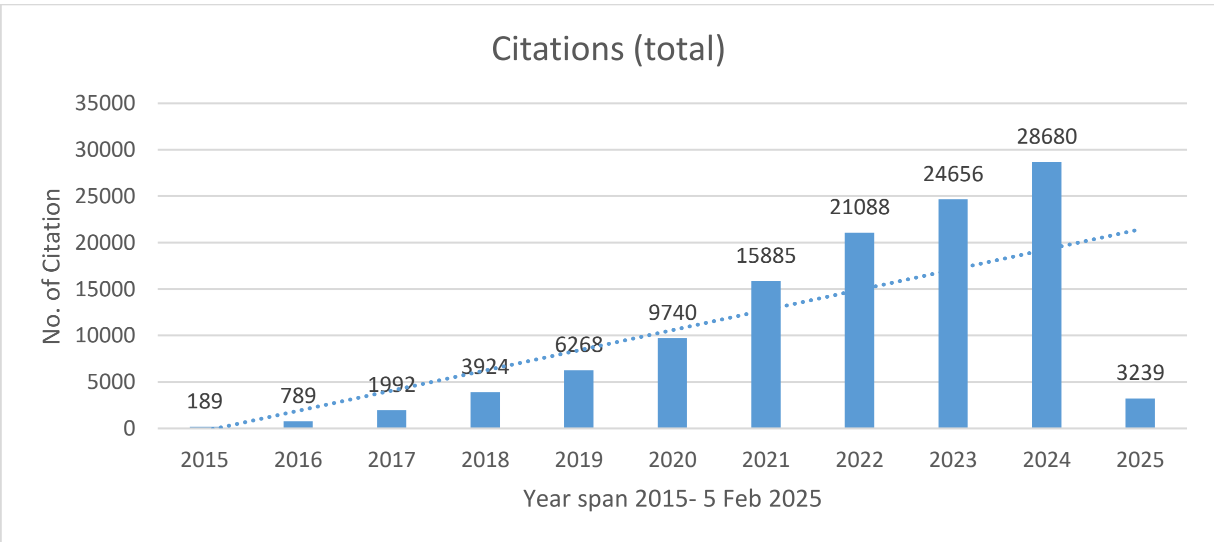

Fig. 4. Trend in Citations

Starting at 189 citations in 2015, the numbers surged exponentially, reaching 28,680 by 2024, with a notable peak in 2023 at 24,656 citations. This exponential growth indicates the increasing relevance of MCDM methodologies in addressing complex renewable energy challenges. The sharp rise in citations, particularly from 2020 onwards, suggests a heightened focus on sustainability and renewable energy research, likely driven by global climate change concerns and policy shifts. The data underscores the importance of MCDM as a critical tool for decision-making in renewable energy development, with its impact and application expanding rapidly in recent years.

The top five researchers with the highest citations in the field of multi-criteria decision-making (MCDM) for sustainable renewable energy development. Edmundas Kazimieras Zavadskas from Vilnius Gediminas Technical University, Lithuania, leads with 3,141 citations and the highest mean citation of 82.66, reflecting his significant impact. Dragan Stevan S Pamucar from the University of Belgrade, Serbia, follows with 4,002 citations, though his mean citation of 56.37 is lower due to a higher number of publications (71). Jian-Qiang Wang from Central South University, China, ranks third with 2,655 citations and a strong mean of 66.38. Muhammet Deveci from the Naval Academy, Turkey, and Muhammad Ilyas Riaz from the University of the Punjab, Pakistan, complete the list, with Riaz having the lowest mean citations (21.20), indicating varying research influence and productivity.

4.4 Co-authorship analysis

Co-authorship analysis in bibliometric studies examines the collaboration patterns among researchers based on their shared publications as shown in Figure 5. By visualizing co-authorship networks, it identifies the most influential and connected scholars in a field. In this analysis, only the largest set of connected researchers is considered, with a maximum of 100 researchers displayed. Publications with more than 25 authors are excluded to maintain meaningful collaboration insights. The strength of relationships between researchers is determined by the number of co-authored publications, helping to reveal key research clusters, interdisciplinary collaborations, and influential contributors shaping the knowledge landscape within a particular domain.

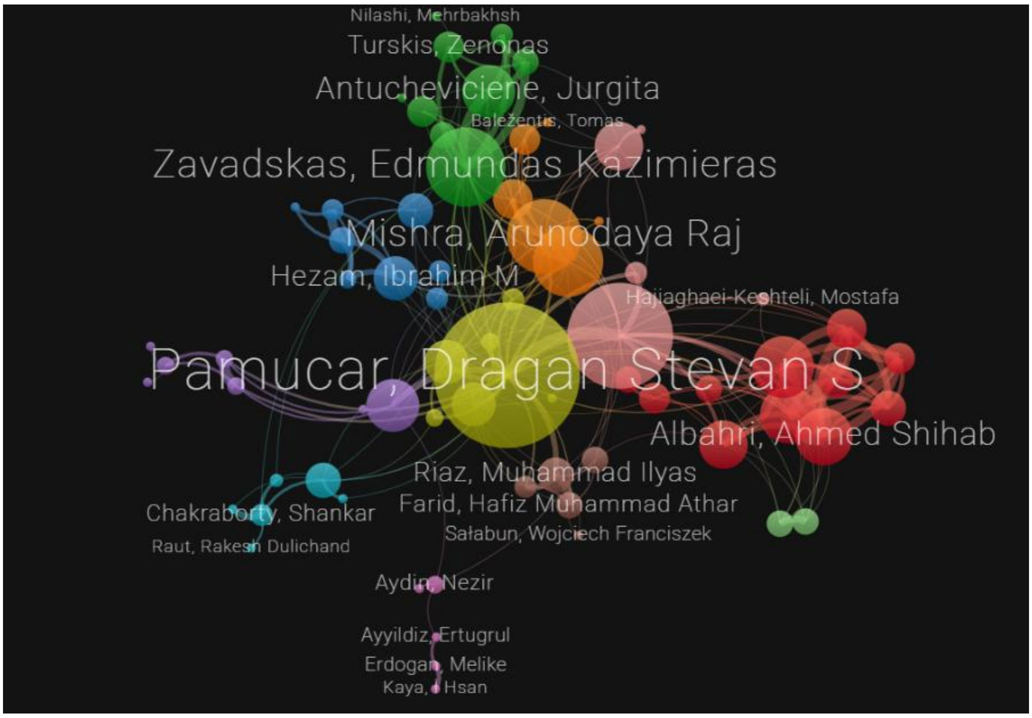

Fig. 5. Co-authorship analysis

4.5 Sources of Publication

In bibliometric analysis, identifying the sources of publication helps determine the most influential journals in a research domain. For multi-criteria decision-making (MCDM) toward sustainable renewable energy development, analyzing top publishing journals provides insights into research impact, trends, and key contributors. Below are the top 10 journals based on publication count, citation impact, and mean citations per paper.

i. Sustainability – Publications: 171, Total Citations: 3,505, Mean Citations per Paper: 20.50. Sustainability is the leading journal in MCDM research related to renewable energy. It publishes a large volume of studies focused on decision-making frameworks, environmental sustainability, and policy-related applications. Despite having the highest number of publications, its citation impact per paper is moderate compared to others.
ii. Journal of Cleaner Production – Publications: 107, Total Citations: 7,833, Mean Citations per Paper: 73.21. The Journal of Cleaner Production has the highest citation impact per paper, indicating strong influence and recognition in MCDM research. It focuses on sustainable production, cleaner energy solutions, and MCDM methods for optimizing industrial and environmental processes. The journal's research is widely referenced in decision-making applications for renewable energy management.
iii. Expert Systems with Applications – Publications: 107, Total Citations: 3,841, Mean Citations per Paper: 35.90. Expert Systems with Applications is a significant journal emphasizing artificial intelligence (AI), machine learning, and expert systems in decision-making. It plays a crucial role in integrating computational intelligence with MCDM methodologies for renewable energy and sustainability applications. Its citation impact per paper suggests a strong research influence in AI-driven decision-making frameworks.
iv. IEEE Access – Publications: 102, Total Citations: 1,886, Mean Citations per Paper: 18.49. IEEE Access is an open-access journal that covers interdisciplinary research, including MCDM applications in energy systems. It provides a broad platform for research dissemination, though its citation impact per paper is relatively lower compared to other top journals. This indicates a mix of fundamental and applied research contributions to decision-making in renewable energy.
v. Applied Soft Computing – Publications: 80, Total Citations: 4,599, Mean Citations per Paper: 57.49. Applied Soft Computing is a key journal in soft computing techniques such as fuzzy logic, neural networks, and evolutionary algorithms for decision-making. It has a strong impact in MCDM research, particularly for optimizing energy management and sustainability solutions. Its high mean citation count suggests significant influence in computational decision-making applications.
vi. Mathematics – Publications: 79, Total Citations: 1,053, Mean Citations per Paper: 13.33. Mathematics is a relevant journal for mathematical modeling and computational methods in MCDM research. It contributes significantly to the development of optimization algorithms and statistical frameworks for decision-making in renewable energy applications. However, its lower mean citation count suggests that it has a more specialized audience compared to other journals in the field.
vii. Symmetry – Publications: 66, Total Citations: 2,832, Mean Citations per Paper: 42.91. Symmetry focuses on symmetry-based models and methodologies in scientific computing, including MCDM applications. It plays a crucial role in developing decision-support systems for sustainable energy management, with a relatively high citation impact per paper. This indicates strong academic recognition in structured and mathematical approaches to decision-making.

viii. Journal of Intelligent & Fuzzy Systems – Publications: 65, Total Citations: 911, Mean Citations per Paper: 14.02. The Journal of Intelligent & Fuzzy Systems specializes in fuzzy logic and intelligent decision-making systems. It is widely used for research on handling uncertainty and multi-criteria evaluations in renewable energy planning and optimization. Despite a lower mean citation count, it remains a valuable source for researchers focusing on fuzzy MCDM approaches.

ix. Energies – Publications: 55, Total Citations: 1,571, Mean Citations per Paper: 28.56. Energies is a leading journal in renewable energy research, covering a wide range of topics, including MCDM applications in energy policy, grid management, and sustainable energy solutions. Its moderate mean citation count suggests its research is well-referenced but not as influential as top-cited journals in this field.

x. Soft Computing – Publications: 54, Total Citations: 1,660, Mean Citations per Paper: 30.74. Soft Computing publishes research on computational intelligence techniques such as evolutionary algorithms, machine learning, and fuzzy systems applied to decision-making. Its contributions to MCDM research focus on optimizing energy efficiency and sustainability strategies. Its mean citation count reflects a strong research impact in computational decision-making frameworks.

Key Insights from the Analysis:

i. Sustainability leads in total publications, while Journal of Cleaner Production has the highest citation impact per paper, making it the most influential journal.

ii. AI and computational intelligence journals such as *Applied Soft Computing*, *Soft Computing*, and *Expert Systems with Applications* play a critical role in integrating advanced decision-making methods into energy sustainability.

iii. Open-access and interdisciplinary journals like *IEEE Access* and *Energies* contribute to broader research dissemination in MCDM applications for renewable energy.

These findings highlight the most influential sources in MCDM research for sustainable renewable energy, providing guidance for researchers on key journals for publication and literature review.

4.6 Country and Organization analysis

The analysis of the top 10 countries contributing to multi-criteria decision-making (MCDM) research in sustainable renewable energy development highlights China's dominance with 528 publications and 20,757 citations, showcasing its strong research output and impact as shown in Figure 6.

India follows with 466 documents and 11,829 citations, reflecting its growing focus on sustainable energy solutions. Iran and Turkey, with 264 and 284 publications respectively, demonstrate significant academic engagement, supported by high citation counts of 10,159 and 9,874. The United States and the United Kingdom, known for their advanced research infrastructure, contribute 132 and 110 documents, receiving 4,350 and 3,538 citations. Australia, Lithuania, Pakistan, and Spain also exhibit noteworthy contributions. This data underscores the global nature of MCDM research, with Asian and European countries leading in impact.

The analysis of the top 10 organizations contributing to multi-criteria decision-making (MCDM) research in sustainable renewable energy development highlights Central South University as the leading institution with 61 publications and 3,493 citations, reflecting its significant impact as shown in Figure 7. The University of Tehran follows closely with 65 documents and 2,640 citations, demonstrating Iran's strong research presence. Sichuan University (37 publications, 2,593 citations) and Vilnius Gediminas Technical University (42 publications, 2,292 citations) also play crucial roles. Zhejiang University, despite only 11 papers, has amassed 1,922 citations, indicating high research influence. Institutions such as Istanbul Technical University, Allameh Tabataba'i University, and North China Electric Power University continue to contribute valuable insights. The University of Pretoria and the University of Electronic Science and Technology of China also show high citation impact, highlighting the global collaboration in MCDM research for sustainable energy solutions.

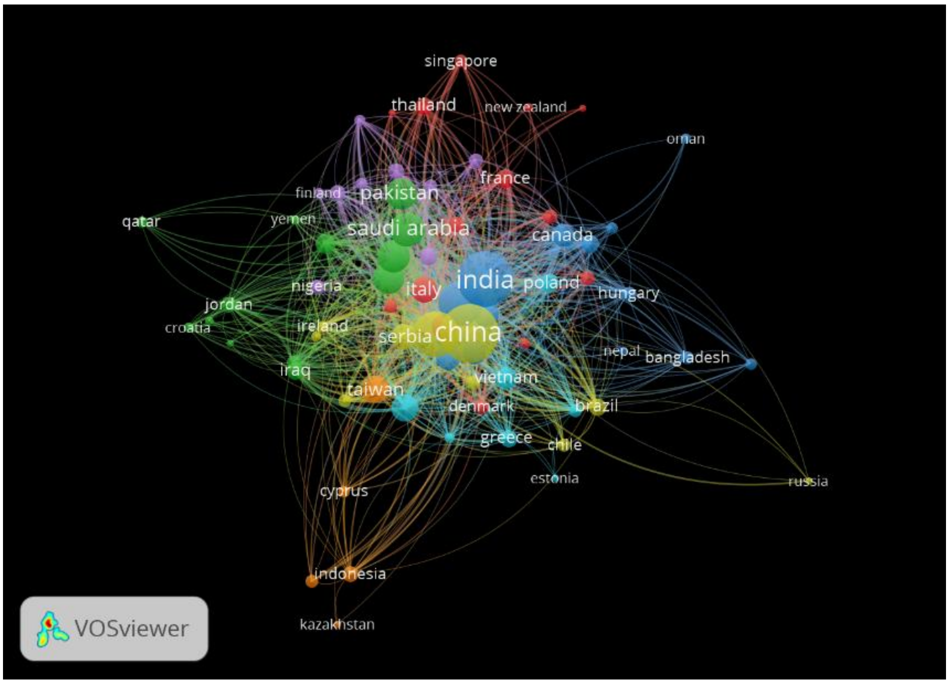

Fig. 6. Country analysis

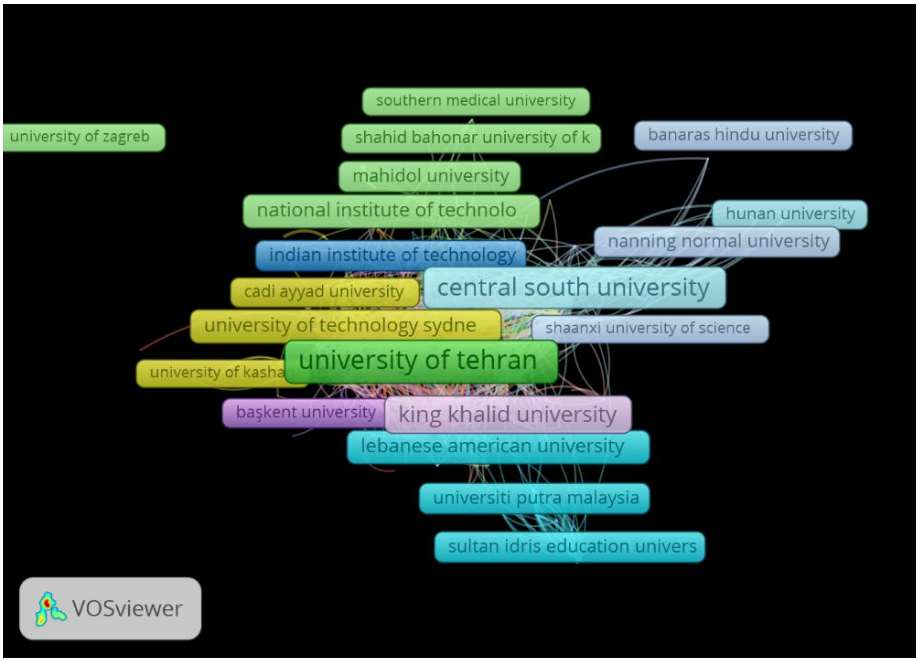

Fig. 7. Organization analysis

4.7 Influential paper analysis

Top 10 Influential Papers in MCDM for Sustainable Renewable Energy Development are listed below:

i. Kumar *et al.,* [47] – 1221 citations. The most influential study, significantly shaping MCDM applications in energy. This study aims to explore the role of MCDM in optimizing sustainable energy planning, addressing technical, social, economic, and environmental constraints [47]. A comprehensive review was conducted on MCDM applications in renewable energy. Results highlight its flexibility in decision-making. Future research should integrate AI-driven models for enhanced energy planning efficiency.
ii. Ren *et al.,* [48] – 559 citations. Key contribution to decision-making frameworks in renewable energy planning. This study aims to extend the TODIM approach using Pythagorean fuzzy sets to address MCDM problems under uncertainty [48]. The methodology integrates prospect theory to model decision-makers' risk behaviors, followed by simulations and a case study. Results validate its effectiveness. Future work should explore hybrid models for broader decision-making applications.
iii. Khosravi *et al.,* [49] – 519 citations. Focuses on optimization techniques integrating MCDM methodologies. This study aims to evaluate MCDM and machine learning methods for flood susceptibility modeling [49]. Using 12 flood conditioning factors, VIKOR, TOPSIS, SAW, NBT, and NB models were tested and validated via AUC. Results showed NBT performed best (AUC = 0.98). Future research should refine hybrid models for improved accuracy.
iv. Şengül *et al.,* [50] – 437 citations. Early work addressing sustainability challenges through MCDM. This study aims to develop an MCDM-based decision support framework for ranking renewable energy supply systems in Turkey [50]. Using Fuzzy TOPSIS and Interval Shannon's Entropy, criteria weights were determined, and sensitivity analysis was performed. Results indicate that hydropower is the most preferred system, followed by geothermal, regulator, and wind power. Future research should integrate hybrid MCDM approaches and real-time data to enhance decision-making accuracy for sustainable energy investments.
v. Keshavarz-Ghorabaee [51] – 429 citations. A recent influential paper, highlighting advanced MCDM models. This study introduces MEREC, a novel objective weighting method in MCDM [51]. The methodology involves computational analyses, including an illustrative example, comparative validation, and simulation-based reliability tests using normally distributed data. Results confirm MEREC's efficiency and stability compared to existing methods. Future research should explore its integration with hybrid MCDM models and real-world decision-making scenarios to enhance applicability and robustness.
vi. Rostamzadeh *et al.,* [52] – 332 citations. Examines MCDM in sustainable energy policy formulation. This study aims to develop a framework for sustainable supply chain risk management (SSCRM) using an integrated fuzzy MCDM approach, combining TOPSIS and CRITIC methods [52]. Through expert panels, seven main criteria and forty-four sub-criteria were identified. Results highlight key risks, with machines, suppliers, and policy risks being dominant. The methodology was successfully applied in a real case company. Future work should focus on refining the framework and expanding its applicability to diverse industries.
vii. Shao *et al.,* [53] – 318 citations. Discusses novel hybrid MCDM frameworks for energy management. This study aims to review MCDM applications in renewable energy site selection by analyzing 85 papers published from 2001 to 2018. The methodology involves content analysis to identify criteria selection, data normalization, criteria weighting, alternative evaluation, and result validation methods [53]. Findings reveal common

criteria across energy sources, with GIS and AHP being widely used. Future research should focus on integrating advanced models for improving decision accuracy and handling dynamic site selection challenges.

viii. Ansari and Kant [54] – 309 citations. Contributions to fuzzy MCDM applications in energy. This study critically analyzes 286 papers on sustainable supply chains (SSC) published from 2002 to 2016. The methodology involves categorizing literature by various factors such as research methodology, industry sector, and MCDM tools [54]. Results show a dominance of qualitative studies, with linear programming being the most used quantitative approach. Future research should focus on expanding quantitative modeling, applying advanced techniques, and developing efficient algorithms for SSC optimization.

ix. Büyüközkan and Güleryüz [55] – 300 citations. Explores multi-criteria frameworks for renewable energy project selection. This study aims to select the most suitable renewable energy resource (RER) in Turkey from an investor's perspective using an integrated DEMATEL and ANP approach [55]. The methodology combines technical, economic, political, and social factors. Results highlight the most appropriate RER for Turkey based on a comprehensive evaluation model. Future research should explore extending this framework to other countries and integrating more advanced techniques for multi-criteria analysis in energy selection.

x. Aboutorab *et al.,* [56] – 297 citations. Investigates MCDM techniques for improving energy efficiency. This paper aims to integrate the Best Worst Method (BWM) with Z-numbers (ZBWM) to address uncertainty in multi-criteria decision-making. The methodology combines BWM with Z-numbers to manage linguistic information and uncertainty [56]. Experimental results show that ZBWM reduces inconsistency compared to BWM. Future research should explore the application of ZBWM in more complex decision-making problems, particularly focusing on handling subjectivity in the fuzzy part of Z-numbers for more accurate results.

These studies highlight the evolving landscape of MCDM applications in sustainable energy, showcasing diverse methodologies and their impact.

4.8. Key findings from the reviewed studies

The reviewed studies on Multi-Criteria Decision-Making (MCDM) for sustainable renewable energy highlight significant advancements in the field. Key findings reveal that MCDM methods, such as TOPSIS, DEMATEL, and BWM, are widely applied to optimize energy planning, site selection, and resource evaluation under varying criteria [57, 58]. The studies demonstrate a shift towards incorporating fuzzy sets, hybrid models, and uncertainty handling techniques like Z-numbers to improve decision accuracy and flexibility. Notably, hydropower, geothermal, and wind energy are prioritized in various decision frameworks, with a focus on integrating technical, economic, and environmental factors. While qualitative studies dominate, there is a growing emphasis on quantitative models, including machine learning and AI-driven approaches, for better forecasting and optimization. Future work should aim to refine these frameworks, extend their application to diverse regions, and explore real-time data integration for dynamic decision-making.

5. Future Research Directions

As the demand for sustainable energy solutions grows, Multi-Criteria Decision-Making (MCDM) methods play a crucial role in optimizing renewable energy planning. While existing studies have successfully applied MCDM techniques to evaluate renewable energy sources, site selection, and supply chain risks, there is still significant room for improvement. Future research should focus on integrating artificial intelligence and machine learning to enhance decision accuracy and automate criteria weighting. Additionally, incorporating advanced fuzzy logic techniques, such as Z-numbers and Pythagorean fuzzy sets, can improve uncertainty handling in decision-making. The use of real-time data from IoT, GIS, and remote sensing technologies should be explored to make MCDM frameworks more adaptive. Expanding the criteria to include socio-economic, policy-related, and environmental justice factors will ensure more holistic decision-making. Further, combining MCDM with multi-objective optimization and blockchain technology can enhance transparency and efficiency. Cross-country comparative studies and improved validation techniques will strengthen the applicability of MCDM in global energy transitions.

6. Conclusion

This comprehensive review highlights the significant role of Multi-Criteria Decision-Making (MCDM) in optimizing sustainable renewable energy development. MCDM techniques, such as TOPSIS, VIKOR, DEMATEL, AHP, and BWM, have been widely applied to address the complex challenges of renewable energy planning, including resource selection, site evaluation, and supply chain risk management. The review also identifies the increasing integration of hybrid models, fuzzy logic approaches, and machine learning methods to enhance decision accuracy. Despite these advancements, challenges remain in handling uncertainty, incorporating dynamic data, and ensuring broader socio-economic and policy considerations in decision frameworks. Future research should focus on AI-driven MCDM approaches, real-time data integration, blockchain-enhanced decision-making, and cross-country comparative studies to refine methodologies further. By addressing these areas, MCDM can continue to be a powerful tool in guiding sustainable energy policies and investment decisions, ensuring efficient and environmentally responsible energy development worldwide.

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Conflicts of Interest

The authors declare no conflicts of interest regarding this research on MCDM for sustainable renewable energy.

References

[1] Sahoo, S. K., Pamucar, D., & Goswami, S. S. (2025). A Review of Multi-Criteria Decision-Making Applications to Solve Energy Management Problems From 2010-2025: Current State and Future Research. *Spectrum of Decision Making and Applications*, *2*(1), 219-241. https://doi.org/10.31181/sdmap21202525

[2] Lebepe, P., & Mathaba, T. N. (2025). Enhancing energy resilience in enterprises: a multi-criteria approach. *Sustainable Energy Research*, *12*(1), 1-20. https://doi.org/10.1186/s40807-025-00148-0

[3] Chung, K. C., Kuo, S. Y., & Xie, Z. M. (2025). Balancing act: The role of risk, cost, benefit, and opportunity in green energy decision making. *Energy & Environment*, 0958305X251315406. https://doi.org/10.1177/0958305X251315406

[4] Khalid, M. (2024). Smart grids and renewable energy systems: Perspectives and grid integration challenges. *Energy Strategy Reviews*, *51*, 101299. https://doi.org/10.1016/j.esr.2024.101299
[5] Hassan, Q., Viktor, P., Al-Musawi, T. J., Ali, B. M., Algburi, S., Alzoubi, H. M., Al-Jiboory, A. K., Sameen, A. Z., Salman, H. M., & Jaszczur, M. (2024). The renewable energy role in the global energy Transformations. *Renewable Energy Focus*, *48*, 100545. https://doi.org/10.1016/j.ref.2024.100545
[6] Al-Awadhi, T., Al Ramimi, W., Al Jabri, K., & Abulibdeh, A. (2025). Solar farms suitability analysis using GIS-Based Analytic Hierarchy Process (AHP) multi-criteria: A case study of Al Duqm–Oman. *Renewable Energy*, *241*, 122295. https://doi.org/10.1016/j.renene.2024.122295
[7] Solangi, Y. A., & Magazzino, C. (2025). Evaluating financial implications of renewable energy for climate action and sustainable development goals. *Renewable and Sustainable Energy Reviews*, *212*, 115390. https://doi.org/10.1016/j.rser.2025.115390
[8] Hossin, M. A., Abudu, H., Katsekpor, J., Lei, M., & Botah, E. B. (2025). Tracking sustainable energy indicators in Africa: New evidence from technique for order of preference by similarity to ideal solution. *Renewable Energy*, *239*, 122167. https://doi.org/10.1016/j.renene.2024.122167
[9] Al-Abadi, A. M., Handhal, A. M., Abdulhasan, M. A., Ali, W. L., Hassan, J. J., & Al Aboodi, A. H. (2025). Optimal siting of large photovoltaic solar farms at Basrah governorate, Southern Iraq using hybrid GIS-based Entropy-TOPSIS and AHP-TOPSIS models. *Renewable Energy*, *241*, 122308. https://doi.org/10.1016/j.renene.2024.122308
[10] Kumar, R., & Pamucar, D. (2025). A Comprehensive and Systematic Review of Multi-Criteria Decision-Making (MCDM) Methods to Solve Decision-Making Problems: Two Decades from 2004 to 2024. *Spectrum of Decision Making and Applications*, *2*(1), 178-197. https://doi.org/10.31181/sdmap21202524
[11] Vimala, J., Surya, A. N., Kausar, N., Pamucar, D., Simic, V., & Salman, M. A. (2025). Extended PROMETHEE method with (p, q)-rung linear Diophantine fuzzy sets for robot selection problem. *Scientific Reports*, *15*(1), 69. https://doi.org/10.1038/s41598-024-81785-1
[12] Ahmmad, J., Mahmood, T., Pamucar, D., & Waqas, H. M. (2025). A novel Complex q-rung orthopair fuzzy Yager aggregation operators and their applications in environmental engineering. *Heliyon*, *11*(1). https://doi.org/10.1016/j.heliyon.2025.e41668
[13] Yalçın, G. C., Kara, K., Işık, G., Simic, V., & Pamucar, D. (2025). Development of a Decision Support System for Performance Measurement of Social Movements. *Cognitive Computation*, *17*(1), 1-27. https://doi.org/10.1007/s12559-024-10385-y
[14] Christanto, S., Runtuk, J. K., & Ng, P. K. (2025). Optimizing Supplier Selection: A Comparative Study of Fuzzy Vikor and Fuzzy Moora for Performance-Based Decision Making. *IEEE Access*. https://doi.org/10.1109/ACCESS.2024.3525362
[15] Sandra, M., Narayanamoorthy, S., Suvitha, K., Pamucar, D., Simic, V., & Kang, D. (2025). An insightful multicriteria model for the selection of drilling technique for heat extraction from geothermal reservoirs using a fuzzy-rough approach. *Information Sciences*, *686*, 121353. https://doi.org/10.1016/j.ins.2024.121353
[16] Rana, R., & Bhambri, P. (2025). Hybrid MCDM (Multi-Criteria Decision-Making) Approaches for Sustainable Energy Management. In *Modern SuperHyperSoft Computing Trends in Science and Technology* (pp. 149-184). IGI Global Scientific Publishing.
[17] Hosouli, S., & Hassani, R. A. (2024). Application of multi-criteria decision making (MCDM) model for solar plant location selection. *Results in Engineering*, *24*, 103162. https://doi.org/10.1016/j.rineng.2024.103162
[18] Parvaneh, F., & Hammad, A. (2024). Application of Multi-Criteria Decision-Making (MCDM) to Select the Most Sustainable Power-Generating Technology. *Sustainability*, *16*(8), 3287. https://doi.org/10.3390/su16083287
[19] Rezk, H., Olabi, A. G., Mahmoud, M., Wilberforce, T., & Sayed, E. T. (2024). Metaheuristics and multi-criteria decision-making for renewable energy systems: Review, progress, bibliometric analysis, and contribution to the sustainable development pillars. *Ain Shams Engineering Journal*, 102883. https://doi.org/10.1016/j.asej.2024.102883
[20] Sahoo, S. K., Choudhury, B. B., & Dhal, P. R. (2024). A bibliometric analysis of material selection using MCDM methods: trends and insights. *Spectrum of Mechanical Engineering and Operational Research*, *1*(1), 189-205. https://doi.org/10.31181/smeor11202417
[21] Mokarram, M., Ronizi, S. R. A., & Negahban, S. (2024). Optimizing biomass energy production in the southern region of Iran: A deterministic MCDM and machine learning approach in GIS. *Energy Policy*, *195*, 114350. https://doi.org/10.1016/j.enpol.2024.114350
[22] Sekeroglu, A. (2024). Site selection for biomass-solar hybrid renewable energy facilities: Spatial modelling based on fuzzy logic-geographic information systems. *Renewable Energy*, *237*, 121775. https://doi.org/10.1016/j.renene.2024.121775
[23] Das, S., Dutta, R., De, S., & De, S. (2024). Review of multi-criteria decision-making for sustainable decentralized hybrid energy systems. *Renewable and Sustainable Energy Reviews*, *202*, 114676.

https://doi.org/10.1016/j.rser.2024.114676
[24] Das, S., De, S., Dutta, R., & De, S. (2024). Multi-criteria decision-making for techno-economic and environmentally sustainable decentralized hybrid power and green hydrogen cogeneration system. *Renewable and Sustainable Energy Reviews*, *191*, 114135. https://doi.org/10.1016/j.rser.2023.114135
[25] Sapkota, K., Shabbiruddin, & Sherpa, K. S. (2024). Wind farm site suitability assessment & validation using geospatially explicit multi-criteria approach: A case study of South Sikkim, India. *International Journal of Green Energy*, *21*(2), 300-327. https://doi.org/10.1080/15435075.2023.2195926
[26] Sahoo, S. K., Choudhury, B. B., & Dhal, P. R. (2024). Exploring the role of robotics in maritime technology: Innovations, challenges, and future prospects. *Spectrum of Mechanical Engineering and Operational Research*, *1*(1), 159-176. https://doi.org/10.31181/smeor11202414
[27] Mohammadi, N., Mostofi, H., & Dienel, H. L. (2023). Policy Chain of Energy Transition from Economic and Innovative Perspectives: Conceptual Framework and Consistency Analysis. *Sustainability*, *15*(17), 12693. https://doi.org/10.3390/su151712693
[28] Ndiritu, S. W., & Engola, M. K. (2020). The effectiveness of feed-in-tariff policy in promoting power generation from renewable energy in Kenya. *Renewable Energy*, *161*, 593-605. https://doi.org/10.1016/j.renene.2020.07.082
[29] Francis, A., & Thomas, A. (2023). System dynamics modelling coupled with multi-criteria decision-making (MCDM) for sustainability-related policy analysis and decision-making in the built environment. *Smart and Sustainable Built Environment*, *12*(3), 534-564. https://doi.org/10.1108/SASBE-09-2021-0156
[30] Kumar, R., & Sahoo, S. K. (2025). A Bibliometric Analysis of Agro-Based Industries: Trends and Challenges in Supply Chain Management. *Decision Making Advances*, *3*(1), 200-215. https://doi.org/10.31181/dma31202568
[31] D'Agostino, D., De Falco, F., Minelli, F., & Minichiello, F. (2024). New robust multi-criteria decision-making framework for thermal insulation of buildings under conflicting stakeholder interests. *Applied Energy*, *376*, 124262. https://doi.org/10.1016/j.apenergy.2024.124262
[32] Sahoo, S. K., & Choudhury, B. B. (2024). Autonomous navigation and obstacle avoidance in smart robotic wheelchairs. *Journal of Decision Analytics and Intelligent Computing*, *4*(1), 47-66. https://doi.org/10.31181/jdaic10019022024s
[33] Zubiria, A., Menéndez, Á., Grande, H. J., Meneses, P., & Fernández, G. (2022). Multi-criteria decision-making problem for energy storage technology selection for different grid applications. *Energies*, *15*(20), 7612. https://doi.org/10.3390/en15207612
[34] Al-Gerafi, M. A., Goswami, S. S., Sahoo, S. K., Kumar, R., Simic, V., Bacanin, N., & Lasisi, A. (2024). Promoting inclusivity in education amid the post-COVID-19 challenges: An interval-valued fuzzy model for pedagogy method selection. *The International Journal of Management Education*, *22*(3), 101018. https://doi.org/10.1016/j.ijme.2024.101018
[35] Muhsen, D. H., Haider, H. T., Al-Nidawi, Y., & Khatib, T. (2019). Optimal home energy demand management based multi-criteria decision making methods. *Electronics*, *8*(5), 524. https://doi.org/10.3390/electronics8050524
[36] Elias, Y. B., Yousef, M. Y., Mohamed, A., Ali, A. A., & Mosa, M. A. (2024). Energy management and demand side management framework for nano-grid under various utility strategies and consumer's preference. *Scientific Reports*, *14*(1), 25757. https://doi.org/10.1038/s41598-024-74509-y
[37] Zebra, E. I. C., van der Windt, H. J., Nhumaio, G., & Faaij, A. P. (2021). A review of hybrid renewable energy systems in mini-grids for off-grid electrification in developing countries. *Renewable and Sustainable Energy Reviews*, *144*, 111036. https://doi.org/10.1016/j.rser.2021.111036
[38] Duran, A. S., & Sahinyazan, F. G. (2021). An analysis of renewable mini-grid projects for rural electrification. *Socio-Economic Planning Sciences*, *77*, 100999. https://doi.org/10.1016/j.seps.2020.100999
[39] Klarin, A. (2024). How to conduct a bibliometric content analysis: Guidelines and contributions of content co-occurrence or co-word literature reviews. *International Journal of Consumer Studies*, *48*(2), e13031. https://doi.org/10.1111/ijcs.13031
[40] Kumar, A., Sah, B., Singh, A. R., Deng, Y., He, X., Kumar, P., & Bansal, R. C. (2017). A review of multi criteria decision making (MCDM) towards sustainable renewable energy development. *Renewable and sustainable energy reviews*, *69*, 596-609. https://doi.org/10.1016/j.rser.2016.11.191
[41] Sahoo, S. K., & Goswami, S. S. (2023). A comprehensive review of multiple criteria decision-making (MCDM) Methods: advancements, applications, and future directions. *Decision Making Advances*, *1*(1), 25-48. https://doi.org/10.31181/dma1120237
[42] Segura-Robles, A., Parra-González, M. E., & Gallardo-Vigil, M. Á. (2020). Bibliometric and collaborative network analysis on active methodologies in education. *Journal of New Approaches in Educational Research*, *9*(2), 259-274. https://doi.org/10.7821/naer.2020.7.575
[43] Alamoodi, A. H., Zaidan, B. B., Albahri, O. S., Garfan, S., Ahmaro, I. Y., Mohammed, R. T., & Malik, R. Q. (2023). Systematic review of MCDM approach applied to the medical case studies of COVID-19: trends, bibliographic

analysis, challenges, motivations, recommendations, and future directions. *Complex & intelligent systems*, *9*(4), 4705-4731. https://doi.org/10.1007/s40747-023-00972-1

[44] Walters, W. H., & Wilder, E. I. (2015). Worldwide contributors to the literature of library and information science: top authors, 2007–2012. *Scientometrics*, *103*, 301-327. https://doi.org/10.1007/s11192-014-1519-9

[45] van Wesel, M. (2016). Evaluation by citation: Trends in publication behavior, evaluation criteria, and the strive for high impact publications. *Science and Engineering Ethics*, *22*(1), 199-225. https://doi.org/10.1007/s11948-015-9638-0

[46] Dua, J., Lathabai, H. H., & Singh, V. K. (2023). Measuring and characterizing research collaboration in SAARC countries. *Scientometrics*, *128*(2), 1265-1294. https://doi.org/10.1007/s11192-022-04606-0

[47] Kumar, A., Sah, B., Singh, A. R., Deng, Y., He, X., Kumar, P., & Bansal, R. C. (2017). A review of multi criteria decision making (MCDM) towards sustainable renewable energy development. *Renewable and sustainable energy reviews*, *69*, 596-609. https://doi.org/10.1016/j.rser.2016.11.191

[48] Ren, P., Xu, Z., & Gou, X. (2016). Pythagorean fuzzy TODIM approach to multi-criteria decision making. *Applied soft computing*, *42*, 246-259. https://doi.org/10.1016/j.asoc.2015.12.020

[49] Khosravi, K., Shahabi, H., Pham, B. T., Adamowski, J., Shirzadi, A., Pradhan, B., & Prakash, I. (2019). A comparative assessment of flood susceptibility modeling using multi-criteria decision-making analysis and machine learning methods. *Journal of Hydrology*, *573*, 311-323. https://doi.org/10.1016/j.jhydrol.2019.03.073

[50] Şengül, Ü., Eren, M., Shiraz, S. E., Gezder, V., & Şengül, A. B. (2015). Fuzzy TOPSIS method for ranking renewable energy supply systems in Turkey. *Renewable energy*, *75*, 617-625. https://doi.org/10.1016/j.renene.2014.10.045

[51] Keshavarz-Ghorabaee, M., Amiri, M., Zavadskas, E. K., Turskis, Z., & Antucheviciene, J. (2021). Determination of objective weights using a new method based on the removal effects of criteria (MEREC). *Symmetry*, *13*(4), 525. https://doi.org/10.3390/sym13040525

[52] Rostamzadeh, R., Ghorabaee, M. K., Govindan, K., Esmaeili, A., & Nobar, H. B. K. (2018). Evaluation of sustainable supply chain risk management using an integrated fuzzy TOPSIS-CRITIC approach. *Journal of Cleaner Production*, *175*, 651-669. https://doi.org/10.1016/j.jclepro.2017.12.071

[53] Shao, M., Han, Z., Sun, J., Xiao, C., Zhang, S., & Zhao, Y. (2020). A review of multi-criteria decision making applications for renewable energy site selection. *Renewable Energy*, *157*, 377-403. https://doi.org/10.1016/j.renene.2020.04.137

[54] Ansari, Z. N., & Kant, R. (2017). A state-of-art literature review reflecting 15 years of focus on sustainable supply chain management. *Journal of cleaner production*, *142*, 2524-2543. https://doi.org/10.1016/j.jclepro.2016.11.023

[55] Büyüközkan, G., & Güleryüz, S. (2016). An integrated DEMATEL-ANP approach for renewable energy resources selection in Turkey. *International journal of production economics*, *182*, 435-448. https://doi.org/10.1016/j.ijpe.2016.09.015

[56] Aboutorab, H., Saberi, M., Asadabadi, M. R., Hussain, O., & Chang, E. (2018). ZBWM: The Z-number extension of Best Worst Method and its application for supplier development. *Expert Systems with Applications*, *107*, 115-125. https://doi.org/10.1016/j.eswa.2018.04.015

[57] Rad, M. A. V., Fard, H. F., Khazanedari, K., Toopshekan, A., Ourang, S., Khanali, M., & Kasaeian, A. (2024). A global framework for maximizing sustainable development indexes in agri-photovoltaic-based renewable systems: Integrating DEMATEL, ANP, and MCDM methods. *Applied Energy*, *360*, 122715. https://doi.org/10.1016/j.apenergy.2024.122715

[58] Ayan, B., Abacıoğlu, S., & Basilio, M. P. (2023). A comprehensive review of the novel weighting methods for multi-criteria decision-making. *Information*, *14*(5), 285. https://doi.org/10.3390/info14050285