

Bibliometric Exploration of Green Skills Development in Vocational Education for Renewable Energy Workforce Sustainability

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Abstract—The global transition toward renewable energy systems and sustainable industrial development has increased the importance of green skills development within vocational education and workforce preparation. This study aims to explore the scientific development, intellectual structure, and emerging research trends related to green skills development in vocational education for renewable energy workforce sustainability. A bibliometric research design was employed using data retrieved from the Scopus database. The literature search was conducted using the keywords related to vocational education, sustainability, and energy, resulting in 139 English-language publications published between 2006 and 2026 after applying the PRISMA screening procedure. Bibliometric analysis was performed using Scopus analytical tools and VOSviewer software to examine publication trends, subject area distribution, keyword co-occurrence, and co-citation networks. The findings indicate that research in this field has experienced substantial growth, particularly after 2020, reflecting increasing global concern regarding renewable energy transition, green workforce readiness, and sustainable vocational transformation. The keyword co-occurrence analysis identified “sustainable development,” “renewable energy,” “vocational training,” and “energy efficiency” as dominant and highly interconnected themes within the research landscape. Meanwhile, the co-citation analysis revealed that the intellectual structure of the field is strongly influenced by sustainability theory, human capital development, vocational transformation, and renewable energy transition frameworks. The study also demonstrates that sustainability-oriented vocational education has become increasingly interdisciplinary through the integration of digital technologies, artificial intelligence, and green innovation systems. The findings provide important theoretical and practical implications for policymakers, educational institutions, and industry stakeholders in developing adaptive curricula and sustainable workforce strategies. This study contributes to the advancement of bibliometric scholarship by systematically mapping the evolution of green vocational education research within the context of global energy transition and workforce sustainability.

Keywords: green skills; vocational education; renewable energy; workforce sustainability; green workforce; energy transition

1. INTRODUCTION

The global transition toward sustainable development and renewable energy systems has substantially transformed workforce demands across industrial and educational sectors worldwide (Dirir, 2026). International sustainability agendas increasingly emphasize the importance of human capital development to support low-carbon economic transformation and environmentally responsible industrial practices (Edbais & Hossain, 2025). The implementation of Sustainable Development Goals, particularly SDG 4, SDG 7, SDG 8, SDG 9, and SDG 13, has encouraged governments and institutions to redesign educational systems capable of producing sustainable and adaptive workforces (Bădîrcea et al., 2025). Renewable energy industries currently require technical workers equipped with interdisciplinary green competencies, digital literacy, and sustainability-oriented vocational capabilities to address rapid technological advancements (Tsai et al., 2025). Recent studies indicate that sustainable energy sectors are experiencing accelerated labor market expansion, particularly in solar, geothermal, and green infrastructure industries requiring vocationally trained human resources (Edomah, 2025). The increasing integration of green technologies into industrial systems has also reshaped technical and vocational education and training institutions globally (Wickramasinghe & Wickramasinghe, 2026). Furthermore, vocational institutions are increasingly expected to contribute not only to workforce preparation but also to environmental sustainability and green innovation ecosystems (Bulut et al., 2026). Research conducted in several developing countries demonstrates that vocational education systems are undergoing significant curricular reforms to align technical skills with renewable energy competencies and sustainable production systems (Carpio Camacho et al., 2026). Consequently, green skills development has emerged as a strategic educational priority for supporting renewable energy workforce sustainability in both developed and emerging economies (Sulistyo et al., 2025).

The growing urgency of climate change mitigation and global energy transition has intensified international attention toward sustainable workforce development within vocational education systems (Jonek-Kowalska, 2026). Several countries have initiated policy frameworks promoting green vocational transformation to reduce environmental degradation and increase renewable energy adoption across industrial sectors (Teymurova et al., 2025). The International Energy Agency and various sustainability organizations have continuously highlighted the shortage of skilled labor capable of operating renewable energy technologies and supporting energy transition programs globally (Lu & Wan, 2025). In response to these challenges, vocational education institutions are increasingly integrating sustainability principles into technical curricula, reskilling programs, and workforce development initiatives (Wickramasinghe & Wickramasinghe, 2026). Research focusing on Africa’s renewable energy sector shows that green vocational education significantly contributes to sustainable employment generation and environmentally responsible industrial development (Edomah, 2025). Similarly, studies in Asia indicate that

renewable energy literacy among students strongly influences public acceptance and long-term sustainability awareness regarding clean energy adoption (Pambudi et al., 2025). Technological innovation has further accelerated the need for vocational systems capable of adapting to smart energy technologies, digital transformation, and green industrial ecosystems (Ngcobo & Gupta, 2026). The emergence of artificial intelligence, mixed reality learning environments, and intelligent vocational platforms has also reshaped educational strategies supporting renewable energy workforce competencies (Nedusezhiyan et al., 2025). Therefore, understanding the intellectual development and research trajectory of green skills development in vocational education has become increasingly important for supporting future sustainable workforce policies and educational reforms (Kimani et al., 2026).

Previous scholarly discussions concerning vocational education and sustainability have primarily focused on curriculum transformation, employability enhancement, and institutional readiness toward sustainable development agendas (Bulut et al., 2026). Several studies have explored the integration of sustainability principles into technical and vocational education and training systems, particularly in developing countries experiencing industrial and technological transitions (Carpio Camacho et al., 2026). Research conducted in South and Southeast Asia highlights that sustainability-oriented vocational curricula have become central instruments for supporting green economic transformation and industrial adaptation (Wickramasinghe & Wickramasinghe, 2026). Other studies also emphasize the significance of engineering education and technical competency development in supporting renewable energy infrastructure and industrial sustainability initiatives (Kwateng & Leong, 2025). Furthermore, renewable energy education has increasingly incorporated practical and experimental learning approaches, especially in electrical engineering and wind energy training systems (Akatimagool & Chumchuen, 2026). Studies involving geothermal energy literacy among students additionally demonstrate that educational exposure significantly influences sustainable energy acceptance and public awareness formation (Pambudi et al., 2025). Research within maritime and blue economy sectors also confirms that vocational institutions play essential roles in creating sustainable leadership and environmentally responsible workforce development (Cahyadi et al., 2025). Simultaneously, green hospital awareness and environmentally oriented healthcare education further indicate the growing interdisciplinary nature of sustainability-based vocational competencies (Doğan Kaya & Çelik Bekleviç, 2026). These findings collectively suggest that vocational education has become increasingly interconnected with renewable energy transition and sustainable workforce formation across multiple industrial domains (Tarkar et al., 2026).

Despite the increasing scholarly attention toward green vocational education and renewable energy workforce development, existing literature remains fragmented across disciplines, geographical contexts, and methodological approaches (Dahuri et al., 2025). Most previous studies focused on conceptual frameworks, policy implementation, or sector-specific sustainability practices rather than systematically mapping the scientific structure of the field itself (Edbais & Hossain, 2025). Bibliometric studies concerning vocational sustainability remain relatively limited, particularly those integrating renewable energy workforce sustainability with green skills development and technical education systems (Dahuri et al., 2025). Existing bibliometric explorations have generally concentrated on maintenance strategies, engineering education, or institutional sustainability without specifically analyzing the intellectual evolution of green skills research within renewable energy-oriented vocational contexts (Kimani et al., 2026). Additionally, global collaboration patterns, emerging thematic clusters, and influential contributors within this field remain insufficiently explored in current literature (Chusi et al., 2025). The rapid expansion of interdisciplinary sustainability research has further complicated efforts to identify dominant knowledge structures and future research directions systematically (Dirir, 2026). Moreover, the integration of digital technologies, artificial intelligence, and smart learning systems into renewable energy vocational training introduces new dimensions that require comprehensive scientific mapping (Ngcobo & Gupta, 2026). Previous studies also rarely examine how green workforce development aligns with broader sustainability transition agendas and global industrial transformation frameworks (Al Abbasi et al., 2025). Consequently, there is a substantial need for a bibliometric investigation capable of synthesizing publication trends, thematic evolution, and scientific collaboration within this emerging research domain (Tsai et al., 2025).

The present study addresses these limitations by conducting a comprehensive bibliometric exploration of green skills development in vocational education for renewable energy workforce sustainability using Scopus-indexed publications (Dahuri et al., 2025). This study specifically investigates publication growth, influential authors, institutional productivity, thematic clusters, and emerging research trends within the field (Bulut et al., 2026). By employing bibliometric visualization techniques, this research aims to identify the intellectual structure and scientific evolution shaping sustainability-oriented vocational education research globally (Kimani et al., 2026). The study also examines collaboration networks and keyword co-occurrence patterns to understand interdisciplinary linkages among vocational education, renewable energy, and workforce sustainability research domains (Chusi et al., 2025). Furthermore, the analysis contributes to understanding how educational systems respond to global sustainability challenges through green workforce preparation and technical skill transformation (Edomah, 2025). The findings are expected to provide valuable insights for policymakers, vocational institutions, curriculum developers, and renewable energy stakeholders seeking evidence-based educational strategies for sustainable workforce development (Wickramasinghe & Wickramasinghe, 2026). Scientifically, this study contributes to the advancement of bibliometric scholarship by integrating sustainability education, vocational transformation, and renewable energy workforce perspectives into a unified analytical framework (Dirir, 2026). In practical terms, the results may support future curriculum innovation, institutional collaboration, and policy formulation related to sustainable technical and

vocational education systems (Sulistyo et al., 2025). Therefore, this research offers both theoretical and practical significance in strengthening the global discourse surrounding green vocational education and renewable energy workforce sustainability (Bădîrcea et al., 2025).

2. RESEARCH METHODOLOGY

This study employed a bibliometric research design to systematically examine the scientific development of vocational education and sustainable energy research indexed in the Scopus database. Bibliometric analysis was selected because it enables researchers to quantitatively evaluate publication trends, research productivity, scientific collaboration, and thematic evolution within a specific field of study. The research focused on identifying the intellectual structure and emerging research directions associated with green skills development and renewable energy workforce sustainability. As illustrated in Figure 1, the research process followed a structured PRISMA-based screening procedure to ensure transparency and consistency during article selection and data extraction. The study utilized Scopus as the primary source of bibliographic data because it provides extensive coverage of high-quality international scientific publications across multidisciplinary subject areas. Furthermore, bibliometric visualization and network mapping were conducted using VOSviewer software to generate scientific relationship patterns among keywords, sources, and research themes.

The literature search strategy was carefully designed to obtain relevant publications related to vocational education and sustainable energy research. The search query applied in the Scopus database was formulated as follows: (TITLE-ABS-KEY (vocational) AND TITLE-ABS-KEY (sustainable AND energy)) AND (LIMIT-TO (LANGUAGE, "English")). This search string was specifically developed to capture publications discussing vocational education within the context of sustainability and energy transition studies. The search process was conducted within the Scopus database on May 28, 2026, as presented in Figure 1. To maintain consistency and relevance, the study restricted the search to English-language publications published between 2006 and 2026. The inclusion of TITLE-ABS-KEY ensured that the selected documents explicitly contained the keywords within the title, abstract, or author keywords, thereby improving the relevance and precision of the retrieved records.

Following the initial search process, the retrieved publications underwent a screening and filtering stage based on the PRISMA framework presented in Figure 1. The initial identification process generated 143 documents from the Scopus database related to vocational and sustainable energy research themes. Subsequently, duplicate and irrelevant records were carefully examined to ensure dataset accuracy and reliability during bibliometric analysis. Four records were excluded from the dataset because they were published in languages other than English, specifically Thai and Russian publications. After completing the screening and eligibility verification process, a total of 139 publications were considered suitable for bibliometric investigation. The PRISMA approach was adopted in this study because it provides a transparent and systematic framework for identifying, screening, and selecting scientific literature within evidence-based research processes.

The bibliometric analysis in this study relied on two primary analytical tools, namely Scopus analytical features and VOSviewer software. Scopus Analysis was utilized to generate descriptive statistical information regarding publication trends, subject area distributions, citation performance, source productivity, and document characteristics within the selected dataset. The analysis of publication trends by year enabled the researchers to observe the growth and evolution of vocational and sustainable energy studies over the twenty-year observation period. In addition, publication by subject area analysis was conducted to identify dominant academic disciplines contributing to this research field, including engineering, environmental science, social science, and energy studies. The analysis of top sources and top documents further helped identify influential journals, highly cited publications, and major scientific contributors within the research domain. As indicated in Figure 1, these analytical stages were conducted after the completion of the PRISMA screening process to ensure that only relevant publications were included in the bibliometric mapping.

VOSviewer software was employed to perform advanced bibliometric visualization and scientific network mapping within the selected publications. The software was specifically used to analyze co-occurrence networks among author keywords and research themes associated with vocational education and sustainable energy studies. Co-occurrence analysis enabled the researchers to identify dominant research clusters, thematic relationships, and emerging research directions within the scientific landscape. The visualization results generated by VOSviewer also facilitated the interpretation of keyword connectivity and interdisciplinary interactions among sustainability, vocational education, renewable energy, and workforce development topics. In addition, network visualization and density visualization features provided a clearer understanding of how research themes evolved and interacted throughout the publication period. Therefore, the integration of Scopus analytical tools and VOSviewer software provided a comprehensive methodological framework for investigating the intellectual structure and scientific development of vocational and sustainable energy research, as summarized in Figure 1.

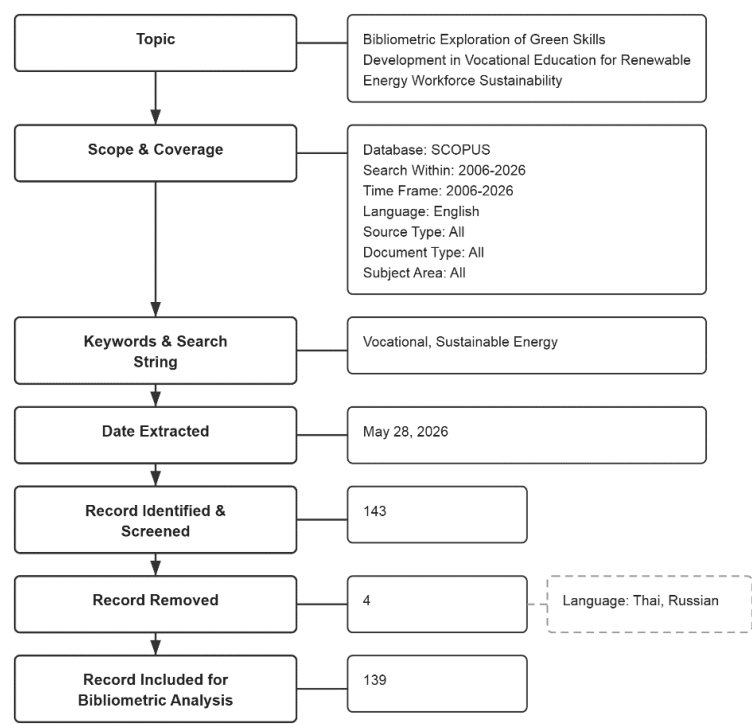


Figure 1. PRISMA Flow Diagram of Literature Selection and Bibliometric Screening Process

3. RESULT AND DISCUSSION

3.1 Meta-Analysis

3.1.1 Publication Trend by Year

The analysis of publication trends is essential in bibliometric studies because it provides an overview of the scientific growth and research dynamics within a particular field over time. In this study, the publication trend analysis was conducted to identify the development trajectory of research related to vocational education and sustainable energy from 2006 to 2026. The annual distribution of publications demonstrates how academic attention toward sustainability-oriented vocational education has evolved in response to global environmental, technological, and industrial transformations. Figure 2 presents the number of scientific publications indexed in Scopus during the observation period. The trend analysis also helps reveal periods of research stagnation, gradual development, and accelerated scientific expansion within the selected topic. Furthermore, understanding publication growth patterns allows researchers to identify critical moments influencing the emergence of new sustainability-oriented educational discussions. The bibliometric trend additionally reflects the increasing interdisciplinary integration between vocational education, renewable energy systems, and sustainable workforce development. In this context, publication growth can also be interpreted as an indicator of increasing global awareness regarding green skills and renewable energy transitions. Therefore, the annual publication trend shown in Figure 2 provides important insights into the evolution and future direction of vocational and sustainable energy research.

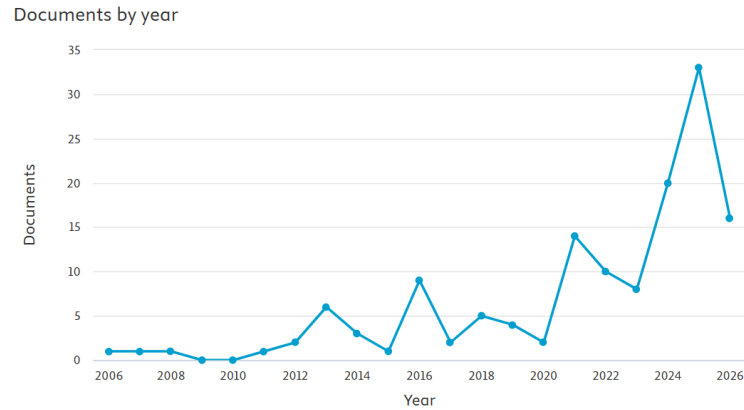


Figure 2. Publication Trend by Year of Vocational and Sustainable Energy Research (2006–2026)

Figure 2 illustrates that the publication trend experienced several developmental phases characterized by fluctuating yet progressively increasing scientific output over the twenty-year observation period. During the early stage between 2006 and 2011, the number of publications remained relatively low and stable, indicating that research concerning vocational education and sustainable energy was still emerging and had not yet become a major scientific focus. A gradual increase began to appear between 2012 and 2015, where publication growth reflected increasing international attention toward sustainability education and renewable energy transition initiatives. The publication trend experienced a temporary decline around 2016 and 2019, suggesting that the field was still undergoing conceptual and thematic consolidation during its developmental stage. However, a substantial increase became visible after 2020, where publication output grew significantly and reached a notable acceleration between 2023 and 2025. The highest publication peak occurred in 2025, with more than thirty indexed documents, indicating a strong expansion of scientific interest toward green vocational education and renewable energy workforce sustainability. This sharp increase may have been influenced by global commitments toward carbon neutrality, Industry 4.0 transformation, renewable energy investment, and the implementation of Sustainable Development Goals across educational sectors. In addition, the integration of digital technologies, artificial intelligence, and sustainability-oriented workforce development likely contributed to the rapid expansion of interdisciplinary research within this field. Although a decline appears in 2026, the reduction is most likely associated with incomplete indexing coverage because data collection was conducted before the completion of the publication year, as shown in Figure 2.

The publication trend presented in Figure 2 also reflects several important momentum shifts influencing the evolution of vocational and sustainable energy research globally. The increasing number of publications after 2020 corresponds with intensified international discussions surrounding climate change mitigation, green economic transformation, and renewable energy workforce readiness. Many governments and educational institutions have increasingly emphasized green competency development and sustainability integration within vocational training systems, thereby stimulating higher scientific productivity in related research areas. Furthermore, the rapid development of renewable energy technologies has created new industrial demands requiring technically skilled and environmentally literate workers, which subsequently attracted broader academic attention. The expansion of sustainability-related funding schemes, international collaborations, and policy-driven educational reforms may also explain the accelerated publication growth observed during the last five years. Another contributing factor is the growing recognition that vocational education institutions play strategic roles in supporting sustainable industrial ecosystems and green labor market transformation. The emergence of interdisciplinary themes involving artificial intelligence, digital learning systems, smart energy technologies, and sustainability education further broadened the scope of research within this domain. Based on the observed publication trajectory, future studies concerning vocational education and sustainable energy are predicted to continue expanding, particularly in areas related to green workforce readiness, renewable energy competencies, digital sustainability skills, and environmentally adaptive vocational curricula. Therefore, the publication trend shown in Figure 2 suggests that this research area will remain highly relevant and continue attracting substantial scientific interest in the coming years.

3.1.2 Top Sources and Documents

The analysis of top publication sources is important in bibliometric research because it helps identify the journals and conference proceedings that contribute most significantly to the development of a scientific field. In this study, the source analysis was conducted to evaluate the productivity and influence of journals publishing research related to vocational education and sustainable energy. Figure 3 illustrates the distribution of documents per year by source and highlights the dominant publication outlets within the research domain. The visualization demonstrates that several journals and conference proceedings consistently contributed to the dissemination of sustainability-oriented vocational education research during the observation period. Among the most productive sources, *Lecture Notes in Networks and Systems* and *BIO Web of Conferences* showed noticeable publication growth, particularly after 2022, indicating increasing interdisciplinary interest in technological innovation and sustainability education. In addition, journals such as *Sustainability (Switzerland)* and conference proceedings associated with environmental science and mining management also demonstrated meaningful contributions to the field.

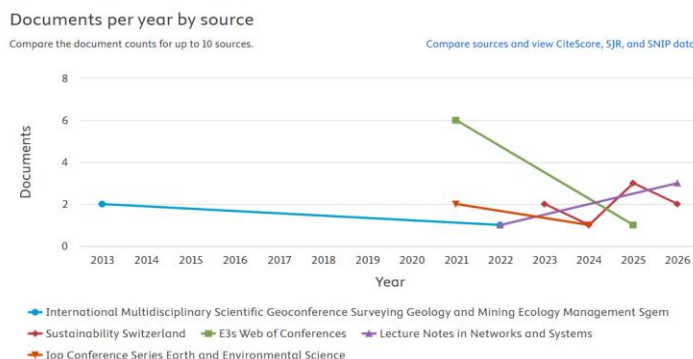


Figure 3. Top Sources and Documents in Vocational and Sustainable Energy Research

The dominance of these publication sources reflects the growing academic integration between renewable energy systems, engineering education, sustainability transformation, and workforce development studies. Furthermore, the presence of internationally indexed journals and reputable conference proceedings indicates that vocational and sustainable energy research has gained wider scientific recognition across multidisciplinary academic communities. Therefore, the publication patterns presented in Figure 3 reveal how influential journals and scientific forums have played strategic roles in shaping the intellectual development of sustainability-oriented vocational education research.

Figure 3 further indicates that the development of vocational and sustainable energy research is strongly influenced by journals focusing on sustainability, engineering, environmental science, and technological innovation. The increasing productivity of sources such as *Sustainability (Switzerland)* suggests that sustainability-oriented vocational education has become closely associated with broader discussions concerning climate action, renewable energy transition, and sustainable industrial development. Meanwhile, conference-based publication outlets such as *BIO Web of Conferences* and *Lecture Notes in Networks and Systems* demonstrate the rapid expansion of emerging interdisciplinary topics involving smart technologies, green innovation, and digital transformation in vocational education systems. The dominance of these publication platforms also reflects the dynamic nature of the research field, where conference proceedings often become early dissemination channels for innovative and evolving sustainability discussions. In terms of scientific quality and reputation, many of the dominant journals indexed in Scopus possess strong international visibility and are recognized within high-impact sustainability and engineering categories. Their contribution significantly enhances the credibility and global accessibility of research concerning renewable energy workforce sustainability and green skills development. Moreover, the concentration of publications within sustainability-oriented journals indicates that vocational education research is increasingly positioned as an essential component of sustainable development strategies and green economic transformation. The publication trend additionally demonstrates that interdisciplinary collaboration between environmental science, technical education, and renewable energy research communities continues to strengthen over time. Consequently, the dominance of these publication sources, as shown in Figure 3, confirms that vocational education and sustainable energy research has evolved into an internationally relevant and scientifically expanding field within contemporary sustainability scholarship.

3.1.3 Publication by Subject Area

The analysis of publication distribution by subject area provides important insights into the disciplinary structure and academic orientation of vocational and sustainable energy research. In bibliometric studies, subject area classification is essential for understanding how different scientific disciplines contribute to the development of a research field. Figure 4 presents the distribution of publications across several academic subject areas indexed within the Scopus database during the observation period. The visualization demonstrates that the research topic is highly multidisciplinary, involving contributions from social sciences, engineering, energy studies, environmental science, computer science, and business-related disciplines. Among these categories, Social Sciences represents the largest proportion with 16.9% of total publications, followed by Engineering with 15.2% and Energy with 13.8%. The dominance of Social Sciences indicates that vocational education and sustainable energy discussions are strongly associated with educational transformation, workforce development, sustainability policy, and social adaptation toward renewable energy transitions. At the same time, the significant contribution from Engineering and Energy subject areas reflects the technical and industrial dimensions of renewable energy systems, green technologies, and vocational skill requirements. Environmental Science and Computer Science also contribute substantially to the research landscape, demonstrating that sustainability challenges increasingly require technological innovation, environmental management, and digital transformation within vocational education systems. Therefore, the subject area distribution presented in Figure 4 confirms that vocational and sustainable energy research has evolved into an interdisciplinary scientific domain integrating educational, technological, environmental, and industrial perspectives.

Documents by subject area

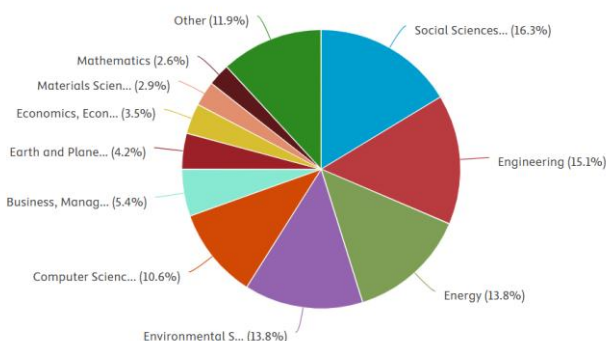


Figure 4. Publication Distribution by Subject Area in Vocational and Sustainable Energy Research

3.1.4 Keyword Co-occurrence Network Analysis

Based on Figure 5, the keyword “sustainable development” appears as the most dominant and influential term within the network, as indicated by its central position, large node size, and extensive interconnections with other keywords. This finding demonstrates that sustainable development functions as the primary conceptual foundation linking vocational education, renewable energy, and workforce sustainability studies. Several keywords frequently appearing together include “students,” “curricula,” “vocational training,” “renewable energy,” “energy efficiency,” “sustainability,” and “teaching,” indicating that educational transformation toward green competencies has become a

major research concern. The green cluster emphasizes educational dimensions such as curricula, teaching methods, and student engagement, while the red cluster highlights renewable energy, employment, and vocational training issues associated with industrial workforce demands. Meanwhile, the blue cluster focuses on technical and operational themes such as energy efficiency, waste management, and optimization, reflecting the technological orientation of sustainable workforce preparation. The yellow and purple clusters further demonstrate the integration of sustainable development goals, environmental protection, and apprenticeship-based learning within vocational education systems. The strong co-occurrence relationships among these keywords indicate that researchers increasingly view green skills as a multidimensional concept involving education policy, industrial transition, sustainability awareness, and labor market adaptation simultaneously. Moreover, the presence of interconnected themes related to e-learning, educational computing, and planning suggests that digital transformation also contributes significantly to sustainability-oriented vocational education. Overall, the network visualization confirms that research on green skills development has evolved into a comprehensive interdisciplinary domain that combines sustainability education, renewable energy transition, and workforce resilience in response to global environmental challenges.

3.1.5 Co-citation Network and Intellectual Structure Analysis

The co-citation network analysis provides a deeper understanding of the intellectual foundation and scholarly structure underlying research on green skills development, vocational education, and renewable energy workforce sustainability. Through co-citation mapping generated using VOSviewer, the analysis identifies groups of authors and references that are frequently cited together within the scientific literature. This approach is essential for revealing the theoretical traditions, dominant scientific contributions, and knowledge clusters that shape the evolution of the research field. The visualization also demonstrates how influential scholars are interconnected through citation relationships, indicating shared conceptual orientations and methodological similarities. In bibliometric studies, authors with larger nodes and stronger link strengths are generally considered highly influential because their works serve as major references for subsequent studies. Furthermore, the clustering patterns observed in the network reflect the existence of several intellectual subdomains related to sustainability education, vocational training, renewable energy transition, and workforce development. The co-citation structure therefore helps explain how scientific knowledge within this field has evolved through interdisciplinary integration and collaborative academic discourse. In addition, the network highlights the centrality of sustainability-oriented educational frameworks in shaping contemporary discussions on green workforce competencies. The complete co-citation network visualization is presented in Figure 6.

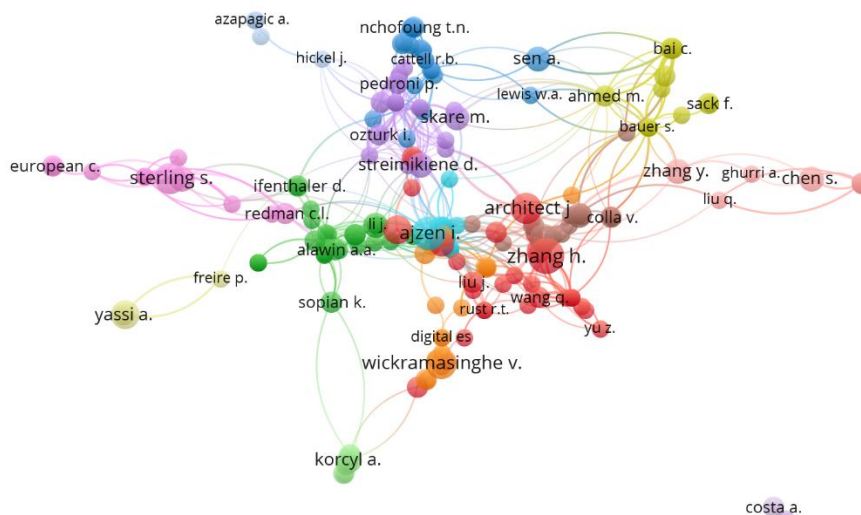


Figure 6. Co-citation Network Visualization of Authors and References

Based on Figure 6, several authors emerge as highly influential within the intellectual structure of the field, particularly Zhang H., Wickramasinghe V., Skare M., Ahmed M., and Pedroni P., whose nodes appear larger and occupy more central positions within the network. Their strong co-citation relationships indicate that their works have significantly contributed to the theoretical and empirical development of sustainability-oriented vocational education and renewable energy workforce studies. The red cluster, centered around Zhang H. and related scholars, primarily reflects research associated with industrial transformation, sustainability transition, and workforce adaptation in renewable energy sectors. Meanwhile, the green cluster emphasizes educational sustainability, institutional transformation, and human capital development, demonstrating the growing importance of vocational education in supporting green economic transitions. The purple and blue clusters illustrate methodological and theoretical contributions related to sustainability measurement, economic development, and interdisciplinary policy analysis. In addition, the yellow cluster highlights research associated with environmental governance, technological innovation,

and sustainable planning, indicating that the field increasingly integrates policy and innovation perspectives into workforce sustainability discussions. The existence of multiple interconnected clusters confirms that the intellectual structure of this research domain is highly multidisciplinary and draws knowledge from education studies, environmental science, economics, labor studies, and energy transition research simultaneously. Moreover, the dense interconnections among influential authors suggest that the field has matured into a coherent scholarly network with strong theoretical integration and collaborative citation behavior. Overall, the co-citation analysis demonstrates that the theoretical foundation of green skills development research is built upon sustainability theory, human capital development, vocational education transformation, and renewable energy transition frameworks, which collectively shape the scientific direction of future workforce sustainability studies.

3.2 Research Implications and Future Research Directions

The findings of this bibliometric study provide several important theoretical and practical implications for the development of research concerning green skills, vocational education, and renewable energy workforce sustainability. From a theoretical perspective, the results confirm that the discourse surrounding green workforce competencies has evolved into a multidimensional research domain integrating sustainability theory, human capital theory, and vocational education transformation frameworks. The strong interconnections among keywords and co-cited references indicate that contemporary studies increasingly position vocational education as a strategic mechanism for accelerating sustainable economic transition and renewable energy adaptation. This finding contributes to the enrichment of sustainability education literature by demonstrating that green skills are no longer interpreted solely as environmental awareness, but also as technical, digital, managerial, and adaptive competencies required within modern labor markets. Furthermore, the intellectual structure analysis reveals that research in this field still tends to be fragmented across educational studies, environmental science, and workforce policy research, thereby indicating the need for stronger interdisciplinary integration. From a practical standpoint, the study highlights the necessity for vocational institutions, policymakers, and industrial stakeholders to redesign curricula that align with renewable energy industry demands and sustainable development priorities. The increasing emphasis on teaching, curricula, students, and vocational training within the co-occurrence network also suggests that educational institutions must incorporate experiential learning, green technology training, and sustainability-oriented competencies into vocational programs. In addition, the findings imply that governments and industries should strengthen collaborative partnerships to ensure workforce readiness for green economic transformation and future clean energy employment opportunities. Overall, the bibliometric evidence presented in Figure 2 - Figure 6 demonstrates that sustainability-oriented vocational education has become a central pillar in supporting long-term renewable energy workforce resilience and industrial sustainability transitions.

Despite the significant contributions of this study, several limitations and research gaps remain evident and create opportunities for future scholarly exploration. One important limitation is that the analysis relied exclusively on the Scopus database, which may exclude relevant publications indexed in other scientific databases such as Web of Science or Google Scholar. In addition, bibliometric analysis primarily emphasizes publication patterns, citation relationships, and network structures, while providing limited capacity to evaluate the substantive quality, methodological rigor, or contextual depth of individual studies. The findings also indicate that research concerning green skills in vocational education remains heavily concentrated on sustainability discourse and renewable energy transition, whereas empirical investigations focusing on digital-green integration, artificial intelligence adoption, green entrepreneurship, and workforce adaptability remain relatively underexplored. Another noticeable research gap concerns the limited attention given to developing countries and regional vocational systems, particularly in emerging economies where renewable energy workforce transformation faces different institutional and infrastructural challenges. Future research therefore should combine bibliometric approaches with systematic literature reviews, qualitative content analysis, or empirical case studies to produce more comprehensive and context-sensitive insights. Moreover, future studies could explore longitudinal analyses concerning the evolution of green competencies in response to technological disruption, climate policy transformation, and labor market digitalization. The emergence of themes such as e-learning, educational computing, and sustainability planning also indicates substantial opportunities for novelty through investigations into AI-supported green vocational learning ecosystems and smart sustainability training models. Another promising direction involves examining how vocational education institutions can integrate industry 5.0 principles, digital sustainability, and renewable energy innovation into competency-based workforce development frameworks. Consequently, the future trajectory of this research field lies not only in expanding theoretical integration but also in developing transformative educational models capable of supporting inclusive, adaptive, and technologically resilient green workforce ecosystems in the era of global energy transition.

4. CONCLUSION

This bibliometric study concludes that research concerning green skills development in vocational education for renewable energy workforce sustainability has experienced substantial growth and increasing interdisciplinary integration over the last two decades. The findings demonstrate that sustainability-oriented vocational education has evolved into a strategic research domain closely associated with renewable energy transition, workforce resilience,

digital transformation, and sustainable industrial development. The keyword co-occurrence and co-citation analyses further reveal that sustainable development, vocational training, renewable energy, and workforce adaptability constitute the primary conceptual foundations shaping the intellectual structure of the field. In theoretical terms, this study contributes to the advancement of sustainability education literature by integrating human capital development, vocational transformation, and renewable energy workforce perspectives into a unified analytical framework. Practically, the results imply that educational institutions, policymakers, and industrial stakeholders must strengthen collaboration in designing adaptive curricula, green competency training, and sustainability-oriented workforce preparation strategies aligned with future labor market demands. The study also confirms that emerging themes such as artificial intelligence, digital sustainability, smart learning systems, and green innovation are increasingly influencing the future direction of vocational education research. Nevertheless, this research remains limited by its exclusive reliance on the Scopus database and the inherent limitations of bibliometric methods, which primarily emphasize publication patterns and citation structures rather than detailed qualitative evaluation of individual studies. Therefore, future research is recommended to integrate bibliometric analysis with systematic literature reviews, empirical investigations, and comparative regional studies to generate more comprehensive insights into sustainable vocational education and renewable energy workforce transformation in the context of global energy transition.

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