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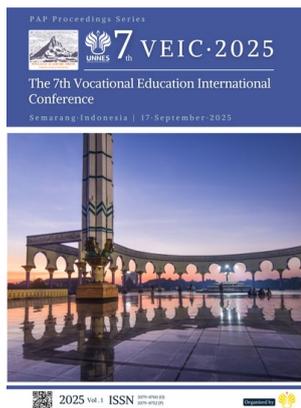
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From Green Skills to Sustainable Workforce: Mapping Two Decades of Research on Vocational Education for Sustainability Transition

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Abstract: The global shift toward a green economy has repositioned vocational education as a central mechanism for sustainable workforce development. This study maps two decades (2005–2025) of research on green skills and sustainability transition in vocational education to identify publication trends, thematic structures, and emerging research directions. Using a bibliometric approach, 527 Scopus-indexed documents were analyzed through VOS viewer and the Bibliometric R package to produce co-occurrence networks, thematic maps, and temporal evolution visualizations. The findings indicate a clear shift from early studies focused on human capital, labour markets, and technical training toward sustainability-oriented and eco-digital competencies. Five dominant thematic clusters: green skills, vocational education, workforce development, innovation policy, and Industry 4.0, demonstrate the growing intersection between digital transformation and environmental sustainability. European countries, especially the UK and Germany, continue to lead global scholarship, while increasing contributions from Asia reflect expanding contextual diversity. Overall, this study highlights how vocational education has transformed from an economic instrument into a strategic platform for sustainability transition. The convergence of digitalization and green competencies forms the basis of emerging eco-digital TVET, underscoring the need for integrated pedagogical and policy approaches, particularly in developing countries.

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Keywords: green skills; sustainable transition; sustainable workforce; vocational education; bibliometric analysis

1. Introduction

The climate crisis and global pressure towards a green economic transformation have exacerbated the need for a workforce with environmentally friendly competencies. The demand for technical and non-technical skills that support green innovation, energy efficiency, waste management, and environmental adaptation has grown significantly faster than the supply of these skills. For example, demand for green skills increased by 11.6% between 2023 and 2024, while the talent pool grew by only 5.6% [1]. Furthermore, empirical analysis shows that environmental regulations increase the demand for technical, analytical, and scientific competencies in green jobs [2]. In the education sector,

the OECD emphasizes that vocational education (VET/TVET) is strategically positioned as a gateway to transformation, as most of the “middle” jobs that are being transformed by the green transition are typically filled by vocational graduates [3].

Various challenges arise when vocational education is tasked with becoming a driver of a green workforce. At the labor market level, cross-country studies reveal a significant mismatch between the demand for green skills and the availability of talent. In contrast, worker mobility from the “brown” sector to green jobs is hindered by geographic barriers and the transferability of competencies. Less than 1% of fossil workers transition to green jobs, and co-location is a significant barrier to just transition [4,5]. In TVET institutions, the OECD emphasizes the need for curriculum reform, teacher capacity building, and industry partnerships to address the surge in demand for green skills in the construction, transportation, and energy sectors. However, implementation remains uneven [6]. The integration of learning technology offers opportunities for work-ready practice, but is hampered by the costs of devices, infrastructure readiness, educator training, and curriculum integration [7,8]. On the evidence side, bibliometric studies face database selection bias, keyword taxonomic inconsistencies, and data cleaning issues across databases [9]. Furthermore, variability and citation lag in recent publications can distort evolutionary influence and thematic maps, requiring calibrated interpretation of trends [10]. These challenges also present opportunities for research to design contextual, tech-enabled, and evidence-based skills pathways that support sustainability transitions.

Research on green skills and sustainability transitions in the context of vocational education has grown rapidly, but is generally fragmented and lacks integration within a comprehensive conceptual framework. Several studies have highlighted the increase in publications on green skills and green jobs, but most focus on the context of employment policy and macroeconomics [11,12]. Empirical studies examining the integration of green skills in vocational education and training are still limited to sectoral case studies such as renewable energy, manufacturing, and construction without addressing the systemic and pedagogical dimensions of education [13,14]. Some studies have analyzed the relationship between TVET and sustainability, but have not yet conducted bibliometric-based scientific mapping to identify the network of concepts, actors, and the direction of global research evolution [15]. Furthermore, the literature is still limited in bridging the relationship between green competence frameworks and sustainability transition pathways [16,17]. This gap is the novelty of this study, which provides a bibliometric analysis that maps two decades of global research on green skills and sustainability transitions in vocational education.

The need to understand the research landscape on green skills and sustainability transition in vocational education is becoming increasingly urgent as global pressures towards a green economy and clean energy transition increase. According to the International Energy Agency, decarbonization efforts in the energy sector alone are expected to create more than 14 million new green skills-based jobs by 2030 [18]. However, the World Economic Forum asserts that 60% of vocational education institutions worldwide are not yet fully prepared to integrate sustainability competencies [19]. In this context, bibliometric-based research is urgently needed to map knowledge dynamics, identify research hotspots, and direct education and training strategies towards the green transition [20,21]. Scientifically, this article enriches the theoretical understanding of the relationship between TVET, green workforce development, and sustainability transformation [22]. Practically, the results support educators and policymakers in designing evidence-based and relevant educational interventions for the green industry [23].

This study aims to answer three main research questions formulated based on the literature gap and the urgency of mapping global knowledge on green skills and sustainability transition in vocational education.

RQ1: How has global research on green skills and sustainability transition in vocational education evolved over the past two decades (2005–2025)?

RQ2: What are the main thematic clusters and conceptual linkages among the keywords related to green skills, vocational education, and sustainability transition?

RQ3: How do the thematic evolutions and recent publication trends suggest emerging research directions in green workforce development and sustainability-oriented vocational education?

2. Methods

This study uses a bibliometric analysis approach to map the development of global research on green skills and sustainability transition in the context of vocational education over the past two decades (2005–2025). Bibliographic data was obtained from the Scopus database, which is internationally recognized for its extensive coverage of highly reputable journals in the fields of education, environmental science, and social sciences. Data collection was conducted in September 2025 using the Advanced Search feature.

Keywords used for search: "green skills" OR "environmental skills" OR "sustainability competences" OR "green competencies" OR "green jobs" OR "sustainable workforce" OR "skills development" OR "human capital" AND "vocational education" OR "TVET" OR "technical and vocational education" OR "vocational training". The search results were filtered to include English-language journal articles and reviews, published between 2005 and 2025. The data retrieval process was carried out by exporting metadata into .csv format for data processing in Microsoft Excel and the VOS viewer application.

After data collection, screening, and data cleaning were performed to remove duplication, standardize author and institutional names, and standardize key terms (e.g., combining "green skill" and "green skills"). The data were analyzed in stages according to three leading research focuses: global publication trend analysis, keyword network and thematic cluster analysis, and identification of thematic evolution and future research directions.

2.1. Preparation of Tools and Materials

Preparation of tools and materials was conducted before the bibliographic data collection process. The Scopus database was used as the primary source because it has a wide coverage of reputable journals, provides accurate citation information, and complete and well-structured metadata for bibliometric analysis. Digital applications were used to assist the data processing process. Microsoft Excel 365 was used to manage raw bibliographic data, remove duplications, and conduct initial descriptive analysis. VOS viewer version 1.6.xx was applied to map the co-occurrence network and visualize thematic clusters between keywords, authors, and countries. Bibliometric (R-Studio package) was used for advanced analysis, such as thematic evolution and trend topic visualization.

2.2. Data Collection

Data collection was conducted by retrieving metadata from the Scopus database, accessed in September 2025. Scopus was chosen because of its global reputation as a provider of comprehensive and credible scientific indices in the fields of education, environment, and social sciences. The data obtained spanned the period from 2005 to 2025, with inclusion criteria being English-language scientific articles and review articles that had undergone peer review. Meanwhile, publications in the form of proceedings, books, book chapters, and non-academic documents were excluded from the dataset because they did not meet scientific criteria. All search result metadata was exported in .csv format.

2.3. Data Filtering and Visualization

Data filtering was performed to ensure that all data used in the analysis met the criteria for completeness and relevance to the research topic. This process began with checking for document duplication, keyword suitability, and metadata validity. After the

filtering process, all valid entries were manually analyzed and verified to ensure consistency of terms and uniformity of author names and affiliations. Bibliometric data visualization was employed to illustrate the relationships between research elements comprehensively. This visualization was performed using VOS viewer and Bibliometric (R-Studio). VOS viewer was used to map relationships between keywords (co-occurrence mapping), author collaboration networks (co-authorship), and relationships between publication sources (co-citation analysis). Meanwhile, Bibliometric was used to analyze thematic evolution, trend topics visualization, and conceptual structure mapping based on the publication period 2005–2025.

The visualization process generated three main types of maps: a network visualization that illustrates the relationships between concepts, a temporal visualization that displays the evolution of themes over time, and a density visualization that shows the intensity of the emergence of specific ideas in the literature. The results of each map were used to answer three research questions, specifically identifying global publication trends (RQ1), key thematic patterns (RQ2), and future research directions in the context of continuing vocational education (RQ3).

2.4. Data Analysis

Data analysis was conducted to interpret the results of the bibliometric mapping generated from the previous visualization process. This analysis aimed to identify publication trends, conceptual relationships between topics, and the direction of global research evolution related to green skills and sustainability transition in vocational education. Data analysis included an examination of quantitative indicators such as the number of publications per year, citation rate, author productivity, institutional affiliation, and country of origin of publications.

3. Results

3.1. RQ1: How Has Global Research on Green Skills and Sustainability Transition in Vocational Education Evolved over the past Two Decades (2005–2025)?

Scopus data analysis from 2005 to 2025 shows that research on green skills and sustainability transition in the context of vocational education has experienced exponential growth over the past two decades. This increase began to be seen in 2016, coinciding with the emergence of Education for Sustainable Development (ESD) within the framework of the Sustainable Development Goals (SDG 4.4). This pattern indicates that the issue of green skills has transformed from an ecological concept to a strategic agenda for global vocational education [24].

Based on Figure 1, the number of publications shows a consistent increase from 2005 to 2025, with a sharp spike after 2019, marking a phase of accelerated research in the field of green skills and sustainability transition. The peak of publications occurs in 2025 with over 100 articles, reflecting the global shift towards sustainable workforce transformation. The blue line shows the actual number of publications, while the red line shows the predicted trend (forecast) with 95% confidence limits. Based on the results of performance analysis, the average annual publication growth exceeded 18%, with a notable spike from 2019 to 2023, coinciding with the wave of green transition policies in Europe and Asia [25]. Geographically, the most considerable contributions came from European countries such as the UK, Germany, and the Netherlands, which are known to have sustainability-oriented TVET policy ecosystems [26]. In the Asian region, China and Indonesia are emerging as new research centers, in line with the increasing support for green workforce development policies and vocational curriculum reform [27,28].

3.2. RQ2: What Are the Main Thematic Clusters and Conceptual Linkages among the Keywords Related to Green Skills, Vocational Education, and Sustainability Transition?

A thematic analysis was conducted to identify the conceptual structure and interconnections between research topics related to green skills and sustainability transition in the context of vocational education. This analysis utilized the co-occurrence of author keywords in the Scopus dataset from 2005 to 2025.

Figure 2 shows the co-occurrence analysis, which yields five main thematic clusters representing global research focuses over the past two decades. Cluster 1 (red) encompasses keywords such as green skills, sustainability competencies, and environmental education, highlighting conceptual dimensions related to sustainable skills development. Cluster 2 (blue) focuses on vocational education, curriculum, and training, representing the integration of the sustainability agenda into the vocational education system. Cluster 3 (green) highlights the relationship between the green economy, employment, and workforce development, indicating the importance of the green transition in the work sector. Cluster 4 (yellow) illustrates the integration of policy, innovation, and the SDGs, reflecting the engagement of public policy and education system reform. Meanwhile, Cluster 5 (purple) introduces new themes, including digital transformation, Industry 4.0, and eco-digital skills, indicating the convergence of technology and sustainability.

These findings confirm that green skills research has evolved from a conceptual discourse to a multidisciplinary issue encompassing education, economics, and technology [31-33]. The close relationship between vocational education, human capital, and employment demonstrates that vocational education now plays a role not only as an educational institution but also as a crucial agent in developing a sustainability-oriented workforce. This co-occurrence analysis involved a total of 66 keywords that met the minimum occurrence threshold (≥ 3). The three keywords with the highest frequency of occurrence were vocational education (34 times), human capital (32 times), and green skills (27 times). All three had a total link strength above 100, indicating strong conceptual relationships with various other terms in the research network. Topics such as training, employment, and sustainability also had high connectivity (>80), indicating a central position in the knowledge structure of this field. This pattern suggests that research on green skills and sustainability transition has evolved in tandem with issues of human capital development, vocational education, and employment policy [34,35].

Figure 3 displays a keyword density visualization that shows the density of research topics based on the frequency of occurrence and the strength of the relationship between keywords in the field of green skills and sustainability transition. Yellow indicates areas with the highest density (hot zones), while green and blue indicate areas with medium and low density. The analysis results suggest that the areas with the highest density are centered on the keywords 'human capital,' 'vocational training,' and 'vocational education.' These three terms form the center of gravity of the research, confirming that vocational education plays a key role in developing sustainability-oriented skills needed in the green economy [11, 13]. The high density around human capital indicates a paradigm shift from merely preparing the workforce to strengthening adaptive capacity for environmental and digital transformation [23, 35].

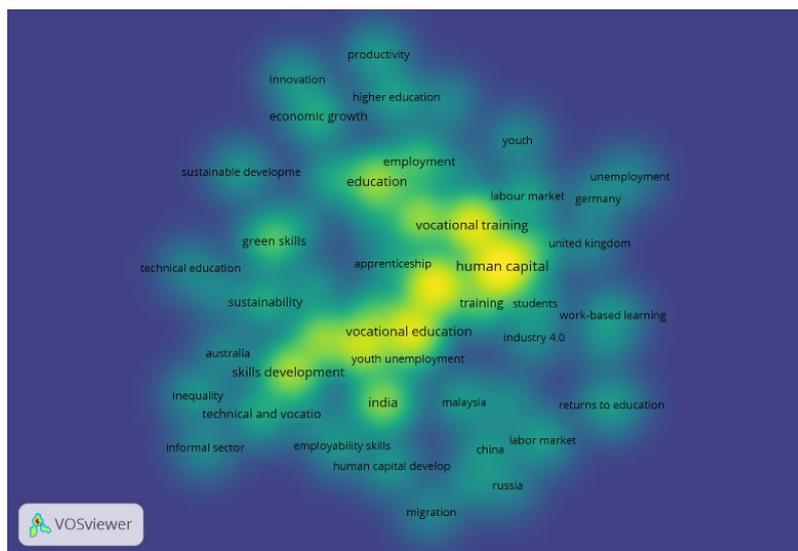


Figure 3. keyword density visualization.

The green-yellow zones, such as green skills, skills development, training, and employment, indicate topics that have been actively researched over the past five years. This theme highlights the growing connection between education for sustainable development (ESD) and workforce reskilling in vocational education policy, particularly following the adoption of SDG 4.4 [36]. Meanwhile, the blue-green areas, featuring keywords such as digital transformation, Industry 4.0, and eco-innovation, indicate the emergence of new themes (emerging topics) linking sustainability with the digitalization of industrial processes and learning (eco-digital pathways) [37].

Figure 4 illustrates a thematic map generated through co-word analysis, which categorizes research themes on green skills and sustainability transition into four conceptual quadrants. Each theme's position is determined by two key indicators: centrality (the degree of relevance to the field) and density (the degree of theme development). This map illustrates the dynamics of global research that links vocational education, sustainability, and the green economy through four main theme typologies.

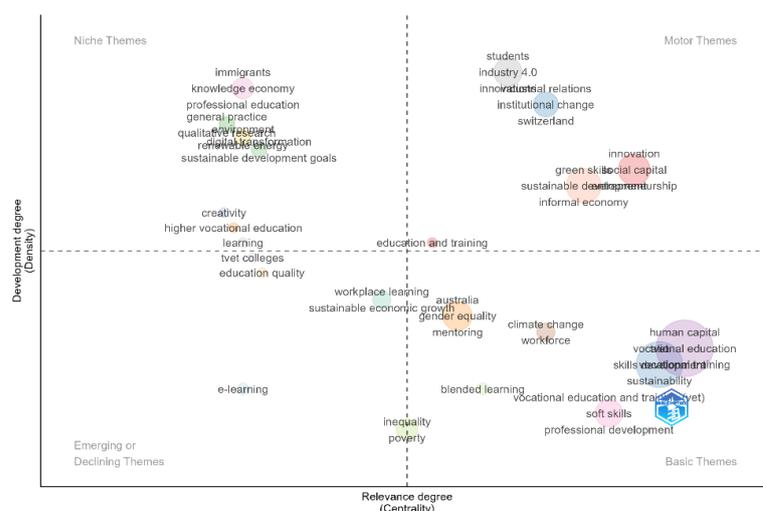


Figure 4. Thematic Map.

1) Quadrant I – Motor Themes

This cluster contains themes with high centrality and density, indicating the most mature and influential themes in this field. Keywords such as green skills, social capital,

innovation, and entrepreneurship are prevalent in this area. These findings suggest that innovation and social capital have become key drivers in the development of vocational education, where green skills are linked to the innovative and collaborative capacity of the workforce [38]. In other words, the research orientation has shifted from the conception of environmental education to a green economic transformation based on social innovation [33].

2) Quadrant II – Basic Themes

The basic cluster represents the scientific foundations that underpin various studies, with key keywords including human capital, vocational education and training (VET), skills development, professional development, and sustainability. High centrality values confirm that these concepts constitute the dominant framework connecting the dimensions of education, employment, and sustainability [25,26]. The clustering of vocational education and sustainability suggests that vocational education is now regarded as a primary mechanism for enhancing human capital to support the national green transition.

3) Quadrant III – Niche Themes

Themes in this area, such as the knowledge economy, professional education, and qualitative research, have high density but low centrality. This means these topics have been developed in depth by specific research groups, but their contributions remain limited to particular communities. Studies on the knowledge economy and professional education generally focus on regional policies and contexts (e.g., Europe and the OECD) and have not been widely applied to developing country contexts [39]. However, these themes have the potential to become new drivers when linked to the green innovation and digital TVET agendas in the future.

4) Quadrant IV – Emerging or Declining Themes

This section displays themes with low centrality and density, such as e-learning, inequality, and poverty. This pattern suggests that the online learning issue, which once dominated the pandemic, is now experiencing a decline in relevance, being replaced by more applicable topics such as work-based learning and eco-digital skills. Nevertheless, the theme of inequality remains essential because it highlights the gap in access to green education and job opportunities between developed and developing countries [11, 34]. Thus, this area represents a new research direction that integrates equity, gender equality, and green digitalization into vocational education and training policy.

The analysis reveals that themes with centrality values greater than 0.5 and density greater than 0.4 (e.g., green skills, innovation, human capital, and sustainability) are the most dominant clusters. Meanwhile, approximately 20% of themes fall into the emerging zone, indicating a continuously evolving research dynamic. Overall, this thematic map demonstrates a shift in global focus from human capacity building to the integration of eco-digital transformation as a new foundation for sustainable vocational education.

3.3. RQ3: How Do the Thematic Evolutions and Recent Publication Trends Suggest Emerging Research Directions in Green Workforce Development and Sustainability-Oriented Vocational Education?

Figure 5 illustrates the temporal evolution of research on green skills and sustainability transitions in the context of vocational education (TVET), based on an overlay visualization of the results from the VOS viewer analysis. The colors indicate the chronology of topic emergence, from dark blue (2016) to yellow (2022), demonstrating the field's transformation from a traditional educational approach to full integration with the green transition and digitalization agenda. In the early phase (2016–2018), the color blue marked the dominance of terms such as human capital, vocational education, employment, and the labor market. These themes reflected the research focus on human capital formation and the relationship between vocational education and labor productivity, which was still economically oriented [40]. Research during this period

emphasized the efficiency of education as an investment in human resources, without addressing the environmental dimension.

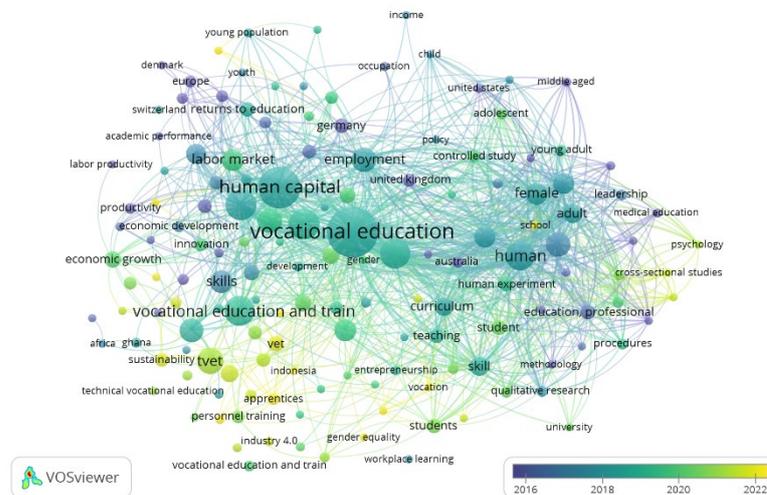


Figure 5. Overly visualization.

The transition phase (2019–2020) is colored green, indicating the emergence of new topics, including skills development, sustainability in TVET, technical vocational education, economic growth, and apprenticeship. The emergence of the term "sustainability TVET" marks an effort to integrate sustainability principles into vocational education and training (TVET) policies and curricula [20]. This shift coincides with the momentum of the globalization of SDG 4.4, which emphasizes the importance of relevant skills for sustainable development. In this phase, vocational education is beginning to be seen as a means of driving a green economy (green-driven workforce).

The current phase (2021–2022), marked in yellow, features terms such as Industry 4.0, gender equality, innovation, entrepreneurship, workplace learning, and eco-digital TVET. These themes demonstrate the cross-domain integration of digital transformation and sustainability transition, where vocational learning is geared toward producing an adaptive workforce capable of innovating in a low-carbon economy [41,42]. The presence of keywords such as gender equality and students also indicates increased attention to social and justice aspects in green vocational education, in line with the concept of just transition [11, 23].

Overall, this visualization confirms that the global literature is experiencing a shift in focus from economic-driven vocationalism to the eco-digital human capital paradigm, namely a skills development model that emphasizes the balance between economic competitiveness, social inclusiveness, and environmental sustainability.

Figure 6 shows a temporal map of keywords used by researchers over the past two decades (2005–2025). This visualization illustrates how each keyword has evolved, with the size of the bubbles representing the frequency of occurrence (term frequency) and the length of the lines indicating the duration of research activity. Overall, this trend indicates a shift in research focus from employment and productivity issues to sustainable vocational education and green transformation. The evolution of research shows three main, interconnected phases. During the early period (2005–2012), the research focus remained on classic themes, including labor markets, employment, and vocational education, with an approach grounded in human capital theory that emphasized the connection between vocational education and industry needs [25]. Entering the 2015–2020 period, there was a significant shift towards topics such as skills development, green skills, and sustainability, in line with the implementation of the 2030 Agenda and SDG 4.4, which emphasizes education for sustainability. The 2020–2025 phase marked the emergence of

new themes that combine digitalization and sustainability, such as Industry 4.0, innovation, and eco-digital TVET, which demonstrate a strong integration between technological transformation and the green transition. This shift confirms the new direction of global vocational education towards the development of an adaptive and sustainability-oriented green workforce.

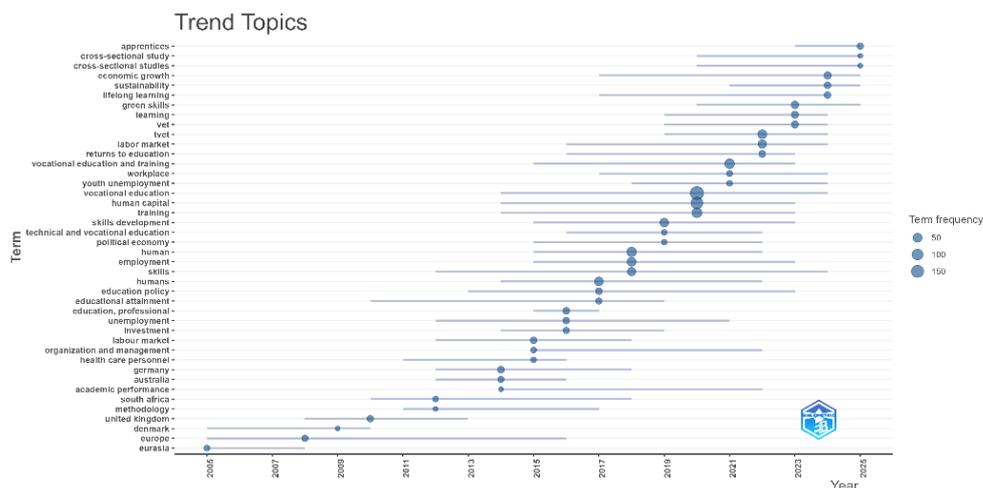


Figure 6. Temporal Evolution and Global Research Trends.

Green skills, vocational education, and training have the highest term frequency (>150) and have been consistently occurring since 2018. In contrast, topics such as technical education, employment, and policy have shown a decrease in relevance since 2020. This confirms that research is now shifting from discussing policy and employment to exploring green competencies and sustainable vocational learning innovations. This finding supports recent literature that emphasizes the importance of integrating eco-digital competencies in TVET and confirms that the transition towards green workforce development is not only technical, but also involves broader social and pedagogical aspects.

Figure 7 illustrates the evolution of green skills and vocational education research themes over three main periods: (1) 2005–2012, (2) 2013–2018, and (3) 2019–2025. Each color block represents a dominant thematic cluster, while the connecting lines indicate conceptual continuity or evolutionary relationships between themes across time.

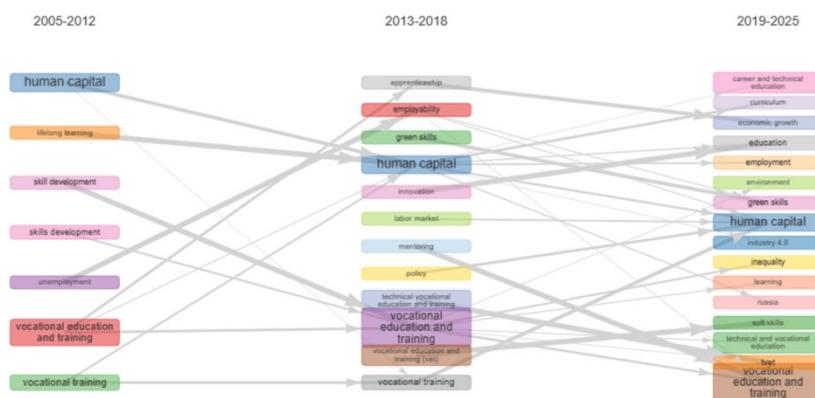


Figure 7. Thematic Evolution in Green Skills and Vocational Education Research (2005–2025).

Phase 1 (2005–2012): Foundations of Human Capital and Vocational Education

In the initial period, research themes remained centered on classic concepts, including human capital, vocational education and training, and skills development. The primary focus of the research centered on the contribution of vocational education to enhancing job skills, improving productivity, and reducing unemployment [43]. This theme suggests that vocational education was viewed as an economic tool rather than a means for environmental sustainability.

Phase 2 (2013–2018): Transition Towards Skills Development and Green Skills

The thematic map illustrates the emergence of new themes, including green skills, employability, innovation, and policy [44]. The human capital theme remained intact but transformed into a foundation for the development of a green economy and lifelong learning. This period marked the beginning of the strong influence of the UNESCO Global Action Program on Education for Sustainable Development (2015–2019), which encouraged the integration of sustainability issues into TVET.

Phase 3 (2019–2025): Digital Integration and Sustainability

Topics have diversified with the emergence of Industry 4.0, eco-digital TVET, the environment, and curriculum innovation [45]. The theme of green skills has become a key bridge between vocational education and the sustainability transition agenda. The emergence of career and technical education, along with the development of soft skills, strengthens the research orientation towards adaptive and sustainable future workforce competencies.

4. Discussion

The sharp growth of publications post-2016 signals a shift in TVET policy from workforce preparation to green transition competencies. This is due to the epistemic reorientation that employability needs to be complemented by cross-disciplinary sustainability competencies (systemic, anticipatory, normative, collaborative), such as the key sustainability competencies framework. The map shows the growing convergence of eco-digital and green skills alongside Industry 4.0/digital transformation. This convergence is vital because low-emission productivity in the manufacturing and service sectors is heavily supported by the integration of datafication, automation, and resource efficiency, so green competencies without digital competencies risk being inoperable in the workplace.

The innovation/entrepreneurship cluster inherent in green skills emphasizes that TVET is no longer simply a “technology follower,” but rather a producer of innovation for the green economy. This aligns with the ILO’s agenda on skills for the green transition, which emphasizes the formation of an innovation ecosystem, not just individual reskilling. On the other hand, the emergence of gender equality/inequality as a trend topic broadens the scope from economic efficiency to transitional justice (just transition), an area often under-recognized in mainstream TVET studies.

Theoretically, this study contributes to the “eco-digital TVET” model, where green skills serve as an integration node between sustainability competencies and innovative production technology capabilities, which together explain why innovation clusters become driving themes. Methodologically, it is demonstrated that combining co-occurrence, thematic maps, and thematic evolution yields insights that are not attainable when the three are analyzed separately, particularly in revealing long-term “conceptual flows.” Practically, the implication is that TVET curriculum design needs to link systemic-normative competencies (ESD) with data-automation capabilities (Industry 4.0), strengthen work-based learning, and include indicators of returns to (green) education so that the relevance of the green labor market is measured.

5. Conclusion

A bibliometric analysis of 20 years of publications (2005–2025) shows that research on green skills and sustainability transition in vocational education has undergone a thematic shift from an economic approach to a broader sustainability orientation. Since 2016, global attention has increased rapidly, with the dominant topics of green competencies, eco-digital skills, and workforce development, marking the integration of digital transformation and the green agenda. These results confirm that vocational education now plays a strategic role in supporting the transition to a sustainable workforce, where competence development is no longer solely oriented towards productivity but also towards social innovation and ecological awareness. These findings provide an essential conceptual basis for directing vocational education policies and practices that are adaptive to global sustainability challenges, while also opening up space for further research that examines the empirical dimensions of applying eco-digital competences in various industrial contexts and developing countries.

6. Limitations and Future Research

This study has several limitations that should be noted. First, this bibliometric analysis only used the Scopus database, so it is possible that relevant literature from other sources, such as Web of Science or Dimensions, was not included. Second, this study focused on bibliographic data without delving into the qualitative content of each publication, so thematic interpretation remains descriptive. Third, the representation of the study's geographic context suggests a dominance of developed countries. In contrast, contributions from developing countries, such as Indonesia, remain limited, underscoring the need for a more balanced cross-regional study. Future research is recommended to combine bibliometric analysis with a content analysis approach or a systematic literature review to gain a deeper understanding of the methodological, pedagogical patterns, and empirical impacts of applying green skills and eco-digital competencies in vocational education.

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References

1. Gonzalez-Ehlinger, E.; Stephany, F. Skills or degree? The rise of skill-based hiring for AI and green jobs. *The Rise of Skill-Based Hiring for AI and Green Jobs* 2024, pp. 1-50.
2. Vona, F.; Marin, G.; Consoli, D.; Popp, D. Environmental regulation and green skills: an empirical exploration. *Journal of the Association of Environmental and Resource Economists* 2018, vol. 5(4), pp. 713-53.
3. Kuczera, M. Vocational education and training (VET) and the green transition: Insights from labour market data. *OECD Social, Employment, and Migration Working Papers* 2025, Vol. 327, pp. 1-71.
4. Greenspon, J.; Raimi, D. Matching geographies and job skills in the energy transition. *The Extractive Industries and Society* 2024, vol. 17, pp. 101397.
5. Lim, J.; Aklin, M.; Frank, M.R. Location is a major barrier for transferring US fossil fuel employment to green jobs. *Nature Communications* 2023, vol. 14(1), pp. 5711.
6. OECD. *How the Green Transition Reshapes Vocational Education and Training*. OECD Publishing, 2025.
7. Santilli, T.; Ceccacci, S.; Mengoni, M.; Giaconi, C. Virtual vs. traditional learning in higher education: A systematic review of comparative studies. *Computers & Education* 2024, vol. 227, pp. 105214.
8. Samala, A.D.; Rawas, S.; Rahmadika, S.; Criollo, C.S.; Fikri, R.; Sandra, R.P. Virtual reality in education: global trends, challenges, and impacts—game changer or passing trend?. *Discover Education* 2025, vol. 1, pp. 1-45.

9. Thelwall, M.; Kousha, K.; Stuart, E.; Makita, M.; Abdoli, M.; Wilson, P.; Levitt, J. Do bibliometrics introduce gender, institutional or interdisciplinary biases into research evaluations?. *Research Policy* 2023, vol. 52(8), pp. 104829.
10. Hu, J.; Li, C.; Ge, Y.; Yang, J.; Zhu, S.; He, C. Mapping the evolution of digital health research: bibliometric overview of research hotspots, trends, and collaboration of publications in JMIR (1999-2024). *Journal of Medical Internet Research* 2024, vol. 26, pp. e58987.
11. Aggarwal, A. *Global framework on core skills for life and work in the 21st century*. ILO: Geneva, 2021.
12. Persson-Thunqvist, D.; Gustavsson, M.; Halvarsson-Lundqvist, A. The role of VET in a green transition of industry: a literature review. *International Journal for Research in Vocational Education and Training* 2023, vol. 10(3), pp. 361-82.
13. Peter, D.; Peter, M.; Peter, P. Mapping the landscape of TVET education: a global bibliometric analysis. *Asian Education and Development Studies* 2025, vol. 14(5), pp. 1179-1204.
14. Abd-Rahman, N.H.; Zubairi, Y.Z.; Jani, R.; Abdul-Batau, M.F.; Shamsudheen, M.I.; Ishak, N.A.; Hanafi, H.; Abdul Bahri, E.N. Governance structures and systemic challenges shaping the future of the technical and vocational education and training (TVET) workforce. *Education and Training* 2025, pp. 1-21.
15. Mante, D.A.; Okoye, M.C.; Hui, X. A Systematic Literature Review of Technical and Vocational Education and Training (TVET) Systems: An insight from China and Sub-Saharan Africa. *Pedagogy and Psychology of Sport* 2025, vol. 23, pp. 64486-.
16. Sposab, K.; Rieckmann, M. Development of sustainability competencies in secondary school education: A scoping literature review. *Sustainability* 2024, vol. 16(23), pp. 10228.
17. Bianchi, G. *Sustainability competences*. Publications Office of the European Union 2020, vol. 1(1), pp. 1-73.
18. Armiento, M.; Lelli, M.; Andrews, C.; Idini, B.; Ruff, R. Analysing the global workforce dynamics of the energy transition: main findings from the World Energy Employment report 2023. *Discover Sustainability* 2025, vol. 6(35).
19. Di-Battista, A.; Grayling, S.; Hasselaar, E.; Leopold, T.; Li, R.; Rayner, M.; Zahidi, S. *Future of jobs report 2023*. In World Economic Forum: Geneva, 2023, pp. 978-2.
20. Pavlova, M. Emerging environmental industries: impact on required skills and TVET systems. *International Journal of Training Research* 2019, vol. 17(1), pp. 144-58.
21. Dönmez, İ. Sustainability in educational research: Mapping the field with a bibliometric analysis. *Sustainability* 2024, vol. 16(13), pp. 5541.
22. David, R.; Daniels, C. Greening Technical and Vocational Education and Training for Energy Transition in Nigeria. *Journal of Education for Sustainable Development* 2024, vol. 18(2), pp. 101-21.
23. Ayuba, Z.G.; Datol, I.G.; Aluwong, E.B. Greening technical vocational education and training (TVET) for combating climate change and promoting sustainable development in Nigeria. *BW Academic Journal* 2024, vol. 1(3), pp. 43-9.
24. Suhendra, T.; Subagiyo, L.; Basir, A. Development of a Guidebook for Green Skills Implementation in Vocational Schools to Support Green Economy Transformation. *Edunesia: Jurnal Ilmiah Pendidikan* 2025, vol. 6(2), pp. 678-93.
25. Langthaler, M.; McGrath, S.; Ramsarup, P. Skills for green and just transitions: Reflecting on the role of vocational education and training for sustainable development. *ÖFSE Briefing Paper* 2021, vol. 30, pp. 5-24
26. Busemeyer, M.R.; Stutzmann, S.; Tober, T. Digitalization and the green transition: Different challenges, same policy responses?. *Regulation & Governance* 2025, vol. 19(2), pp. 422-47.
27. Huang, F. Transformations in higher vocational education in Japan. *Vocation, Technology & Education* 2024, vol. 1(1), pp. 1-11.
28. Juwitasari, R. Education for Sustainable Development (ESD) in Post-modernity: A Case Study of Japanese Value Manifestation in Vocational Education in Greater Mekong Sub-Region Country. *Journal of Technical Education and Training* 2024, vol. 16(3), pp. 216-31.
29. Singh, A.; Yadav, J.; Sharma, S. Research on Green Skills and Workforce Sustainability: A Bibliometric Analysis. *IUP Journal of Soft Skills* 2025, vol. 19(2), pp. 46.
30. Crespo-Castellanos, J.M.; Rodríguez-de-Castro, A.; Mateo-Girona, M.R. Trends and perspectives in education for sustainable development in the teaching of geography in Spain. *Sustainability* 2021, vol. 13(23), pp.13118.
31. Tomassi, A.; Caforio, A.; Romano, E.; Lamponi, E.; Pollini, A. The development of a competence framework for environmental education complying with the European qualifications framework and the European green deal. *The Journal of Environmental Education* 2024, vol. 55(2), pp. 153-79.
32. Klassen, J. International organisations in vocational education and training: a literature review. *Journal of Vocational Education & Training* 2025, vol. 77(3), pp. 792-818.
33. Yaqub, R.M.; Rehman, H.M.; Manzoor, S.F.; Daud, M. Fostering Sustainability in Vocational Training Institutes: The Intersection of Green Human Resource Management (GHRM) and Green Technical Vocational Education and Training (GTVET) Skills. *Contemporary Journal of Social Science Review* 2024, vol. 2(4), pp. 1243-69.
34. Toro, G.; Nimerenco, I.; Mocanu, S. Bibliometric analysis of green skills development: Trends, international collaboration, and implications for Sustainable Development Goals. *J. Green Econ. Low-Carbon* 2024, vol. 3(4), pp. 235-47.
35. Muaddab, H. Promoting green skill and green vocational education for a circular economy: a literature review. *Journal of Education: Development and Review (JEDAR)* 2024, vol. 1(1), pp. 8-20.

36. Wiek, A.; Withycombe, L.; Redman, C.L. Key competencies in sustainability: a reference framework for academic program development. *Sustainability science* 2011, vol. 6(2), pp. 203-18.
37. UNESCO. *Greening Technical and Vocational Education and Training: A Practical Guide for Institutions*. UNESCO-UNEVOC International Centre: Germany, 2017.
38. Subrahmanyam, S. Developing Green Skills for Sustainable Careers. In *Integrating AI and Sustainability in Technical and Vocational Education and Training (TVET)*. IGI Global Scientific Publishing: USA, 2025, pp. 101-126.
39. Li, J.; Huang, M. International comparative analysis of the industry-education relationship in vocational education and training: From the perspective of economic sociology. *Vocation, Technology & Education* 2024, vol. 1(3), pp. 1-10.
40. Sakdapat, N. Approaches for sustainable professional skill development for vocational education students in Thailand. *F1000Research* 2024, vol. 13, p.401.
41. Tahir, U.; Babar, H. The Role of Policy in Developing a Skilled Workforce for a Green Economy. *Green Environmental Technology* 2024, vol. 1(2), pp. 78-87.
42. Herrero-Rámila, C.; Castaño-Muñoz, J.; Romero-Rodríguez, S., and Moreno-Morilla, C. Key Drivers of Inclusive Digital Transformation of European Vocational Education and Training Systems. *Apprenticeships in England–Initial or Continuing VET* 2025, p.263.
43. Brundiars, K.; Barth, M.; Cebrián, G.; Cohen, M.; Diaz, L.; Doucette-Remington, S.; Dripps, W.; Habron, G.; Harré, N.; Jarchow, M.; Losch, K. Key competencies in sustainability in higher education: Toward an agreed-upon reference framework. *Sustainability science* 2021, vol. 16(1), pp. 13-29.
44. Schönstein, R.F.; Budke, A. Teaching action competence in education for sustainable development—a qualitative study on teachers’ ideas, opinions, attitudes and self-conceptions. In *Frontiers in Education* 2024, vol. 8, p. 1256849.
45. Abina, A.; Temeljotov-Salaj, A.; Cestnik, B.; Karalič, A.; Ogrinc, M.; Kovačič-Lukman, R.; Zidanšek, A. Challenging 21st-century competencies for STEM students: companies’ vision in Slovenia and Norway in the light of global initiatives for competencies development. *Sustainability* 2024, vol. 16(3), p. 1295.

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