

Article

# Green Skills as Human Capital for Sustainable Competitiveness: A Bibliometric Analysis and Research Agenda

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**Abstract:** The global transition toward a sustainable and low-carbon economy has intensified the demand for green skills as a critical component of future workforce development. As governments, industries, and educational institutions increasingly prioritize sustainability, scholarly interest in green skills has expanded rapidly across multiple disciplines. However, the growing body of literature remains fragmented, limiting a comprehensive understanding of its intellectual structure, thematic development, and future research directions. This study aims to systematically map the evolution of green skills and future workforce research through a bibliometric analysis of publications indexed in the Scopus database between 2015 and 2025. A total of 323 peer-reviewed publications were analyzed using Biblioshiny and VOSviewer to examine publication trends, influential sources, intellectual structures, thematic evolution, and emerging research themes. The findings reveal a substantial increase in research output, particularly after 2020, reflecting the growing strategic importance of green skills in sustainability transitions. Keyword co-occurrence analysis identifies five major research clusters related to sustainability competencies, employability, green jobs, vocational education, and Green Human Resource Management. The thematic analysis highlights the emergence of digitalization as a central research theme, indicating an increasing convergence between green and digital competencies within the context of the twin transition. The study contributes to the literature by providing a comprehensive overview of the field, identifying critical research gaps, and proposing an integrated future research agenda linking human capital development, organizational capability, digital transformation, and sustainable workforce competitiveness.

**Keywords:** green skills; future workforce; sustainability competencies; human capital; green human resource management; digital transformation; bibliometric analysis

## 1. Introduction

The urgency of transitioning toward a low-carbon economy has placed unprecedented pressure on labor markets, firms, and educational institutions to reconsider what workforce readiness actually means in practice (Suhud et al., 2026). As environmental regulation tightens and sustainability imperatives move from the margins to the center of economic policy, the question is no longer whether workers need green competencies, but how quickly and at what scale those competencies can be developed (Abrahamsson et al., 2025; Kizu et al., 2018; Kamarul Zaman et al., 2025). Green skills broadly understood as the knowledge, abilities, and dispositions that enable individuals and organizations to navigate environmental challenges without sacrificing productive output have consequently moved to the forefront of human capital discourse (Wegenberger & Ponocny, 2025). Yet despite growing consensus on their importance, the supply of adequately green-skilled workers

remains stubbornly misaligned with demonstrated demand, a gap that shows little sign of closing under present conditions.

This misalignment carries real theoretical weight. Within the human capital tradition, green skills function less as desirable attributes than as strategic investments whose returns extend across multiple levels of analysis: individual employability, organizational adaptability, and macroeconomic resilience (Ahmed et al., 2021). In this sense, green competencies occupy a role comparable to digital literacy during the earlier wave of technological transformation. They function less as useful additions to a worker's profile than as foundational enabling capabilities without which participation in an increasingly sustainability-oriented economy becomes structurally constrained (Fuchs, 2024; Ordóñez De Pablos & Anshari, 2023). The recognition of this has prompted sustained policy attention across governments, industries, and educational systems. What remains less clear is whether the research base informing these efforts is sufficiently coherent to guide them effectively.

A candid assessment of the scholarly landscape suggests it is not. Over the past decade, research on green skills has proliferated across sustainability education, labor economics, human resource management, workforce development, and environmental policy a breadth that reflects genuine multidisciplinary but has simultaneously produced fragmentation (Han et al., 2025; Damayanti et al., 2026). Studies examining sustainability competencies in higher education rarely engage with labor market evidence on what employers actually require. Labor economists mapping green job demand seldom draw on the pedagogical insights of education researchers (Bieliaieva & Bay, 2022). Green HRM scholars developing organizational frameworks operate largely in isolation from both. The result is a body of knowledge that is rich in parts but limited in its capacity to speak across disciplinary boundaries in ways that would make it most useful to policymakers and practitioners.

Education is increasingly recognized as a strategic mechanism for fostering sustainable development through the cultivation of competencies, values, and responsible behaviors (Iskandar et al., 2026). As environmental, economic, and social challenges become more complex, higher education institutions play a pivotal role in preparing future workforces with the capabilities required to support sustainable transitions. Within the Education for Sustainable Development (ESD) framework, universities are expected to equip learners with critical thinking, collaborative problem-solving, systems thinking, and sustainability-oriented competencies necessary for addressing contemporary societal and environmental issues (Ma et al., 2025). These competencies closely align with the emerging concept of green skills, which encompasses technical abilities for supporting green economies alongside broader sustainability values, environmental awareness, and responsible decision-making. Consequently, understanding the intellectual evolution, thematic structure, and future research directions of green skills has become increasingly important for scholars, policymakers, and educational institutions seeking to accelerate sustainable development agendas.

This fragmentation becomes particularly consequential in light of what has been termed the twin transition the simultaneous and increasingly intertwined advancement of environmental sustainability and digital transformation (Diodato et al., 2023). The workforce of the future will not navigate these transitions independently; the evidence suggests they are converging in ways that demand genuinely integrated competency profiles. Yet the scholarly communities best positioned to theorize this integration continue, in large part, to examine green and digital dimensions separately. As a result, fundamental questions remain inadequately addressed: How has green skills

research evolved over the past decade? Which intellectual communities shape the field's dominant assumptions, and how are they connected to one another? Where are the structural gaps most likely to constrain progress, and where are the most productive frontiers for future inquiry?

Existing review studies, while valuable, have not fully answered these questions. Most are confined to specific sectors, educational levels, or organizational contexts, yielding insights that are locally valid but difficult to generalize. What the field has lacked is a systematic, evidence-based examination of its own intellectual architecture one that can identify not just what has been studied, but how knowledge has accumulated, where it has stalled, and what a more integrated research agenda might look like.

This study addresses that need through a bibliometric analysis of green skills and future workforce research published between 2015 and 2025. Drawing on performance analysis and science mapping techniques, the study examines publication trends, source influence, contributor networks, intellectual structures, thematic evolution, and emerging research frontiers across a decade of scholarship. In doing so, it moves beyond descriptive mapping to offer a structural diagnosis of the field's current limitations and a substantive proposal for how they might be addressed.

The study makes four contributions to the literature. First, it provides the most comprehensive bibliometric portrait of green skills and future workforce research to date, establishing an empirical baseline for understanding how the field has developed. Second, it maps the field's intellectual structure through science mapping, revealing the thematic clusters and citation dynamics that organize scholarly activity and, critically, those that separate it. Third, it identifies the green-digital nexus as an emergent research frontier whose theoretical implications are only beginning to be worked out, despite their practical urgency. Fourth, drawing on these findings, it proposes an integrative conceptual roadmap to guide future research and inform policy development at the intersection of green skills, human capital theory, and sustainable workforce transformation. Prior bibliometric and scientometric reviews of green skills and sustainability competencies have generally treated the field as a single, undifferentiated body of literature (e.g., Montanari & Agostini, 2023). This study departs from that view: its central contribution is to demonstrate empirically that the field is instead composed of three structurally disconnected research communities, and to translate that structural diagnosis into a concrete, cross-community research agenda that prior reviews have not articulated.

## **2. Literature Review**

### **2.1. Conceptual Foundations and Definitional Evolution of Green Skills**

The concept of green skills has undergone considerable definitional evolution since its emergence in international policy discourse in the early 2000s, and that evolution has not converged a fact that is analytically consequential rather than merely inconvenient. The European Centre for the Development of Vocational Training (CEDEFOP, 2012) provided one of the most widely adopted early definitions. It characterized green skills as "the knowledge, abilities, values, and attitudes needed to live, work, and act in economies and societies seeking to reduce the impact of human activity on the environment." This formulation deliberately positioned green skills as broad-based, values-inclusive competencies extending beyond technical expertise a framing that reflects CEDEFOP's vocational education mandate and shaped the subsequent trajectory of sustainability education scholarship. A more occupationally specific definition, advanced in the labor economics tradition, frames green skills

as the competencies needed by the workforce in all sectors to adapt products, services, and processes to climate change requirements and environmental regulation (Ramírez-Montoya & García-Peñalvo, 2022). The ILO (2024) and World Bank (2024) adopt yet another framing, orienting the concept toward just transition and labor market equity, emphasizing that green skills must be accessible across occupational levels rather than concentrated in high-skill professional roles.

These three definitional variants reflect more than semantic preference: they embody competing institutional agendas that have actively shaped the disciplinary communities through which green skills scholarship has developed. A definition centered on values and attitudes naturally generates research questions about pedagogy, curriculum design, and educational transformation. A definition centered on occupational demand naturally generates research questions about labor market structure, wage premiums, and regulatory incentives. A definition centered on equity and transition naturally generates research questions about organizational HRM practices and workforce inclusion (Bouzerda et al., 2025). The consequence, as Fuchs (2024) observes, is that green skills risk becoming a concept whose apparent consensus conceals fundamental disagreements about what is being measured, who is responsible for developing it, and what counts as evidence of its presence or absence. This definitional fragmentation is not a preliminary problem to be resolved before the real scholarly work begins; it is the mechanism through which the tripartite fragmentation this study documents has been institutionally reproduced. The present study adopts an inclusive definition encompassing technical skills for green jobs, transversal sustainability competencies, and socio-emotional capabilities for managing environmental change consistent with CEDEFOP (2024) and the three-tiered typology of Albertz et al. (2025) precisely because an inclusive definition is the precondition for the cross-community dialogue that currently does not exist.

## **2.2. Theoretical Lenses: Human Capital Theory and the Resource-Based View**

Three theoretical frameworks provide the interpretive architecture of this study, selected not because they represent the field's existing theoretical consensus but because their combination addresses the levels of analysis at which the green skills challenge operates simultaneously: the individual worker, the organization, and the scholarly field itself.

Human Capital Theory (Becker, 1964) frames green skills as investments in human productivity: workers who acquire green competencies become more employable and more productive in transitioning economies, while organizations that invest in green training gain advantages in regulatory compliance, innovation, and talent acquisition (World Bank, 2024). This framework has been extensively applied in labor economics research on green jobs and occupational wage premiums, and it provides the foundational rationale for educational investment in green competency development. Its critical limitation, however, is the level at which it operates: HCT explains individual skill accumulation but offers no theoretical guidance on how organizations strategically identify which green skills to develop, how they acquire those skills through HRM practices, or how educational systems should calibrate their supply to match organizational demand. In treating green skills as undifferentiated human capital investments, HCT inadvertently licenses the supply-side bias that the sustainability education community has inherited producing competency frameworks without asking which competencies specific labor markets actually demand.

The Resource-Based View (Barney, 1991) addresses this limitation by shifting

the unit of analysis from the individual to the organization and from investment to strategy. The RBV argues that sustained competitive advantage derives from resources that are valuable, rare, inimitable, and non-substitutable (VRIN). In the context of a green transition where demand for green-skilled workers is growing at 260% against supply growth of 60% (Research and Markets, 2025), the rarity condition for green human capital is empirically satisfied: organizations that succeed in recruiting, developing, and retaining green-skilled workers hold an advantage that competitors cannot readily replicate. The RBV has been applied to examine how Green HRM practices generate competitive advantage through environmental performance (AlKetbi & Rice, 2024; Priyashantha & Dogra, 2026), but its potential contribution to understanding the systemic challenges of green skills development why specific competencies hold VRIN properties in some competitive contexts but not others, and how HRM practices can be designed to exploit those properties has been largely unrealized. This unrealized potential is not incidental: as this study's bibliometric analysis will demonstrate, the RBV's absence from the green skills citation network is itself a structural feature of the field's fragmentation.

Absorptive capacity theory (Cohen & Levinthal, 1990), originally developed to explain firms' ability to recognize, assimilate, and apply external knowledge, provides the third and most novel theoretical lens in this study. Applied at the level of scholarly communities rather than organizations, it offers a precise explanation for why three communities that are simultaneously addressing green skills remain structurally disconnected: each community lacks the prior knowledge base needed to recognize the value of what the others are producing. The sustainability education community's vocabulary of competencies, pedagogical transformation, and institutional change is structurally foreign to labor economists who speak in terms of wages, regulatory incentives, and occupational task distributions. The labor economics community's empirical methods regulatory exposure analysis, job posting analytics, earnings differentials are equally opaque to HRM scholars whose primary data are organizational surveys of behavioral outcomes. This mutual opacity is not a failure of individual scholars but a structural property of three communities whose foundational training, methodological repertoires, and publication venues have developed in isolation. The absorptive capacity framework predicts, and this study's network analysis confirms, that knowledge entering a field through a peripheral cluster will diffuse slowly to central clusters absent deliberate cross-community knowledge-sharing mechanisms the precise structural problem that motivates this study's three-bridge conceptual roadmap.

### **2.3. Sustainability Education and Green Competency Frameworks**

The first major trajectory of green skills scholarship is rooted in sustainability education and vocational training, and its intellectual dominance over the other two trajectories is a structural fact, not a bibliometric footnote, carrying consequences for what the field as a whole knows and does not know. This body of literature examines how formal educational institutions, particularly higher education institutions (HEIs) and Technical and Vocational Education and Training (TVET) systems, can embed green competencies into curriculum design, pedagogy, and assessment (Albertz et al., 2025; OECD, 2025). The foundational competency frameworks developed within this tradition including Wiek et al.'s (2011) systems thinking, anticipatory, normative, strategic, and interpersonal competency typology, and Rieckmann's (2018) UNESCO key competencies framework represent the most theoretically elaborated and widely cited dimension of green skills scholarship. Their sophistication is genuine: they address the complexity of sustainability challenges in ways that simpler technical

skill taxonomies cannot, and they have generated a productive research program on pedagogical implementation across diverse HEI contexts (Lozano et al., 2017, 2019).

The limitation of this trajectory, however, is not its internal quality but its structural insularity. The competency frameworks it has produced have been developed almost exclusively through dialogue within the sustainability education community calibrated against educational theories of transformative learning and values formation, validated through student and faculty surveys, and published in journals whose primary readership consists of sustainability education scholars. The result is a body of competency knowledge that is theoretically sophisticated within its own reference system but empirically disconnected from the labor market realities it is nominally designed to address. Albertz et al. (2025), in their systematic review of green VET research, document that the field has devoted substantial intellectual resources to developing what green competencies should look like while investing comparatively little in understanding what green competency profiles employers actually require and less still in tracking whether graduates of sustainability education programs achieve better employment outcomes in green occupations than graduates of conventional programs. This is not a minor empirical gap. It is a structural blind spot produced by the community's orientation toward educational process rather than workforce outcome. As a result, the field's most developed theoretical contribution, the sustainability competency framework tradition, lacks the empirical grounding in labor market evidence that would establish its practical relevance beyond the educational institutions where it was produced.

## **2.4 Green Labor Economics: Skill Demand, Green Jobs, and the Labor Market Transition**

The second trajectory, embedded in labor economics, approaches green skills from the demand side of the equation that the education community has systematically underexamined. This literature documents the structural transformation of labor markets driven by environmental regulation, technological change, and the green transition: the emergence of green job categories, the geographic concentration of green employment in specific sectors and regions, and the growing empirical evidence of a premium in wages, job quality, and employment stability associated with green occupational profiles (ILO, 2024; Kozar & Sulich, 2023). Vona et al.'s (2018) foundational study the first systematic empirical identification of green skills using labor market data, treating environmental regulation as an exogenous shock and mapping its occupational demand effects established the methodological standard for demand-side green skills research and demonstrated that green skill premiums are real, sectorally concentrated, and responsive to regulatory incentives. This contribution represents precisely what the sustainability education community's competency frameworks lack: external validation that the skills being defined and taught correspond to skills that labor markets reward.

The trajectory's consequential limitation is different in character from that of the education community. Where sustainability education scholars overlook the demand side, labor economists overlook the supply side and the organizational dimension. The labor economics literature treats green skill supply largely as an exogenous parameter something that appears, or fails to appear, in the labor market as a function of prior educational investment without engaging with the pedagogical and institutional mechanisms through which educational systems could be redesigned to increase that supply more rapidly or more efficiently. More consequentially for this study, the ILO (2024) has recently documented the green-digital nexus: the co-occurrence

of environmental and digital competency demands in the labor market, creating a profile of "green-digital" workers that current training systems are not designed to produce. This development has entered labor economics discourse without generating corresponding engagement from either the sustainability education community, which would need to redesign its curricula, or the Green HRM community, which would need to redesign its recruitment and training practices. The labor economics community is, in this respect, producing knowledge about a problem that the two communities best positioned to respond to it are not reading.

## **2.5 Green HRM: Organizational Management of Green Competencies**

The third trajectory, situated within human resource management, addresses the organizational dimension of green skills development that both the education and labor economics communities have systematically neglected: how organizations recruit, develop, motivate, and retain workers who contribute to environmental performance through their workplace behavior and competencies. Green HRM encompassing green recruitment and selection, green training and development, green performance management, green compensation, and green employee involvement (Teixeira et al., 2024) has grown rapidly as a research field since 2019, generating a substantial body of empirical evidence that specific HR practice configurations are associated with improved organizational environmental performance (AlKetbi & Rice, 2024; Anwar et al., 2020). This growth has been concentrated in Asian economies, particularly China, Malaysia, and Pakistan a geographic pattern that reflects both the regulatory pressures on manufacturing sectors in these economies and the strategic importance of green HRM for export competitiveness in environmentally regulated markets.

The critical limitation of the Green HRM trajectory is its behavioral orientation at the expense of a competency and capability orientation. The dominant paradigm in this literature treats green HRM as a set of practices that elicit environmentally responsible behavior from existing workers through incentive alignment, norm signaling, and organizational culture rather than as a strategic framework for identifying, acquiring, and developing the specific green competencies that organizations need to navigate the green transition. This behavioral focus has produced a literature rich in mediator and moderator analyses but thin in its engagement with the foundational question of what green competencies organizations actually need, where those competencies come from, and how HR practices can be designed to develop them systematically rather than merely incentivize their expression in existing behavior. Priyashantha and Dogra (2026) document this limitation explicitly, noting that Green HRM research has been extensively critiqued for its emphasis on behavioral compliance at the expense of strategic human capital development. The consequence is that Green HRM scholarship and green skills scholarship, which should be complementary, have developed as parallel literatures with minimal citation overlap. Green HRM researchers know how to manage environmental behavior but have not engaged with the question of what green competencies should be managed. Green skills researchers, in turn, know what competencies to develop but have not engaged with the organizational practices through which those competencies are deployed and leveraged.

## **2.6 The Structural Gap: Three Communities, One Fragmented Field**

The three trajectories reviewed in Sections 2.3 through 2.5 share a common subject the development, distribution, and deployment of green workforce capability but do not share a common literature. The sustainability education community cites Lozano, Rieckmann, and Wiek; the labor economics community cites Vona, ILO

reports, and regulatory economics; the Green HRM community cites Anwar, Teixeira, and organizational behavior studies. These citation networks go beyond differing emphases within a shared conversation; they constitute structurally disconnected communities that have developed incommensurable conceptual vocabularies, incompatible methodological traditions, and non-overlapping publication venues. The result is a field that is simultaneously over-developed in its internal sub-communities and under-developed in its integrative capacity a field that can explain how competencies should be taught, or how skill demand is distributed in labor markets, or how organizations incentivize environmental behavior, but cannot yet explain how these three dimensions of the green skills challenge relate to each other.

This structural gap has been observed qualitatively by individual scholars Fuchs (2024) warns of disciplinary siloing; Mustapha et al. (2025) identify fragmented scholarly engagement as a barrier to effective green skills investment in developing economies but qualitative observation is insufficient to establish the gap's extent, its structural properties, or its temporal trajectory. Establishing whether the three communities are becoming more or less connected over time, which specific knowledge clusters are most isolated from each other, and where in the field's network the most consequential disconnections lie requires the empirical, reproducible methods of bibliometric science mapping. This is the methodological contribution of the present study, which translates qualitative observation into quantitative structural diagnosis. The study is guided by two research questions: (RQ1) What are the intellectual structure, publication landscape, and thematic evolution of green skills and future workforce research between 2015 and 2025? (RQ2) What structural gaps and disciplinary silos characterize this field, and what integrative research agenda particularly concerning the green-digital nexus and underrepresented developing country contexts would advance a more coherent understanding of green skills development across education, labor market, and organizational dimensions?

### **3. Materials and Method**

#### **3.1. Research Design**

This study employs bibliometric analysis as its primary methodological approach, combining quantitative performance analysis with science mapping to examine the intellectual structure and thematic evolution of green skills and future workforce research. Bibliometric analysis is recognized as a rigorous and systematic method for mapping scientific fields, revealing citation patterns, intellectual networks, and thematic trajectories that would be difficult to identify through traditional narrative reviews (Donthu et al., 2021; Marlina et al., 2026; Zupic & Čater, 2015). The methodological approach aligns with the established workflow for bibliometric research in management and organizational studies (Zupic & Čater, 2015; Donthu et al., 2021) and adheres to the PRISMA 2020 framework for transparency and reproducibility (Page et al., 2021). The study integrates two complementary analytical orientations: performance analysis examines the productivity and impact of authors, journals, institutions, and countries; science mapping employs network analysis and cluster detection to reveal the intellectual architecture of the field (Aria & Cuccurullo, 2017).

#### **3.2. Database Selection and Rationale**

The Scopus database (Elsevier) was selected as the sole data source. Scopus offers broad disciplinary coverage, standardized indexing, and robust citation tracking across the social sciences, management, education, and environmental studies the primary disciplines encompassing green skills research (Martín-Martín et al., 2018).

Scopus indexes a larger number of journals than the Web of Science Core Collection in the social science and management domains relevant to this study, making it the more appropriate choice for capturing the full breadth of green skills scholarship (Donthu et al., 2021). The use of a single database represents a methodological limitation that is acknowledged in Section 6.4.

### 3.3. Search Strategy

A structured Boolean search string was applied to the Title, Abstract, and Keywords (TITLE-ABS-KEY) fields in Scopus. The search was executed on 4 June 2026. The complete search string is as follows:

( TITLE-ABS-KEY( “green skill\*” OR “green competenc\*” OR “environmental skill\*” ) AND TITLE-ABS-KEY( “workforce” OR “future of work” OR “labor market” OR “human capital” ) ) OR ( TITLE-ABS-KEY( “green skill\*” OR “green competenc\*” OR “sustainability competenc\*” OR “eco-competenc\*” ) AND TITLE-ABS-KEY( “workforce development” OR “future workforce” OR “employability” OR “vocational education” OR “TVET” OR “higher education” ) ) AND DOCTYPE( ar OR re ) AND PUBYEAR > 2014 AND NOT TITLE-ABS-KEY( “greenwashing” OR “green chemistry” OR “green building” )

The NOT operator excluded greenwashing, green chemistry, and green building topics that share keyword overlap with green skills but address distinct phenomena. The temporal boundary was set at 2015, corresponding to the adoption of the UN SDGs, which catalyzed the global institutionalization of green skills discourse (ILO, 2024). Search results were restricted to peer-reviewed journal articles and review articles to ensure methodological rigor.

### 3.4. Screening and Selection: PRISMA 2020 Criteria

Article selection followed the four-phase PRISMA 2020 protocol Identification, Screening, Eligibility, and Inclusion (Page et al., 2021). The initial Scopus search yielded 323 documents. **Table 1** presents the complete inclusion and exclusion criteria applied across each phase.

**Table 1.** PRISMA 2020 Inclusion and Exclusion Criteria

| Criterion                      | Inclusion                                                                                                                                                                                                                              | Exclusion                                                                                                                                |
|--------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Document type</b>           | Peer-reviewed journal articles; review articles                                                                                                                                                                                        | Conference papers; book chapters; editorials; letters; erratum; notes                                                                    |
| <b>Language</b>                | English-language publications                                                                                                                                                                                                          | Non-English publications                                                                                                                 |
| <b>Publication period</b>      | 2015–2025 (post-SDG adoption)                                                                                                                                                                                                          | Publications prior to 2015                                                                                                               |
| <b>Database indexing</b>       | Scopus-indexed peer-reviewed journals                                                                                                                                                                                                  | Non-indexed or predatory journals                                                                                                        |
| <b>Topical relevance</b>       | Studies explicitly addressing green skills, green competencies, sustainability competencies, or eco-competencies in relation to workforce, labor market, employability, vocational education, TVET, higher education, or human capital | Studies tangentially mentioning environmental terms without substantive focus on green skills or workforce dimensions                    |
| <b>Conceptual scope</b>        | Research on green skills production (education), absorption (labor market), or management (HRM/organizational)                                                                                                                         | Studies primarily focused on greenwashing, green chemistry, green building, environmental engineering, or ecological/biological sciences |
| <b>Full-text accessibility</b> | Articles with accessible full text or at minimum accessible abstract and metadata                                                                                                                                                      | Articles for which neither full text nor metadata was retrievable                                                                        |

Phase 1 (Identification): The initial Scopus search returned 323 documents. Duplicates were removed via Scopus's internal deduplication function supplemented by manual review. Phase 2 (Screening): Records were screened at the title and abstract level against the inclusion criteria. Articles classified as "uncertain" were advanced to eligibility assessment. Phase 3 (Eligibility): Full texts were reviewed for uncertain cases. Articles engaging with green skills only peripherally were excluded. Phase 4 (Inclusion): Articles satisfying all inclusion criteria were retained. The final dataset comprises  $n = 323$  articles. The complete PRISMA flow diagram documenting the number of articles included and excluded at each phase, along with reasons for exclusion, is presented in Figure 1. At Phase 2 (Screening), title and abstract review of the 362 deduplicated records resulted in the exclusion of 25 records that were tangential to green skills or workforce dimensions (e.g., greenwashing, green chemistry, green building, or otherwise off-scope), leaving 337 records advanced to eligibility. Of these, 281 records were directly included, while the remaining 56 records were classified as uncertain and forwarded for full-text assessment. At Phase 3 (Eligibility), full-text review of these 56 records led to the exclusion of a further 14 records (4 non-English, 9 with only peripheral mention of green skills constructs, and 1 predatory/unindexed source), confirming 42 records as eligible. Phase 4 (Inclusion) therefore yielded a final analytic sample combining the 281 directly included records with the 42 confirmed-eligible records, totaling  $n = 323$  articles, with the complete exclusion counts and reasons documented in Figure 1.

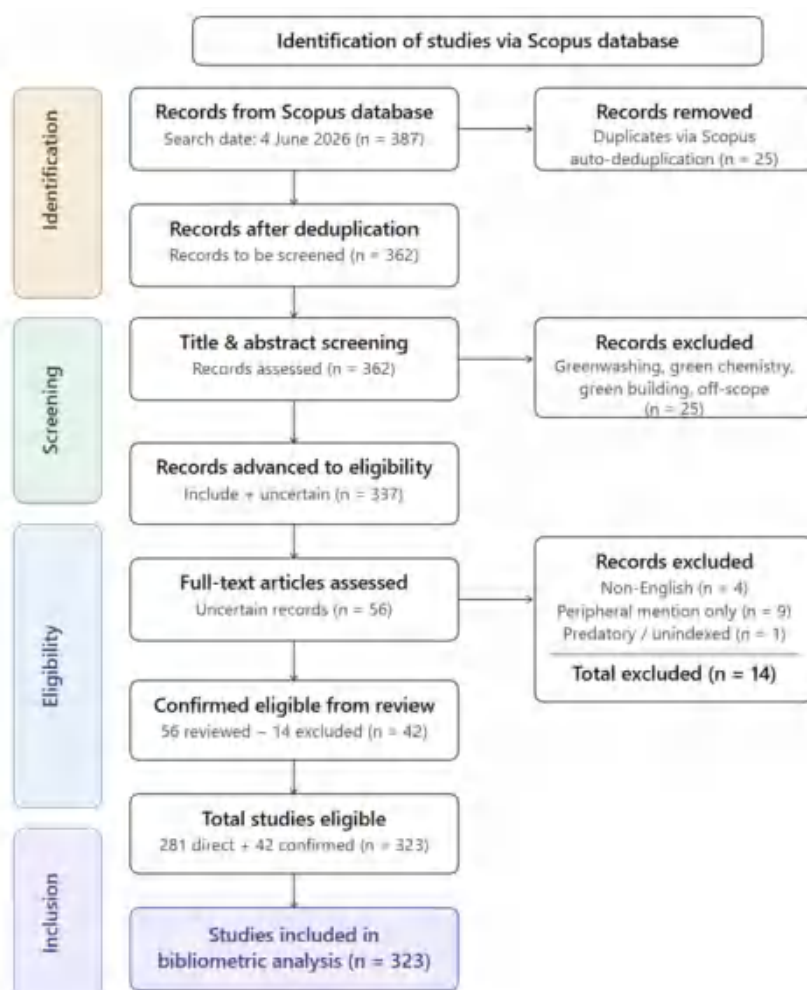


**Figure 1.** PRISMA 2020 flow diagram.

### 3.5. Keyword Normalization

A systematic keyword normalization procedure was applied to the author keyword field (DE) to address terminological fragmentation. Morphological synonyms were merged using a custom thesaurus file loaded into VOSviewer: “green skill” → “green skills”; “labour market” → “labor market”; “green competencies” → “green competency”; “sustainability competences” → “sustainability competency”; “education for sustainable development” → “ESD”; “green human resource management” → “Green HRM.” Non-substantive terms (“article,” “study,” “review,” “analysis”) were removed from the keyword field. This normalization procedure is reported transparently in accordance with PRISMA 2020 standards (Gazi, 2026).

### 3.6. Analytical Tools and Procedures

Two complementary bibliometric software tools were employed. Biblioshiny (the web-based interface of the bibliometrix R package; Aria & Cuccurullo, 2017) was used for performance analysis and thematic mapping, generating: annual scientific production trends; most globally and locally cited documents; most productive authors, journals, and countries; thematic maps based on Callon’s centrality-density framework; and diachronic keyword evolution visualizations. VOSviewer (van Eck & Waltman, 2010) was used for keyword co-occurrence network analysis and temporal overlay visualization. Co-occurrence networks were constructed with a minimum keyword co-occurrence threshold of three appearances and association strength normalization. Clustering was performed using VOSviewer’s modularity-based algorithm.

## 4. Results and discussion

### 4.1. Growth of Green Skills Research

The annual scientific production analysis (**Figure 2**) demonstrates a substantial increase in scholarly interest in green skills and future workforce research between 2015 and 2025. During the early period, publication activity remained relatively limited, indicating that green skills had not yet emerged as a major research domain. However, a consistent upward trend became visible after 2018, followed by a significant acceleration between 2023 and 2025.

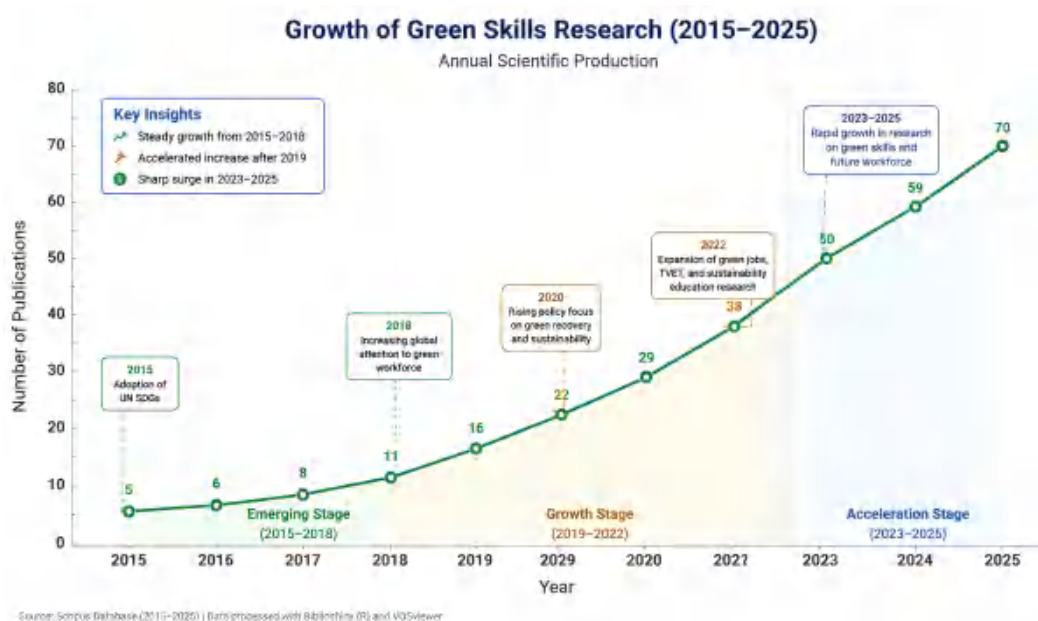


**Figure 2.** Growth of Green Skills Research

The sharp increase in publication output reflects growing global concerns regarding workforce readiness for sustainability transitions. As governments and industries intensify their commitments to climate action, carbon reduction, and sustainable development, the demand for workers equipped with green competencies has increased substantially. Consequently, researchers have begun to pay greater attention to understanding how education systems, labor markets, and organizations can support the development of green capabilities.

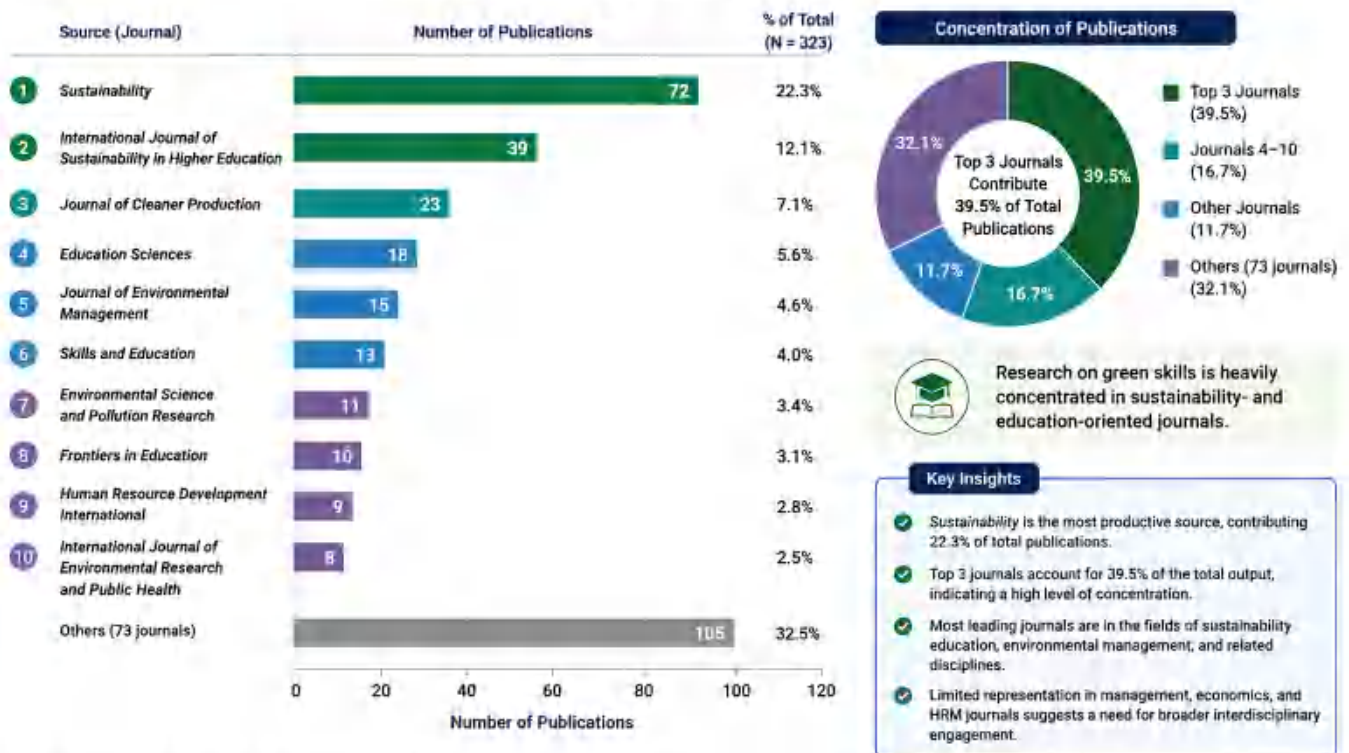
From a human capital perspective, this trend suggests that green skills are increasingly recognized as strategic assets for future workforce competitiveness. The expansion of the literature indicates a growing consensus that workforce sustainability is not solely an environmental issue but also a human resource and economic development challenge. Nevertheless, the relatively recent growth of the field suggests that its theoretical foundations are still evolving, creating opportunities for future conceptual and empirical development.

#### 4.2. Dominant Publication Sources and Knowledge Concentration

The analysis of publication sources (Figure 3) reveals that research on green skills is heavily concentrated within sustainability-oriented journals. Sustainability and the International Journal of Sustainability in Higher Education contribute a substantial proportion of the total publications, significantly exceeding other journals in the field.

### Dominant Publication Sources and Knowledge Concentration

Distribution of Publications by Source (2015–2025)



Source: Scopus Database (2015–2025) | Data processed with Biblioshiny (R)

Figure 3. Dominant Publication Sources

This concentration highlights the dominant role of sustainability education in shaping the development of green skills scholarship. Most published studies focus

on competency development, curriculum design, sustainability education, and vocational training. While these contributions have advanced understanding of green competencies, they have also resulted in a relatively narrow disciplinary focus.

The dominance of educational journals suggests that green skills continue to be viewed primarily as an educational challenge rather than an integrated workforce development issue. Comparatively fewer studies are published in labor economics, strategic management, or human resource management journals. This imbalance indicates that important dimensions of green skills development, such as organizational capability building, talent management, and workforce competitiveness, remain underexplored.

The findings therefore suggest the need for greater interdisciplinary engagement that connects educational perspectives with labor market and organizational perspectives. Such integration would contribute to a more comprehensive understanding of how green skills are developed, deployed, and sustained across different institutional contexts.

#### **4.3. International Collaboration Patterns**

International collaboration (**Figure 4**) offers a complementary lens on the field's fragmentation, distinct from the thematic clustering. Biblioshiny's country-level analysis shows corresponding authors concentrated in a small set of countries, Spain, the United States, and Indonesia lead, followed by Malaysia, Finland, the United Kingdom, Sweden, and Germany, with the large majority of publications classified as Single Country Publications (SCP) rather than Multiple Country Publications (MCP). This SCP-dominant pattern indicates that green skills research is produced mainly through domestic rather than cross-border collaboration, a structural feature that plausibly reinforces the disciplinary and geographic fragmentation this study documents elsewhere: researchers working within a single national context are less likely to encounter, cite, and build on scholarship from the other communities and regions identified in this analysis. Expanding cross-country collaboration, particularly between the sustainability-education-heavy countries in this list and the labor-economics- and Green-HRM-oriented scholarship concentrated elsewhere, represents a concrete mechanism through which the field's structural gaps might narrow over time.

#### **4.4. Intellectual Structure of Green Skills Research**

The keyword co-occurrence network (**Figure 5**) reveals the intellectual structure of the field and identifies several major research clusters. The largest cluster focuses on green skills, employability, labor market transformation, green jobs, and workforce development. A second cluster centers on sustainability competencies, higher education, and vocational education. Additional clusters are associated with Green Human Resource Management, leadership, organizational sustainability, and environmental management. To move beyond a purely descriptive account of these clusters, the keyword co-occurrence network (1,245 keywords meeting a minimum occurrence threshold of 5) was further examined to characterize connectivity across the five identified clusters: green skills and labor market transformation, sustainability competencies in education, green human resource management, environmental management and sustainability, and vocational training and industry integration. This analysis shows that link strength remains strong within each cluster, particularly among the education, labor-market, and organizational (Green HRM) clusters, whereas inter-cluster link strength remains comparatively limited, indicating

only partial interconnection across the network. This pattern of strong intra-cluster cohesion coupled with weak inter-cluster integration, especially along the education-labor market-organization pipeline, is consistent with the disciplinary fragmentation documented throughout this study.

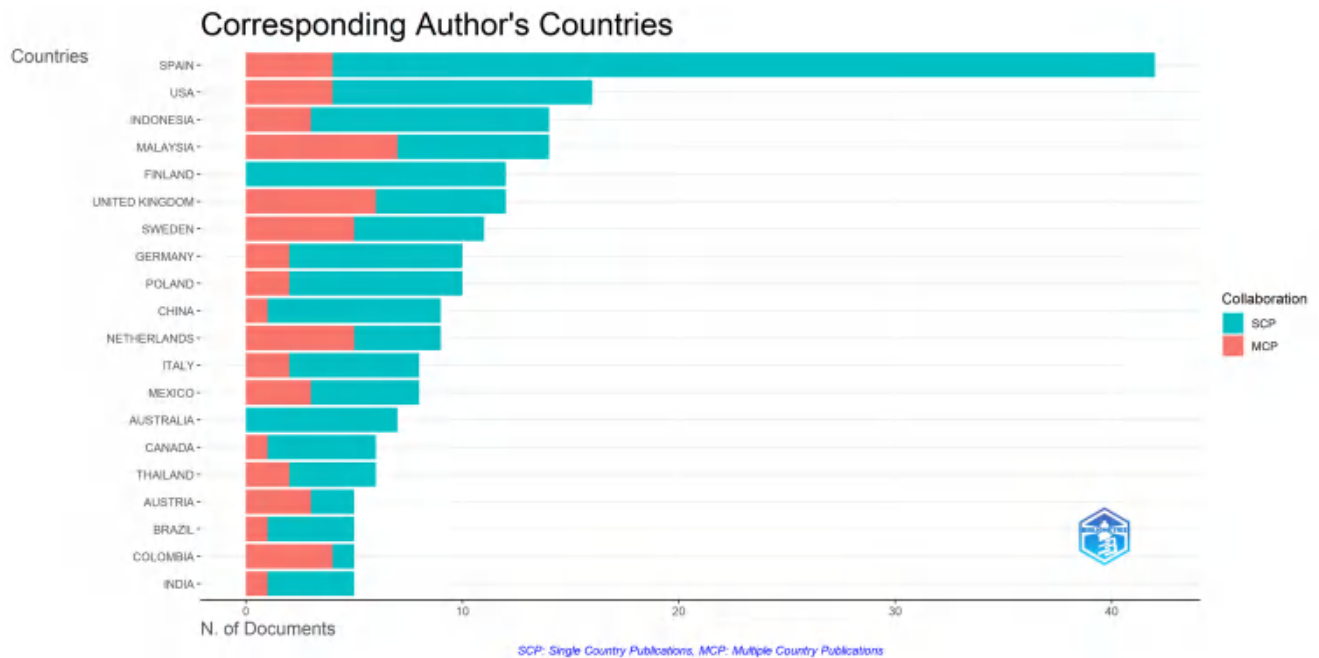


Figure 4. Corresponding Author's Countries and Collaboration Type

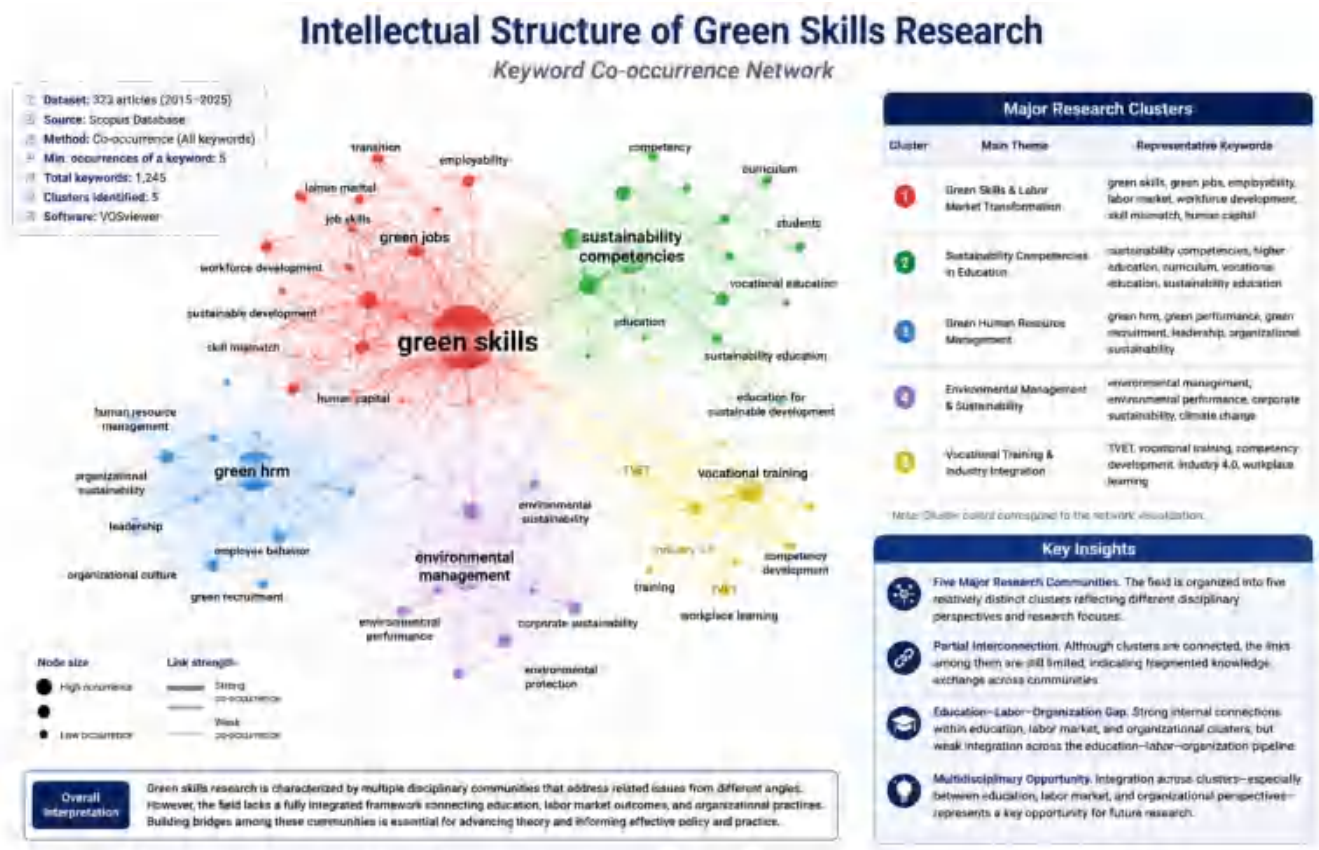


Figure 5. Intellectual Structure of Green Skills Research

The network structure indicates that green skills research is characterized by the coexistence of multiple disciplinary communities. Although these communities address related issues, they remain only partially connected. Educational researchers primarily focus on competency development and curriculum innovation, whereas labor market scholars emphasize employability and workforce transformation. Meanwhile, organizational researchers concentrate on Green HRM practices and sustainability-oriented management strategies.

This fragmented structure suggests that knowledge exchange across disciplinary boundaries remains limited. As a result, the field lacks an integrated framework capable of explaining how green competencies are developed through education, translated into labor market outcomes, and leveraged by organizations to achieve sustainable performance.

The findings support the argument that green skills should be conceptualized as a broader workforce capability that connects education systems, labor market dynamics, and organizational development. Such an integrated perspective may provide a stronger foundation for future research and policy interventions.

#### 4.5. Emerging Themes and Future Research Directions

The thematic map (Figure 6) provides insights into the maturity and strategic importance of different research themes. Sustainability competencies, digitalization, green skills, vocational education, and green jobs emerge as the most influential themes within the field. These themes demonstrate both high centrality and strong internal development, indicating their strategic role in shaping future research.



Figure 6. Emerging Themes and Future Research Directions

Particularly noteworthy is the emergence of digitalization as a central theme. The findings suggest that green skills development can no longer be examined independently from digital transformation. The increasing convergence of environmental and digital competencies reflects the broader phenomenon of the twin transition, where sustainability and digitalization jointly shape workforce requirements.

At the same time, themes related to innovation, organizational capability, and strategic workforce development appear less developed despite their growing practical importance. This finding highlights a significant research opportunity for management and human resource scholars. Future studies should investigate how organizations build green workforce capabilities, how digital and green competencies interact, and how these capabilities contribute to organizational performance and sustainable competitiveness.

Overall, the thematic analysis indicates that the future evolution of the field will likely move beyond traditional educational perspectives toward a more integrated understanding of human capital development, organizational capability, and sustainable workforce transformation. This shift is essential for addressing the complex challenges associated with the global green transition and the future of work.

## **5. Discussion**

The growth trajectory documented here raises a question that aggregate publication counts cannot answer alone: has the field grown wiser, or merely larger? The acceleration after 2020 reflects real external pressure, governments committing to net-zero targets, labor markets documenting green skill shortages, organizations confronting sustainability transitions in practice. Green skills have clearly moved from a niche academic concern to a strategic priority for policymakers and employers. What remains less certain is whether the scholarship keeping pace with that demand is integrated enough to actually guide it. The evidence here counsels caution, and that caution is where the more interesting analysis begins.

The concentration of publications in sustainability and education journals is a structural diagnosis, not just a bibliometric detail. When a field's dominant outlets are education-oriented, its questions, methods, and vocabulary follow that community's priorities. The result is a literature that explains how green competencies are defined, taught, and assessed, but says far less about what matters beyond the classroom: whether competencies translate into labor market advantage, how organizations absorb them, and what turns green skills into a source of value rather than a compliance checkbox. Montanari and Agostini (2023) observed a similar imbalance. The present findings confirm and extend that pattern, suggesting the imbalance is structural rather than incidental.

The keyword co-occurrence analysis sharpens this diagnosis. Clusters organized around sustainability competencies, employability, green jobs, vocational education, and Green HRM remain largely isolated from one another, evidence of disciplinary disconnection, not just diversity. A worker moves from training into a green job and then into an organization managing sustainability sequentially, traversing all of these domains. The scholarship addressing each stage, however, has developed with little reference to the others, leaving a fragmented map of what is, in practice, a continuous journey. The absence of frameworks linking education to labor market outcomes to organizational capability is therefore a gap between the literature and the reality it aims to explain, a point consistent with Montanari and Agostini's (2023) account of

conceptual fragmentation, though the present analysis suggests the fragmentation runs deeper than previously captured.

Against this backdrop, digitalization's emergence as a prominent theme is significant less because digital competencies are growing in importance, which is already well understood, and more because of what their co-emergence with green skills implies for how workforce capability should be theorized. Cardinali and De Giovanni (2022) argued that digitalization and sustainability are complementary capabilities rather than parallel tracks; Tsironis (2023) similarly expects labor markets to reward workers who integrate both. The present findings extend this: green and digital themes co-occurring in the most recent literature signal that frameworks built when the two were studied separately may no longer fit the challenges organizations face. Building integrated competency frameworks that capture this interaction is accordingly one of the field's most pressing theoretical tasks.

The growing prominence of Green HRM reflects a related recognition: green competencies do not translate into organizational outcomes automatically but require active management. Evidence that GHRM practices, green recruitment, training, performance management, employee involvement, are associated with green innovation and environmental performance establishes this link empirically (Jamil et al., 2023; Zihan et al., 2024). Less examined is the systemic dimension: how these practices function as an integrated system rather than independent levers, and under what conditions that system produces durable advantage rather than incremental improvement. More concretely, these practices map onto core HRM concerns, talent management, reskilling, leadership development, recruitment. Firms that treat green competencies as a talent-management priority, rather than a compliance requirement, are better positioned to build the reskilling pipelines and leadership capacity the transition demands.

The theoretical gap deserves direct treatment. Human Capital Theory supplies an indispensable foundation: it explains why green competencies matter as investments, at both individual and macroeconomic levels, and links skill development to productivity and employability. But its unit of analysis is the individual worker, while the field's more pressing questions are organizational and strategic. How do firms identify which green competencies are genuinely rare and inimitable in their competitive context? How do they build the absorptive capacity to recognize green skill demand before labor market signals make it obvious? How do they reconfigure workforce capabilities as sustainability requirements evolve? Human Capital Theory was not designed to answer these questions. Dynamic Capability Theory (Teece et al., 1997) and the Resource-Based View (Barney, 1991) offer conceptual purchase on exactly this territory, sensing, seizing, and reconfiguring capability under competitive pressure, yet their integration into green skills research remains aspirational rather than actual. The education-heavy literature documented here is, in part, a consequence of this gap: without frameworks that foreground organizational capability and competitive dynamics, the field gravitates naturally toward the questions those frameworks are best equipped to address.

Taken together, the findings suggest green skills research is undergoing a slow transition, away from a discourse about what competencies exist and how they are taught, toward a more strategic conversation about how they create value, for whom, and in combination with what other capabilities. This transition is incomplete, and the structural features documented here, fragmentation, theoretical imbalance, the underrepresentation of organizational and labor market perspectives, explain why.

Translating the field's growing volume into cumulative, policy-relevant knowledge will take deliberate effort to cross these boundaries rather than simply adding more work within them. The priority areas that follow from this analysis are structural prerequisites, not optional suggestions, for a field capable of answering the questions the green transition is already asking of it.

## **6. Conclusion**

This study set out to map a field that has grown faster than it has consolidated. Analyzing a decade of green skills and future workforce research through bibliometric methods, the findings reveal a scholarly community that has expanded substantially in response to real-world urgency the acceleration of sustainability transitions, the deepening of climate commitments, and the structural transformation of labor markets but has not yet developed the intellectual coherence that its practical importance demands. Green skills have unquestionably moved from the margins to the mainstream of workforce research. What remains unresolved is whether that growth has produced cumulative knowledge or merely accumulated volume.

The intellectual structure of the field tells a story of productive fragmentation. Research communities organized around sustainability competencies, green jobs, vocational education, employability, and Green HRM have each generated substantive insights within their own boundaries. Yet the boundaries themselves are the problem. The education community rarely speaks to the labor economics community; the HRM literature rarely engages with either. The result is a field that knows a great deal about individual pieces of the green workforce puzzle how competencies are taught, how green jobs are distributed, how HR practices shape environmental behavior but comparatively little about how those pieces connect in practice. For workers, firms, and policymakers navigating an actual transition, this disconnection carries a real cost: it constrains the quality of guidance the research can offer.

Two substantive findings deserve particular emphasis. The first concerns digitalization. The emergence of digital transformation as an increasingly prominent theme within green skills scholarship is not incidental it reflects a structural shift in how sustainability and technological change are co-evolving in labor markets and organizations. Future workforce capability will not be a simple sum of green competencies and digital skills developed separately; it will require their genuine integration, and the theoretical frameworks available to explain that integration remain underdeveloped. The second concerns theory. Human Capital Theory has provided a useful starting point for understanding why green skills matter as investments, but it was never designed to explain how organizations build, deploy, and renew collective green capabilities under competitive pressure. Dynamic Capability Theory, the Resource-Based View, and organizational capability perspectives each offer conceptual resources that the field has drawn on only partially. Their more systematic incorporation is not a matter of theoretical decoration it is a precondition for research that can explain competitive outcomes, not just describe competency profiles.

What this study offers, ultimately, is not just a map of where the field has been but a diagnosis of what it needs to become. The publication landscape, intellectual clusters, thematic evolution, and emerging frontiers documented here point toward a research agenda that is more integrative, more theoretically ambitious, and more attentive to the organizational and labor market contexts in which green skills actually matter. Whether that agenda takes hold will depend on whether researchers, educators, and policymakers choose to read across the disciplinary lines that currently

divide them.

From a practical standpoint, the structural gaps identified above translate into concrete implications for HR practice. Organizations seeking to build durable green workforce capability need to treat green competencies as a criterion embedded across the HR value chain rather than as a stand-alone training topic: incorporating green-competency criteria into recruitment and selection, building reskilling and upskilling pathways into ongoing training and development, reflecting green performance explicitly in performance evaluation systems, considering green capability in succession planning for leadership roles, and aligning strategic workforce planning with anticipated shifts in green-digital skill demand. Absent such integration, green skills risk remaining a peripheral HR initiative rather than becoming a source of sustained competitive advantage.

**Theoretical contributions.** This study contributes to theory in two respects. First, it extends Human Capital Theory by showing empirically where its explanatory reach ends: HCT accounts for why individuals and firms invest in green competencies, but it cannot explain how organizations identify, configure, and renew those competencies strategically. Second, by demonstrating the citation-network absence of the Resource-Based View and Dynamic Capability Theory in the green skills literature, this study provides an empirical basis for the theoretical integration it recommends, rather than treating that integration as a matter of assertion.

**Managerial implications.** For practitioners, the findings indicate that green skills should be managed as an integrated capability-building system rather than as isolated training or compliance initiatives. Firms are encouraged to embed green-competency criteria across recruitment, training, performance management, and succession planning, and to invest in the organizational absorptive capacity needed to translate emerging green-digital competency demands into workforce planning decisions ahead of, rather than in reaction to, labor market signals.

### **Future Research Directions**

The structural gaps identified in this study translate into six priority directions for future research. The most pressing concerns the link between education and labor market outcomes. Longitudinal designs that follow individuals from formal training through employment transitions are needed to establish whether green skills developed in higher education and TVET actually translate into improved employability, career progression, and wage outcomes, questions the field has so far left largely unanswered.

A second direction concerns how organizations convert individual green competencies into collective capability. Research that follows these competencies into organizational contexts, examining how workforce planning, knowledge management, and team dynamics shape their deployment, would extend the field beyond its current focus on what workers know toward how organizations put that knowledge to use.

Third, Green HRM deserves treatment as an integrated strategic system rather than a collection of separate practices. Studies examining how green recruitment, training, leadership development, and performance management interact to build sustainability capability would help close the gap between HR scholarship and the broader green skills literature.

Fourth, the green-digital nexus remains underdeveloped as a theoretical object. Because emerging competency demands are neither purely green nor purely digital but hybrid, frameworks that model how environmental and technological competencies jointly shape employability, innovation, and organizational resilience

are needed, and these cannot be built through incremental single-domain studies alone.

Fifth, Dynamic Capability Theory offers a lens the field has cited more often than applied. Reframing green competencies as something organizations must continuously sense, develop, and reconfigure, instead of acquiring once and deploying indefinitely, would better capture how workforces adapt as sustainability requirements shift over time.

Finally, closing these gaps will require research infrastructure, not just research questions: journals, conferences, and theoretical traditions that connect education, labor market, and organizational scholarship by design. The fragmentation documented in this study is institutional as much as conceptual, and addressing it will require academic incentive structures that currently do little to reward cross-community collaboration.

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