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From Safety to Sustainability: A Bibliometric Perspective on Technological Transformation in Agricultural Systems

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Abstract

Agricultural systems are undergoing rapid transformation driven by technological innovation, environmental pressures, and increasing demands for sustainable production. However, the integration of worker safety within sustainability-oriented agricultural transitions remains insufficiently understood. This study aims to systematically map the scientific landscape of research related to occupational health and safety, technological innovation, and environmental sustainability in agricultural and agroindustrial systems using a bibliometric approach. Bibliographic data were collected from the Scopus database, resulting in 98 peer-reviewed articles published between 1981 and 2026. Bibliometric and network analyses were conducted using VOSviewer and Biblioshiny to identify publication trends, influential contributors, collaborative structures, thematic evolution, and emerging research directions. The findings reveal a substantial increase in research activity after 2016, reflecting growing scientific attention toward integrating worker protection with sustainable agricultural transformation. The field's intellectual structure is dominated by interconnected themes, including risk assessment, ergonomics, climate-related exposure, mechanization, digital agriculture, artificial intelligence, wearable technologies, and environmental management. Thematic evolution analysis indicates a shift from conventional safety concerns to technology-driven, predictive approaches to agricultural risk management. The study also demonstrates that technological advancement simultaneously creates opportunities for improved efficiency and environmental monitoring while introducing new occupational risks and governance challenges. Although research productivity remains concentrated in developed economies, global collaboration is gradually expanding. Overall, the study highlights that future agricultural sustainability depends not only on environmental and technological performance but also on the creation of safe, inclusive, and socially resilient working systems.

Keywords: Precision governance, Climate resilience, Smart farming, Socio-technical systems, Labor vulnerability.

1 | Introduction

Agriculture and agroindustrial activities remain fundamental to global economic development, food production, and rural livelihoods [1], [2]. However, the rapid intensification of agricultural systems has also

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generated substantial environmental and occupational challenges worldwide. The agricultural sector accounts for nearly 70% of global freshwater withdrawals and contributes significantly to greenhouse gas emissions, environmental degradation, biodiversity loss, and resource depletion [3], [4]. At the same time, agriculture continues to be recognized as one of the most hazardous occupational sectors globally, with workers frequently exposed to machinery-related accidents, pesticide poisoning, ergonomic stress, heat exposure, and unsafe working environments [5–7]. These conditions have intensified global concerns regarding the sustainability of agricultural production systems and the long-term balance between economic productivity, environmental protection, and worker well-being.

In response to these challenges, innovation and technological advancement have become increasingly central to sustainability transformation within agricultural and agroindustrial systems [8], [9]. Recent developments in mechanization, automation, digitalization, precision agriculture, artificial intelligence, and smart farming technologies have accelerated across multiple agricultural sectors as part of broader efforts to improve productivity and environmental performance [10], [11]. Technological innovation is expected not only to optimize production efficiency and resource management but also to reduce occupational risks, strengthen workplace safety systems, improve environmental monitoring, and support environmentally sustainable production practices [12], [13]. Consequently, the integration of occupational health and safety, technological innovation, and environmental sustainability has emerged as an increasingly important research area within environmental economics, sustainable development, and agricultural management studies [14–16].

Despite growing scientific attention toward sustainability and technological transformation in agriculture, the existing literature remains fragmented across disciplinary boundaries [17–19]. Previous studies have widely explored agricultural sustainability, green innovation, environmental management, climate-smart agriculture, and precision farming systems [20–23]. Other studies have separately examined occupational safety, worker health, labor protection, and risk management within agricultural environments. However, limited attention has been directed toward understanding how innovation-driven sustainability research intersects with occupational health and safety concerns in agricultural and agroindustrial systems [24], [25]. Existing reviews have also tended to focus on specific technologies, environmental outcomes, or production efficiency, while comprehensive evaluations integrating occupational safety, technological innovation, and environmental sustainability remain relatively limited [26–31].

The growing expansion of interdisciplinary research has further produced a complex, dispersed body of scientific literature. As research themes continue to evolve across environmental economics, agricultural innovation, workplace safety, and sustainability science, it becomes increasingly difficult to identify dominant research trends, intellectual structures, collaborative networks, and emerging thematic areas within the field [32–35]. Understanding the development of these interconnected research domains is essential for identifying future research priorities, improving sustainability-oriented innovation strategies, and supporting evidence-based environmental and occupational policy development.

Bibliometric analysis has become an increasingly valuable approach for systematically evaluating scientific development and mapping research landscapes across interdisciplinary fields. Bibliometric techniques enable researchers to identify publication trends, influential authors, highly cited studies, collaborative networks, conceptual structures, and emerging research themes within large scientific datasets [25], [36–42]. Compared with conventional narrative reviews, bibliometric approaches provide a more comprehensive and objective understanding of research evolution and knowledge structures. In the context of agricultural sustainability and occupational safety, bibliometric analysis offers important opportunities to examine how technological innovation and environmental concerns have shaped contemporary research agendas and patterns of scientific collaboration over time.

Several bibliometric studies have investigated sustainability transitions, agricultural innovation, environmental management, and smart farming technologies [43–45]. Nevertheless, bibliometric investigations specifically integrating occupational health and safety, innovation, and environmental sustainability within agricultural and agroindustrial contexts remain scarce. This gap is important because worker safety and occupational well-being constitute critical dimensions of sustainable agricultural development, particularly in technologically evolving production systems [46]. A comprehensive understanding of how these themes have developed and interacted is therefore necessary to support sustainable agricultural transformation and environmentally responsible innovation.

Therefore, this study aims to systematically map and analyze the scientific landscape of research on occupational health and safety, technological innovation, and environmental sustainability within the agricultural and agroindustrial sectors. Specifically, this study seeks to identify publication trends, influential journals, productive authors and countries, collaborative networks, dominant research themes, and emerging topics within the existing literature. By providing a comprehensive bibliometric overview, this study contributes to a deeper understanding of the evolving relationship among innovation, occupational safety, and environmental sustainability in agricultural systems, while also offering insights for future research, environmental policy formulation, and sustainable agricultural management practices.

2 | Materials and Methods

2.1 | Data Source and Search Strategy

This study employs the Scopus database as the primary source of bibliographic data. Scopus was selected due to its extensive multidisciplinary coverage, particularly in environmental sciences, agricultural systems, occupational health, and engineering-related fields, which are central to the scope of this study. Compared to other databases, Scopus provides broader journal coverage and greater consistency in metadata, including abstracts, author keywords, citations, and affiliation data, which are essential for robust bibliometric and network analyses.

A systematic search was conducted using the following query applied to all fields:

(agriculture or agricultural or agribusiness or agroindustry or farming or plantation) and ("occupational health" or "occupational safety" or OHS or OSH or "worker safety") and (innovation or technology or digitalization or mechanization or automation) and (environment* or sustainability or "environmental economics" or "green economy" or "environmental management")

The initial search retrieved 28,009 documents. The search was then refined using Scopus filtering tools to ensure it remained within the research scope. The final dataset consisted of 106 articles, which were subsequently screened according to the inclusion criteria. After applying document-type filtering (article), language restriction (English), and temporal coverage (1981–2026), a final dataset of 98 articles was obtained for analysis.

2.2 | Inclusion Criteria and Data Screening

The study included only peer-reviewed journal articles indexed in Scopus. The inclusion criteria were defined as follows:

I. documents related to agriculture, agribusiness, agroindustry, farming, or plantation systems.

II. studies addressing occupational health, occupational safety, or worker safety dimensions.

III. research involving innovation, technology, mechanization, automation, or digitalization.

IV. studies incorporating environmental sustainability, environmental management, or related green economy perspectives.

Conference papers, book chapters, editorials, and non-English publications were excluded to ensure consistency in quality and comparability of bibliometric indicators. No duplicate removal process was required because the dataset was retrieved exclusively from a single database (Scopus).

2.3 | Bibliometric and Network Analysis

Bibliometric and network analyses were conducted using VOSviewer version 1.6.20 and the Biblioshiny (R package Bibliometrix) package in R version 4.5.2 via RStudio.

Co-authorship analysis (authors and countries) and keyword co-occurrence analysis were performed using VOSviewer. Author keywords were used as the unit of analysis for co-occurrence mapping. A minimum threshold of 1 occurrence was applied to ensure the inclusion of emerging and less frequent, but potentially relevant, research themes. Network visualizations were generated using full-counting methods, and only connected items were displayed in the final network maps.

To improve keyword consistency and reduce semantic redundancy, a thesaurus file was applied in VOSviewer. This process included standardizing synonyms, merging keyword variations, and excluding irrelevant terms such as country names and non-thematic identifiers.

2.4 | Thematic Evolution Analysis

The thematic evolution of the research field was analyzed using Biblioshiny (Bibliometrix R package). Author keywords were used as the primary unit of analysis, with a maximum number of 250 words per segment and a minimum cluster frequency of 5. The temporal evolution was divided into two cutting points, namely 2017 and 2023, to capture shifts in thematic development across three periods: 1981–2017, 2018–2023, and 2024–2026. This approach allows identification of thematic continuity and emerging transitions in research focus over time.

2.5 | Performance Analysis and Normalization

Performance indicators, including publication counts, citation counts, and Total Link Strength (TLS), were analyzed in Microsoft Excel. To ensure comparability across different metrics, a min–max normalization approach was applied using the following formula:

$$N_x = \frac{X_i - X_{min}}{X_{max} - X_{min}}, \quad (1)$$

where N_x represents the normalized value, X_i is the observed value, and X_{min} and X_{max} are the minimum and maximum values of the dataset, respectively.

An Overall Score (OS) was then calculated as the arithmetic mean of normalized indicators to provide a composite measure of performance:

$$OS = \frac{N_{Pub} + N_{Cit} + N_{TLS}}{3}, \quad (2)$$

This normalization approach was adopted to prevent dominance of a single metric and to ensure balanced comparison across productivity, citation impact, and collaboration strength.

2.6 | Identification and Synthesis of Highly Cited Publications

Highly cited publications were identified by ranking all documents in the final dataset by citation count. The top 10 most-cited articles were selected for an in-depth qualitative synthesis. Each publication was systematically reviewed based on its abstract and key findings to identify thematic focus areas, methodological contributions, and implications for occupational health and safety, technological innovation, and environmental sustainability in agricultural systems.

The synthesis aimed to integrate quantitative bibliometric results with qualitative insights to better understand the intellectual structure and foundational knowledge base of the research field.

3 | Result

3.1 | Publication and Citation Trends in Agricultural Occupational Safety, Innovation, and Environmental Sustainability Research

A total of 98 documents were retrieved from the Scopus database based on the selected search query and filtering criteria. *Fig. 1* presents the annual distribution of publications and citations related to occupational health and safety, technological innovation, and environmental sustainability within agricultural and agroindustrial systems from 1981 to 2026.

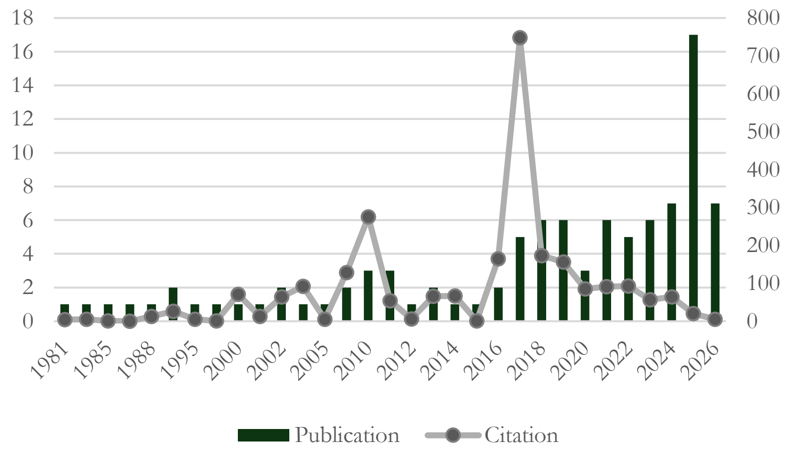

Fig. 1. Annual trends of publications and citations in agricultural occupational safety, innovation, and environmental sustainability research.

As shown in *Fig. 1*, publication output remained relatively limited during the early stages of research development. Between 1981 and 2010, annual scientific output generally ranged from 1 to 3 publications, indicating that the field was still in its developmental phase. A more noticeable increase in publication activity emerged after 2016, with publication output continuing to rise in subsequent years. The highest number of publications was recorded in 2025, with 17 documents, followed by 7 in 2024 and 2026.

Citation patterns demonstrated fluctuating trends throughout the observation period. Several years showed relatively high citation impacts despite low publication output, suggesting the presence of influential foundational studies within the field. The highest citation count was recorded in 2017, with 748 citations, followed by 275 citations in 2010 and 173 citations in 2018. Earlier publications in 2000, 2003, and 2008 also received substantial citation counts compared with the number of documents published during those years.

Overall, the trends presented in *Fig. 1* indicate a gradual expansion of research concerning occupational safety, innovation, and environmental sustainability in agricultural and agroindustrial contexts, particularly during the last decade. The increasing publication frequency in recent years reflects the growing scientific attention devoted to sustainability-oriented technological transformation and worker safety within agricultural systems.

3.2 | Major Scientific Contributors in Agricultural Occupational Safety, Innovation, and Environmental Sustainability Research

Table 1 presents the leading publication sources based on normalized publication and citation metrics within the research domain of occupational health and safety, innovation, and environmental sustainability in agricultural and agroindustrial systems. The analysis demonstrates that the research landscape spans multidisciplinary journals covering agricultural health, environmental science, toxicology, ergonomics, sustainability, and environmental management.

As shown in *Table 1*, the Journal of Agromedicine emerged as the most productive publication source, contributing 9 documents totaling 190 citations. The journal also recorded the highest normalized publication value (N.Pub = 1.00) and the highest Overall Score (OS = 0.67), indicating its dominant contribution to the development of the research field. This finding underscores the strong relevance of agricultural health and occupational safety to sustainability-oriented agricultural research.

Table 1. Top sources based on normalized publication and citation in agricultural occupational safety, innovation, and environmental sustainability research.

Sources	Publications	Citations	N.Pub	N.Cit	OS
Journal of agromedicine	9	190	1.00	0.34	0.67
Toxicology and applied pharmacology	1	565	0.00	1.00	0.50
Applied ergonomics	2	328	0.13	0.58	0.35
Science of the total environment	3	164	0.25	0.29	0.27
Aquaculture	3	47	0.25	0.08	0.17
International journal of environmental research and public health	3	31	0.25	0.05	0.15
International journal of life cycle assessment	2	97	0.13	0.17	0.15
Journal of hazardous materials	2	93	0.13	0.16	0.14
Regulatory toxicology and pharmacology	2	67	0.13	0.12	0.12
Renewable agriculture and food systems	1	111	0.00	0.20	0.10

Note: Pub = publications; Cit = citations; N-Pub/Cit = normalized values (max = 1.000); OS = Overall Score (composite index).

In terms of citation impact, Toxicology and Applied Pharmacology achieved the highest citation performance with 565 citations despite contributing only one publication. The journal had the highest normalized citation value (N.Cit = 1.00), suggesting a highly influential publication in the dataset. Similarly, Applied Ergonomics demonstrated substantial scientific influence with 328 citations across two publications, highlighting the importance of ergonomics and workplace safety perspectives in agricultural innovation and sustainability research.

Several environmental and sustainability-oriented journals also showed notable contributions. Science of the Total Environment published 3 papers and received 164 citations. At the same time, the International Journal of Environmental Research and Public Health and the International Journal of Life Cycle Assessment contributed to the field's environmental management and sustainability dimensions. In addition, journals such as the Journal of Hazardous Materials and Regulatory Toxicology and Pharmacology highlight the relevance of environmental risk assessment, toxicological exposure, and occupational hazards in agricultural systems.

Overall, the distribution of publication sources demonstrates the interdisciplinary nature of the research field, integrating agricultural health, environmental sustainability, toxicology, ergonomics, and technological innovation within agricultural and agroindustrial contexts.

Table 2 presents the leading authors based on normalized publication, citation, and total link strength metrics within the research domain of occupational safety, innovation, and environmental sustainability in agricultural and agroindustrial systems. The results indicate that the scientific landscape is characterized by relatively dispersed author contributions, with several researchers demonstrating notable performance in publication productivity, citation impact, and collaborative strength.

As shown in *Table 2*, Størkersen Kristine and Thorvaldsen Trine were the most productive authors, each contributing 3 publications. Both authors also recorded the highest normalized publication value (N.Pub = 1.00) and a high overall score (OS = 0.65), indicating strong research productivity and collaborative influence within the dataset. Rodriguez Anabel also demonstrated a substantial scholarly contribution, with two publications and the highest total link strength (TLS = 16), suggesting an important role in research collaboration networks.

In terms of citation impact, Beezhold Donald H., Iavicoli Ivo, Leso Veruscka, and Shvedova Anna A. achieved the highest citation performance, with each author recording 565 citations from a single publication. These authors also obtained the highest normalized citation value (N.Cit = 1.00), indicating the presence of highly influential publications within the research field. In addition, Douphrate David I. and Hagevoort G. Robert demonstrated notable citation influence, each contributing two publications with 75 citations.

Table 2. Top authors based on normalized publication, citation, and total link strength in agricultural occupational safety, innovation, and environmental sustainability research.

Author	Publications	Citations	TLS	N.Pub	N.Cit	N.TLS	OS
Størkersen, Kristine	3	47	14	1.00	0.08	0.88	0.65
Thorvaldsen, Trine	3	47	14	1.00	0.08	0.88	0.65
Rodriguez, Anabel	2	37	16	0.50	0.07	1.00	0.52
Holmen, Ingunn Marie	2	47	10	0.50	0.08	0.63	0.40
Beezhold, Donald H.	1	565	3	0.00	1.00	0.19	0.40
Iavicoli, Ivo	1	565	3	0.00	1.00	0.19	0.40
Leso, Veruscka	1	565	3	0.00	1.00	0.19	0.40
Shvedova, Anna A.	1	565	3	0.00	1.00	0.19	0.40
Abas, Azlan	2	4	10	0.50	0.01	0.63	0.38
Ali, Mohamad Xazaquan Mansor	2	4	10	0.50	0.01	0.63	0.38
Arifin, Kadir	2	4	10	0.50	0.01	0.63	0.38
Juhari, Mohammad Lui	2	4	10	0.50	0.01	0.63	0.38
Douphrate, David I.	2	75	6	0.50	0.13	0.38	0.34
Hagevoort, G. Robert	2	75	6	0.50	0.13	0.38	0.34
Botobekov, Arstanaly	2	0	8	0.50	0.00	0.50	0.33

Note: Pub = publications; Cit = citations; TLS = Total Link Strength; N-Pub/Cit/TLS = normalized values (max = 1.000); OS = Overall Score (composite index).

The co-authorship network visualization presented in *Fig. 2* further illustrates the collaborative relationships among authors within the dataset. The network consisted of 18 authors grouped into two major clusters, with 90 links and a total link strength of 91. Cluster 1 was dominated by recently published collaborative studies with relatively high normalized citation values, while Cluster 2 included authors with stronger citation performance and broader collaborative relationships. Rodriguez Anabel recorded the highest total link strength within the co-authorship network, reinforcing the author’s prominent collaborative role in the research landscape.

Overall, the author's analysis demonstrates that the field remains relatively interdisciplinary and collaborative, involving researchers from occupational health, environmental management, agricultural safety, and sustainability-related disciplines. The coexistence of highly cited foundational authors and emerging collaborative networks also indicates the continuing development and diversification of research concerning occupational safety, innovation, and environmental sustainability in agricultural systems.

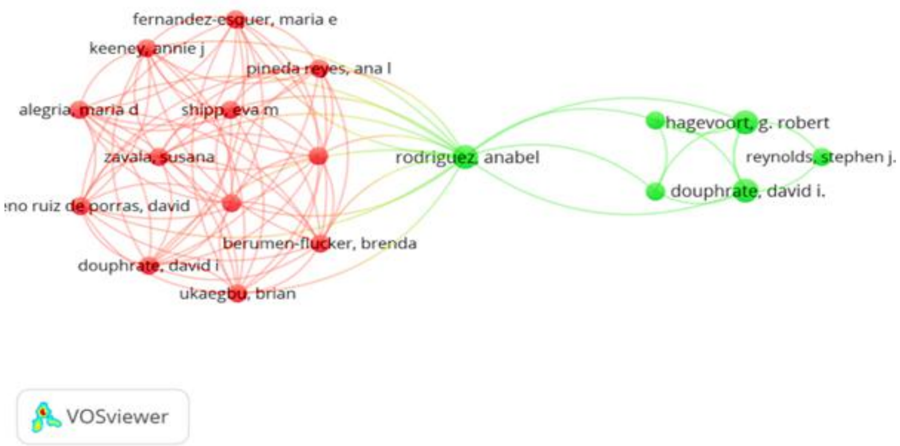

Fig. 2. Author collaboration network based on co-authorship analysis in agricultural occupational safety, innovation, and environmental sustainability research.

Table 3 presents the leading country contributions based on normalized publication, citation, and total link strength metrics within the research field of occupational health and safety, innovation, and environmental sustainability in agricultural and agroindustrial systems. The results reveal that research productivity and scientific influence are concentrated among several developed countries, particularly those with strong research capacity in environmental science, agricultural innovation, and occupational health.

As shown in *Table 3*, the United States emerged as the leading contributor across all evaluated indicators, recording 32 publications, 1,381 citations, and the highest total link strength (TLS = 14). The country also achieved the highest normalized publication, citation, and collaboration values (N.Pub = 1.00; N.Cit = 1.00; N.TLS = 1.00), resulting in the highest overall score (OS = 1.00). These findings indicate the United States' dominant scientific and collaborative role in the research landscape.

The United Kingdom, Italy, and Brazil also made substantial research contributions, each publishing 8 papers. Among these countries, Italy showed particularly strong citation performance with 711 citations, indicating a high scientific impact relative to publication output. The United Kingdom demonstrated strong collaborative influence, recording the same total link strength value as the United States (TLS = 14), suggesting extensive international research collaboration within the field. Brazil contributed notable publication productivity and collaborative engagement, reflecting the growing relevance of sustainability and occupational safety research within agricultural economies.

Table 3. Top countries based on normalized publication, citation, and total link strength in agricultural occupational safety, innovation, and environmental sustainability research.

Country	Publications	Citations	TLS	N.Pub	N.Cit	N.TLS	OS
United States	32	1381	14	1.00	1.00	1.00	1.00
United Kingdom	8	266	14	0.23	0.19	1.00	0.47
Italy	8	711	4	0.23	0.51	0.29	0.34
Brazil	8	198	8	0.23	0.14	0.57	0.31
Canada	5	173	7	0.13	0.13	0.50	0.25
Australia	3	153	5	0.06	0.11	0.36	0.18
South Africa	3	54	6	0.06	0.04	0.43	0.18
Germany	3	74	5	0.06	0.05	0.36	0.16
Netherlands	2	72	5	0.03	0.05	0.36	0.15
China	5	28	3	0.13	0.02	0.21	0.12

Note: Pub = publications; Cit = citations; TLS = Total Link Strength; N-Pub/Cit/TLS = normalized values (max = 1.000); OS = Overall Score (composite index).

Several other countries, including Canada, Australia, Germany, South Africa, the Netherlands, and China, also contributed to the field's development. Canada recorded five publications and 173 citations, while Australia demonstrated relatively high citation performance despite producing only three publications. China contributed five publications but showed comparatively lower citation impact and collaboration strength within the dataset.

The country collaboration network presented in *Fig. 3* further illustrates the global structure of scientific collaboration in the field. The network consisted of 24 countries grouped into six clusters, with 40 links and a total link strength of 45. The United States and the United Kingdom emerged as the most connected countries, recording 12 and 11 links, respectively, indicating their central roles in international research collaboration. Italy also demonstrated substantial citation influence within the collaboration network, recording 711 citations and the highest normalized citation score among major contributing countries.

In addition, several developing and emerging economies, including Brazil, South Africa, India, Nigeria, Ethiopia, and Pakistan, were represented in the collaboration network, reflecting the increasingly global and interdisciplinary nature of research on agricultural sustainability, occupational safety, and technological innovation. Overall, the country analysis demonstrates that the field is characterized by extensive international collaboration and multidisciplinary research engagement across both developed and developing agricultural economies.

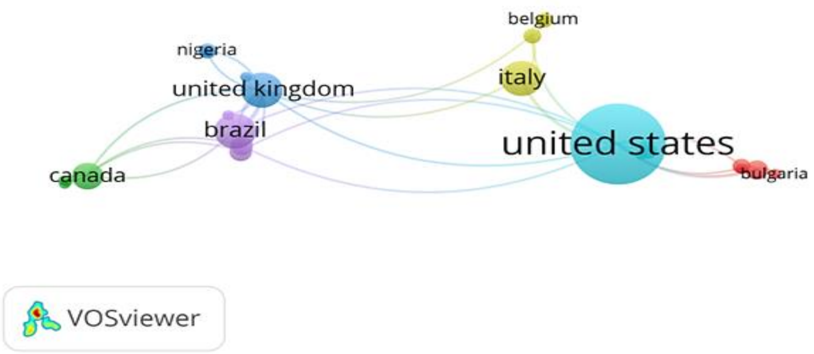

Fig. 3. Country collaboration network based on co-authorship analysis in agricultural occupational safety, innovation, and environmental sustainability research.

3.3 | Thematic Structure and Evolution in Agricultural Occupational Safety, Innovation, and Environmental Sustainability Research

Fig. 4 illustrates the keyword co-occurrence network generated from author keywords, consisting of 137 items grouped into 18 thematic clusters with 374 links and a total link strength of 382. The network visualization demonstrates the multidimensional nature of research related to occupational health and safety, technological innovation, and environmental sustainability within agricultural and agroindustrial systems. The network's interconnected structure indicates that the field integrates themes of worker protection, environmental management, sustainability practices, technological transformation, and agricultural modernization.

As presented in *Fig. 4*, the keyword "occupational health and safety" emerged as the most dominant term, with 16 occurrences and the highest total link strength (TLS = 46). Other highly connected keywords included "agriculture" (7 occurrences; TLS = 25), "safety" (6 occurrences; TLS = 21), "risk assessment" (4 occurrences; TLS = 16), "technology" (4 occurrences; TLS = 16), "sustainability" (4 occurrences; TLS = 15), "ergonomics" (3 occurrences; TLS = 14), and "pesticides" (3 occurrences; TLS = 13). These findings indicate that occupational safety, technological advancement, sustainability, and environmental risk management constitute the core conceptual structure of the research field.

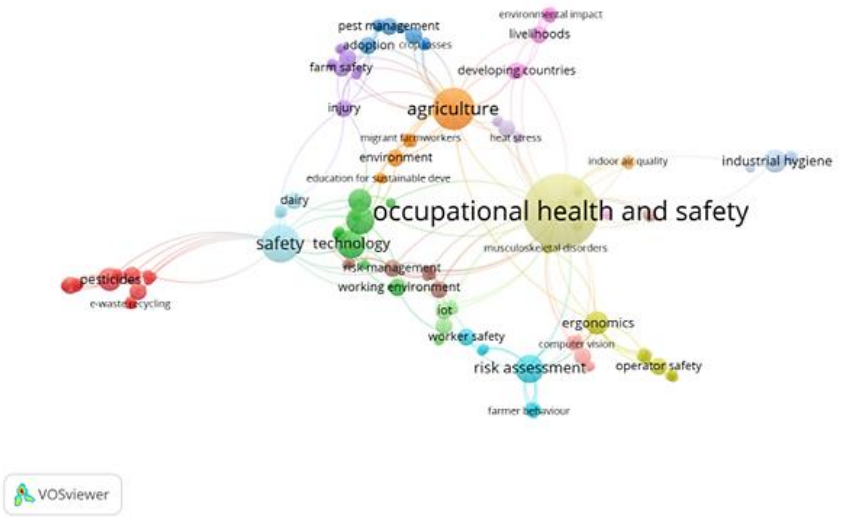

Fig. 4. Network visualization of keyword co-occurrence in agricultural occupational safety, innovation, and environmental sustainability research.

The clustering analysis further demonstrates the diversity of research themes within the dataset (*Table 4*). Cluster 1 primarily focused on pesticide exposure, occupational hazards, and protective strategies among agricultural workers through keywords such as pesticides, exposure, health hazards, and Personal Protective Equipment (PPE). Cluster 2 emphasized sustainability-oriented agricultural management and technological integration, as reflected in keywords such as sustainability, technology, mechanization, management, and working environment. Meanwhile, Cluster 3 highlighted innovation adoption and environmentally friendly agricultural practices through themes associated with pest management, crop protection, and biological control.

Several clusters reflected the growing role of emerging technologies in agricultural occupational safety research. Cluster 10 concentrated on artificial intelligence, computer vision, explainable AI, and agricultural machinery, indicating the increasing application of smart technologies in precision agriculture and automated farming systems. Similarly, Cluster 11 highlighted digital monitoring technologies, including IoT, wearable sensors, smartphone applications, and health monitoring systems, to improve workplace safety and environmental surveillance in agricultural settings.

Table 4. Keyword clusters in agricultural occupational safety, innovation, and environmental sustainability research.

Cluster	Main Keywords	Thematic Interpretation
Cluster 1	pesticides, exposure, health hazards, PPE, pesticide safety, risk perceptions, agricultural extension	Focuses on pesticide exposure, occupational health risks, and protective strategies among agricultural workers, emphasizing health protection and safety awareness in farming activities.
Cluster 2	sustainability, technology, mechanization, management, agriculture, working environment	Represents the integration of sustainability, technological advancement, and management practices in agricultural systems, particularly regarding workplace conditions and operational efficiency.
Cluster 3	pest management, pesticide, crop protection, biological control, adoption, diffusion of innovations	Highlights innovation adoption in sustainable pest management and crop protection practices, including the diffusion of agricultural technologies and environmentally friendly approaches.
Cluster 4	ergonomics, machine learning, operator safety, horticulture, vibration risk, hand-held sprayer	Emphasizes ergonomic assessment and emerging technologies to improve machinery operation safety and reduce physical risks in agricultural work environments.
Cluster 5	farming, farm safety, injury, safety innovation, certification, cotton	Focuses on occupational safety management and injury prevention in farming systems, including safety innovation and agricultural certification practices.
Cluster 6	risk assessment, worker safety, machinery safety, self-propelled machines, geographic information system (GIS), farmer behavior	Represents technological and risk-based approaches for improving worker safety, machinery operation, and safety monitoring in modern agricultural systems.
Cluster 7	agriculture, environment, sustainable management of agriculture, education for sustainable development, migrant farmworkers	Highlights sustainable agricultural development and environmental management while considering labor-related and educational dimensions in agricultural sustainability.
Cluster 8	innovation, workplace safety, risk management, technological advancements, fish farming, fertilizer manufacturing	Focuses on innovation-driven workplace safety and risk management strategies across agricultural and agroindustrial production sectors.
Cluster 9	environmental impact, sustainable intensification, technology diffusion, farm robots, UAVs, livelihoods	Represents emerging technological transformation in agriculture, including automation and digital agriculture, alongside sustainability and livelihood considerations.
Cluster 10	artificial intelligence, computer vision, explainable AI, agricultural machinery, viticulture	Highlights the application of artificial intelligence and smart technologies in precision agriculture, machinery systems, and automated agricultural operations.
Cluster 11	IoT, wearable sensors, thermal comfort, agricultural workers, health monitoring, smartphone app	Focuses on digital monitoring technologies and wearable systems for occupational health surveillance and environmental condition monitoring in agricultural workplaces.
Cluster 12	occupational health and safety, industrial hygiene, occupational hazards, safety technology, regulatory compliance	Represents core occupational health and safety governance themes, including industrial hygiene, regulatory frameworks, and hazard mitigation in agricultural industries.

Table 4. Continued.

Cluster	Main Keywords	Thematic Interpretation
Cluster 13	occupational health and safety, dangerous sectors, wearable technology, psychosocial stress model, forest mechanization	Highlights occupational safety challenges in high-risk agricultural and forestry sectors, including psychosocial and technological dimensions of worker protection.
Cluster 14	climate change, heat stress, outdoor labor, farmworker health, extreme weather	Focuses on climate-related occupational health risks, particularly heat stress and environmental exposure affecting outdoor agricultural workers.
Cluster 15	safety, dairy, training, mobile learning, m-learning	Represents occupational safety training and learning systems in the agricultural sector, particularly dairy farming, and digital-based safety education approaches.
Cluster 16	indoor air quality, indoor environment, particulate matter (PM), traditional greenhouse	Highlights environmental exposure and air-quality monitoring in controlled agricultural environments, such as greenhouses and indoor farming systems.
Cluster 17	environmental exposure, heat management, heat stress disorders, wearable electronic devices	Focuses on environmental monitoring and wearable technologies for managing occupational heat stress and exposure risks among agricultural workers.
Cluster 18	biomass energy, geothermal energy, energy production	Represents sustainability and renewable energy themes associated with agricultural and environmental management systems.

Environmental sustainability and climate-related concerns also appeared prominently across multiple clusters. Cluster 14 addressed climate change, heat stress, outdoor labor, and farmworker health, reflecting growing attention to climate-related occupational risks in agriculture. Cluster 16 focused on indoor environmental conditions, including indoor air quality and particulate matter exposure within greenhouse environments, while Cluster 18 emphasized renewable energy and sustainable energy production themes associated with agricultural environmental management.

Overall, the keyword co-occurrence network reveals that the research field has evolved into an interdisciplinary domain integrating occupational safety, environmental sustainability, technological innovation, climate-related risks, and digital transformation within agricultural systems. *Fig. 5* presents the thematic evolution of the research field between 1981 and 2026. The results indicate the continuity and gradual transformation of several major themes over time. The theme "agriculture" demonstrated continuity from the 1981–2017 period into 2018–2023, with a weighted inclusion index of 0.50 and five occurrences, indicating its sustained centrality within the literature. Similarly, "occupational health" showed strong thematic continuity across all observed periods, including from 1981–2017 to 2018–2023 and subsequently into 2024–2026. The weighted inclusion index of 1.00 during the earlier transition indicates complete thematic continuity, suggesting that occupational health has consistently remained a core research theme throughout the field's development.

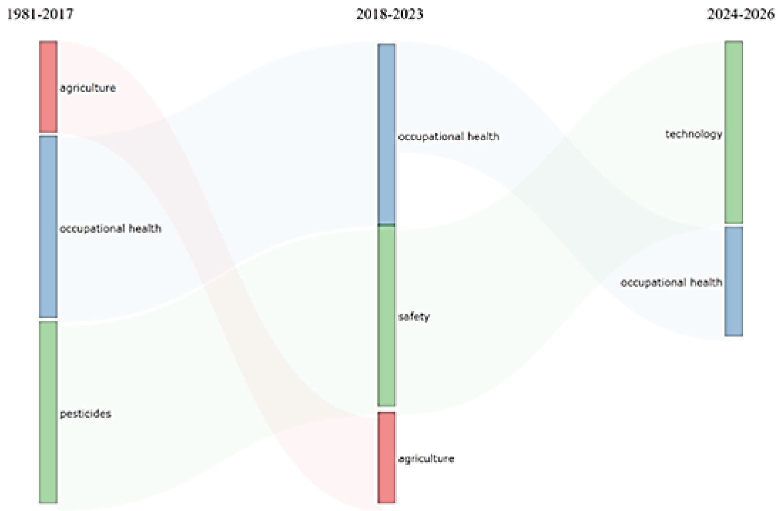

Fig. 5. Thematic evolution (1981-2026) in agricultural occupational safety, innovation, and environmental sustainability research.

The thematic evolution analysis also demonstrates shifts toward technology-oriented research themes in recent years. The transition from "safety" during 2018–2023 toward "technology" in 2024–2026 reflects the increasing integration of digitalization, automation, and technological innovation within occupational safety and environmental management research. In addition, the evolution from "pesticides" to "safety" suggests a gradual expansion from specific occupational hazard concerns toward broader workplace safety and risk management perspectives within agricultural systems.

Collectively, the thematic evolution results indicate that the research domain has progressed from traditional agricultural and occupational health concerns toward more integrated themes involving sustainability, technological innovation, environmental monitoring, and smart agricultural systems.

3.4 | Intellectual Structure and Highly Cited Publications in Agricultural Occupational Safety, Innovation, and Environmental Sustainability Research

Table 5 presents the most highly cited publications in agricultural occupational safety, innovation, and environmental sustainability research. The citation patterns indicate that studies integrating technological innovation, occupational health, and sustainability dimensions have received significant scholarly attention. The most cited publication was authored by Iavicoli et al. [47], which received 565 citations and discussed the opportunities and occupational risks associated with nanotechnology applications in agriculture. This finding demonstrates the growing importance of advanced technologies and emerging environmental health concerns in agricultural systems.

The second most cited study, conducted by Fathallah [48], focused on musculoskeletal disorders in labor-intensive agriculture and emphasized the role of ergonomics and mechanization in reducing occupational injuries. The high citation impact of this publication reflects the ongoing concern about worker health and safety in physically demanding agricultural work. Similarly, Damalas and Abdollahzadeh [49] highlighted unsafe pesticide handling practices among farmers and the importance of PPE, training, and behavioral interventions to minimize occupational exposure risks.

Several highly cited studies also emphasized the relationship between technological advancement and sustainability in agricultural production systems. Sassenrath et al. [50] explained how mechanization, conservation systems, and information technologies contributed to improved productivity, worker safety, and environmental sustainability. In addition, Souza et al. [51] demonstrated that advanced bioenergy production technologies could reduce occupational accidents while improving broader social sustainability outcomes in agroindustrial systems. These findings indicate that agricultural innovation is increasingly focused on balancing productivity, environmental management, and occupational well-being.

Table 5. Top highly cited publications in agricultural occupational safety, innovation, and environmental sustainability research.

Authors	Title	Year	Cited by
Iavicoli et al. [47]	Nanotechnology in agriculture: Opportunities, toxicological implications, and occupational risks	2017	565
Fathallah [48]	Musculoskeletal disorders in labor-intensive agriculture	2010	257
Damalas and Abdollahzadeh [49]	Farmers' use of PPE during handling of plant protection products: Determinants of implementation	2016	129
Sassenrath et al. [50]	Technology, complexity, and change in agricultural production systems	2008	111
Hejazi et al. [52]	Landfarming operation of oily sludge in an arid region - Human health risk assessment	2003	92
Dumont and Baret [53]	Why are working conditions a key issue of sustainability in agriculture? A comparison between agroecological, organic, and conventional vegetable systems	2017	90
O'Neill [54]	Ergonomics in industrially developing countries: Does its application differ from that in industrially advanced countries?	2000	71
Boverhof et al. [55]	Approaches and considerations for the assessment of immunotoxicity for environmental chemicals: A workshop summary	2014	67
Souza et al. [51]	Social life cycle assessment of first and second-generation ethanol production technologies in Brazil	2018	59
Yu et al. [56]	Informal processing of electronic waste at Agbogbloshie, Ghana: workers' knowledge about associated health hazards and alternative livelihoods	2017	49

The highly cited publications also reveal growing attention to environmental and occupational risk management. For example, Hejazi et al. [52] examined the occupational health risks associated with environmentally friendly landfarming technologies, particularly airborne Volatile Organic Compounds (VOCs). Likewise, Boverhof et al. [55] discussed innovative approaches for evaluating environmental chemical hazards and their implications for occupational health protection. These studies demonstrate that environmental sustainability initiatives in agriculture must also consider worker exposure and safety risks.

Furthermore, social and labor dimensions emerged as important themes in the literature. Dumont and Baret [53] questioned whether agroecological and organic farming systems necessarily improve working conditions. At the same time, O'Neill [54] emphasized the importance of ergonomics and participatory approaches for sustainable livelihoods in developing-country agriculture. Meanwhile, Yu et al. [56] highlighted the importance of worker awareness and environmental health education in hazardous occupational sectors linked to agricultural livelihoods.

Overall, the synthesis presented in *Table 6* demonstrates that four interconnected themes strongly shape the intellectual foundation of this research field: 1) occupational health and worker safety, 2) technological innovation and mechanization, 3) environmental sustainability and risk management, and 4) social sustainability and labor conditions. These findings indicate that contemporary agricultural research increasingly adopts an interdisciplinary perspective that integrates technological advancement with worker protection and sustainable environmental management.

Table 6. Synthesis of highly cited publications in agricultural occupational safety, innovation, and environmental sustainability research.

Author and Year	Focus Area	Key Findings
Iavicoli et al. [47]	Nanotechnology, occupational risk assessment, and sustainable agriculture	The study highlights how nanotechnology innovations, such as nanofertilizers, nanopesticides, nanosensors, and nanoremediation, can improve agricultural productivity and environmental sustainability. However, these technologies also introduce new occupational health and safety risks for agricultural workers through exposure to nanomaterials. The authors emphasize the importance of occupational risk assessment, regulatory frameworks, and worker safety management in technologically advanced agricultural systems.
Fathallah [48]	Ergonomics, mechanization, and worker health in agriculture	This publication demonstrates that musculoskeletal disorders remain a major occupational health issue in labor-intensive agriculture. Ergonomic interventions, mechanization, engineering controls, and worker-centered technologies can significantly reduce physical risks and improve worker safety. The study also emphasizes the importance of integrating technological innovation with social and cultural considerations to achieve sustainable improvements in occupational health in agriculture.
Damalas and Abdollahzadeh [49]	Pesticide safety, PPE adoption, and occupational exposure	The study reveals that many farmers exhibit unsafe practices in pesticide handling and PPE use. Training, education, and risk perception strongly influence safety practices. The findings underline the need for innovative safety interventions and occupational health education to minimize environmental and human exposure risks in agricultural production systems.
Sassenrath et al. [50]	Agricultural technology adoption, mechanization, and sustainability	The authors explain how technological advancements, mechanization, conservation systems, and information technologies have transformed agriculture by improving productivity, worker safety, and environmental sustainability. However, they also note challenges such as intensification, resource dependency, and environmental pressures. The study emphasizes balancing innovation, occupational safety, and sustainable agricultural management.
Hejazi et al. [52]	Environmental management, waste treatment, and occupational exposure	This study evaluates landfarming technology for the treatment of oily sludge in arid agricultural environments. Although the technology is considered environmentally sustainable and energy efficient, the research identifies serious occupational health risks associated with airborne VOCs. The findings stress the importance of environmental monitoring and worker protection in environmentally oriented agricultural technologies.
Dumont and Baret [53]	Agroecology, green jobs, and working conditions	The study investigates whether ecologically oriented farming systems improve occupational conditions. Results show that agroecological and organic systems do not automatically guarantee better working conditions or occupational health outcomes. Socio-economic factors, mechanization levels, and labor management practices strongly influence worker well-being and sustainability transitions in agriculture.
O'Neill [54]	Ergonomics, sustainable livelihoods, and agricultural labor	This publication discusses how ergonomics interventions can improve productivity, worker safety, and living conditions in developing-country agriculture. The study highlights low-cost technological and participatory approaches as important strategies for sustainable agricultural development and occupational health improvement, particularly among subsistence farming communities.
Boverhof et al. [55]	Environmental toxicology, chemical safety, and testing innovation	The paper discusses innovative approaches to assessing immunotoxicity associated with environmental chemicals. Although broader than agriculture alone, the findings are highly relevant for occupational and environmental health management in agrochemical-intensive agricultural systems. The study supports integrating advanced testing technologies and safer regulatory practices to reduce health risks associated with environmental exposures.
Souza et al. [51]	Social sustainability, bioenergy, and occupational impacts	The study evaluates sugarcane biorefinery systems using social life cycle assessment and input-output analysis. Advanced agricultural and industrial technologies reduced occupational accidents while improving wages, education levels, and workforce quality. The findings demonstrate how technological innovation and sustainability-oriented production systems can improve occupational safety and social outcomes in agroindustry.
Yu et al. [56]	Occupational hazards, environmental contamination, and worker awareness	This research identifies significant occupational health risks among e-waste workers and highlights low awareness regarding environmental and health hazards. The study emphasizes that effective technological and environmental interventions require worker education, occupational safety awareness, and sustainable livelihood alternatives, such as farming.

4 | Discussion

The findings of this study demonstrate that research concerning occupational health and safety, technological innovation, and environmental sustainability in agricultural systems has experienced substantial expansion during the last decade, reflecting a broader transformation in how agricultural sustainability is conceptualized within contemporary scientific discourse. Historically, agricultural sustainability research has primarily emphasized productivity enhancement, resource efficiency, and environmental conservation, while occupational health and worker protection have often been treated as secondary or isolated concerns. However, the rapid increase in publications after 2016 indicates that worker safety and occupational well-being are increasingly recognized as integral components of sustainable agricultural development rather than peripheral social issues [57]. This transition reflects growing awareness that agricultural sustainability cannot be achieved solely through technological intensification or environmental management if production systems continue to expose workers to hazardous conditions, unsafe technologies, ergonomic burdens, and climate-related occupational risks [58].

The results further suggest that the evolution of agricultural innovation has fundamentally reshaped the structure of occupational and environmental risks within agricultural systems. Highly cited publications within the dataset consistently demonstrate that technological modernization simultaneously creates opportunities and vulnerabilities. Mechanization, precision agriculture, artificial intelligence, digital monitoring systems, and nano-enabled agricultural technologies have contributed to improved productivity, environmental monitoring, and operational efficiency [59], [60]. At the same time, these innovations have introduced new forms of occupational exposure, technological dependency, ergonomic complexity, and environmental uncertainty, requiring adaptive governance and risk management approaches. This duality is particularly evident in the prominence of studies related to nanotechnology, pesticide exposure, environmental toxicology, and mechanization. The findings, therefore, challenge techno-optimistic assumptions that innovation inherently produces sustainable outcomes. Instead, the bibliometric evidence indicates that technological advancement in agriculture functions as a socio-technical transition in which environmental performance, worker protection, and production efficiency must be continuously negotiated and balanced.

The dominance of "occupational health and safety," "technology," "risk assessment," "sustainability," and "ergonomics" within the keyword co-occurrence network reinforces the emergence of an integrated research paradigm linking worker well-being with technological and environmental transformation, rather than operating as separate research domains. Occupational safety, environmental management, and digital innovation increasingly interact within interconnected agricultural systems. This convergence reflects the growing development of human-centered sustainability frameworks in agriculture, in which technological systems are evaluated not only by productivity outcomes but also by their implications for worker exposure, labor conditions, environmental resilience, and long-term social sustainability. The strong linkage between occupational health themes and environmental sustainability clusters also suggests that contemporary agricultural risks are increasingly systemic rather than isolated. Environmental degradation, climate stress, technological intensification, and occupational hazards now interact across multiple dimensions of agricultural production systems.

One of the most significant findings of this study is the growing integration of digital technologies within occupational safety and environmental management research. The emergence of clusters in artificial intelligence, IoT, computer vision, wearable sensors, smartphone applications, UAVs, and explainable AI demonstrates that agricultural safety management is increasingly transitioning toward data-driven, predictive systems [61]. This evolution reflects the broader expansion of Agriculture 4.0 and smart farming paradigms, where digital technologies are no longer limited to productivity optimization but are also utilized to monitor worker conditions, detect hazards, manage environmental exposure, and improve workplace safety performance [62]. In this context, the thematic evolution from "safety" toward "technology" during the 2024–2026 period represents more than a simple thematic shift; it reflects the restructuring of occupational safety governance through digitalization and automation. Agricultural safety is progressively evolving from reactive hazard mitigation toward proactive, technology-assisted risk prediction and environmental surveillance systems [63].

Nevertheless, the findings also reveal that substantial structural and ethical challenges characterize digital transformation in agriculture. While advanced technologies may improve monitoring capacity and reduce certain physical risks, they may also intensify inequalities between technologically advanced agricultural systems and labor-intensive farming environments, particularly in developing economies. Several highly cited studies emphasize that technological solutions alone are insufficient to achieve sustainable agricultural transformation when institutional support, worker training, regulatory capacity, and social protection mechanisms remain limited. The persistence of themes related to pesticide exposure, PPE adoption, ergonomic stress, and worker awareness demonstrates that many agricultural systems continue to face fundamental occupational safety challenges despite rapid technological advancement. Consequently, the effectiveness of smart agricultural technologies ultimately depends not only on innovation capacity but also on accessibility, worker participation, education, behavioral adaptation, and the quality of governance.

The thematic prominence of climate-related risks further indicates that environmental sustainability and occupational safety are becoming increasingly inseparable within agricultural systems. Clusters associated with climate change, heat stress, outdoor labor, environmental exposure, and farmworker health demonstrate that climate-related environmental pressures directly affect occupational well-being and labor productivity. This finding is particularly important because agricultural workers are among the most environmentally exposed labor groups globally. The growing prominence of themes related to heat-stress management, wearable monitoring systems, and environmental surveillance technologies suggests that climate adaptation in agriculture is increasingly expanding beyond production resilience toward occupational resilience. In other words, climate-smart agriculture is gradually evolving into climate-safe agriculture, in which adaptation strategies must simultaneously protect ecosystems, production systems, and workers.

The intellectual structure analysis also highlights the growing importance of social sustainability within agricultural innovation research. Highly cited studies on ergonomics, participatory approaches, green jobs, labor conditions, and social life-cycle assessment collectively demonstrate that sustainable agricultural transformation cannot be reduced to environmental performance indicators alone. The findings from Dumont and Baret [53], for instance, reveal that ecologically oriented farming systems do not automatically produce better labor conditions or occupational outcomes. Similarly, O'Neill [54] emphasizes that participatory ergonomics and low-cost interventions may be more practical and socially effective than highly sophisticated technologies in many agricultural contexts. These findings collectively suggest that sustainability transitions in agriculture remain deeply influenced by socio-economic structures, labor relations, institutional conditions, and cultural practices. As a result, worker well-being should not be treated merely as a byproduct of sustainability policies, but rather as a core indicator of whether sustainability transitions are socially equitable and operationally effective.

The country collaboration patterns identified in this study further reveal important geopolitical dimensions within the development of agricultural sustainability research. The dominance of the United States, the United Kingdom, and several European countries reflects the concentration of scientific infrastructure, funding capacity, and technological research ecosystems within developed economies. However, the growing participation of countries such as Brazil, India, South Africa, Nigeria, Pakistan, and Ethiopia indicates that occupational safety and sustainability challenges are increasingly recognized as global concerns, particularly within agricultural economies experiencing rapid environmental change and technological transformation. This pattern is highly significant because many developing countries remain dependent on labor-intensive agricultural systems while simultaneously facing climate vulnerability, limited occupational safety infrastructure, and unequal access to technological innovation [64]. Consequently, future sustainability-oriented agricultural policies must address not only technological advancement but also issues of equity, institutional capacity, technological accessibility, and social inclusion across different agricultural regions.

From a theoretical perspective, this study contributes to the broader literature on sustainability transitions and socio-technical systems by demonstrating that occupational health and worker safety constitute central dimensions of agricultural sustainability rather than complementary policy considerations. The bibliometric evidence indicates that agricultural research is increasingly moving away from productivity-centered modernization models toward integrated socio-technical sustainability frameworks in which environmental resilience, digital innovation, worker protection, and social well-being are deeply interconnected. This shift reflects an important transformation in sustainability science itself, in which technological progress is increasingly evaluated by multidimensional criteria encompassing environmental, occupational, economic, and social impacts.

In practice, the findings highlight the need to develop worker-centered innovation strategies within agricultural modernization programs. Policymakers and agricultural industries should ensure that occupational risk assessment, ergonomic design, environmental monitoring systems, worker education, and inclusive governance mechanisms accompany sustainability-oriented technological adoption. Likewise, digital agriculture initiatives should prioritize not only efficiency gains but also worker protection, climate adaptation, and equitable access to technology. Without integrating occupational safety into sustainability-oriented innovation policies, agricultural modernization may unintentionally reproduce new forms of inequality, environmental exposure, and labor vulnerability despite improvements in productivity and environmental performance.

Finally, this study identifies several important directions for future research. Although emerging themes such as artificial intelligence, wearable technologies, climate adaptation systems, and precision agriculture are becoming increasingly prominent, empirical evidence regarding their long-term occupational, environmental, and social implications remains limited. Future research should therefore move beyond technological performance evaluation toward more comprehensive investigations of how innovation reshapes labor relations, occupational vulnerability, environmental governance, and social sustainability across different agricultural contexts. Greater attention should also be directed toward underrepresented regions in the Global South, where labor-intensive agriculture, exposure to climate change, and limited occupational protection systems may pose sustainability challenges that differ substantially from those observed in technologically advanced agricultural economies. In this regard, future interdisciplinary research integrating environmental science, occupational health, engineering, agricultural economics, and sustainability governance will be essential for supporting agricultural systems that are not only technologically advanced and environmentally efficient but also socially just and safe for workers.

5 | Conclusion

This study demonstrates that research on occupational health and safety, technological innovation, and environmental sustainability in agricultural and agroindustrial systems has grown significantly and evolved into an increasingly interdisciplinary field. The findings indicate that agricultural sustainability is no longer viewed solely in terms of productivity and environmental efficiency, but also in terms of worker protection, occupational well-being, and technological governance. Emerging themes such as artificial intelligence, IoT, wearable technologies, precision agriculture, and climate-related occupational risks reflect the ongoing transition toward digitally integrated and sustainability-oriented agricultural systems.

The study further highlights that technological innovation creates both opportunities and challenges. While mechanization and smart technologies improve productivity, environmental monitoring, and safety management, they also introduce new occupational risks, technological inequalities, and governance concerns. Therefore, sustainable agricultural transformation requires a balanced approach that integrates technological advancement with environmental resilience, worker safety, and social sustainability.

Future research should focus on the long-term occupational and environmental impacts of digital agriculture, particularly in developing countries where labor-intensive farming and climate vulnerability remain significant challenges. More empirical and comparative studies are also needed to evaluate worker-centered innovation, climate adaptation, and equitable access to agricultural technologies.

This study is limited by its reliance on the Scopus database, English-language journal articles, and bibliometric methods that emphasize publication patterns rather than practical implementation outcomes. Nevertheless, the study provides important insights into the evolving relationship between innovation, sustainability, and occupational safety in modern agricultural systems.

Authors' Contributions

G. M. I.: Writing-original draft, Methodology, Data Curation, Conceptualization, Software, Formal Analysis, and Visualization, and Validation. M. I. D.: Validation, Writing-Review & Editing, Software, and Formal Analysis. E. H. K.: Validation, Writing-Review & Editing, and Formal Analysis. M. H.: Validation, Writing-Review & Editing, and Formal Analysis. T. K.: Validation, Writing-Review & Editing, and Formal Analysis. W. S.: Validation, Writing-Review & Editing, and Formal Analysis. Z. Z.: Validation, Writing-Review & Editing, and Formal Analysis. The authors have read and agreed to the published version of the manuscript.

Data Availability

The data is available on request from the corresponding author.

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Conflict of Interest

There are no competing interests to declare.

Consent for Publication

The authors have given consent for the publication of this manuscript.

Ethics Approval and Consent to Participate

The authors confirm that this research did not involve human participants or animal subjects.

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