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From Control to Coexistence: Reframing Integrated Pest Management under Climate and Environmental Change

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Abstract

This study examines the evolution of research on integrated pest management (IPM) in relation to climate change and environmental impacts through a bibliometric analysis of Scopus-indexed publications from 2003 to 2026. By integrating publication trends, collaboration networks, keyword co-occurrence, and conceptual structure mapping, the study identifies a significant post-2019 expansion reflecting increasing global urgency toward sustainable agriculture. The findings reveal a structural shift from pesticide-dependent approaches to ecologically based and climate-adaptive strategies, with growing integration of biodiversity, ecosystem services, and agroecology within IPM frameworks. Conceptual analysis further indicates that IPM functions as a transitional bridge between conventional and sustainability-oriented paradigms. Despite expanding international collaboration, research contributions remain geographically concentrated, highlighting a mismatch between knowledge production and vulnerability to climate-driven pest risks. The study underscores an ongoing paradigm transition and emphasizes the need for inclusive, context-specific, and climate-resilient IPM strategies.



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1. Introduction

Agricultural systems worldwide are increasingly challenged by the combined pressures of climate change, environmental degradation, and the growing demand for food production [1–4]. Climate change is widely recognized as a major driver of shifts in pest distribution, population dynamics, and outbreak frequency, thereby threatening crop productivity and global food security [5–10]. Rising temperatures, altered precipitation patterns, and increased climate variability have been shown to

intensify pest infestations and expand the geographical range of insects, weeds, and plant diseases [11, 12]. These changes not only increase crop losses but also complicate pest management strategies across diverse agroecosystems.

In response to these challenges, integrated pest management (IPM) has been widely promoted as a sustainable approach to pest control that combines biological, cultural, physical, and chemical methods to minimize economic, environmental, and human health

risks [13–18]. IPM aims to reduce reliance on synthetic pesticides while maintaining effective pest suppression through ecosystem-based strategies. Numerous studies have demonstrated that IPM can reduce pesticide use, enhance biodiversity, and improve ecosystem services, making it a key component of sustainable agricultural systems. However, the effectiveness of IPM is increasingly influenced by climate change, which alters pest–host interactions, disrupts biological control mechanisms, and introduces new uncertainties into decision-making processes [19].

The relationship between climate change and pest dynamics is complex and multidimensional. Climate variability affects not only pest populations but also crop susceptibility and the effectiveness of control measures. As a result, pest management strategies must adapt to changing environmental conditions, requiring more resilient and flexible approaches [20–22]. This has led to growing interest in climate-smart agriculture, agroecological practices, and adaptive pest management strategies that can respond to environmental variability while maintaining productivity and sustainability.

At the same time, the environmental impacts of pest management practices have become a major global concern. Conventional pesticide-intensive approaches have been associated with soil degradation, water contamination, biodiversity loss, and negative effects on non-target organisms [23, 24]. Excessive pesticide use also contributes to the development of pest resistance, further reducing the effectiveness of chemical control methods [25–27]. In contrast, environmentally sustainable pest management emphasizes reduced chemical inputs, enhanced ecosystem services, and long-term ecological balance [13]. The integration of environmental considerations into pest management is therefore essential to achieve sustainable agricultural development.

Given these interconnections, the nexus between integrated pest management, climate change, and environmental impacts represents a rapidly evolving research domain. The inclusion of key concepts such as pests (including insects, weeds, and diseases), agricultural systems (crops and farming practices), and environmental sustainability reflects the complexity of this field. Pest-related factors are central to agricultural productivity, while agricultural systems provide the context in which pest management strategies are implemented [20]. Environmental impact and sustainability considerations ensure that these strategies are evaluated not only in terms of effectiveness but also in terms of their ecological consequences [28, 29].

Despite the growing body of literature, research on the intersection of IPM, climate change, and environmental impacts remains fragmented across disciplines, regions, and methodological approaches. Existing studies often focus on specific components, such as pest biology, climate modeling, or environmental assessment, without providing a comprehensive understanding of how these elements interact at the global scale. This fragmentation limits the ability to identify overarching trends, research gaps, and emerging themes within the field.

Bibliometric analysis offers a systematic and quantitative approach to mapping the intellectual structure and evolution of scientific research. By analyzing publication patterns, collaboration networks, keyword co-occurrence, and citation relationships, bibliometric methods enable the identification of dominant themes, influential studies, and emerging research directions. Such approaches are particularly valuable in interdisciplinary fields, where knowledge is dispersed across multiple domains. In recent years, bibliometric analysis has been increasingly used to explore sustainability-related topics, providing insights into research dynamics and supporting evidence-based decision-making [30–33].

This study aims to provide a comprehensive bibliometric analysis of the research landscape on integrated pest management, climate change, and environmental impacts. Specifically, the study examines publication trends, key sources, author and country contributions, thematic structures, citation patterns, and conceptual relationships within the field. By integrating quantitative network analysis with qualitative synthesis, this study contributes to a deeper understanding of how research in this domain has evolved over time.

The novelty of this study lies in its integrative approach, which simultaneously examines the interconnections between IPM, climate change, and environmental sustainability within a unified analytical framework. Previous bibliometric studies have examined aspects of sustainable agriculture, pest management, and climate-related research; however, these analyses often treat these domains separately or do not explicitly focus on the integrative nexus between IPM, climate change, and environmental sustainability. As a result, the intellectual structure and thematic evolution of this interconnected research area remain insufficiently explored.

Therefore, this study addresses this gap by providing a comprehensive bibliometric analysis that maps the development, conceptual structure, and emerging trends of IPM research within the context of climate change and environmental challenges. Unlike previous studies that

focus on single dimensions, this research captures the multidimensional nature of pest management under changing environmental conditions. Furthermore, the use of thematic evolution and conceptual structure analysis provides new insights into the dynamic development of research themes and their relationships.

Overall, this study provides a comprehensive overview of the scientific landscape in this field and identifies key directions for future research. The findings are expected to support researchers, policymakers, and practitioners in developing more sustainable and climate-resilient pest management strategies.

2. Materials and Methods

2.1. Data Collection and Search Strategy

This study employed a bibliometric approach to analyze the scientific literature on integrated pest management (IPM), climate change, and environmental impacts. The data were retrieved from the Scopus database in April 2026, which is widely recognized as one of the largest and most comprehensive sources of peer-reviewed scientific publications.

The analysis was limited to the Scopus database and English-language publications to ensure data consistency, standardized indexing, and compatibility with bibliometric tools such as VOSviewer and Bibliometrix. Scopus provides broad coverage of peer-reviewed literature across agricultural and environmental sciences and is widely used in bibliometric studies.

However, this selection may introduce a degree of database and language bias, particularly by underrepresenting research published in non-English languages or in regionally indexed journals. This is especially relevant in the context of IPM and climate-related agricultural research, which is actively conducted in regions where local-language publications are prevalent.

The search string was developed through an iterative process. Initially, key terms related to Integrated Pest Management (IPM), climate change, and environmental aspects were identified based on prior literature and domain knowledge. These terms were then combined using Boolean operators (AND, OR) to construct a preliminary query.

Pilot searches were conducted to evaluate the relevance and coverage of the retrieved records. Based on the results, the search string was refined by adjusting keyword combinations, adding synonyms, and removing ambiguous terms to improve precision and recall. The

final query was selected as it provided a balanced representation of the research domain.

The search query was constructed to capture the intersection between IPM, climate change, pest-related dynamics, agricultural systems, and environmental sustainability. The following query was applied:

("integrated pest management" OR IPM) AND ("climate change" OR "climate variability") AND (pest* OR insect* OR weed* OR disease*) AND (agriculture OR crop*) AND ("environmental impact" OR "ecological impact" OR "environmental sustainability")

The initial search across all fields yielded 3,448 documents, which were subsequently refined to 549 documents using the TITLE-ABS-KEY restriction to ensure relevance. Further filtering was applied to include only final published articles (243 documents) and English-language publications (239 documents). No restriction was applied to the publication year, resulting in a dataset covering the period from 2003 to 2026.

To ensure thematic specificity, the search strategy was intentionally designed with a high-precision approach by requiring the co-occurrence of key concepts related to IPM, climate change, agriculture, and environmental impact within the TITLE-ABS-KEY fields. While this approach may limit recall by excluding studies that address these themes implicitly, it enhances the relevance and internal consistency of the dataset for bibliometric mapping.

An exploratory search using broader query combinations (e.g., removing environmental or agricultural constraints) resulted in a substantially larger dataset but introduced a significant proportion of records not directly aligned with the IPM–climate–environment nexus. Therefore, the final query represents a trade-off between inclusiveness and conceptual precision, which is consistent with established practices in focused bibliometric analyses.

2.2. Data Processing and Analysis Tools

The bibliographic data were exported from Scopus in CSV format and processed using Microsoft Excel, VOSviewer (version 1.6.20), and R software through the Bibliometrix package (Biblioshiny interface). Microsoft Excel was used for data organization, descriptive analysis, normalization, and the calculation of composite indicators, including the overall score used for ranking entities based on publication, citation, and collaboration performance.

VOSviewer was employed for network-based analyses, including co-authorship (sources, authors, and countries) and keyword co-occurrence analysis. The software enables visualization of relationships based on link

strength and clustering of related items. The clustering and normalization procedures followed the default settings of VOSviewer, which are based on the association strength method.

In addition, R Bibliometrix (Biblioshiny) was used to perform advanced bibliometric analyses, including thematic evolution, conceptual structure mapping using multiple correspondence analysis (MCA), and historiographic mapping of influential publications.

2.3. Bibliometric and Network Analysis

Several bibliometric techniques were applied to examine the structure and evolution of the research field. Publication trends were analyzed using annual publication and citation data to identify the growth trajectory of the literature over time. These data were further processed descriptively to enable comparison across years.

Source, author, and country contributions were evaluated using normalized indicators, including publication counts, citation counts, and total link strength (TLS). All indicators were scaled between 0 and 1 to ensure comparability and were combined into a composite overall score to support ranking and comparative assessment.

The composite overall score (OS) was calculated as the average of normalized publication count (N.Pub), normalized citation count (N.Cit), and normalized total link strength (N.TLS), as expressed in Equations (1)–(2):

$$OS = \frac{N.Pub + N.Cit}{2} \quad (1)$$

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

All indicators were normalized using min–max scaling (range 0–1) to ensure comparability across metrics. Equal weighting was applied to provide a balanced representation of productivity (publications), scientific impact (citations), and collaborative connectivity (total link strength), without prioritizing any single dimension.

It should be noted that the use of equal weighting represents a simplifying assumption. Alternative weighting schemes may yield slightly different ranking outcomes, and future studies may explore the sensitivity of composite indicators to different weighting configurations.

Co-authorship analysis was conducted to explore collaboration patterns among authors, sources, and countries. A minimum threshold of one document and zero citations was applied to include all contributing

entities in the collaboration network. The threshold parameters used in the network analyses were intentionally set at relatively low levels (e.g., minimum of one document for co-authorship and three occurrences for keywords) to ensure broad inclusion of entities and to capture the overall structure of the research field. This approach is particularly suitable for exploratory bibliometric mapping, where the objective is to identify general patterns, thematic diversity, and emerging connections rather than to focus exclusively on highly prominent nodes.

It is acknowledged that lower thresholds may introduce a degree of noise and increase network density. However, preliminary testing with stricter thresholds resulted in more fragmented networks and the exclusion of emerging or less-represented topics, which are important for understanding the evolving nature of the field. Therefore, the selected thresholds represent a trade-off between inclusiveness and interpretability, consistent with the exploratory scope of this study.

Keyword co-occurrence analysis was performed using author keywords to identify major research themes and their interrelationships. A minimum occurrence threshold of three was applied to ensure the inclusion of relevant and frequently used keywords. To improve consistency, a synonym unification process was conducted using an external TXT file to merge equivalent terms. All analyses employed the full counting method, where each occurrence or link was fully counted without fractional weighting.

2.4. Thematic and Conceptual Structure Analysis

The thematic structure of the research field was examined using keyword co-occurrence networks generated by VOSviewer. The resulting keyword clusters were interpreted to represent major thematic areas, and further synthesized through qualitative analysis to provide a structured understanding of research themes.

To analyze the temporal evolution of research topics, thematic evolution analysis was conducted using Biblioshiny. The dataset was divided into three time periods: 2003–2012, 2013–2018, and 2019–2026. These intervals were selected to capture the early development phase, the transitional stage, and the recent expansion of the field.

Furthermore, conceptual structure analysis was performed using multiple correspondence analysis (MCA) to identify relationships among key concepts and to map the intellectual structure of the research domain based on their distribution across dimensions and clusters.

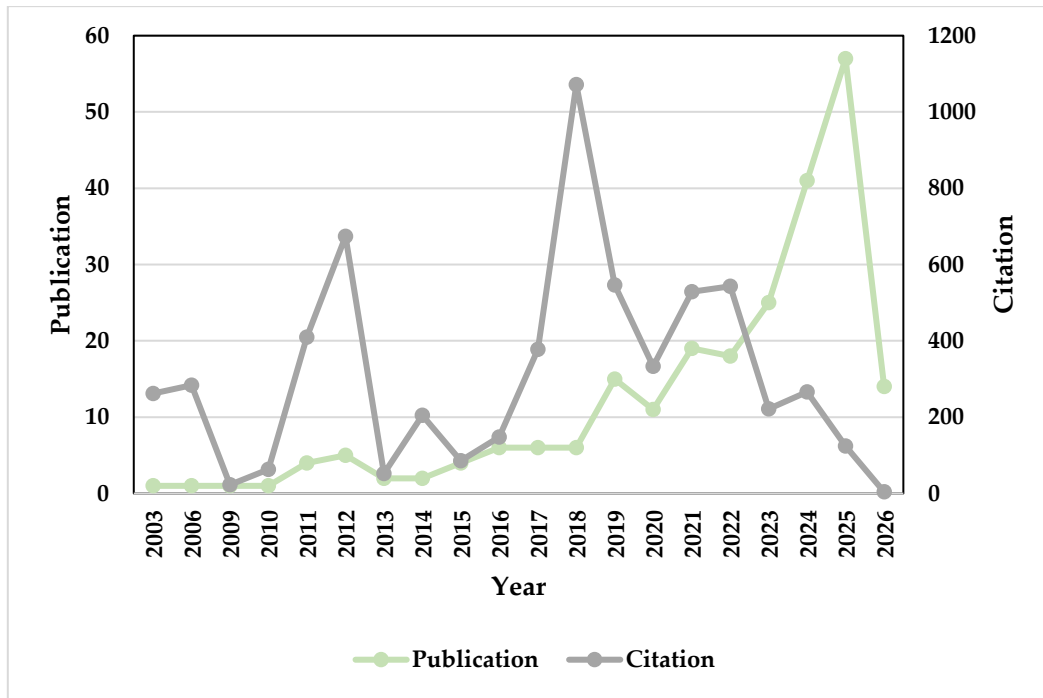


Figure 1. Annual publications and citations in the integrated pest management, climate change, and environmental impacts.

The conceptual structure was analyzed using Multiple Correspondence Analysis (MCA) to explore relationships among keywords and to reduce high-dimensional data into a lower-dimensional conceptual space. The interpretation of dimensions was based on the relative positioning, proximity, and clustering of keywords. Consistent with common practice in bibliometric studies, the first two dimensions were retained for interpretation as they provide the most meaningful visualization of the conceptual structure.

2.5. Citation Analysis and Qualitative Synthesis

Citation analysis was conducted to identify influential publications within the field based on total citation counts. Highly cited articles were systematically compiled and comparatively analyzed to highlight their contributions to the development of the research domain.

In addition, a qualitative synthesis of selected highly cited publications was performed by identify research focus, principal findings, and their contributions to the interconnections between integrated pest management, climate change, and environmental impacts. This approach allows for a deeper interpretation of the knowledge structure beyond quantitative metrics.

3. Results and Discussion

3.1. Publication Trends

The temporal evolution of publications and citations in the field of integrated pest management under climate

change and environmental impact contexts is illustrated in [Figure 1](#). Overall, the results reveal a clear transition from a relatively slow growth phase to a rapidly expanding research domain in recent years.

During the early period (2003–2012), research output remained limited, with annual publications ranging from one to five documents. Despite the low volume, several years exhibited relatively high citation counts, notably 2006 (284 citations) and 2012 (674 citations), indicating the presence of influential foundational studies that have shaped subsequent research developments.

The period from 2013 to 2018 marks a phase of gradual expansion, with publications increasing modestly to between two and six per year. A significant citation peak is observed in 2018 (1,072 citations), suggesting the emergence of highly impactful studies that contributed to consolidating the field, particularly in relation to sustainability and environmental considerations.

A pronounced acceleration in publication output is evident from 2019 onwards. The number of publications increased substantially from 15 in 2019 to a peak of 57 in 2025, reflecting a growing scholarly interest in the intersection of integrated pest management, climate change, and environmental sustainability. While citation counts in the most recent years (e.g., 2025–2026) remain comparatively low, this pattern is consistent with the shorter time window available for citation accumulation.

The most recent phase (2023–2026) represents the highest level of research productivity across the entire

Table 1. Top five years in the integrated pest management, climate change, and environmental impacts research.

| Year | Publication | Citation | N.Pub | N.Cit | OS |
|------|-------------|----------|-------|-------|------|
| 2025 | 57 | 124 | 1.00 | 0.11 | 0.56 |
| 2018 | 6 | 1072 | 0.09 | 1.00 | 0.54 |
| 2024 | 41 | 266 | 0.71 | 0.25 | 0.48 |
| 2021 | 19 | 529 | 0.32 | 0.49 | 0.41 |
| 2022 | 18 | 543 | 0.30 | 0.50 | 0.40 |

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

Table 2. Top sources based on normalized publication and citation metrics in the integrated pest management, climate change, and environmental impacts research.

| Journals | Publication | Citation | N.Pub | N.Cit | OS |
|---------------------------------------|-------------|----------|-------|-------|------|
| Pest Management Science | 8 | 60 | 1.00 | 0.08 | 0.54 |
| Frontiers in Sustainable Food Systems | 8 | 41 | 1.00 | 0.06 | 0.53 |
| Journal of Economic Entomology | 2 | 651 | 0.14 | 0.88 | 0.51 |
| Nature Sustainability | 1 | 744 | 0.00 | 1.00 | 0.50 |
| Journal of Integrated Pest Management | 7 | 51 | 0.86 | 0.07 | 0.46 |

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

Table 3. Top authors based on normalized publication, citation, and collaboration metrics in the integrated pest management, climate change, and environmental impacts research.

| Journals | Publication | Citation | TLS | N.Pub | N.Cit | N.TLS | OS |
|------------------------|-------------|----------|-----|-------|-------|-------|------|
| Gaillard, Gérard | 2 | 109 | 25 | 1.00 | 0.15 | 0.93 | 0.69 |
| Sutanto, K.D. | 2 | 5 | 27 | 1.00 | 0.01 | 1.00 | 0.67 |
| Wiratno | 2 | 5 | 27 | 1.00 | 0.01 | 1.00 | 0.67 |
| Tonnang, Henri E. Z. | 2 | 20 | 23 | 1.00 | 0.03 | 0.85 | 0.63 |
| Ghafar, Muhammad Adeel | 2 | 5 | 23 | 1.00 | 0.01 | 0.85 | 0.62 |

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

study period, highlighting the increasing relevance of this topic within the broader agricultural and environmental research landscape. Complementary insights are provided in [Table 1](#), which identifies the top five years based on normalized metrics, offering a more nuanced understanding of research impact beyond absolute publication and citation counts.

Collectively, these findings indicate a shift from foundational research toward a more mature and rapidly growing field, characterized by increasing research intensity and expanding thematic relevance.

3.2. Sources, Authors, and Country Contributions

The distribution of publications across journals, authors, and countries provides insight into the structural composition of research on integrated pest management (IPM), climate change, and environmental impacts.

As shown in [Table 2](#), the most productive journals are *Pest Management Science* and *Frontiers in Sustainable Food Systems*, each contributing 8 publications and achieving the highest normalized publication score (N.Pub = 1.00). Despite their relatively moderate citation counts, both journals exhibit strong overall performance (OS = 0.54 and 0.53, respectively), indicating a balanced contribution in terms of productivity and impact. In contrast, *Nature*

Sustainability and the *Journal of Economic Entomology* demonstrate exceptionally high citation performance (744 and 651 citations, respectively), reflected in their top normalized citation scores (N.Cit = 1.00 and 0.88), although their publication counts remain limited. This suggests that while some journals dominate in productivity, others exert disproportionate influence through highly cited contributions.

At the author level ([Table 3](#)), productivity is relatively evenly distributed, with all top authors contributing two publications each. However, differences emerge when considering citation and collaboration metrics. Gaillard, G. stands out with the highest citation count (109) and a strong collaboration profile (TLS = 25), resulting in the highest overall score (OS = 0.69). Similarly, Sutanto, K.D. and Wiratno achieve the highest collaboration intensity (TLS = 27; N.TLS = 1.00), highlighting their central roles in co-authorship networks despite lower citation counts. Tonnang, H.E.Z. also demonstrates notable influence through a combination of citations and collaboration strength. These patterns indicate that both citation impact and collaborative connectivity contribute to author prominence in this research field.

The co-authorship structure visualized in [Figure 2](#) further supports these findings, revealing a network composed

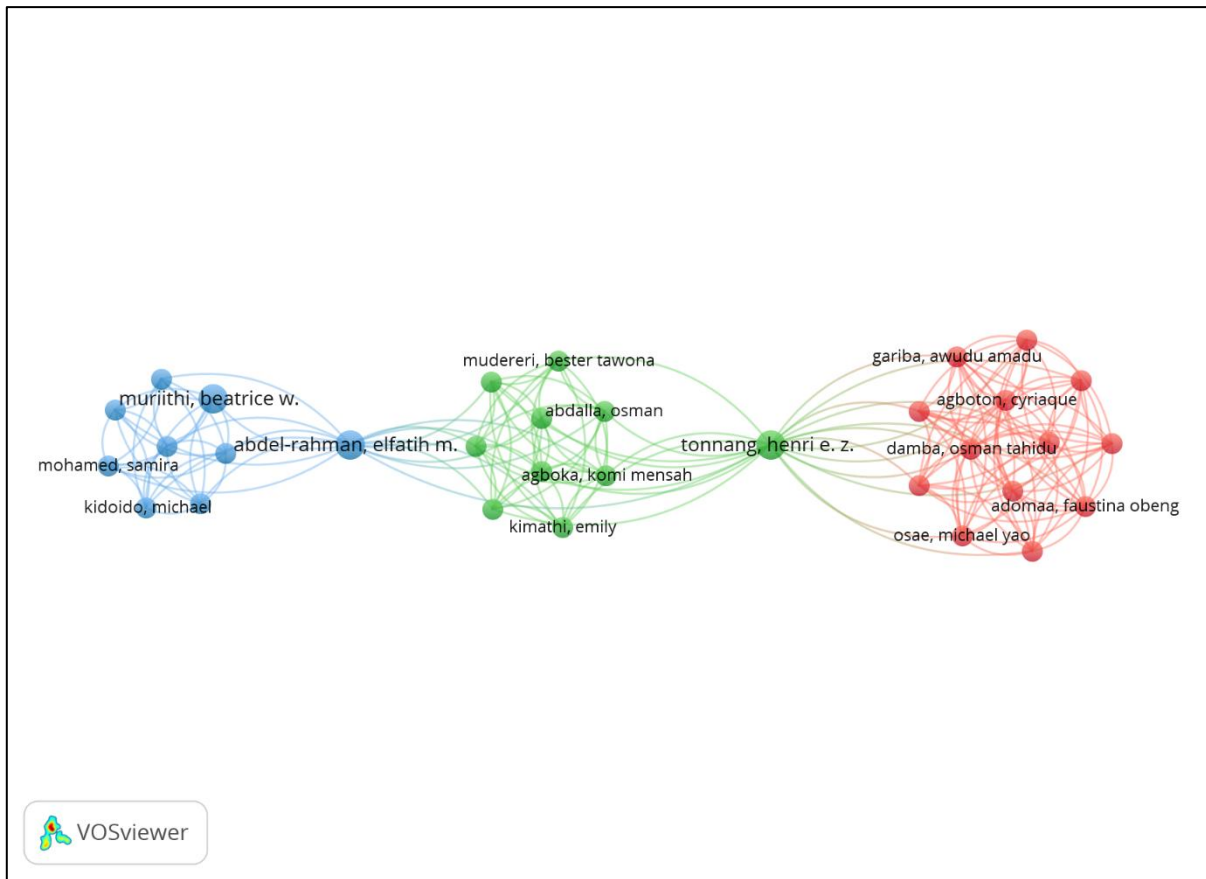


Figure 2. Author collaboration network based on co-authorship analysis in the integrated pest management, climate change, and environmental impacts research.

Table 4. Top countries based on normalized publication, citation, and collaboration metrics in the integrated pest management, climate change, and environmental impacts research.

| Countries | Publication | Citation | TLS | N.Pub | N.Cit | N.TLS | OS |
|----------------|-------------|----------|-----|-------|-------|-------|------|
| United States | 48 | 2081 | 62 | 1.00 | 1.00 | 0.86 | 0.95 |
| Germany | 20 | 1380 | 72 | 0.40 | 0.66 | 1.00 | 0.69 |
| Australia | 16 | 884 | 59 | 0.32 | 0.42 | 0.82 | 0.52 |
| France | 21 | 594 | 58 | 0.43 | 0.29 | 0.81 | 0.51 |
| United Kingdom | 14 | 1178 | 46 | 0.28 | 0.57 | 0.64 | 0.49 |

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

of 32 authors grouped into 3 distinct clusters with 182 links. The relatively dense network suggests active collaboration among researchers, with several authors exhibiting high link strength values, indicating their bridging roles across clusters.

From a geographical perspective, [Table 4](#) shows that the United States dominates the field, leading in publications (48), citations (2081), and overall score (OS = 0.95). Germany follows with the highest collaboration strength (TLS = 72; N.TLS = 1.00), indicating a central role in international research networks. Other key contributors include Australia, France, and the United Kingdom, each demonstrating a balance between productivity, citation impact, and collaboration.

The global collaboration pattern is further illustrated in [Figure 3](#), which maps co-authorship relationships across 71 countries, forming 10 clusters with 367 links and a total link strength of 514. The network indicates a high degree of international collaboration, with several countries acting as hubs that connect different regional clusters. Countries such as the United States, Germany, and Australia exhibit strong connectivity, while emerging contributors (e.g., Indonesia, Kenya, and Ethiopia) show increasing participation in recent years, as reflected in their average publication years.

Overall, these results highlight a research landscape characterized by a combination of highly influential journals, collaborative author networks, and strong international participation, with leading contributions

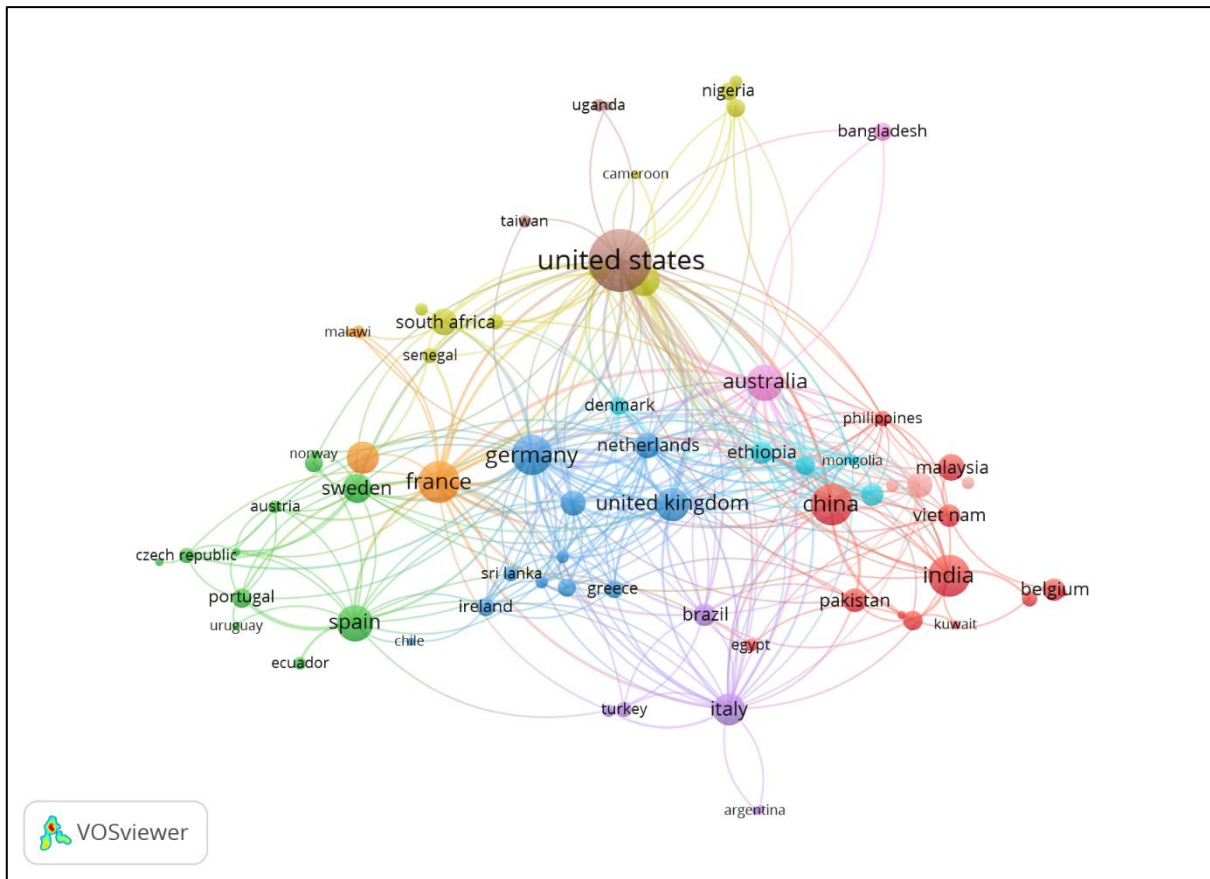


Figure 3. Country collaboration network based on co-authorship analysis in the integrated pest management, climate change, and environmental impacts research.

concentrated in a few key countries while broader global engagement continues to expand.

3.3. Thematic Structure and Evolution of Research

The thematic structure of research on integrated pest management (IPM), climate change, and environmental impacts is illustrated through keyword co-occurrence analysis and thematic evolution. The interpretation of thematic clusters is inherently interpretative and based on the co-occurrence patterns of keywords generated through VOSviewer. While clustering algorithms group terms based on statistical proximity, the labeling and conceptual interpretation of clusters require analytical judgment. Therefore, the thematic labels presented in this study should be understood as indicative rather than definitive representations of underlying research domains.

As shown in Figure 4, the keyword co-occurrence network consists of 820 items grouped into 59 clusters, with 3,246 links and a total link strength (TLS) of 3,319, indicating a highly interconnected research landscape. Among all keywords, *integrated pest management* emerges as the most dominant term, with the highest occurrences (69), links (30), and total link strength (71), confirming its

central role in the literature. Other highly connected keywords include *biological control*, *biodiversity*, *ecosystem services*, and *pesticides*, suggesting that ecological approaches and environmental considerations are closely linked to IPM research.

The clustering structure, summarized in Table 5, reveals seven major thematic groups. Cluster 1 focuses on agroecological and sustainability-oriented pest management, characterized by keywords such as *agroecology*, *organic farming*, and *life cycle assessment*. Cluster 2 highlights climate adaptation and sustainable innovation, with terms such as *climate change*, *climate-smart agriculture*, and *biopesticide*, indicating growing attention to adaptive strategies in response to environmental change.

Cluster 3 centers on environmental impacts and pesticide-based pest management, reflecting concerns related to *pesticides*, *environmental impact*, and crop-specific contexts such as *rice*. Cluster 4 represents agricultural systems and climate-related crop protection, linking *agriculture*, *sustainable agriculture*, and *temperature* as key drivers of pest dynamics.

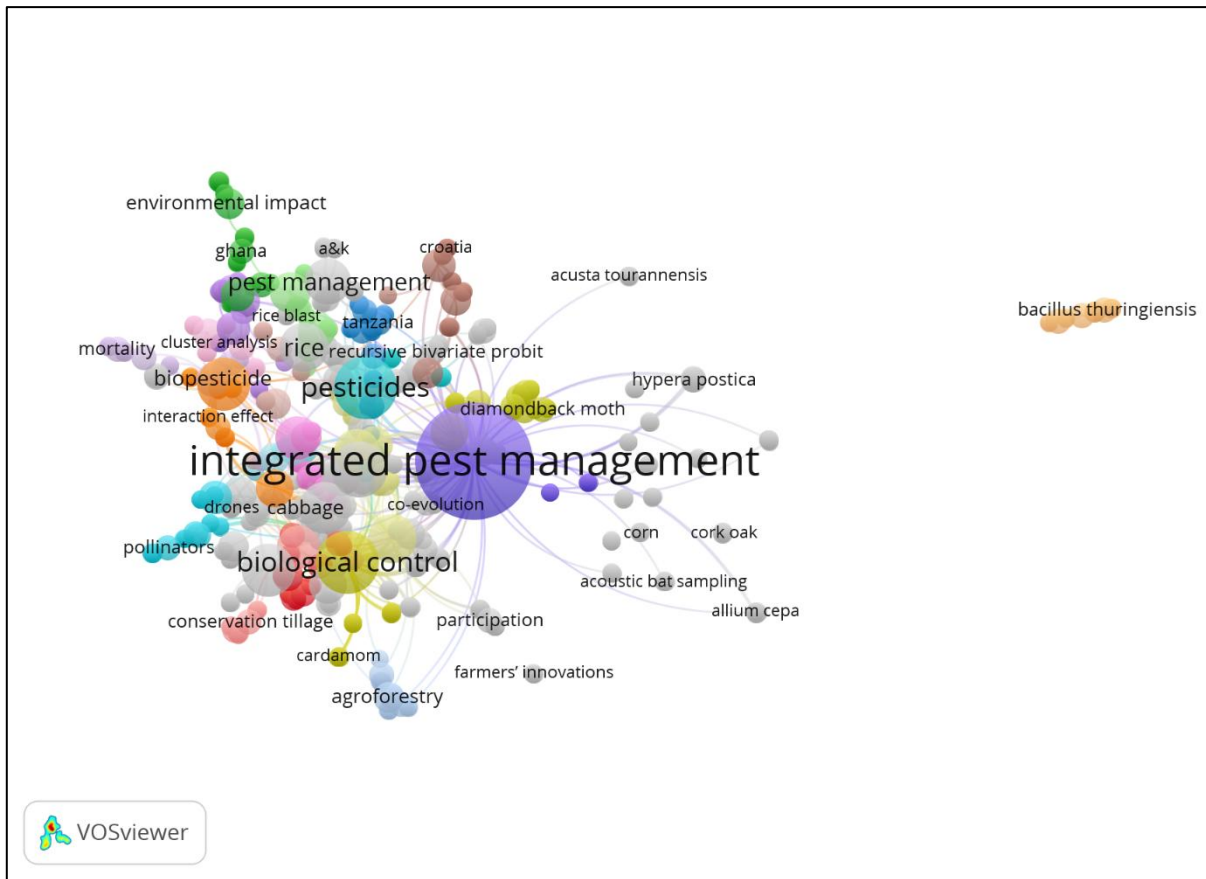


Figure 4. Network visualization of keyword co-occurrence in the integrated pest management, climate change, and environmental impacts research.

Table 5. Keyword clusters in the integrated pest management, climate change, and environmental impacts research.

| Cluster | Main Keywords | Thematic Interpretation |
|-----------|---|---|
| Cluster 1 | agroecology, sustainability, organic farming, life cycle assessment | Agroecological and sustainability-oriented pest management |
| Cluster 2 | climate change, climate-smart agriculture, adoption, biopesticide, environmental sustainability | Climate adaptation and sustainable innovation in IPM |
| Cluster 3 | pesticides, pest management, rice, environment, environmental impact | Environmental impacts and pesticide-based pest management |
| Cluster 4 | agriculture, sustainable agriculture, IPM, crop protection, temperature | Agricultural systems and climate-related crop protection |
| Cluster 5 | biological control, plant protection, invasive species, risk assessment, solanum tuberosum | Biological control and pest risk management |
| Cluster 6 | biodiversity, ecosystem services, soil health, maize, predators | Ecosystem services and biodiversity in pest regulation |
| Cluster 7 | integrated pest management, biocontrol, ecological intensification, semiochemicals | Core IPM strategies and ecological pest control innovations |

Cluster 5 emphasizes biological control and pest risk management, incorporating terms such as *biological control*, *invasive species*, and *risk assessment*, while Cluster 6 focuses on ecosystem services and biodiversity, highlighting the ecological regulation of pests through *biodiversity*, *soil health*, and *predators*. Finally, Cluster 7 represents the core IPM strategies and ecological innovations, including *biocontrol*, *ecological intensification*, and *semiochemicals*, which are closely integrated with the central concept of IPM.

The temporal development of these themes is further illustrated in Figure 5, which presents the thematic evolution across three time periods (2003–2012, 2013–2018, and 2019–2026). The results indicate strong thematic continuity of *integrated pest management*, which persists across all periods with a perfect inclusion index (1.00), highlighting its foundational role in the field. Over time, the concept evolves by incorporating related approaches such as *biological control*, reflecting

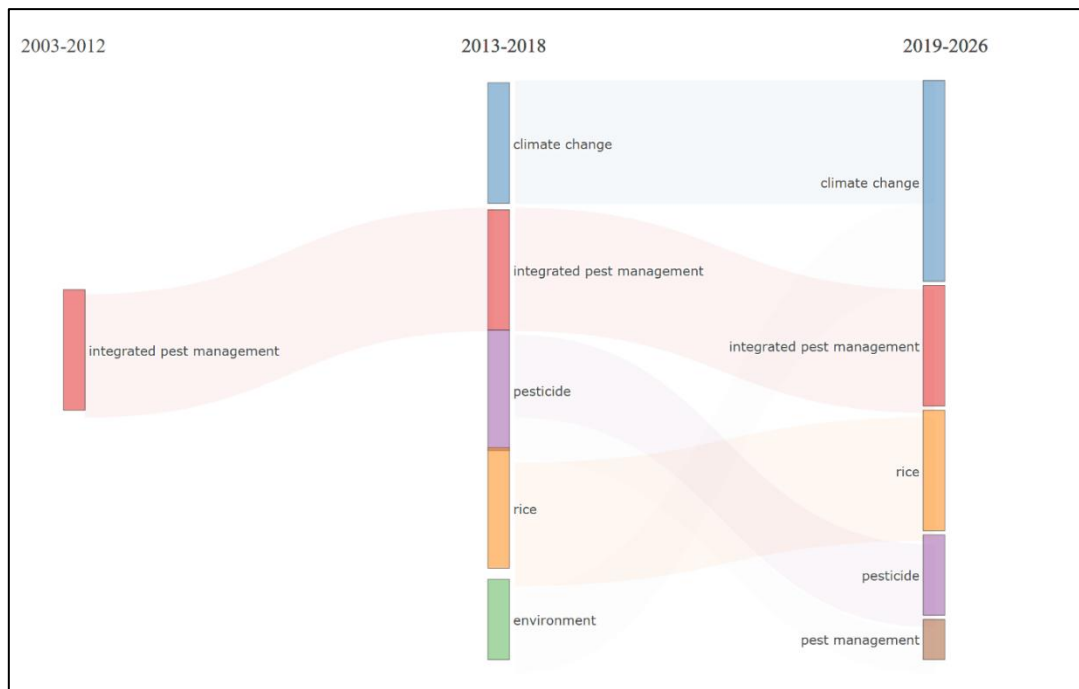


Figure 5. Thematic evolution (2003-2026) in the integrated pest management, climate change, and environmental impacts research.

increasing integration of ecological strategies within IPM frameworks.

Similarly, *climate change* demonstrates a stable and continuous trajectory from the middle to the most recent period, indicating its growing importance as a contextual driver of pest management research. The linkage between *environment* and *climate change* suggests a conceptual shift from general environmental concerns toward more specific climate-related challenges.

In contrast, themes related to *pesticides* show partial continuity, with lower inclusion and stability indices, indicating a gradual transition from conventional pesticide-based approaches toward broader *pest management* strategies. Meanwhile, crop-specific themes such as *rice* remain stable but relatively specialized, reflecting their importance in particular agricultural contexts rather than across the entire field.

Overall, the results reveal a clear evolution from conventional, pesticide-centered approaches toward more integrated, ecological, and climate-responsive pest management strategies. The strong persistence of core themes alongside the emergence of sustainability- and climate-oriented concepts highlights the dynamic yet coherent development of the research field.

3.4. Citation Analysis and Influential Publications

The citation analysis highlights the most influential publications shaping research on integrated pest management (IPM), climate change, and environmental

impacts. As presented in Table 6, the most highly cited publication is Pretty et al. [34], with 744 citations, followed by Zalucki et al. [35] with 541 citations. Other highly influential studies include Dislich et al. [36], Kramer et al. [37], and Lotter [38], each contributing more than 250 citations.

These publications span a wide temporal range (2003–2019), indicating that both foundational and more recent studies continue to shape the field. The diversity of source titles, including *Nature Sustainability*, *Journal of Economic Entomology*, and *Biological Reviews*, suggests that influential research is distributed across interdisciplinary journals covering sustainability, ecology, and agricultural sciences.

The historiographic structure shown in Figure 6 further illustrates the intellectual development of the field. Early contributions, such as Lotter [38], form the foundational cluster emphasizing organic agriculture and agroecological principles. Subsequent studies expand on these foundations by integrating environmental assessment approaches, such as life cycle assessment and ecosystem-based management. Over time, the network evolves to include more applied and system-oriented studies, linking IPM with climate change, environmental impact, and agricultural sustainability. The clustering pattern indicates a progression from conceptual and ecological foundations toward more integrated and interdisciplinary research themes.

A more detailed synthesis of influential studies is provided in Table 7, which categorizes key publications

Table 6. Top influential publications in in the integrated pest management, climate change, and environmental impacts research.

| No. | Authors | Title | Year | Source Title | Cited by | Ref. |
|-----|---------------------|---|------|---|----------|------|
| 1 | Pretty et al. | Global assessment of agricultural system redesign for sustainable intensification | 2018 | Nature Sustainability | 744 | [34] |
| 2 | Zalucki et al. | Estimating the economic cost of one of the world's major insect pests, <i>Plutella xylostella</i> (Lepidoptera: Plutellidae): Just how long is a piece of string? | 2012 | Journal of Economic Entomology | 541 | [35] |
| 3 | Dislich et al. | A review of the ecosystem functions in oil palm plantations, using forests as a reference system | 2017 | Biological Reviews | 287 | [36] |
| 4 | Kramer et al. | Reduced nitrate leaching and enhanced denitrifier activity and efficiency in organically fertilized soils | 2006 | Proceedings of the National Academy of Sciences of the United States of America | 284 | [37] |
| 5 | Lotter | Organic agriculture | 2003 | Journal of Sustainable Agriculture | 262 | [38] |
| 6 | Birch et al. | How agro-ecological research helps to address food security issues under new IPM and pesticide reduction policies for global crop production systems | 2011 | Journal of Experimental Botany | 198 | [39] |
| 7 | Ricci et al. | Trust to Go Green: An Exploration of Consumer Intentions for Eco-friendly Convenience Food | 2018 | Ecological Economics | 194 | [40] |
| 8 | de Bon et al. | Pesticide risks from fruit and vegetable pest management by small farmers in sub-Saharan Africa: A review | 2014 | Agronomy for Sustainable Development | 177 | [41] |
| 9 | Despotović et al. | Factors affecting farmers' adoption of integrated pest management in Serbia: An application of the theory of planned behavior | 2019 | Journal of Cleaner Production | 165 | [42] |
| 10 | Van den Berg et al. | Chemical Control and Insecticide Resistance in <i>Spodoptera Frugiperda</i> (Lepidoptera: Noctuidae) | 2022 | Journal of Economic Entomology | 110 | [43] |

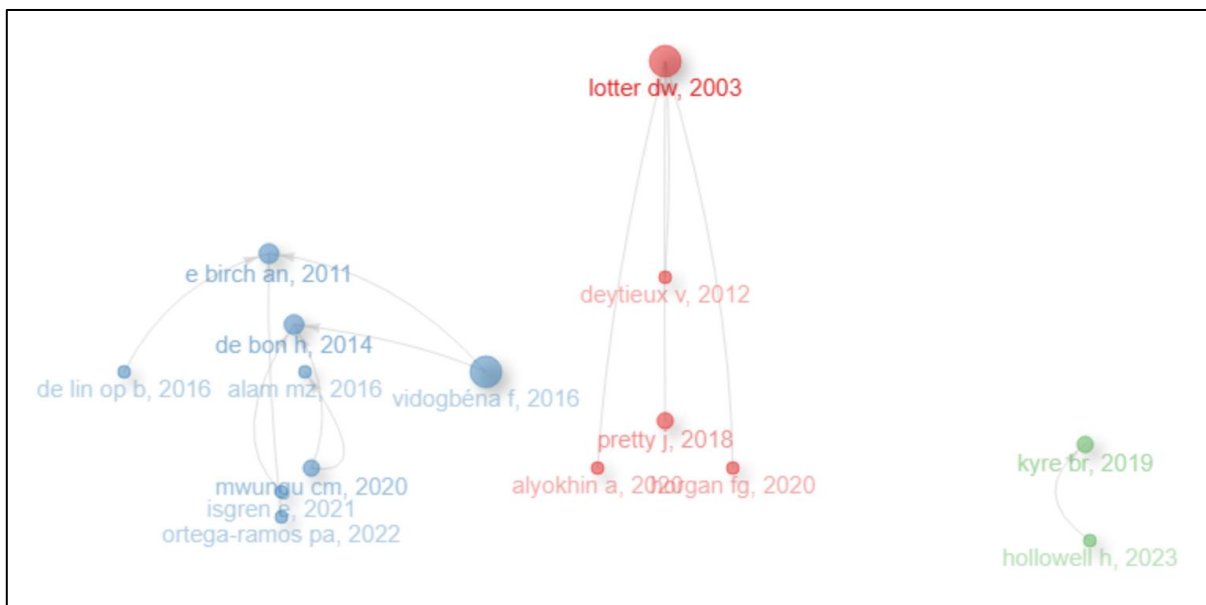


Figure 6. Historiographic map of influential publications in the integrated pest management, climate change, and environmental impacts research.

based on their focus areas, findings, and contributions to the IPM-climate-environment nexus. The results show that several core themes dominate highly cited research. First, sustainable intensification and system redesign emerge as central topics, emphasizing the need to integrate ecological principles into agricultural systems. Second, economic analyses of pest impacts highlight the

significant financial burden of pest outbreaks and the role of IPM in reducing costs and environmental externalities. Third, studies on ecosystem functions and land-use change underscore the importance of maintaining biodiversity and ecosystem services in agricultural landscapes.

Table 7. Synthesis of highly cited publications in the integrated pest management, climate change, and environmental impacts research.

| No. | Author and Year | Focus Area | Key Findings | Contribution to IPM, Climate, and Environmental Nexus | Ref. |
|-----|----------------------------|--|--|--|------|
| 1 | Pretty et al. (2018) | Sustainable intensification and agricultural system redesign | Sustainable intensification requires systemic redesign beyond efficiency improvements; large-scale adoption already occurring globally | Demonstrates how IPM and related practices support environmentally sustainable agriculture and resilience under changing climatic conditions | [34] |
| 2 | Zalucki et al. (2012) | Economic impact of pest outbreaks under climate influence | Global cost of <i>Plutella xylostella</i> exceeds USD 4-5 billion annually; climate-driven pest dynamics significantly affect losses | Highlights economic and environmental benefits of IPM in reducing pesticide use and mitigating climate-driven pest risks | [35] |
| 3 | Dislich et al. (2017) | Ecosystem functions and land-use change | Oil palm expansion reduces most ecosystem functions compared to forests; management practices can mitigate impacts | Shows role of IPM and ecological practices in maintaining ecosystem services and reducing environmental degradation | [36] |
| 4 | Kramer et al. (2006) | Organic vs conventional farming and environmental impact | Organic and integrated systems reduce nitrate leaching and improve soil microbial activity | Provides evidence that IPM-related practices reduce environmental pollution and enhance agroecosystem sustainability | [37] |
| 5 | Lotter (2003) | Organic agriculture and sustainability | Organic farming reduces pesticide use, pollution, and biodiversity loss while maintaining economic viability | Establishes foundation for environmentally sustainable pest management approaches aligned with IPM principles | [38] |
| 6 | Birch et al. (2011) | IPM and food security under global change | IPM reduces pesticide use, enhances yields, and integrates ecological services for pest control | Positions IPM as a key strategy for sustainable agriculture under climate change and resource constraints | [39] |
| 7 | Ricci et al. (2018) | Consumer behavior and eco-friendly food systems | Consumer trust influences adoption of IPM-labelled products; environmental awareness shapes purchasing decisions | Connects IPM with market-driven sustainability and environmental awareness in food systems | [40] |
| 8 | de Bon et al. (2014) | Pesticide risks in smallholder agriculture | Excessive pesticide use increases environmental and health risks; IPM and agroecology reduce these risks | Highlights IPM as a solution to reduce environmental and human health impacts in developing regions | [41] |
| 9 | Despotović et al. (2019) | Farmer adoption of IPM practices | Behavioral factors influence adoption; attitudes and norms more important than knowledge | Emphasizes socio-economic drivers in scaling environmentally sustainable IPM practices | [42] |
| 10 | Van den Berg et al. (2022) | Pest resistance and insecticide overuse | Over-reliance on insecticides drives resistance; IPM offers more sustainable long-term control | Reinforces IPM as a critical strategy to reduce environmental impact and improve resilience to pest outbreaks under climate variability | [43] |

In addition, environmental impact assessments demonstrate that integrated and organic farming systems can significantly reduce pollution and improve soil health compared to conventional practices. Research on IPM and food security further highlights its role in balancing productivity and sustainability under climate change pressures. Meanwhile, socio-economic studies emphasize the importance of behavioral and institutional factors in influencing farmer adoption of IPM practices.

More recent contributions, such as Van den Berg et al. [43], reflect increasing attention to emerging challenges, including pest resistance and the limitations of chemical control strategies. These studies reinforce the importance of integrated and diversified pest management approaches in enhancing resilience to climate variability and reducing environmental impacts.

Overall, the citation analysis reveals a coherent body of literature that has progressively evolved from foundational agroecological concepts toward integrated, climate-responsive, and sustainability-oriented pest management frameworks. The persistence of highly cited early studies alongside newer contributions indicates both continuity and innovation within the field.

3.5. Conceptual Structure

The conceptual structure of research on integrated pest management (IPM), climate change, and environmental impacts is examined using Multiple Correspondence Analysis (MCA), as presented in Figure 7. The analysis maps the relationships among key keywords across two principal dimensions (Dim1 and Dim2), revealing the underlying conceptual organization of the field.

The MCA results indicate that the research landscape is primarily structured along two main axes. Dim1 appears

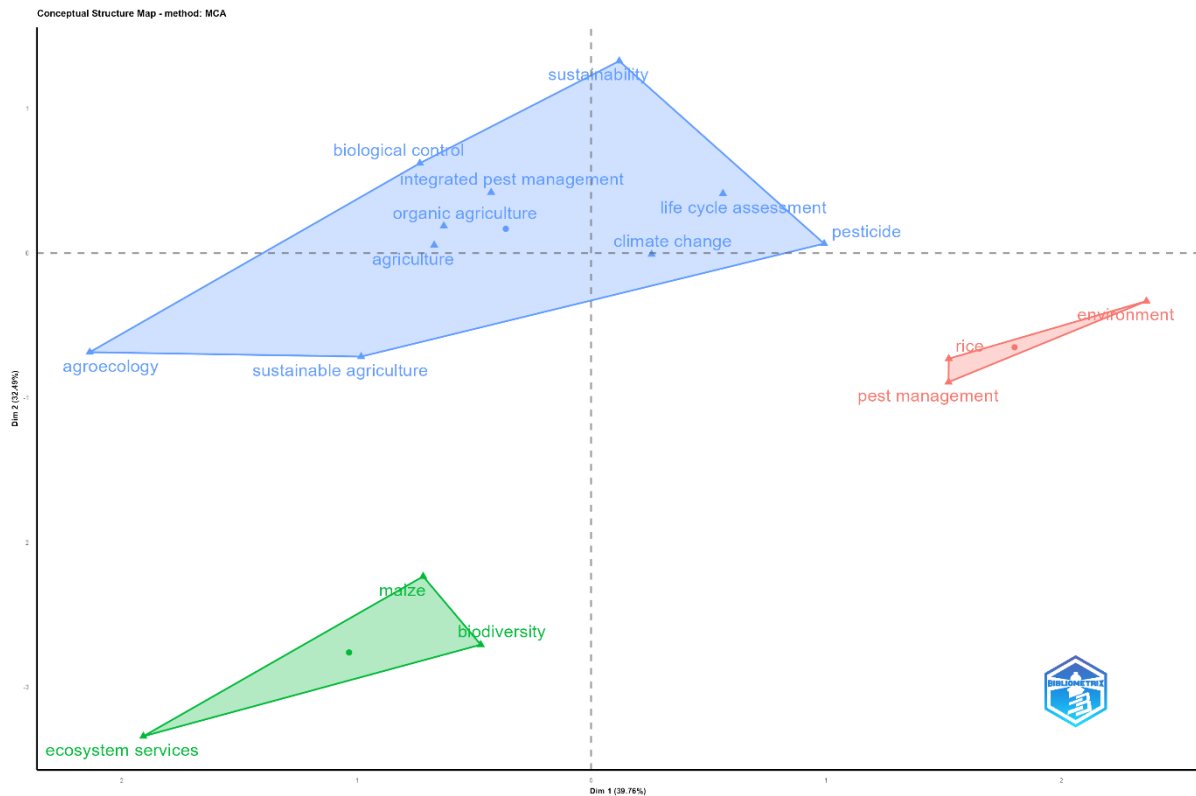


Figure 7. Conceptual structure of the integrated pest management, climate change, and environmental impacts based on multiple correspondence analysis.

to differentiate between conventional, input-intensive approaches and more sustainable, ecology-based strategies. Keywords such as *pesticide* and *rice* are positioned on the positive side of Dim1, suggesting their association with more conventional and crop-specific management practices. In contrast, terms such as *agroecology*, *sustainable agriculture*, *organic agriculture*, and *biological control* are located on the negative side, reflecting a stronger orientation toward ecological and sustainability-driven approaches.

Dim2, on the other hand, distinguishes between ecosystem-level perspectives and management-focused strategies. Keywords such as *biodiversity* are positioned at the lower end of Dim2, indicating their strong association with ecosystem functions and ecological processes. Meanwhile, terms such as *integrated pest management* and *biological control* are located in the upper part of the map, representing applied pest management strategies that integrate ecological principles into practice.

The clustering pattern further supports this conceptual differentiation. The majority of core keywords, including *integrated pest management*, *pesticide*, *biological control*, *organic agriculture*, *sustainable agriculture*, *climate change*, and *agroecology*, are grouped within Cluster 1, indicating a highly interconnected core research theme that

integrates environmental, agricultural, and climate-related dimensions.

In contrast, Cluster 2, represented by *rice* and *pest management*, reflects a more application-oriented and commodity-specific research focus. Meanwhile, Cluster 3, represented by *biodiversity*, highlights a distinct ecological dimension that is somewhat separated from the main cluster, emphasizing its specialized role in understanding ecosystem-based pest regulation.

Overall, the conceptual structure reveals a clear dichotomy between conventional and sustainable approaches, as well as between applied management and ecological perspectives. At the same time, the proximity of key terms such as *integrated pest management*, *climate change*, and *biological control* indicates a strong integration of these themes, suggesting that contemporary research increasingly adopts a holistic and interdisciplinary approach to addressing agricultural and environmental challenges.

3.6. Discussion

The rapid increase in publications after 2019 indicates that the integration of integrated pest management (IPM), climate change, and environmental impact has become an increasingly important global research priority. This trend reflects a growing scientific and policy

focus on sustainable agricultural practices in response to climate variability, pest outbreaks, and environmental degradation. The notable rise in publications around 2019 coincides with the increasing global emphasis on climate action and sustainability agendas, including the implementation phase of the Paris Agreement and the acceleration of the Sustainable Development Goals (SDGs) [44]. This period also aligns with accumulating evidence that climate change is altering pest distribution, increasing pest pressure, and affecting crop protection strategies [45]. As a result, IPM is increasingly recognized as a key approach for reducing environmental impacts while maintaining agricultural productivity under changing climatic conditions [46].

The distribution of sources, authors, and countries reveals that research in this field is still largely dominated by developed countries, particularly the United States, Germany, and the United Kingdom, which exhibit high publication output, citation impact, and collaboration strength. This pattern is consistent with previous bibliometric studies showing that climate change and agricultural sustainability research are often led by institutions in the Global North due to stronger research funding and infrastructure [47]. However, this dominance also highlights a persistent imbalance in global knowledge production, where regions that are most vulnerable to climate change and pest-related risks, particularly in Africa and parts of Asia, remain relatively underrepresented. At the same time, the presence of international collaboration networks suggests a gradual expansion of research participation, indicating that transnational cooperation is increasingly recognized as essential for addressing global agricultural challenges.

The thematic structure of the field highlights IPM as the central and most interconnected research theme, forming the backbone of the knowledge network. The prominence of keywords such as “integrated pest management,” “biological control,” and “ecological intensification” indicates a strong shift toward environmentally sustainable pest control strategies. At the same time, the coexistence of clusters related to “pesticides,” “pest management,” and “environmental impact” suggests that conventional approaches remain relevant, particularly in contexts where rapid pest suppression is required [48]. This duality reflects a structural tension in the field, where the need for immediate pest control often conflicts with long-term environmental sustainability goals [49, 50]. A growing body of literature has emphasized that excessive pesticide use contributes to environmental pollution, biodiversity loss, and risks to human health, reinforcing the urgency of transitioning toward more sustainable and

integrated pest management strategies.

The thematic evolution analysis further demonstrates that IPM has remained a stable and dominant research theme across all time periods, confirming its role as the backbone of sustainable pest management research. In contrast, climate change has emerged more prominently in recent years, indicating a shift toward understanding how changing climatic conditions influence pest dynamics and management practices. The observed transition from “pesticide” to broader terms such as “pest management” and sustainability-related concepts suggests a conceptual evolution from reactive control measures toward more preventive, knowledge-intensive, and ecologically based approaches. This shift reflects an increasing recognition that sustainable pest management requires the integration of ecological principles, technological innovation, and adaptive strategies under conditions of climate uncertainty [51].

The conceptual structure analysis provides further insight into the intellectual organization of the field. The first dimension appears to represent a gradient from conventional, input-intensive agricultural systems toward more sustainable and agroecological approaches, while the second dimension reflects a distinction between ecological processes and application-specific practices. Keywords such as “agroecology,” “sustainable agriculture,” and “biological control” are positioned within the sustainability-oriented domain, whereas “pesticide” and “pest management” are located closer to conventional practices. This positioning suggests that IPM functions as a conceptual bridge that integrates traditional pest control methods with emerging sustainability-oriented approaches. The coexistence of these concepts within the same analytical space confirms that the field is not characterized by a complete paradigm shift, but rather by an ongoing transition in which conventional and ecological approaches continue to interact.

Unlike previous studies that tend to examine IPM, climate change, or environmental impacts in isolation, this study provides an integrated bibliometric perspective that reveals how these domains are increasingly interconnected within the scientific literature. The findings are consistent with prior research emphasizing that IPM is a critical strategy for achieving sustainable agriculture under climate change. Studies have shown that IPM can reduce pesticide use, enhance ecosystem services, and improve resilience to climate-induced pest outbreaks. In addition, ecological approaches such as biological control and agroecology have been widely recognized for their role in supporting biodiversity conservation and long-term agricultural sustainability. At

the same time, economic analyses indicate that pest-related losses remain substantial at the global scale, highlighting the continued need for effective and scalable pest management strategies.

From a practical perspective, the increasing integration of IPM with climate change considerations has important implications for agricultural policy and management. Policymakers are encouraged to promote IPM adoption through regulatory frameworks, extension services, and financial incentives, particularly in developing regions where pesticide misuse and environmental risks are more prevalent. Furthermore, the integration of IPM with climate-smart agriculture practices can enhance the adaptive capacity of farming systems and improve resilience to climate variability. Future research should focus on developing context-specific and scalable IPM strategies that incorporate climate projections, farmer behavior, and socio-economic conditions, as well as the role of digital technologies in pest monitoring and decision-making.

Despite these contributions, several limitations should be acknowledged. First, the analysis is based on bibliographic data retrieved from a single database, which may not capture all relevant publications and may introduce database-related bias. Second, the use of predefined keywords may limit the scope of the dataset and exclude relevant studies that use different terminologies. Third, bibliometric methods primarily identify patterns and relationships within the literature and do not provide direct evidence of causal mechanisms between IPM practices, climate change, and environmental outcomes. Future studies may benefit from combining bibliometric approaches with systematic reviews or empirical analyses to better understand the causal relationships and real-world impacts of IPM under changing climatic conditions.

A key limitation of this study relates to the use of a single database (Scopus) and the restriction to English-language publications. While this approach ensures data consistency and analytical comparability, it may lead to the underrepresentation of research from regions where scientific output is frequently published in local languages or indexed in alternative databases. This limitation is particularly relevant when interpreting the observed geographic distribution of research output. The apparent dominance of countries such as the United States and Germany may partly reflect differences in database coverage and publication practices rather than purely underlying research activity. Conversely, regions such as Africa and parts of Southeast Asia may be more active in locally oriented or non-English publications that are not fully captured in Scopus. Therefore, the findings

related to geographic imbalance should be interpreted with caution, as they may reflect both actual disparities in research capacity and structural biases in bibliographic databases. Future studies incorporating multiple databases, such as Web of Science or regional indexing systems, would provide a more comprehensive representation of global research dynamics.

Overall, this study demonstrates that research on IPM, climate change, and environmental impacts is rapidly evolving toward a more integrated and sustainability-oriented paradigm. The convergence of ecological, technological, and socio-economic perspectives suggests that IPM will continue to play a central role in addressing future agricultural challenges. In this context, IPM is not only a pest control strategy but also a critical component of the transition toward resilient and sustainable food systems under climate uncertainty.

4. Conclusions

This study demonstrates that the IPM–climate–environment research domain is undergoing a measurable paradigm reconfiguration rather than incremental growth. The evidence shows a distinct post-2019 acceleration, marking a transition from a citation-driven foundational phase to a productivity-intensive expansion phase aligned with global climate and sustainability agendas. Thematic and conceptual analyses consistently indicate a shift away from pesticide-centric control toward ecologically grounded and climate-adaptive strategies, where biodiversity, ecosystem services, and agroecological practices are increasingly embedded within IPM.

However, this transition remains incomplete. The persistence of pesticide-related themes alongside ecological approaches reflects a structural duality, positioning IPM as a mediating framework rather than a fully dominant paradigm. At the same time, the concentration of knowledge production in developed countries reveals a critical imbalance, as regions most exposed to climate-sensitive pest risks remain underrepresented.

Taken together, these findings suggest that the future of IPM lies not only in ecological innovation, but in its capacity to operationalize context-specific, climate-resilient strategies while addressing structural inequalities in global research participation. Bridging this gap is essential for advancing IPM as a truly transformative approach to sustainable agriculture under climate uncertainty.

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