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INTEGRATED PEST AND DISEASE MANAGEMENT TECHNOLOGIES: A BIBLIOMETRIC ANALYSIS, SYSTEMATIC REVIEW, AND FUTURE RESEARCH DIRECTIONS

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ABSTRACT
Integrated Pest and Disease Management (IPDM) has emerged as a cornerstone of sustainable crop protection by integrating biological, cultural, mechanical, ecological, and judicious chemical approaches to reduce pest and disease incidence while minimizing environmental impacts. This study presents a comprehensive bibliometric analysis coupled with a systematic literature review to evaluate global research trends, identify knowledge gaps, and propose future research directions in IPDM technologies. Bibliographic data were retrieved from the Scopus database following PRISMA 2020 guidelines, resulting in 64 eligible publications published between 2016 and 2026. Bibliometric analyses were performed using Biblioshiny (RStudio) and VOSviewer to examine publication trends, leading journals, institutional and country contributions, and keyword co-occurrence networks, while the systematic review synthesized emerging technologies and adoption challenges. The findings reveal a substantial increase in IPDM research, with the United States and the University of Göttingen leading scientific output. Research has increasingly focused on biological control, integrated weed management, precision agriculture, artificial intelligence, remote sensing, and digital decision-support systems. However, widespread adoption remains constrained by socio-economic barriers, inadequate extension services, limited field validation of innovative technologies, and insufficient policy support. The review identifies critical research priorities, including climate-smart and farmer-centric IPDM strategies, integration of AI- and IoT-based monitoring systems, long-term evaluation of biological control technologies, standardized adoption metrics, and strengthened interdisciplinary collaboration. Collectively, these findings provide a comprehensive roadmap for advancing resilient, environmentally sustainable, and economically viable IPDM systems that can enhance global food security and sustainable agricultural development.

KEYWORDS: research gap, integrated pest and disease management, future directions, bibliometric analysis, PRISMA

INTRODUCTION
Agricultural production worldwide is increasingly threatened by the growing incidence of insect pests, plant pathogens, invasive species, and herbicide-resistant weeds, resulting in substantial yield losses, reduced crop quality, and economic instability. Excessive reliance on synthetic pesticides has accelerated resistance development, disrupted ecosystem services, threatened biodiversity, and raised concerns regarding environmental contamination and human health. Consequently, sustainable crop protection strategies have become a global research priority (Norsworthy et al., 2012; Deguine et al., 2021).
Integrated Pest and Disease Management (IPDM) has emerged as a comprehensive and ecologically sound approach that integrates cultural, biological, mechanical, physical, host resistance, and need-based chemical methods to suppress pest and disease populations below economic threshold levels while minimizing adverse environmental impacts (Deguine et al., 2021). Recent technological advances have further strengthened IPDM through the incorporation of precision agriculture, biological control agents, microbiome engineering,

semiochemical-based monitoring, artificial intelligence, predictive modelling, remote sensing, and digital decision-support systems (Tidemann et al., 2024; Wallace et al., 2025).
Recent research has demonstrated that biological control agents, entomopathogenic fungi, parasitoids, beneficial microbial communities, and harvest weed seed control technologies can substantially improve the sustainability and effectiveness of integrated management programmes (Miano et al., 2022; Świergiel et al., 2016; Tidemann et al., 2024). Likewise, predictive pest forecasting models and ecosystem-based management approaches have enhanced the capacity for early intervention and precision pest management (Wallace et al., 2025).
Despite remarkable scientific progress, several barriers continue to limit the widespread adoption of IPDM technologies. These include insufficient farmer awareness, inadequate extension services, inconsistent implementation of biological control strategies, region-specific knowledge gaps, economic constraints, and limited integration of emerging technologies into practical farming systems (Farooq et al., 2022; Jeffers et al., 2025). Furthermore, although numerous studies have focused on individual components of IPDM, the existing literature remains fragmented across disciplines, crops, pests, diseases, and geographical regions.
In recent years, the rapid expansion of IPDM research has generated a diverse body of scientific literature, making it increasingly difficult for researchers and policymakers to identify influential publications, emerging technologies, collaborative research networks, and future research priorities. Bibliometric analysis has become an effective tool for quantitatively mapping scientific development, identifying research hotspots, collaboration networks, and thematic evolution, while systematic reviews provide qualitative synthesis of existing evidence and technological advancements.
However, to date, no comprehensive review has integrated bibliometric analysis with a systematic synthesis of Integrated Pest and Disease Management technologies at the global scale. Such an integrated assessment is essential to understand the evolution of IPDM research, identify underexplored areas, evaluate emerging technologies, and establish future research priorities that can enhance sustainable crop protection and facilitate wider adoption of IPDM practices.
Therefore, this review aims
1. To visualise global research trends in Integrated Pest and Disease Management technologies using bibliometric analysis
2. To identify research gaps while proposing future research directions to enhance the development, adoption, and sustainability of IPDM technologies worldwide.

2. METHODOLOGY

2.1 Research Design

This study employed a combined bibliometric analysis and systematic literature review (SLR) approach to comprehensively evaluate the global research landscape on Integrated Pest and Disease Management (IPDM) technologies. Bibliometric analysis was used to quantify publication trends, scientific productivity, collaboration patterns, and thematic evolution, while the systematic literature review provided an in-depth qualitative synthesis of the existing knowledge, identified research gaps, and proposed future research directions. The integration of these two approaches ensured both quantitative mapping and qualitative interpretation of the research domain.

2.2 Data Source

The bibliographic data were retrieved exclusively from the Scopus database, one of the world's largest multidisciplinary indexing databases, due to its extensive coverage of peer-reviewed journals, conference proceedings, and review articles. Scopus was selected because of its high-quality metadata, citation indexing, and compatibility with bibliometric software such as Bibliophagy and VOS viewer.

2.3 Search Strategy

A comprehensive literature search was performed using keywords related to Integrated Pest and Disease Management (IPDM) technologies. The search query was formulated using appropriate Boolean operators (AND, OR) and truncation symbols to maximize the retrieval of relevant publications from the Scopus database. The complete search strategy, including the search string and associated parameters, is presented in Table 1.

Table 1. Combination of keywords used and the total number of publications from databases

Data bases	Search terms	Numbers of articles
Scopus	"Integrated Pest and Disease Management" OR "Integrated Pest Management" OR "Integrated Disease Management" OR "IPM" OR "IDM" AND "research gap*" OR "knowledge gap*" OR "evidence gap*" AND "Future research direction*" OR "future perspective*"OR "research agenda"	261

2.4 Inclusion and Exclusion Criteria

Inclusion and exclusion criteria were established for the initial screening of the publications listed in Table 2.

Table 2. The Inclusion and exclusion criteria

Criteria	Inclusion	Exclusion
Time span	2016 – 2026	<2016
Document type	Article	Conference papers, Book chapters, review, Editorial
Languages	English	Non-English
Source type	Journal	Trade journal
Publication stage	Final	Press
Open access	All open access	Restricted access

2.5 Study Selection

The study followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines to ensure a transparent and systematic process for the identification, screening, eligibility assessment, and selection of relevant publications. Initially, all records were retrieved from the Scopus database using the predefined search strategy. Subsequently, duplicate records were identified and removed to ensure data accuracy. The remaining publications were screened based on their titles and abstracts according to the predefined inclusion and exclusion criteria. Eligible studies were then subjected to a full-text review to determine their relevance to the objectives of the study. Only publications directly addressing Integrated Pest and Disease Management (IPDM) technologies were included in the final dataset for bibliometric analysis and systematic review. The complete study selection process following the PRISMA 2020 framework is presented in Figure 1

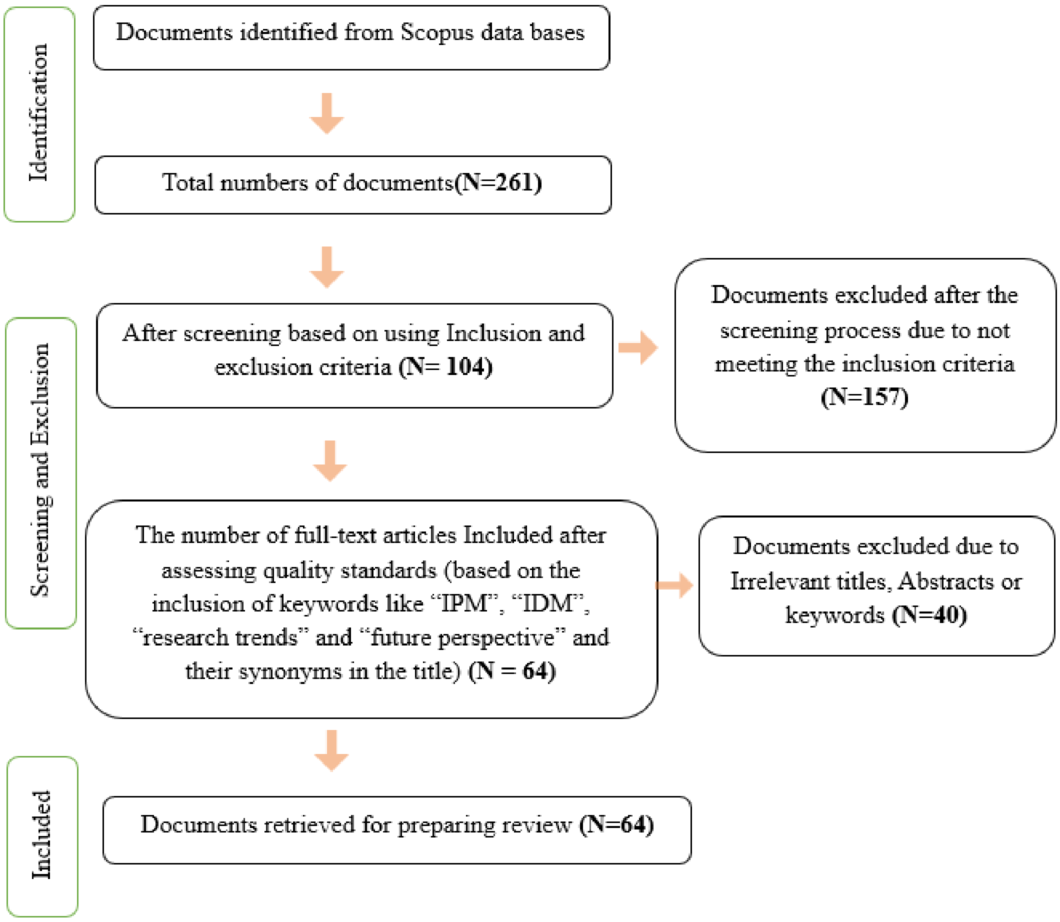

Fig. 1. PRISMA 2020 flow diagram illustrating the literature search and study selection process for the systematic review.

A total of **261** publications were initially retrieved from the Scopus database using the predefined search strategy. During the screening process, **157** records were excluded based on the established inclusion and exclusion criteria, including duplicate records and publications that did not meet the scope of the study. Following the application of the database's automatic filters, **104** publications remained for further evaluation. Subsequently, the titles and keywords of these publications were carefully screened for relevance, resulting in the selection of **64** studies for full-text assessment. After a thorough eligibility review, all 64 publications were included in the final dataset for the systematic literature review and bibliometric analysis. The complete study selection procedure, following the PRISMA 2020 framework, is illustrated in Figure 1. The selected publications were subsequently analysed using Bibliometric (Biblioshiny) in R Studio and VOS viewer to perform bibliometric mapping, visualize research trends, and identify emerging themes and future research directions in Integrated Pest and Disease Management (IPDM) technologies.

3. RESULT AND DISCUSSION

3.1. To visualise the global research trends3.1.1. Most Relevant sources

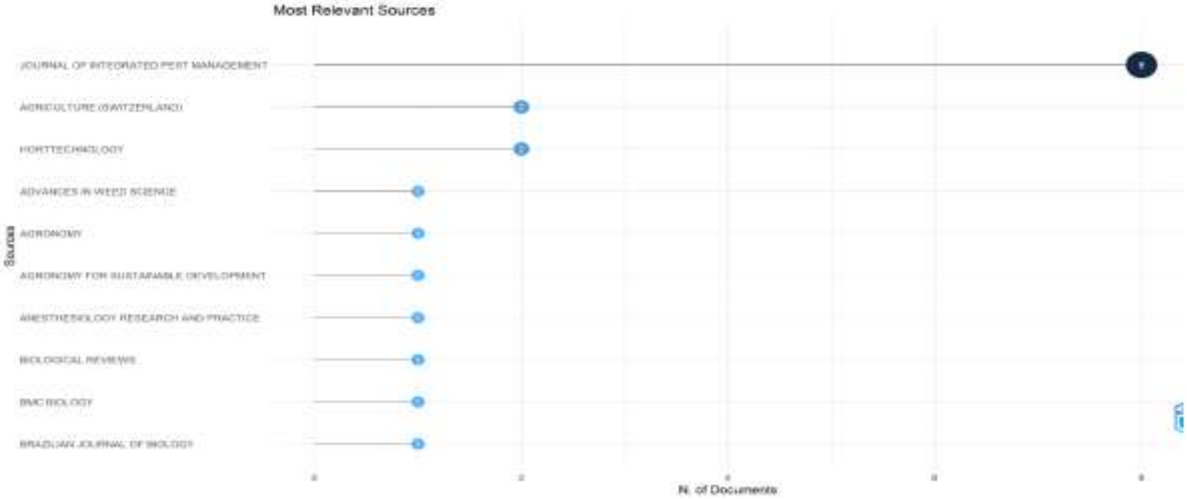

Figure. 2. Most Relevant sources

Figure 2 illustrates the most relevant publication sources contributing to the selected literature dataset. Among all the sources, the Journal of Integrated Pest Management emerged as the most productive journal, contributing eight publications, indicating its significant role in disseminating research related to the study domain. Agriculture (Switzerland) and Hort Technology ranked second, with two publications each, reflecting their moderate contribution to the research field. The remaining journals, including Advances in Weed Science, Agronomy, Agronomy for Sustainable Development, Anaesthesiology Research and Practice, Biological Reviews, BMC Biology, and Brazilian Journal of Biology, each contributed one publication. The distribution of publications demonstrates that the research output is concentrated in a few highly productive journals while several other sources provide complementary contributions. This pattern indicates that the subject area is multidisciplinary, with research disseminated across journals focusing on integrated pest management, sustainable agriculture, agronomy, horticulture, and biological sciences, thereby highlighting the broad scientific interest and interdisciplinary nature of the field.

3.1.2. Most Relevant Affiliation

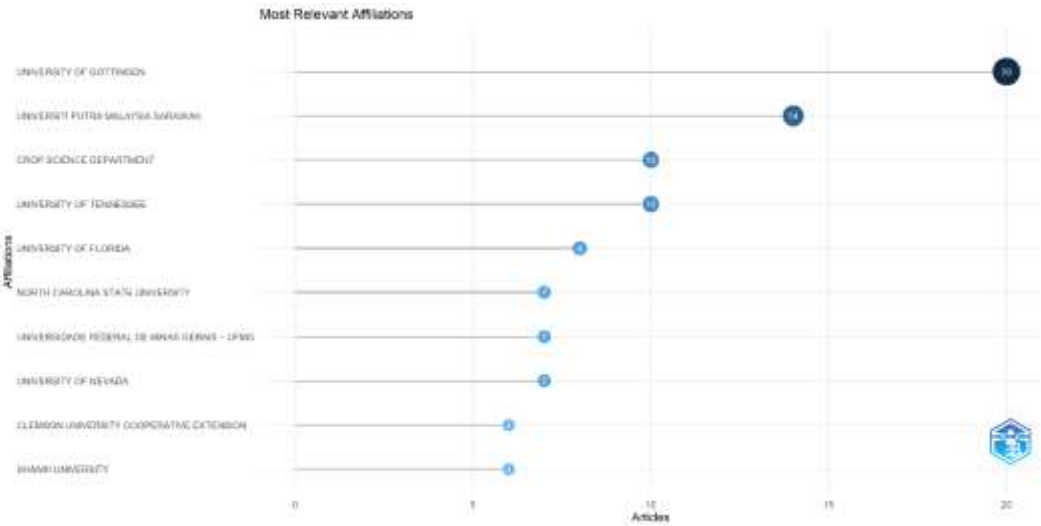

Figure. 3. Most Relevant Affiliation

Figure 3 presents the most relevant institutional affiliations contributing to the selected body of literature. Among the identified institutions, the University of Göttingen recorded the highest research output with 20 publications, indicating its prominent role in advancing research within the study domain. It was followed by Universiti Putra Malaysia Sarawak with 14 publications, while both the Crop Science Department and the University of Tennessee contributed 10 publications each. The University of Florida ranked next with eight publications, followed by North Carolina State University, Universidad Federal de Minas Gerais (UFMG), and the University of Nevada, each contributing seven publications. Clemson University Cooperative Extension and Shanxi University each accounted for six publications. Overall, the findings indicate that research contributions are concentrated among a few leading universities and research institutions, reflecting their strong expertise and active involvement in the field. This distribution also highlights the collaborative and international nature of research, with significant contributions originating from institutions across Europe, North America, Asia, and South America.

3.1.3. Affiliation Production overtime

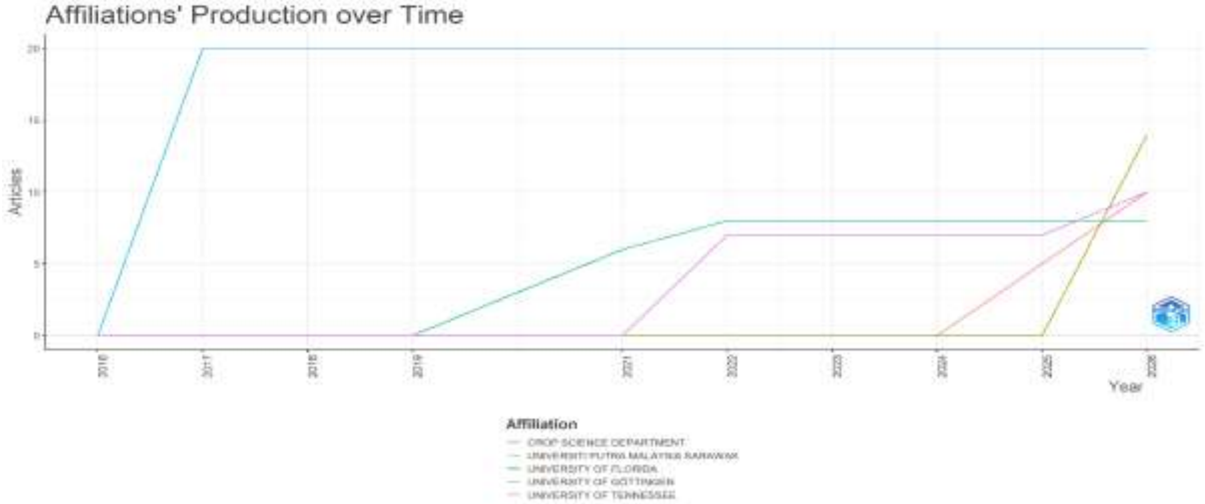

Figure. 4. Affiliation Production overtime

Figure 4 illustrates the temporal trends in research productivity among the leading institutional affiliations included in the bibliometric dataset from 2016 to 2026. The University of Göttingen demonstrates the highest and most consistent research output, reaching 20 publications by 2017 and maintaining this level throughout the study period, reflecting its sustained leadership and long-term commitment to the research domain. University of Florida exhibited gradual growth, increasing from no publications in 2019 to six publications in 2021, and subsequently stabilizing at eight publications from 2022 onwards, indicating steady research engagement. Similarly, the University of Tennessee showed a notable increase, reaching seven publications in 2022 and further expanding to ten publications by 2026, demonstrating continuous institutional development. The Crop Science Department recorded a relatively late but significant increase, rising to ten publications by 2026, while Universiti Putra Malaysia Sarawak experienced the most rapid recent growth, increasing sharply to 14 publications in 2026. Overall, the figure reveals varying patterns of institutional research productivity, with some affiliations maintaining consistent publication performance and others exhibiting substantial growth in recent years. These findings indicate the expanding global participation of universities and research institutions in the field, reflecting increasing scholarly interest and strengthening institutional collaboration over time.

3.1.4. Country production over time

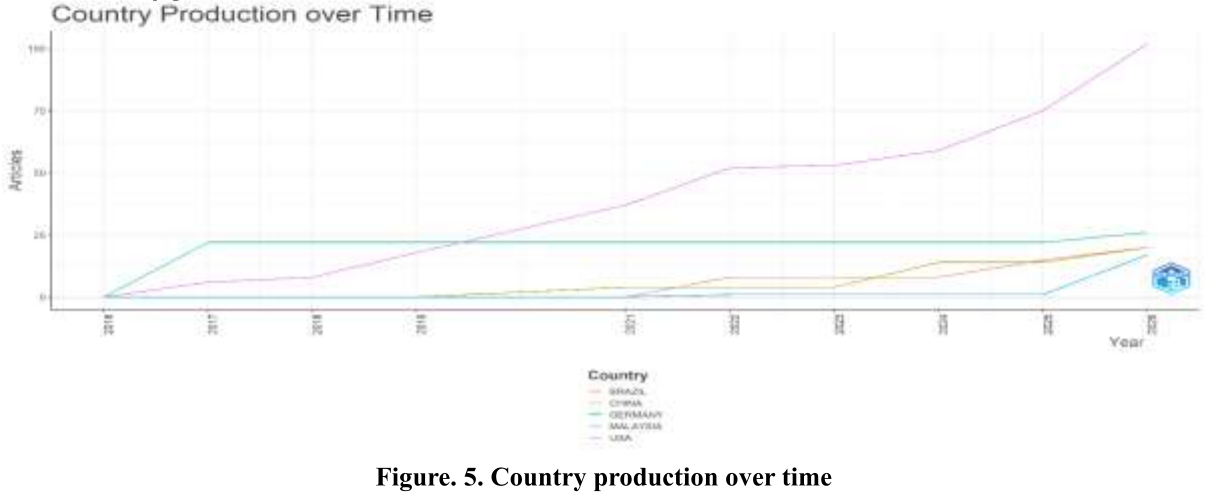

Figure. 5. Country production over time

Figure 5 illustrates the temporal distribution of research publications across the leading contributing countries between 2016 and 2026. The United States of America (USA) demonstrates the highest and most sustained research productivity throughout the study period. Its publication output increased steadily from 2016, surpassed 50 publications by 2022, and exceeded 100 publications by 2026, indicating its dominant position and continued leadership in the research field. Germany emerged as the second most productive country, showing an early increase to approximately 22 publications by 2017 and maintaining relatively stable output before reaching 26 publications in 2026. China exhibited gradual growth, with publication output increasing consistently from 2019 and attaining approximately 25 publications by 2026, reflecting its expanding research involvement. Brazil also demonstrated a progressive increase in scientific contributions, particularly after 2021, reaching around 24 publications by 2026. In contrast, Malaysia maintained minimal publication activity until 2025, followed by a sharp rise to approximately 17 publications in 2026, indicating emerging research interest. Overall, the figure reveals a substantial increase in global scientific productivity over time, with developed nations maintaining leadership while emerging economies demonstrate accelerating research contributions. These trends highlight the growing internationalization of research and the expanding participation of countries in advancing knowledge within the study domain.

3.1.5. Co-occurrence – All keywords

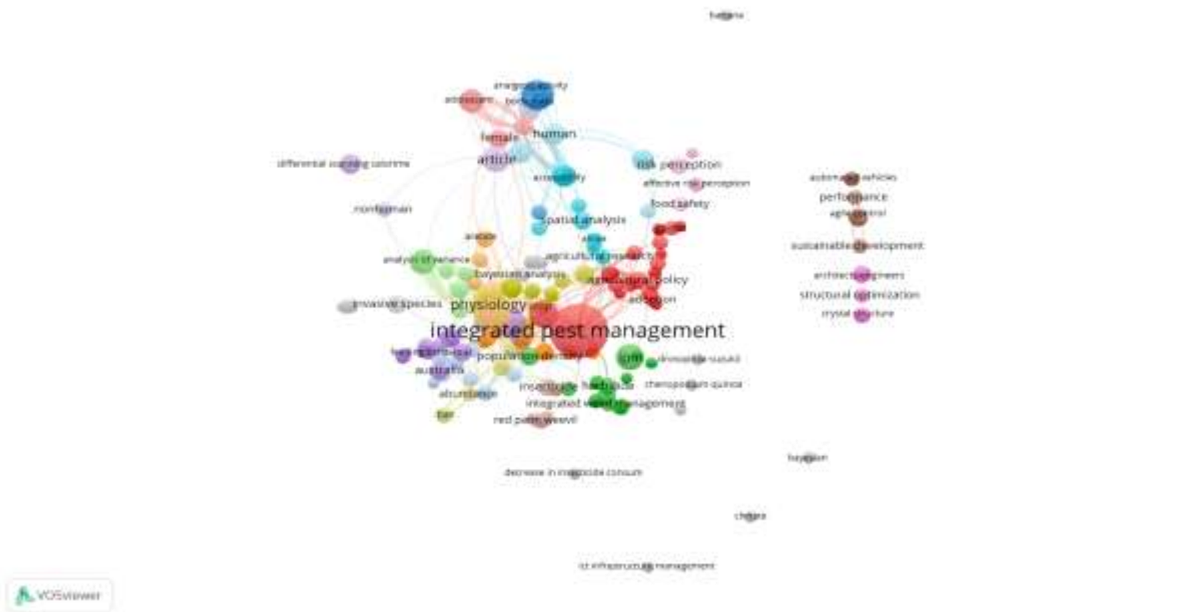

Figure. 6. Co-occurrence – All keywords

Figure 6 presents the co-occurrence network of author keywords generated using VOS viewer, illustrating the conceptual structure and thematic relationships within the selected literature. The size of each node represents the frequency of keyword occurrence, while the connecting lines indicate the strength of co-occurrence between keywords. The keyword “integrated pest management” occupies the central position and appears as the most dominant term, demonstrating its pivotal role in linking multiple research themes. Strong associations are observed with keywords such as agricultural policy, agricultural research, adoption, physiology, crop, insecticide, herbicide, invasive species, food safety, risk perception, spatial analysis, Bayesian analysis, and integrated weed management, indicating the multidisciplinary nature of the research field. The network is organized into several colour-coded clusters, each representing distinct yet interconnected research themes encompassing crop protection, pest management strategies, policy interventions, analytical approaches, ecological sustainability, and biological sciences. Peripheral keywords such as sustainable development, structural optimization, climate, ICT infrastructure management, and automated vehicles indicate emerging interdisciplinary applications extending beyond conventional pest management research. Overall, the co-occurrence network demonstrates that integrated pest management serves as the core research focus, supported by diverse thematic clusters that collectively emphasize sustainable agricultural practices, technological innovation, policy development, and evidence-based decision-making, reflecting the evolving and interdisciplinary nature of the research domain.

3.2. Research Gaps in the Adoption of Integrated Pest and Disease Management (IPDM) Technologies

The reviewed literature reveals that existing research has primarily focused on developing effective pest management technologies, biological control agents, predictive models, and environmentally sustainable alternatives, while comparatively less attention has been devoted to understanding the factors that influence farmers' adoption decisions. Consequently, several interconnected research gaps remain, including behavioural and socio-economic constraints, deficiencies in extension and knowledge transfer systems, limited validation of emerging technologies under field conditions, inadequate policy support, and insufficient integration of digital technologies within practical farming environments.

One of the most frequently reported research gaps concerns the limited understanding of farmers' behavioural and psychological determinants of IPDM adoption. Behavioural factors were consistently identified as stronger predictors of adoption than purely technical characteristics of pest management technologies. Momenpour et al. (2025) demonstrated that attitudes, perceived behavioural control, moral norms, environmental concern, and place attachment significantly influenced wheat farmers' intentions to adopt integrated pest management, whereas subjective norms exerted little influence. Similarly, Creissen et al. (2021) identified multiple socio-economic drivers and constraints affecting IPM implementation among arable farmers, while Lal et al. (2025) showed that education level, farming experience, extension contact, and age significantly influenced farmers' adoption of IPM technologies in tomato cultivation. Furthermore, Muriithi et al. (2024) highlighted the influence of gender, access to agricultural inputs, training opportunities, and market participation on farmers' willingness to implement integrated pest management practices. Although these studies collectively demonstrate that farmer behaviour plays a decisive role in technology adoption, most investigations rely on cross-sectional surveys that measure behavioural intentions rather than actual long-term adoption behaviour. This indicates a substantial research gap regarding longitudinal assessments of farmers' decision-making processes and behavioural changes following extension interventions or policy implementation.

Knowledge dissemination and agricultural extension services represent another major limitation identified throughout the reviewed literature. England et al. (2026) found that although Irish tillage farmers recognised the environmental and agronomic benefits of biological control agents and biostimulants, adoption remained relatively low because of inadequate technical knowledge, uncertainty regarding field performance, and insufficient local validation trials. Comparable findings were reported by Farooq et al. (2022), who demonstrated that farmers possessing greater knowledge of climate-smart agricultural practices were significantly more likely to adopt sustainable production technologies, suggesting that knowledge acquisition directly influences innovation uptake. Wiedemann et al. (2022) further argued that conventional pesticide management research frequently neglects farmers' experiential knowledge and local expertise, thereby creating a disconnect between scientific recommendations and practical implementation. These findings collectively indicate that current extension systems remain largely technology-oriented rather than farmer-centred and participatory. Consequently, insufficient attention has been given to designing effective knowledge transfer mechanisms capable of translating scientific innovations into practical on-farm applications.

The reviewed studies also reveal significant technological and ecological research gaps that limit the practical application of advanced IPDM tools. Several investigations developed innovative modelling frameworks capable of improving pest prediction, biological control planning, and landscape-level pest monitoring. Yonow et al. (2023) developed a population dynamics model for biological control of invasive land snails, demonstrating the importance of incorporating environmental variables into pest management planning. Likewise, Kelly et al. (2023) used simulation modelling to evaluate alternative weed management strategies under reduced pesticide scenarios, revealing important trade-offs between herbicide reduction and weed population dynamics. Requena-Mullor et al. (2026) proposed a spatially explicit pest simulation model that incorporated physical landscape barriers, substantially improving predictions of pest movement and monitoring efficiency. Similarly, Leybourne et al. (2024) highlighted the growing potential of artificial intelligence for pest detection, monitoring, and forecasting, while Jiang et al. (2026) demonstrated that internet use increased the probability of IPM adoption among rice farmers by approximately 30%, emphasising the importance of digital connectivity in agricultural innovation. Despite these technological advances, the reviewed studies consistently acknowledge that many predictive models, simulation tools, and artificial intelligence applications remain insufficiently validated under commercial farming conditions and have not been adequately integrated into extension services or routine farm decision-making processes. Consequently, the gap between technological innovation and practical implementation remains substantial.

Biological control and environmentally sustainable pest management strategies constitute another important area where research gaps persist. Numerous studies identified promising biological alternatives capable of reducing reliance on synthetic pesticides. Jirón-García et al. (2025) demonstrated that coffee pulp extracts possess considerable insecticidal, fungicidal, and antibacterial properties, suggesting their potential as environmentally friendly botanical pesticides. Similarly, Vélez-Ruiz et al. (2026) reported that native Beauveria bassiana isolates exhibited significant pathogenicity against banana weevil under laboratory conditions, indicating considerable potential for biological control programmes. Knapp et al. (2025) further demonstrated that conventional insecticides negatively affected beneficial arthropods, highlighting the ecological importance of reducing pesticide dependence within IPDM systems. However, these studies consistently acknowledged that laboratory findings require validation under diverse agroecological conditions before widespread farmer adoption can be recommended. Research concerning formulation optimisation, commercial scalability, economic feasibility, environmental persistence, compatibility with existing farming systems, and farmer acceptance of biological alternatives remains relatively limited, thereby constraining large-scale implementation.

Several review papers also identified substantial policy and institutional research gaps affecting IPDM adoption. Abdel-Banat et al. (2025), through their comprehensive bibliometric assessment of more than one century of red palm weevil research, concluded that despite significant scientific progress, implementation of integrated management strategies remains fragmented because of insufficient interdisciplinary collaboration and inadequate translation of research findings into practical pest management programmes. Similar conclusions were reached by Al-Zyoud and Shibli (2021), who observed that effective management of red palm weevil continues to be constrained by weak integration of biological control, quarantine regulations, surveillance systems, and early detection technologies. McDougall et al. (2025) further demonstrated that agricultural experts anticipate substantial challenges in reducing pesticide use unless reliable IPDM alternatives become economically viable and practically effective under commercial production conditions. Likewise, Mack et al. (2023) highlighted uncertainties regarding farmers' responses to pesticide-free policy scenarios, emphasising the need for stronger policy evaluation studies. These findings suggest that existing policy research has largely focused on regulatory targets while giving comparatively less attention to farmers' adaptive capacity, economic incentives, and institutional mechanisms supporting IPDM implementation.

The literature additionally highlights deficiencies in measuring and monitoring IPDM adoption. Byrne et al. (2025) developed an IPM adoption metric for horticultural production and reported relatively low to moderate implementation levels among growers, illustrating the need for standardised indicators capable of comparing adoption across different agricultural systems. Similarly, Russo et al. (2025) concluded that inconsistencies in research methodologies, adoption indicators, and evaluation frameworks continue to limit comparisons among studies conducted in different regions. The absence of universally accepted metrics makes it difficult to evaluate progress towards sustainable pest management and hinders evidence-based policy development.

Environmental sustainability and ecosystem-level considerations also remain underrepresented within IPDM adoption research. Dislich et al. (2017) demonstrated that although oil palm production substantially increases agricultural output, conversion of natural forests results in considerable losses of ecosystem functions and biodiversity. These findings suggest that future IPDM research should extend beyond pest suppression to evaluate broader ecological outcomes, including biodiversity conservation, ecosystem services, climate resilience, and sustainable landscape management. Likewise, Ramasamy (2026) argued that current integrated pest management approaches should evolve towards a broader Integrated Plant Health Ecosystem Management (IPHEM) framework that simultaneously considers plant health, environmental sustainability, economic viability, and digital agriculture. However, empirical evidence supporting such comprehensive management frameworks remains scarce.

Collectively, the reviewed studies demonstrate that IPDM research has progressed substantially in developing environmentally sustainable pest management technologies; nevertheless, widespread adoption remains constrained by multiple interrelated behavioural, technological, institutional, ecological, and policy-related challenges. Existing research has predominantly concentrated on technology development, whereas considerably less emphasis has been placed on understanding farmers' adoption behaviour, strengthening extension systems, validating innovative technologies under commercial farming conditions, developing standardised adoption metrics, integrating digital agriculture into routine pest management, and evaluating long-term environmental and socio-economic outcomes. Addressing these interconnected research gaps is essential for facilitating the successful adoption and sustainable implementation of Integrated Pest and Disease Management technologies across diverse agricultural systems.

3.2.1. Future Research Directions for Enhancing the Adoption of Integrated Pest and Disease Management (IPDM) Technologies

The reviewed studies indicate that future research on Integrated Pest and Disease Management (IPDM) should move beyond evaluating individual pest control methods and focus on developing integrated, sustainable, and farmer-oriented management systems. Although substantial progress has been made in biological control, cultural practices, monitoring technologies, biopesticides, and precision agriculture, several challenges continue to limit large-scale adoption. The findings collectively suggest that future IPDM research should prioritize environmentally sustainable technologies, advanced monitoring systems, economic feasibility, and integrated decision-support tools to improve adoption under diverse agricultural conditions.

A major research trend is the development of environmentally friendly alternatives to conventional pesticides. Increasing concerns over pesticide resistance, environmental pollution, and adverse effects on non-target organisms have accelerated research on biological products such as insect-derived chitosan, RNA interference (RNAi), pheromone-based monitoring, and ecological pest management. Insect-derived chitosan has shown considerable potential because of its antimicrobial, insecticidal, and plant defense-inducing properties, while offering advantages such as biodegradability, year-round availability, and lower environmental impact. However, further research is required to optimize formulations, validate field performance, reduce production costs, and establish regulatory frameworks for large-scale commercialization (Andiyappan et al., 2025).

Similarly, RNAi technology has emerged as a promising species-specific pest management strategy. Recent findings demonstrated that the uptake of double-stranded RNA differs among insect tissues, explaining variations in RNAi efficiency across insect species (Shi et al., 2026). These results highlight the need for future research to improve dsRNA delivery systems, increase molecular stability under field conditions, and develop cost-effective

formulations suitable for commercial IPDM applications. Such advances would enhance the practical use of RNAi while reducing dependence on synthetic pesticides.
The reviewed literature also emphasizes the growing importance of precision monitoring and early pest detection. Semiochemical-based technologies, including pheromone traps, provide highly selective monitoring systems that improve pest surveillance and reduce unnecessary pesticide applications. Williams et al. (2025) demonstrated that a synthetic two-component sex pheromone effectively attracted Melanotus verberans males under field conditions, highlighting its potential for sustainable monitoring programs. Likewise, improved sampling methods have enhanced pest detection accuracy. Sturr et al. (2024) reported that quadrat sampling provided more reliable estimates of Asiatic garden beetle populations than conventional methods while requiring fewer samples. These findings indicate that future research should integrate automated monitoring, artificial intelligence, remote sensing, drones, and machine learning to support real-time pest detection and decision-making within IPDM programs.
Several studies further demonstrate that integrating multiple management strategies provides greater long-term sustainability than relying on single control methods. Combining resistant cultivars, cultural practices, biological control, habitat management, and selective pesticide use consistently reduced pest infestations while improving crop productivity. For example, integrating resistant wheat cultivars with tillage and insecticide application effectively managed cereal leafminer populations (Shawawreh et al., 2022), whereas the use of early-flowering pea varieties as trap crops successfully reduced pea weevil infestation (Seidenglanz et al., 2022). Similarly, improved disease management in potato and banana production requires integrating resistant cultivars, biological control, disease forecasting systems, and evidence-based management strategies rather than depending solely on chemical pesticides (Vilvert et al., 2022; Esguera et al., 2024). These findings emphasize that future IPDM research should evaluate the long-term interactions among different management components under varying environmental conditions.
Ecological approaches also represent an important research priority. Semi-natural habitats contribute significantly to biological control, pollination, and soil conservation, thereby enhancing ecosystem services that support sustainable agriculture (Holland et al., 2017). Nevertheless, existing studies remain geographically limited and often fail to evaluate economically relevant indicators such as yield improvement and farm profitability. Long-term, landscape-scale research is therefore required to quantify both ecological and economic benefits of habitat management within IPDM systems. Likewise, recent studies investigating electrical weed management demonstrate that innovative non-chemical technologies can effectively control weeds with minimal crop injury, supporting the development of integrated weed management programs that reduce herbicide dependence (Ringselle et al., 2026).
Economic and social factors remain equally important for the successful adoption of IPDM technologies. Although integrated management practices generally improve crop productivity and environmental sustainability, higher implementation costs and limited technical knowledge often discourage adoption. For example, IPM implementation in date palm production increased productivity but also raised production costs, reducing short-term profitability despite its environmental benefits (Aldakhil et al., 2025). Similar observations have been reported in other production systems, where successful adoption depends on effective extension services, farmer training, policy support, and economic incentives. Therefore, future research should integrate biological performance with socio-economic analyses to better understand farmer behaviour, technology acceptance, and cost-effectiveness.
Several review articles further identify important knowledge gaps that require additional investigation. Future studies should improve pest monitoring systems, develop standardized sampling protocols, evaluate long-term ecosystem impacts, investigate climate change effects on pest dynamics, strengthen integrated disease management strategies, and encourage multidisciplinary collaboration among researchers, extension agencies, policymakers, and farmers (Justus & Long, 2019; Gooch et al., 2025). Greater emphasis should also be placed on translating laboratory innovations into practical field applications through large-scale validation trials and adaptive management approaches.
Overall, the reviewed literature demonstrates that enhancing IPDM adoption requires multidisciplinary research that integrates biological innovations, ecological engineering, precision agriculture, digital technologies, and socio-economic considerations. Future research should focus on developing cost-effective, environmentally sustainable, and farmer-friendly IPDM systems capable of improving pest management while ensuring long-term agricultural productivity and resilience.

CONCLUSION AND FUTURE DIRECTIONS

Integrated Pest and Disease Management (IPDM) has become a fundamental pillar of sustainable agriculture by integrating biological, cultural, mechanical, ecological, and need-based chemical approaches to achieve effective crop protection while minimizing environmental impacts. The present bibliometric analysis and systematic review demonstrate that global research on IPDM has expanded considerably over the last decade, with increasing emphasis on biological control, integrated weed management, precision agriculture, artificial intelligence, remote sensing, and digital decision-support systems. These advancements highlight the transition of IPDM from conventional pest control to a more holistic, knowledge-driven, and technology-enabled approach. However, despite significant scientific progress, the adoption of IPDM remains constrained by socio-economic barriers, inadequate extension services, limited field validation of emerging technologies, inconsistent policy support, and the absence of standardized frameworks for assessing adoption and impact.

Future research should prioritize the development of climate-smart, farmer-centric, and digitally enabled IPDM systems capable of addressing the challenges posed by climate change, pest resistance, and evolving production systems. Greater emphasis is needed on integrating artificial intelligence, machine learning, Internet of Things (IoT)-based monitoring, remote sensing, drones, and predictive modelling to enable real-time pest surveillance and informed decision-making. Long-term, multi-location validation of biological control agents, microbial biopesticides, botanical pesticides, RNA interference technologies, and semiochemical-based monitoring systems under diverse agroecological conditions is essential to facilitate their large-scale adoption. Future studies should also establish standardised indicators to evaluate environmental, economic, and social outcomes of IPDM while strengthening participatory extension models and policy support mechanisms. Furthermore, interdisciplinary collaboration among agronomists, entomologists, plant pathologists, weed scientists, ecologists, economists, data scientists, policymakers, and farmers will be critical for translating research into practice. Collectively, these efforts will accelerate the adoption of resilient, environmentally sustainable, and economically viable IPDM technologies, thereby contributing to global food security and sustainable agricultural development.

REFERENCES

1. Abdel-Banat, B. M. A., El-Shafie, H. A. F., & Faleiro, J. R. (2025). A comprehensive analysis of more than a century of research on red palm weevil, Rhynchophorus ferrugineus: Trends, gaps, and future directions. Journal of Agriculture and Food Research, 24, 102449.
2. Adesina, O. S., Whitfield, S., Sallu, S. M., Sait, S. M., & Pittchar, J. (2023). Bridging the gap in agricultural innovation research: A systematic review of push–pull biocontrol technology in sub-Saharan Africa. International Journal of Agricultural Sustainability, 21(1), Article 2232696.
3. Aldakhil, A. I., Alamri, Y., Alsultan, M., Alduwais, A., Bashir, K., & Alhashim, J. (2025). Evaluating the economic impact of integrated pest management (IPM) on smallholder date palms farmers. Journal of the Saudi Society of Agricultural Sciences, 24, 31.
4. Al-Zyoud, F., & Shibli, R. (2021). Current status, challenges, management and future perspectives of the red palm weevil Rhynchophorus ferrugineus eradication: A review. Journal of Experimental Biology and Agricultural Sciences, 9(6), 697–714.
5. Andiyappan, A., Govindaraj, S., Mookiah, S., Marimuthu, M., Selvaraj, S., & Amirthalingam, S. (2025). Biopesticidal potential of insect derived chitosan for crop protection. Plant Science Today, 12(sp4), 1–16. https://doi.org/10.14719/pst.10807
6. Byrne, J., Lillywhite, R., Creissen, H., Thorne, F., & Walsh, L. (2025). Quantifying integrated pest management adoption in food horticulture. Crop Protection, 191, 107165.
https://doi.org/10.1016/j.cropro.2025.107165
7. Creissen, H. E., Jones, P. J., Tranter, R. B., Girling, R. D., Jess, S., Burnett, F. J., Gaffney, M., Thorne, F. S., & Kildea, S. (2021). Identifying the drivers and constraints to adoption of IPM among arable farmers in the UK and Ireland. Pest Management Science, 77(9), 4148–4158. https://doi.org/10.1002/ps.6452
8. Deguine, J.-P., Aubertot, J.-N., Flor, R. J., Lescourret, F., Wyckhuys, K. A. G., & Ratnadass, A. (2021). Integrated pest management: Good intentions, hard realities. Agronomy for Sustainable Development, 41(3), 38. https://doi.org/10.1007/s13593-021-00689-w
9. Dislich, C., Keyel, A. C., Salecker, J., et al. (2017). A review of the ecosystem functions in oil palm plantations, using forests as a reference system. Biological Reviews, 92(3), 1539–1569.
10. England, M., Merrins, G., McGrath, K., McDougall, R., Thorne, F., Forristal, P. D., Mullins, E., & Kildea, S. (2026). Farmer-reported use and barriers to adoption of biocontrol and biostimulants on Irish tillage farms. Crop Protection, 208, 107703.
11. Esguera, J. G., Balendres, M. A., & Paguntalan, D. P. (2024). Overview of the Sigatoka leaf spot complex in banana and its current management. Tropical Plants, 3, e002. https://doi.org/10.48130/tp-0024-0001
12. Farooq, A., Hassan, A., Ishaq, M., Nawaz, A., Ullah, I., & Hidayatullah. (2022). Farmers' knowledge level regarding climate-smart agricultural production technologies. Sarhad Journal of Agriculture, 38(1), 331–341.
13. Farooq, A., Hassan, A., Ishaq, M., Nawaz, A., Ullah, I., & Ullah, H. (2022). Farmers' knowledge level regarding climate smart agricultural production technologies in Central Plain Valley of Khyber Pakhtunkhwa. Sarhad Journal of Agriculture, 38(1), 331–341. https://doi.org/10.17582/journal.sja/2022/38.1.331.341
14. Gooch, E., Fleming, P. J. S., & Meek, P. D. (2025). The great de-bait: Are manufactured toxic baits a suitable alternative for the control of introduced canids? Wildlife Research, 52, WR25049.
15. Holland, J. M., Douma, J. C., Crowley, L., James, L., Kor, L., Stevenson, D. R. W., & Smith, B. M. (2017). Semi-natural habitats support biological control, pollination and soil conservation in Europe: A review. Agronomy for Sustainable Development, 37, 31.
16. Jeffers, A. H., Ketron, C., Seegers, S., Fowler, B., Turner, S., & Smith, B. (2025). Evaluating Master Gardener integrated pest management (IPM) knowledge. HortTechnology, 35(6), 1003–1010.
17. https://doi.org/10.21273/HORTTECH05760-25
18. Jiang, W., Zhu, J., Zhang, Q., & Razzaq, A. (2026). Internet use shaped farmer adoption of integrated pest management in rural central China. Frontiers in Sustainable Food Systems, 9, 1708905.

https://doi.org/10.3389/fsufs.2025.1708905
19. Jirón-García, E., Rodríguez-Mora, K., Rivera-Méndez, W., & Uribe-Lorío, L. (2025). Botanical pesticides as a sustainable pest control strategy: Case of polyphenolic extracts of coffee pulp (Coffea arabica).
20. Justus, E. J., & Long, E. Y. (2019). Biology and management of the carrot weevil (Listronotus oregonensis) in North America. Journal of Integrated Pest Management, 10(1).
21. Kelly, J. E., Behrendt, K., & Quinn, J. C. (2023). Simulating the population dynamics of barley grass (Hordeum spp.) and impacts of weed management strategies in a southern Australian lucerne pasture. Crop & Pasture Science, 74(9), 888–897.
22. Knapp, R. A., McDougall, R., & Umina, P. A. (2025). Advancing research on overlooked invertebrates in biological control: A case study of local hoverflies and wolf spiders. Agronomy, 15(5), 1203. https://doi.org/10.3390/agronomy15051203
23. Lal, S. P., Sunil Kumar, K. N., & Shukla, G. (2025). Drivers of IPM adoption among hybrid tomato farmers in Karnataka: Insights through mlogit model. Indian Journal of Extension Education, 61(1), 48–54. https://doi.org/10.48165/IJEE.2025.61109
24. Leybourne, D. J., Storer, K. E., Marshall, A., Musa, N., Abel, L., Telling, S., Ellis, S., White, S., Berry, P. M., & Yang, P. (2024). Thresholds and prediction models to support the sustainable management of herbivorous insects in wheat: A review. Agronomy for Sustainable Development, 44, Article 29. https://doi.org/10.1007/s13593-024-00965-5
25. Mack, G., Finger, R., Ammann, J., & El Benni, N. (2023). Modelling policies towards pesticide-free agricultural production systems. Agricultural Systems, 207, 103642. https://doi.org/10.1016/j.agsy.2023.103642
26. Miano, R. N., Mohamed, S. A., Cheseto, X., Ndlela, S., Biasazin, T. D., Yusuf, A. A., Rohwer, E., & Dekker, T. (2022). Differential responses of Bactrocera dorsalis and its parasitoids to headspaces of different varieties of tree-attached mango fruits and the associated chemical profiles. Frontiers in Ecology and Evolution, 10, 1021795. https://doi.org/10.3389/fevo.2022.1021795
27. Momenpour, Y., Choobchian, S., & Sadighi, H. (2025). Understanding wheat farmers' intentions regarding the adoption of integrated pest management. Sustainable Futures, 10, 100866.
28. Muriithi, B., Franchini, R., Kolhoff, P., Seekman, V., Grossman, L., Mulungu, K., Kirscht, H., Ledermann, S., & Khamis, F. M. (2024). Gendered barriers and opportunities for scaling integrated pest management practices along the mango value chain in Kenya. Journal of Integrated Pest Management, 15(1), Article 5. https://doi.org/10.1093/jipm/pmad034
29. Norsworthy, J. K., Ward, S. M., Shaw, D. R., Llewellyn, R. S., Nichols, R. L., Webster, T. M., Bradley, K. W., Frisvold, G., Powles, S. B., Burgos, N. R., Witt, W. W., & Barrett, M. (2012). Reducing the risks of herbicide resistance: Best management practices and recommendations. Weed Science, 60(SP1), 31–62. https://doi.org/10.1614/WS-D-11-00155.
30. Requena-Mullor, J. M., Rodríguez, E., González, M., Castro, A. J., Garau, E., Pérez-Ramírez, I., Peláez-Pérez, Á., & Barranco, P. (2026). Accounting for physical barriers in insect pest modeling: A spatially explicit simulation-based approach. Ecological Informatics, 94, 103629.
31. Ringselle, B., Pourazari, F., Stankovic, M., Fogelberg, F., Markovic, D., & Ninkovic, V. (2026). Low risk of indirect crop damage from low-energy electric weeding of white goosefoot (Chenopodium album) and white mustard (Sinapis alba). Weed Research, 66, e70083.
32. Russo, I., Vecchio, R., Viscecchia, R., Cembalo, L., & De Devitiis, B. (2025). Factors affecting farmers' adoption of sustainable pest management practices: A scoping review. Environment, Development and Sustainability. Advance online publication. https://doi.org/10.1007/s10668-025-06937-3
33. Seidenglanz, M., Arbeález, M. M., Šafář, J., Heděnec, P., Ondráčková, E., & Bajerová, R. (2022). Early flowering field pea variety (Pisum sativum L.) as a trap crop for pea weevils (Bruchus pisorum L.). Plant Protection Science, 58(3), 245–257.
34. Shawawreh, M., Al-Zyoud, F., & Shakhatreh, Y. (2022). Sustainable control tactics of the cereal leafminer Syringopais temperatella in Jordan: Resistant cultivars and combined use of tillage and insecticides. Jordan Journal of Agricultural Sciences, 18(2).
35. Shi, X., Liu, Y., Liu, X., Abbas, M., Merchant, A., Merzendorfer, H., Zhao, Z., Zhou, X., Zhu, K. Y., & Zhang, J. (2026). Cellular uptake of extracellular dsRNA is tissue-dependent in insects. BMC Biology. Advance online publication.
36. Srinivasan, R. (2026). Is this the time to bid farewell to integrated pest management? Frontiers in Insect Science, 6, 1748643. https://doi.org/10.3389/finsc.2026.1748643
37. Sturr, C. E., Richmond, D. S., & Long, E. Y. (2024). Evaluating sampling techniques for quantifying Asiatic garden beetle (Maladera formosae) infestations in commercial mint. Journal of Economic Entomology.
38. Świergiel, W., Meyling, N. V., Porcel, M., & Ramert, B. (2016). Soil application of Beauveria bassiana GHA against apple sawfly, Hoplocampa testudinea (Hymenoptera: Tenthredinidae): Field mortality and fungal persistence. Insect Science, 23(6), 854–868. https://doi.org/10.1111/1744-7917.12233
39. Tidemann, B. D., Harker, K. N., Beckie, H. J., Kubota, H., Zuidhof, J., & Reid, P. (2024). Field testing of a physical impact mill in the Canadian Prairies. Canadian Journal of Plant Science, 104(2), 103–114. https://doi.org/10.1139/CJPS-2023-009

40. Vélez-Ruiz, M. C., Perez-Zambrano, A., Gaibor-Duarte, J. D., Cedeño-Moreira, A. V., & Abasolo-Pacheco, F. (2026). Characterization of native Beauveria bassiana strains isolated from soils and their potential for the biological control of Cosmopolites sordidus in Ecuador. Terra Latinoamericana, 44, e2446.
41. Vilvert, E., Stridh, L., Andersson, B., Olson, Å., Aldén, L., & Berlin, A. (2022). Evidence-based disease control methods in potato production: A systematic map protocol. Environmental Evidence, 11, 6.
42. Wallace, S. T., Nelson, N. G., Reisig, D. D., & Huseth, A. S. (2025). Forecasting interannual abundance of Helicoverpa zea (Lepidoptera: Noctuidae). Journal of Economic Entomology. Advance online publication. https://doi.org/10.1093/jee/toaf011
43. Wiedemann, R., Stamm, C., & Staudacher, P. (2022). Participatory knowledge integration to promote safe pesticide use in Uganda. Environmental Science & Policy, 128, 154–164.
https://doi.org/10.1016/j.envsci.2021.11.018
44. Yonow, T., Kriticos, D. J., Zalucki, M. P., McDonnell, R. J., & Caron, V. (2023). Population modelling for pest management: A case study using a pest land snail and its fly parasitoid in Australia. Ecological Modelling, 482, 110413. https://doi.org/10.1016/j.ecolmodel.2023.110413