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Review Article

Oryctes rhinoceros (Coleoptera: Scarabaeidae) as a Key Pest of Oil Palm: A Systematic Review of Its Biology, Establishment, and Integrated Management Strategies in Malaysia

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ABSTRACT

Oryctes rhinoceros (coconut rhinoceros beetle) is a major pest of oil palm in Malaysia, with its impact intensified under zero-burn replanting systems that create persistent breeding sites. The emergence of the CRB-G (Guam) haplotype, which exhibits reduced susceptibility to *Oryctes rhinoceros* nudiviruses (OrNV), has further compromised conventional biological control strategies, highlighting the need for updated management approaches. This study presents a PRISMA-compliant systematic review, complemented by exploratory bibliometric analysis, to synthesize evidence on the biology, establishment, and management of *O. rhinoceros* in Malaysia. Literature published between 1970 and 2025 was retrieved from major scientific databases using predefined PICOS criteria, yielding 14 studies eligible for qualitative synthesis. The review indicates that residue-intensive replanting practices significantly enhance beetle population persistence, whereas biological control measures, particularly *Metarhizium anisopliae*-based formulations, demonstrate more consistent field efficacy against CRB-G populations than OrNV alone. Pheromone trapping remains an effective tool for monitoring and population suppression when integrated within comprehensive integrated pest management (IPM) programs, while chemical control is increasingly limited by environmental and sustainability concerns. Bibliometric trends reveal a progressive research shift from chemical-based interventions toward biological, molecular, and sustainable IPM strategies. This review consolidates current knowledge, identifies critical gaps regarding CRB-G adaptation, and outlines priorities for developing resilient, sustainable management strategies in Malaysian oil palm systems.

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Introduction

The coconut rhinoceros beetle (*Oryctes rhinoceros* L.) is a major insect pest of young coconut and oil-palm (*Elaeis guineensis* Jacq.) plantations throughout Asia and the

Pacific region. Although the species is not native to Malaysia, it is believed to have originated in South Asia and was first recorded in Peninsular Malaysia in the early twentieth century, coinciding with the expansion of

commercial coconut cultivation and, subsequently, oil-palm plantations (Bedford, 2014; Zelazny et al., 2017). Since its establishment, *O. rhinoceros* has caused recurrent outbreaks characterized by feeding damage to spear leaves and unopened fronds, producing distinctive V-shaped cuts and, under severe infestation, destruction of the apical meristem. Such injury delays canopy closure, increases susceptibility to secondary fungal infections, and results in substantial yield losses during the early stages of plantation establishment. Yield reductions of up to 25% have been reported in young oil-palm stands, together with increased replanting and management costs, placing *O. rhinoceros* among the most economically damaging insect pests of the Malaysian oil-palm industry (Ramle, 2005; Manjeri et al., 2014).

A major shift in plantation management in Malaysia has been the adoption of zero-burn replanting systems, driven by environmental regulations and sustainability certification schemes such as the Malaysian Sustainable Palm Oil (MSPO) and the Roundtable on Sustainable Palm Oil (RSPO) (MPOB, 2020; BSI, 2022). Although zero-burn replanting reduces air pollution and enhances environmental sustainability, it has inadvertently created favorable breeding conditions for *O. rhinoceros*. Large quantities of unprocessed oil-palm residues, including trunks and fronds, provide optimal substrates for larval development. Field studies have shown that poor residue management can extend beetle development for 12-24 months, thereby increasing infestation risk during replanting cycles ((Bakeri et al., 2023). In contrast, rapid shredding or composting of residues significantly reduces larval survival and subsequent adult emergence (Bakeri et al., 2023; MPOB Technical Bulletin, 2020).

O. rhinoceros exhibits biological and ecological traits that further complicate its management. Developmental duration varies widely, with adults emerging within four to nine months depending on temperature, moisture, and substrate quality (Paudel et al., 2023). Adults are strong fliers capable of dispersing between feeding and breeding sites, which exacerbates damage when organic residues are abundant within a locality (Bedford, 2015). The principal aggregation pheromone, ethyl 4-methyloctanoate (E4-MO), produced by males, attracts both sexes and forms the basis of monitoring and suppression strategies widely used for early detection and mass trapping in Malaysian plantations (Guo et al., 2023). The emergence and spread of distinct mitochondrial

lineages, particularly the CRB-G (Guam) haplotype, have further complicated control efforts. Beetles belonging to this lineage exhibit reduced susceptibility to *O. rhinoceros* nudivirus (OrNV) and, in some cases, decreased responsiveness to conventional pheromone attractants (Marshall et al., 2017). Although locally adapted OrNV isolates in Malaysia have shown potential effectiveness against resident beetle populations, accumulating evidence indicates that OrNV efficacy is strongly influenced by compatibility between beetle haplotypes and viral strains ((Hyszczynska-Sawicka et al., 2024; Tanaka et al., 2023). Consequently, genetic characterization of both *O. rhinoceros* populations and OrNV isolates is increasingly recognized as essential for developing effective, context-specific biological control strategies.

OrNV-based biological control has long been a cornerstone of rhinoceros beetle management in Southeast Asia; however, its implementation in Malaysian zero-burn replanting systems faces logistical and biological challenges (Ramle, 2005; Bedford, 2015). In parallel, the development of mycoinsecticides, particularly *Metarhizium anisopliae*, has shown considerable promise as an alternative or complementary control option. Auto-dissemination approaches, in which adult beetles acquire fungal spores from untreated traps, have achieved field mortality rates of 60-70%, highlighting their potential for integration into large-scale management programs (PMC, 2021; MPOB Research, 2022).

Chemical control measures, such as pyrethroid-based crown drenches (e.g., cypermethrin), are still employed as emergency interventions under severe infestation pressure. However, their short residual efficacy and repeated use raise concerns regarding environmental impacts, non-target effects, and compliance with sustainability certification requirements (MPOB Palmoilis Bulletin). These limitations have contributed to a gradual reduction in chemical control and underscore the need for integrated pest management (IPM) approaches that emphasize cultural sanitation, pheromone-based surveillance, and biological control.

Against this backdrop, the present study synthesizes existing literature on the biology, establishment, and management of *O. rhinoceros* in Malaysian oil-palm systems. In addition to a qualitative review, a bibliometric analysis using VOSviewer is conducted to identify research trends, thematic clusters, and collaboration networks. This review aims to consolidate current knowledge, identify critical research gaps, particularly

regarding residue management efficiency and lineage-specific responses to biological control, and provide evidence-based recommendations for sustainable and context-specific management of *O. rhinoceros* in Malaysia.

Materials and Methods

Study design

This study was conducted as a systematic review following the PRISMA 2020 guidelines as shown in (Figure 1), to synthesize existing evidence on the biology, establishment, and management of *O. rhinoceros* in Malaysian oil-palm plantations. Literature identification, screening, eligibility assessment, and final inclusion were carried out in a transparent and reproducible manner. In addition to qualitative synthesis, an exploratory bibliometric analysis was performed using VOSviewer to identify major research themes, keyword co-occurrence patterns, and collaboration networks within the selected literature. The combined use of systematic review methodology and bibliometric mapping enabled an evidence-based synthesis and assessment of research trends, with particular relevance to IPM strategies.

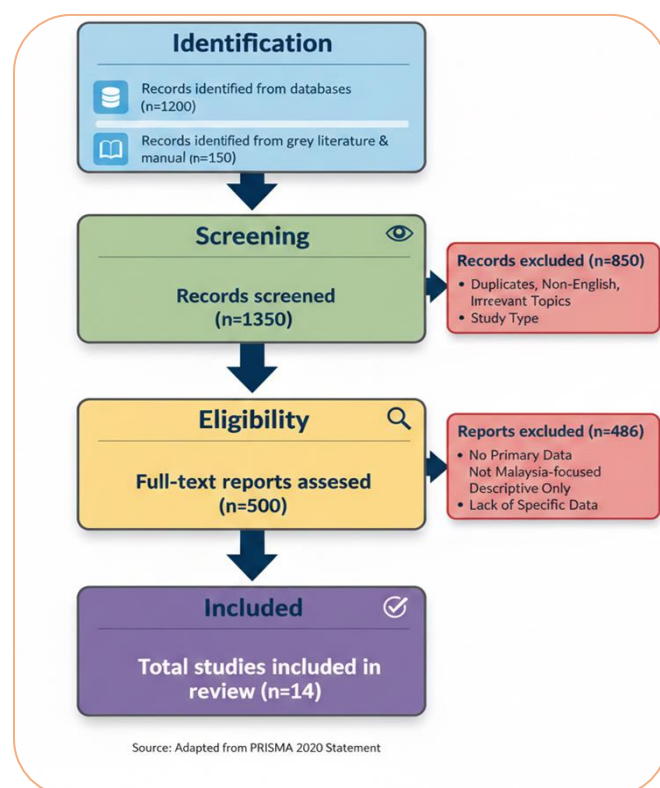


Figure 1. PRISMA 2020 flow diagram for the systematic review of *O. rhinoceros* management in Malaysia.

Selection criteria

Study selection was conducted in accordance with PRISMA 2020 requirements. Peer-reviewed research articles and review papers addressing *O. rhinoceros* in Malaysian oil-palm systems were considered eligible. Grey literature, including technical bulletins, conference proceedings, and postgraduate theses containing substantive empirical or applied management data relevant to the research question, was also included. Most grey literature was sourced from publications of the Malaysian Palm Oil Board (MPOB), the Oil Palm Bulletin, proceedings of the International Palm Oil Congress (PIPOC), and institutional repositories.

Inclusion criteria

Studies were included if they:

- focused on *O. rhinoceros*, a major pest of oil-palm plantations;
- were conducted in Malaysia or reported Malaysian data within a broader Southeast Asian context;
- examined the biology, ecology, population dynamics, or genetic structure of the beetle;
- assessed the influence of plantation management practices, such as zero-burn replanting, on beetle establishment; or
- evaluated control measures, including pheromone trapping, biological control agents, chemical interventions, or integrated pest management approaches.

Only English-language publications published up to 2025 were included to capture both historical developments and recent advances.

Exclusion criteria

Studies were excluded if they were purely descriptive without analytical outcomes, focused on insect pests other than *O. rhinoceros* in Malaysian oil-palm systems, or examined *O. rhinoceros* in non-relevant crops. During screening, duplicate records, editorial or opinion articles lacking primary or secondary research findings, and non-English publications without reliable translations were also excluded.

Search strategy

Systematic literature searches were conducted using Web of Science, Scopus, PubMed, AGRICOLA, and Google Scholar. Search strings were constructed using controlled keywords and Boolean operators, including: (*Oryctes rhinoceros* OR coconut rhinoceros beetle OR CRB) AND (oil palm OR *Elaeis guineensis*) AND

(Malaysia OR Malaysian) AND

(life cycle OR biology OR pheromone OR *Oryctes* nudivirius OR *Metarhizium anisopliae* OR management OR control).

Additional studies were identified through manual screening of reference lists of relevant publications. The final literature search was completed in August 2025.

Study question

The review was guided by the following research question (Table 1):

What evidence exists on the biology, establishment, and management of *O. rhinoceros* in the Malaysian oil-palm industry?

This question informed literature selection and data extraction throughout the review process.

Table 1. PICOS framework for the research question of the present study.

Element	Description
Population (P)	Oil-palm plantations in Malaysia infested with <i>Oryctes rhinoceros</i>
Intervention (I)	Biological control, pheromone trapping, cultural sanitation, and chemical control measures
Comparator (C)	Conventional practices, untreated plots, or alternative pest management approaches
Outcomes (O)	Reduction in beetle population, reduction in palm damage, yield improvement, and sustainability compliance
Study Design (S)	Experimental studies, field trials, molecular studies, and systematic reviews

O. rhinoceros in Malaysia, a PRISMA 2020 flow diagram (Figure 1) was used to trace the process of identification, screening, and selection of studies, when conducting a systematic review of the management of the coconut rhinoceros beetle. Beginning with a sweeping search of five major databases and grey literature sources, including the MPOB, the analysis sought to exclude duplicate and non-English publications, then screened for relevance to Malaysian oil palm systems and management interventions. After which, the 14 studies from 1970 to 2025 were chosen to be integrated into the analysis with qualitative synthesis and mapping.

Data extraction

Data extraction was conducted in a systematic and transparent manner using a standardized template adapted from the Cochrane Handbook for Systematic Reviews of Interventions, with modifications to suit agricultural and entomological research guidelines. For each eligible study, the following information was systematically recorded: author(s), year of publication, study location in Malaysia, study design, experimental or observational approach, life stage of *O. rhinoceros*, type of intervention or management strategy applied, and key study outcomes (Table 2).

Data extraction was restricted to variables relevant to the objectives of the present review, including: (i) the biological and ecological characteristics of *O. rhinoceros* (life cycle, behavior, and genetic or haplotype-related factors); (ii) factors influencing the establishment and

persistence of oil palm systems in Malaysia, particularly under zero-burn replanting practices; and (iii) the effectiveness of control and management strategies, such as pheromone-based monitoring, *Oryctes nudivirius*, *Metarhizium* spp., chemical rescue treatments, and integrated pest management approaches.

In addition, bibliographic metadata (titles, abstracts, author keywords, and citation information) were collected to facilitate bibliometric analysis using VOSviewer. Data extraction was independently performed by two reviewers, and any discrepancies were resolved through discussion to ensure consistency and accuracy.

Results

The primary outcomes assessed across the included studies were parameters directly related to the effectiveness of pest management in Malaysian oil palm plantations, namely adult beetle density, reduction in palm spear damage, and improvements in early palm survival and establishment. These outcomes reflect the biological impact of *O. rhinoceros* and its economic significance during periods of large-scale replanting. Secondary outcomes included the comparative performance of different management strategies, such as mortality rates associated with fungal and viral biocontrol agents, trapping efficiency of pheromone-based systems, and the short-term efficacy of chemical crown drenches. Sustainability-related outcomes were also reported, including compatibility with Malaysian

Sustainable Palm Oil (MSPO) and Roundtable on Sustainable Palm Oil (RSPO) standards, reduced reliance on chemical inputs, and operational feasibility under plantation conditions.

Quality assessment

An adapted checklist commonly used in entomological and plantation-based research was employed to assess the methodological quality and risk of bias of the included studies. For experimental and field trials, assessment criteria included clarity of experimental design, adequacy of replication, use of appropriate controls, and transparency in reporting outcome measures. Observational studies were evaluated based on the clarity of sampling procedures, reproducibility, and robustness of infestation or damage assessment methods. Quality evaluation was independently conducted by two reviewers from different groups, with disagreements resolved through discussion and

consensus.

Statistical analysis

Due to substantial heterogeneity in study designs, interventions, and reported outcome measures, a quantitative meta-analysis was not feasible. Instead, a narrative synthesis was undertaken, supported by systematically tabulated results. Trends in beetle suppression, damage reduction, and overall management effectiveness were summarized using descriptive comparisons across studies. In addition, bibliometric analysis was conducted to complement the qualitative synthesis and to examine research trends, thematic clustering, and collaboration patterns within the literature on *O. rhinoceros* in Malaysia, using VOSviewer. This analysis was exploratory in nature and aimed to identify prevailing research themes rather than to infer statistical relationships between variables, given the focused and context-specific nature of the available data.

Table 2. Summary of studies included in the systematic review.

Author (Year)	Study type	Intervention / focus	Key findings
Gries et al., 1994	Field trial	Aggregation pheromone trapping	Significant reduction in adult beetle catches and spear damage
Hall et al., 2007	Field trial	Pheromone mass trapping	Sustained suppression of beetle populations in young palms
Moslim et al., 2013	Review/ field data	<i>Metarhizium anisopliae</i> Spray	infected adults which escaped, carried over the spores and distributed them to the other healthy adults
Hamid et al. (2005)	Laboratory and field	<i>Metarhizium anisopliae</i> (powder)	High adult and larval mortality under controlled conditions
Manjeri et al., 2014	Observational	Damage–yield relationship	Strong association between spear damage and yield loss
Paudel et al., 2021	Field trial	<i>Metarhizium</i> formulations	Improved persistence and infection rates in plantations
Alfaro et al., 2019	Field study	Pheromone + light traps	Enhanced trap efficacy in young plantations
Ismail et al., 2009	Field trial	Cypermethrin crown drench	Short-term damage reduction; repeated application required
Karim et al., 2019	Survey	Chemical control in smallholders	Limited sustainability and non-target risks
Ripin and Latip (2021)	Observational	Infestation–damage interaction	Spear damage effective as infestation indicator
Marshall et al. (2017)	Molecular	CRB-G and OrNV response	Reduced susceptibility of CRB-G to OrNV
Anggraini et al. (2023)	Molecular	Haplotypes and OrNV incidence	Lineage-specific viral interactions
Tanaka et al. (2023)	Field and molecular	Local OrNV isolates	Improved efficacy against Malaysian populations

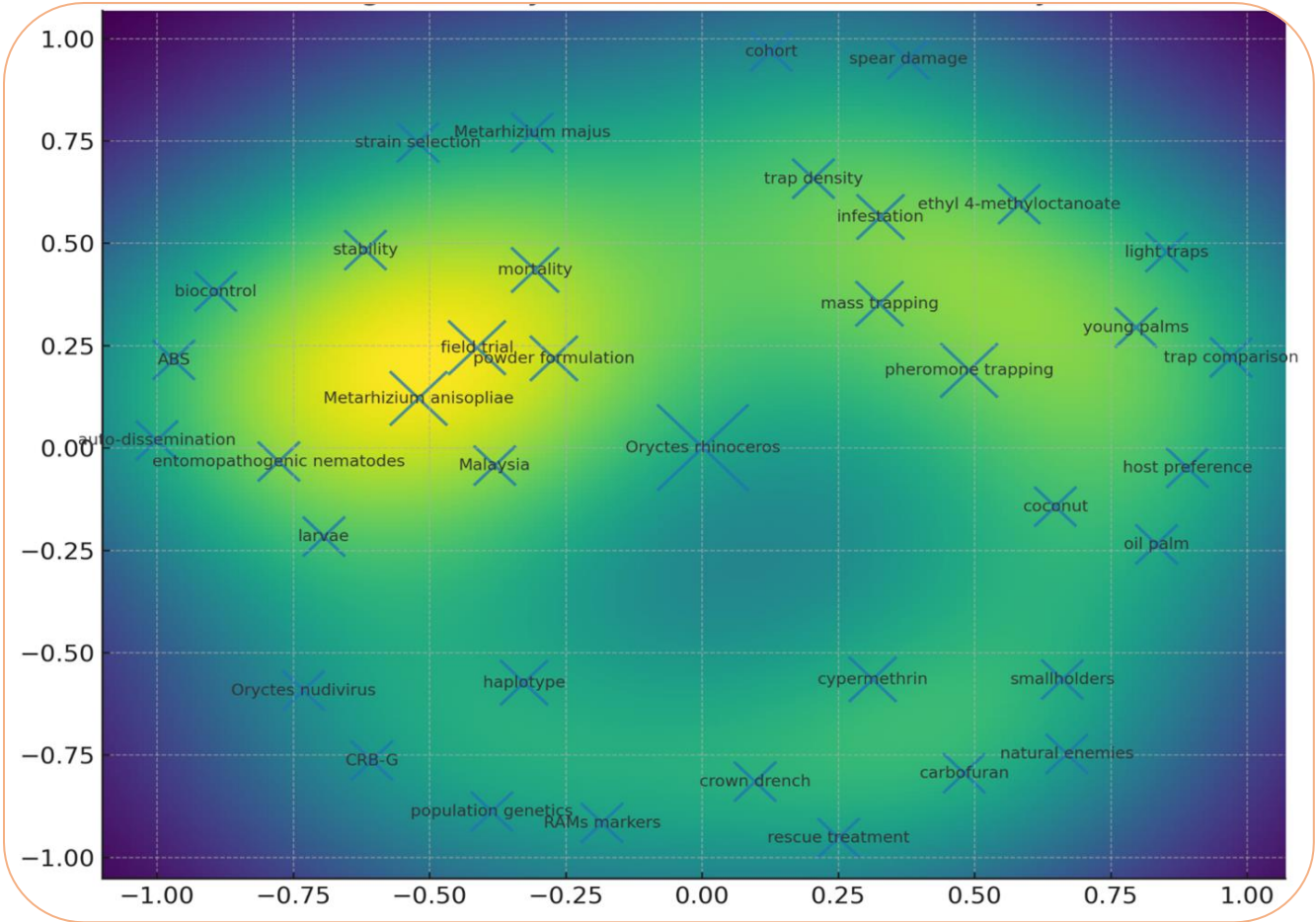


Figure 3. Keyword co-occurrence density map.

Keyword intersection by average publication year

The temporal overlay analysis revealed a clear chronological progression in research priorities (Table 3). Early studies (late 1990s to early 2000s) predominantly emphasized mass trapping and pheromone trapping, reflecting an initial focus on population monitoring and large-scale suppression using semiochemical-based tools (Figure 4). Research during the 2000s and 2010s, characterized by keywords such as *M. anisopliae*, powder formulation, and autodissemination systems, indicated a shift toward fungal

biocontrol approaches. This transition coincided with the broader adoption of IPM strategies and increasing regulatory restrictions on chemical insecticides. More recent publications (2023-2025) are marked by the emergence of molecular and lineage-specific terms, including haplotype, CRB-G, *M. majus*, and *O. nudivirus*. This trend reflects a strategic move toward genetically informed pest management and strain-specific optimization of biocontrol agents, which currently represents a key research focus in Malaysian oil-palm production systems.

Table 3. Temporal evolution of dominant research themes.

Period	Dominant keywords	Primary research focus
1995–2005	Pheromone trapping, mass trapping	Monitoring and population suppression
2006–2015	<i>Metarhizium anisopliae</i> , formulation	Fungal biocontrol development
2016–2022	Autodissemination, IPM	Integration of biocontrol strategies
2023–2025	CRB-G, haplotype, OrNV	Molecular and lineage-specific control

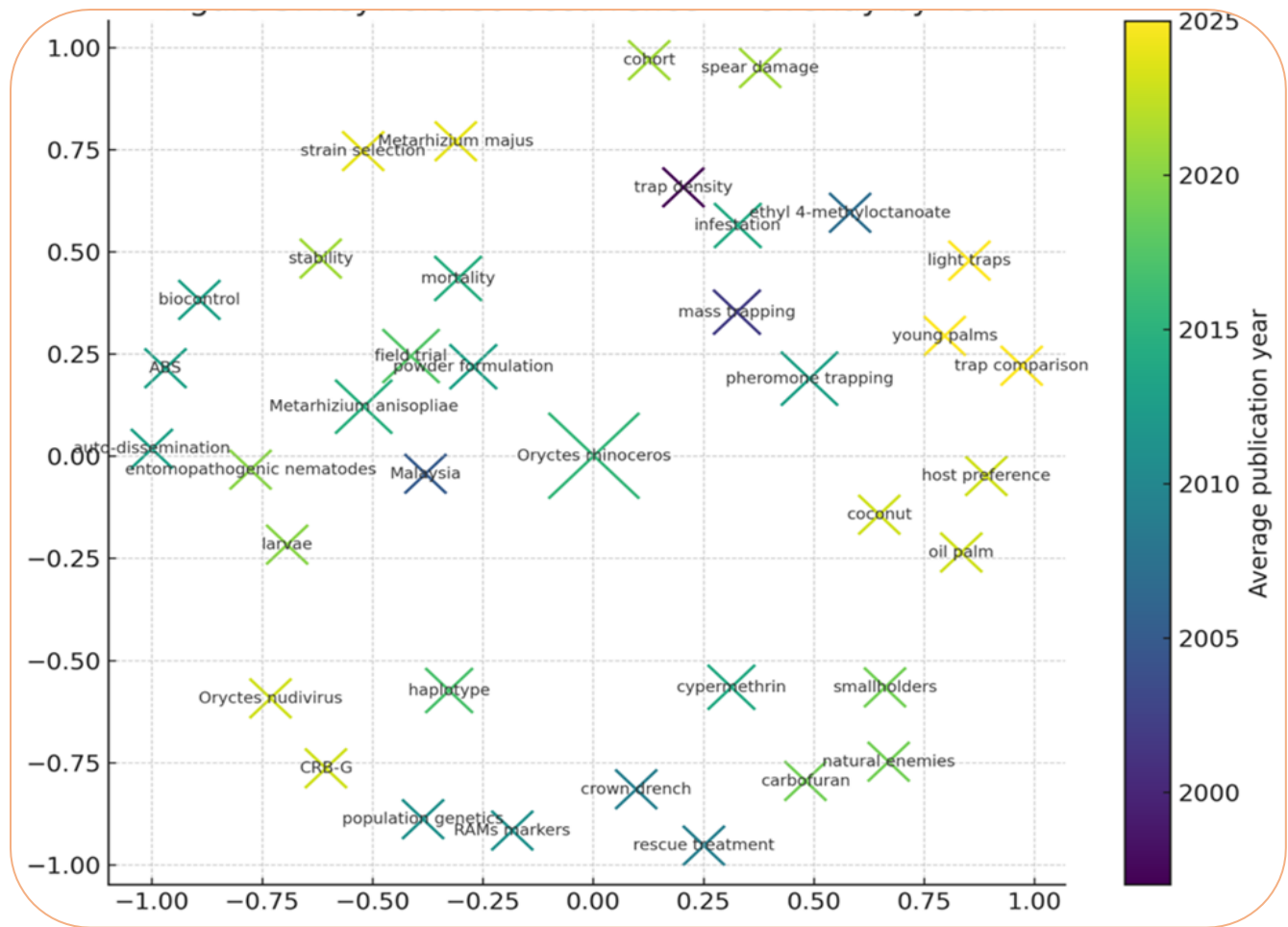


Figure 4. Year-wise keyword co-occurrence analysis.

Co-citation network: sources and journals

The co-citation analysis of publication sources revealed a core group of journals primarily focused on applied entomology and tropical agriculture (Figure 5). Journals such as the Journal of Asia-Pacific Entomology and Crop Protection formed strong citation linkages with studies on pheromone-based and biological control strategies and showed substantial influence in disseminating research on pest management.

Applied plantation-oriented outlets, including the Oil Palm Bulletin and MPOB technical publications, were closely associated with chemical control and field-level implementation studies, highlighting their role in translating research findings into practical applications. More recent trends indicate an increasing contribution of molecular diagnostics to practice-oriented research, as reflected by citations in high-impact international journals such as Scientific Reports. Research on fungal formulations was strongly linked to conference

proceedings, particularly PIPOC, underscoring the importance of applied research forums in advancing the development and adoption of biocontrol technologies.

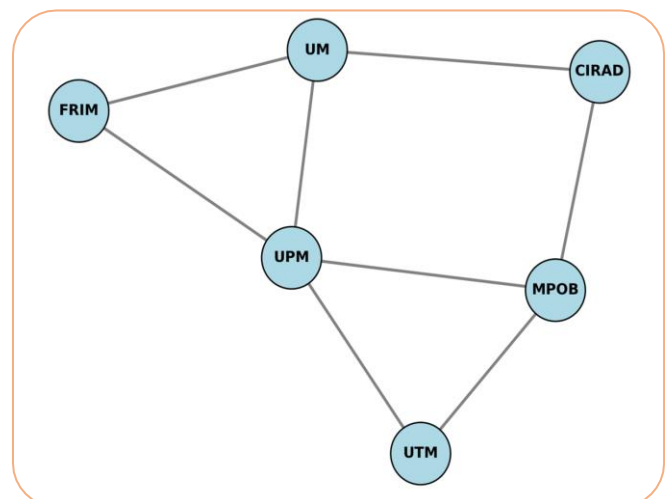


Figure 5. Co-citation network of sources (journals).

Bibliographic coupling – documents

The bibliographic coupling network represents a document-based model organized around shared references (Table 4), in which each group of documents forms a distinct thematic research family. The largest cluster (Figure 6), corresponds to fungal biocontrol research (Hamid, 2005; (Moslim, 2013; Indriyanti, 2020; Paudel, 2021; Villamizar, 2024), indicating a common methodological foundation centered on *Metarhizium* field trials. Another cluster is associated with pheromone-based research (Fee, 1997; Hall, 2007; Santi, 2025), unified by a focus on semiochemical studies. A

smaller but clearly defined cluster comprises chemical control studies (Ismail, 2009; Fathul Karim, 2019), showing limited thematic overlap with the biocontrol and pheromone clusters. Finally, a weakly connected and peripheral group includes observational and genetic studies (Gnanasegaram, 2011; Ripin, 2021; Anggraini, 2023). Overall, the coupling map indicates that while fungal biocontrol and pheromone studies form well-defined research families, chemical and observational studies remain poorly integrated. Greater integration of these approaches into future IPM frameworks could enhance system resilience.

Table 4. Major bibliographic coupling clusters and their research focus.

Cluster	Key Studies	Research Emphasis
Fungal biocontrol	Hamid (2005), Ramle (2013), Indriyanti (2020), Paudel (2021), Villamizar (2024)	<i>Metarhizium</i> -based control
Pheromone studies	Fee (1997), Hall (2007), Santi (2025)	Monitoring and mass trapping
Chemical control	Ismail (2009), Karim (2019)	Short-term rescue treatments
Molecular/observational	Gnanasegaram (2011), Anggraini (2023), Ripin (2021)	Genetics and infestation ecology

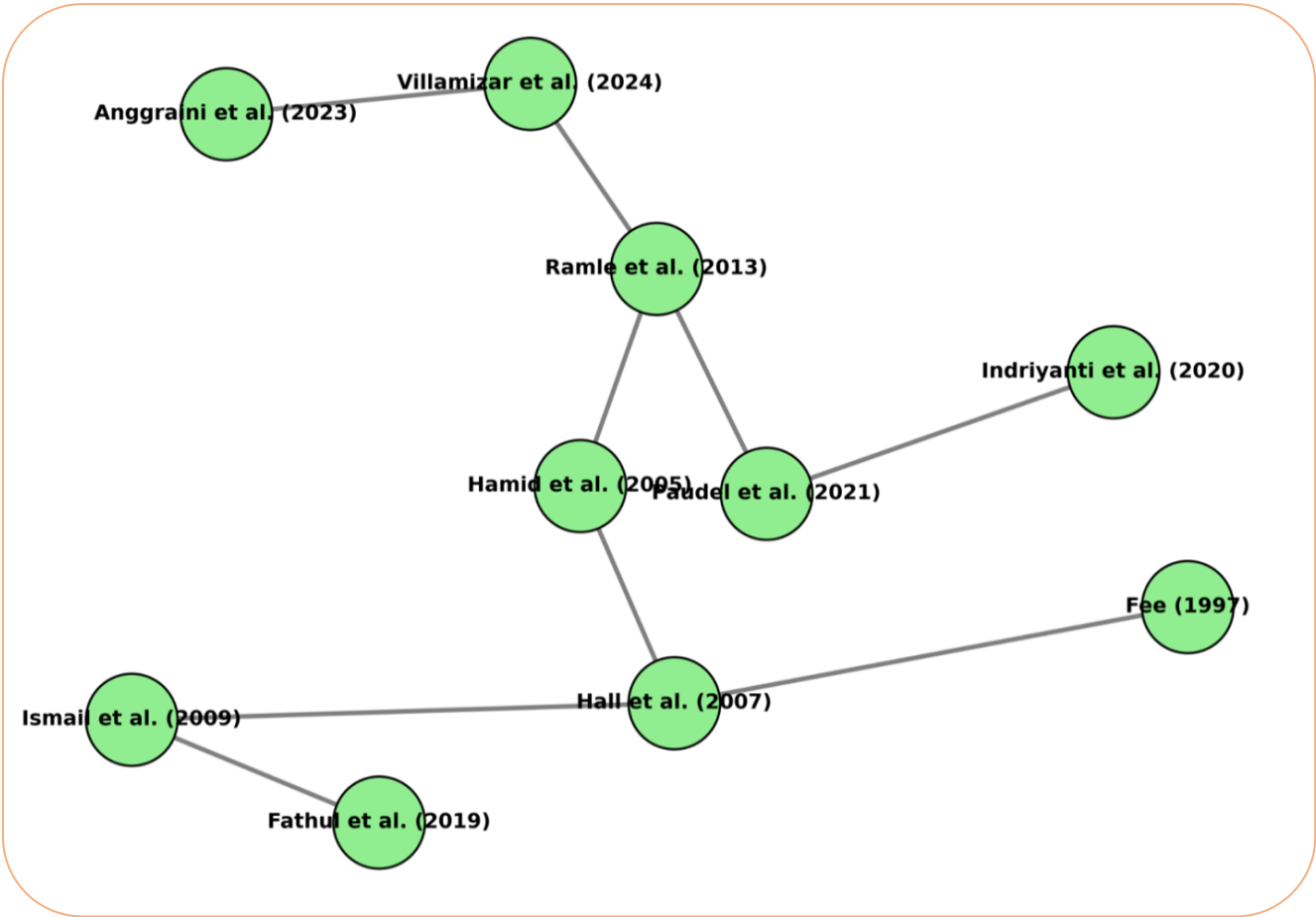


Figure 6. Citation network of research on *O. rhinoceros*.

Combined analysis of bibliometric findings

Overall, the bibliometric analyses indicate a well-structured and dynamic research field. The prominence of fungal biocontrol and its strong co-occurrence with key terms highlights the dominance of fungal agents and pheromone trapping as the primary pillars of *O. rhinoceros* management in Malaysia. Overlay analysis reveals a temporal shift in research focus, with conventional monitoring-based strategies gradually declining and being replaced by biologically and genetically informed approaches. Co-citation and bibliographic coupling analyses further show that studies on fungal biocontrol and pheromones form cohesive research clusters, whereas chemical and purely observational studies remain fragmented, indicating a need for greater integration in future IPM frameworks. Collectively, these findings suggest that although biocontrol-based IPM strategies are now well established, future advancements in Malaysian oil-palm pest management will increasingly depend on molecular diagnostics, targeted strain selection, and enhanced international research collaboration to effectively address lineage-specific threats such as CRB-G.

Discussion

This review, integrating fourteen studies and bibliometric mapping, provides a comprehensive overview of *O. rhinoceros* management in Malaysian oil-palm plantations. A clear trend in the literature is the increasing focus on biological control, particularly the use of entomopathogenic fungi. Research on *M. anisopliae* and related species has consistently demonstrated high pathogenicity against both larval and adult stages, establishing fungal control as a central component of sustainable management. Early studies primarily applied fungal spores broadly, whereas recent efforts emphasize strain-specific preparations and self-dissemination devices that exploit beetle behavior to enhance pathogen release (Lacey et al., 2015; Watatabe et al., 2020). This shift is especially important given that certain haplotypes, such as CRB-G, exhibit reduced susceptibility to *O. nudivir* (OrNV), the conventional viral biocontrol agent (Marshall et al., 2017; Etebari et al., 2020). Consequently, fungal biocontrol has emerged as a focal point in IPM programs in Malaysia.

Pheromone-based approaches remain effective tools for monitoring and control. The male-produced aggregation pheromone, ethyl 4-methyloctanoate, is widely used to

reduce adult populations via mass trapping. Trap efficacy depends on beetle density, proximity to replanting residues, and plantation age (Gries et al., 1994; Huger, 2005). Modifications such as light traps with pheromone baits have increased capture rates, particularly in young plantations with high beetle immigration (Alfaro et al., 2019). Bibliometric analysis identifies pheromone research as the earliest and most consistent thematic cluster, reflecting its foundational role in Malaysian IPM programs.

Chemical control remains controversial. Pyrethroid crown drenches, carbamates, and other insecticides provide temporary reduction in spear damage, requiring repeated applications for sustained effect (Wood, 1988). Moreover, chemical treatments can harm non-target organisms, including natural predators, and may conflict with sustainability standards such as RSPO and MSPO (Basri et al., 2010; Hoong et al., 2011). Bibliometric coupling indicates that chemical control is peripheral compared to fungal and pheromone-based studies, highlighting its limited role in integrated strategies.

Effective IPM relies on ecological and observational studies. Seasonal analyses of infestation and spear damage reveal a strong correlation between beetle activity and damage, validating spear damage as a field-based proxy for infestation pressure (Chung, 1997; Manjeri et al., 2014). Molecular studies indicate high haplotype variation in Malaysian *O. rhinoceros* populations, suggesting the need for lineage-specific biocontrol programs ((Anggraini et al., 2023; Keenan et al., 2019). The emergence of CRB-G haplotypes with reduced OrNV susceptibility underscores the importance of local strain characterization for both viral and fungal biocontrol strategies (Marshall et al., 2017).

Bibliometric analysis highlights strong research collaboration led by Malaysian institutions, notably the MPOB, fostering international partnerships with institutions in the UK and Indonesia. These collaborations have enabled molecular technology transfer, novel fungal formulations, and expanded ecological knowledge of *O. rhinoceros* life cycles (Bedford, 2014; Kamarudin et al., 2017). International engagement is increasingly important as invasive populations threaten oil-palm industries beyond Malaysia (Samsudin et al., 2018).

Critical research gaps remain. Large-scale, long-term evaluations of integrated approaches are lacking; most studies are small-plot and short-term, limiting their

ability to assess the sustained efficacy of fungal inoculations or pheromone grids under high beetle densities. Economic analyses of biocontrol formulations, pheromone networks, and chemical interventions are insufficient, restricting practical guidance for estate managers and smallholders (Sheil et al., 2019; Chong et al., 2020). Ecological studies of natural predators, parasitoids, and biodiversity in oil-palm plantations are also limited, despite their potential to contribute to pest suppression (Foster et al., 2011).

Future research should focus on: (i) molecularly specific biocontrol formulations tailored to local haplotypes, (ii) integrating ecological studies of natural predators and biodiversity into IPM frameworks, (iii) simulating pest behavior under climate change, and (iv) conducting cost-benefit analyses to support evidence-based estate-scale implementation. Such approaches will strengthen flexible, context-specific IPM measures. Overall, pheromone trapping and fungal biocontrol remain central to *O. rhinoceros* management, with increasing emphasis on lineage-specific, molecularly informed strategies. This review underscores the need for adaptive IPM models that account for pest biology, replanting practices, and sustainability requirements, translating molecular and fungal innovations into cost-effective, large-scale interventions across Malaysian plantations.

Conclusion

This systematic review consolidates current knowledge on *O. rhinoceros* in Malaysian oil-palm plantations, integrating biological, ecological, molecular, and management perspectives. Entomopathogenic fungi, particularly *M. anisopliae*, combined with pheromone-based mass trapping, are the most effective strategies for reducing beetle populations and crop damage, forming the foundation of sustainable pest management. Chemical treatments offer short-term relief but pose environmental risks. Molecular analyses reveal the emergence of the CRB-G haplotype, necessitating lineage-specific control approaches. Bibliometric mapping identifies three primary research foci: fungal biocontrol, pheromone monitoring, and genetic lineage analysis. Research networks, led by Malaysian institutions, are strengthened through international collaborations, enhancing molecular and ecological knowledge. The review highlights the need for large-scale, long-term trials, economic evaluations, and adaptive IPM systems to translate laboratory

innovations into operationally viable, sustainable solutions. These insights provide evidence-based guidance for policymakers, plantation managers, and researchers to mitigate the economic and environmental impacts of *O. rhinoceros* in oil-palm production.

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Author Contributions

MAH, KTK and ZS jointly conceived the review, designed the methodology, conducted the systematic literature screening, data extraction, and bibliometric analysis, and led manuscript writing and revision. Other authors contributed to literature support, technical inputs on pest management, contextual validation, and critical review of the manuscript.

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Conflict of Interest

The authors declare no conflict of interest.

Sustainable Development Goals Targeted

SDG 2: Zero Hunger

SDG 12: Responsible Consumption and Production

SDG 15: Life on Land

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