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REVIEW ARTICLE

Environmental risks of pest management practices in smallholder coconut plantations

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ABSTRACT

Oryctes rhinoceros, the coconut rhinoceros beetle, remains one of the most damaging pests of coconut (*Cocos nucifera*) across South and Southeast Asia, the Pacific, and increasingly, new invasion fronts in the Americas. Although climatic alterations may redistribute the geographic footprint of the hazard, predictive assessments underscore non-linear and variable outcomes. Regional expansions in vulnerable or suitable extents are largely contingent upon the analytical scenario and structural parameters of the model utilized. This reinforces the case for treating its management as an environmental, not solely agronomic, concern. The study objectives were to characterize how smallholder-level management choices translate into differentiated environmental and health risk. Smallholder coconut plantations, which supply most world coconut production, are disproportionately exposed because of fragmented land holdings, limited capital, and constrained extension access. This review evaluates the translation of management interventions into distinct environmental and health hazards by systematically reviewing evidence on coconut rhinoceros beetle biology, intervention efficacy, smallholder socioeconomic dynamics, and insecticide risk literature through a standardized four-tier risk framework. Smallholders commonly rely on chemical control options such as organophosphates and pyrethroids. These options carry documented risks: non-target toxicity, soil and water contamination, and occupational exposure. In the absence of beetle-specific metrics, elevated occupational exposure risks are inferred from prevailing normative practices in smallholder agriculture concerning the omission of protective equipment. Biological and cultural alternatives include *O. rhinoceros nudivirus*, *Metarhizium anisopliae*, *Bacillus thuringiensis*, botanical larvicides, and pheromone-based trapping. These present a substantially lower environmental risk profile: laboratory bioassays report 90 to 100 percent larval mortality for *Metarhizium* isolates from East Java, comparable to the up to 98 percent larval and 90 percent adult mortality reported for a granular carbamate alternative, indicating technical efficacy is not the limiting factor, with field-deployed monitoring documented in Jepara and Bengkulu. Uptake of these lower-risk options is nonetheless constrained less by technical efficacy than by production economics, extension access, and the fragmented governance of smallholder replanting and pest-management programs. The evidence suggests that attenuating this risk burden is predominantly constrained by the disparity between existing lower-risk technological interventions and their operational uptake, among other compounding determinants. Risk-management strategies must therefore be designed around smallholder economic and institutional realities rather than efficacy data alone.

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INTRODUCTION

Coconut (*Cocos nucifera* L.) underpins the livelihoods of tens of millions of smallholder farmers across the tropics, and in most producing countries the crop is grown predominantly on smallholdings rather than large corporate estates. Comparative economic assessments within Indonesia indicate that diversified coconut intercropping practices consistently outperform monocropping by securing enhanced returns for smallholders under both national and private economic accounting criteria. Development programs have nonetheless historically still encouraged monocropping (Rani *et al.,* 2018). More broadly, technical efficiency, profitability, and sustainability of coconut smallholdings remain sensitive to several production constraints. These range from ageing palm stands to limited access to credit and extension (Omar and Fasleen, 2020, 2021; Rusli and Isa, 2021; Agus, 2025; Bahri *et al.*, 2026). Among the biotic constraints on smallholder coconut production, the coconut rhinoceros beetle (CRB), *Oryctes rhinoceros* (Linnaeus) (Coleoptera: Scarabaeidae), is one of the most persistent and economically damaging. Adult beetles bore into the crown of the palm to feed, damaging developing fronds and, under repeated attack, killing young or already-stressed palms (Bedford, 1976; Zelazny and Alfiler, 1987; Manley *et al.*, 2018). Larvae develop in decaying organic matter that is often abundant around smallholder plantings, including felled trunks, compost, and other breeding substrates (Fauzana and Ustadi, 2020; Shen *et al.*, 2025). The species' life-history characteristics exacerbate control challenges in smallholder agricultural matrices, wherein fragmented and decentralized breeding substrates limit the efficacy of the centralized sanitation protocols typically enforceable on managed estates. The geographic range of CRB has continued to expand. Beyond its long-established distribution across South and Southeast Asia and the Pacific, recent reports document continuing damage around Port Moresby, Papua New Guinea (Jackson *et al.*, 2025a). Confirmed presence in Timor-Leste carries attendant biosecurity implications (Paudel *et al.*, 2025). Further documentation confirms a sustained outbreak on Efate, Vanuatu (Paudel *et al.*, 2023), marking both this regional expansion and the initial geographic establishment of the species within the Americas (Jackson *et al.*, 2025b). Compounding the invasion risk, a genetically distinct haplotype, historically referred to as Guam biotype (CRB-G)-has been shown to escape control by the region's primary biological control agent, *O. rhinoceros* nudivirus (OrNV) (Marshall *et al.*, 2017; Tanaka *et al.*, 2021). This haplotype has driven renewed outbreaks across several Pacific islands (Anggraini, 2023; Weston *et al.*, 2023), although recent genomic analyses confirm this invasive lineage did not disperse from Guam (Tay *et al.*, 2024). Within Indonesia, field damage and infestation have been documented from East Java (Prastowo *et al.*, 2022), and Rote-Ndao, East Nusa Tenggara (Nenotek *et al.*, 2024). Further cases are reported from Jepara, Central Java (Indriyanti, 2017; Indriyanti *et al.*, 2018), and Yogyakarta (Adi *et al.*, 2023, 2025). This underscores that the problem recurs across the archipelago's smallholder coconut belt, rather than being geographically confined. The management framework for the CRB bridges a continuum from broad-spectrum chemical treatments to precise biological and cultural measures, wherein each intervention tier carries a distinct spectrum of environmental and occupational health hazards. A substantial general literature has established that insecticide use carries environmental risks extending well beyond the target pest. These include risks to pollinators and other non-target organisms (Goulson, 2013; Sponsler *et al.*, 2019; Wan *et al.*, 2025) and contamination of surface water and sediment (Sousa *et al.*, 2016; Top *et al.*, 2023). Occupational and residential exposure of applicators and nearby communities is also documented (Dereumeaux *et al.*, 2020; Oltramare *et al.*, 2023). General studies

on smallholder agriculture practices highlights substantial vulnerabilities during pesticide administration, including negligible use of personal protective equipment, imprecise application dosing, and minimal formal risk-appraisal capacity. In the absence of CRB-specific empirical datasets, these systemic trends are considered broadly applicable to CRB management frameworks. As a result, the environmental risk profile of any CRB control program depends as much on who applies it and under what conditions as on the intrinsic toxicity of the product used. This study synthesizes evidence on CRB management options in smallholder coconut systems through an explicit environmental risk-assessment lens. Existing comprehensive literature has predominantly examined CRB biology and intervention efficacy as standalone objectives (Hassaan *et al.*, 2025; Hosang *et al.*, 2025). The aim of this study is to characterize the comparative hazard, exposure, and risk profile of the control strategies actually available to and adopted by smallholders. This study also examines, through Indonesian and comparable Southeast Asian and Pacific case evidence, why lower-risk options remain under-adopted despite their documented field performance. This study was carried out at the Research Centre for Estate Crops, National Research and Innovation Agency (BRIN), Bogor, Indonesia, in 2026.

METHODOLOGY

Methodologically, this review adopts a narrative synthesis rather than a systematic or quantitative protocol, aligning its scope with the evaluation of operational management cases across smallholder coconut systems rather than providing an exhaustive bibliographic catalog of CRB literature. The evidence base draws on 121 peer-reviewed references across four domains: (i) CRB biology, invasion ecology, and genomics; (ii) chemical, biological, and cultural control efficacy; (iii) smallholder production economics and sociology; and (iv) general insecticide risk-assessment literature, used as a comparative frame where CRB-specific ecotoxicological data are lacking. Findings are presented as direct evidence when derived from studies on *Oryctes rhinoceros* or its management; otherwise, broader insecticide or smallholder literature is used for context and identified accordingly. Following a standardized environmental risk assessment paradigm (hazard identification, exposure assessment, risk characterization, and risk management), the initial phase focuses on the biological and invasive attributes of the CRB that perpetuate its persistent impact. Exposure assessment examines chemical and biological control practices reported in smallholder contexts, with emphasis on Indonesian cases. Risk characterization compares environmental and health profiles of these practices, while risk management considers institutional, economic, and technological factors shaping adoption of lower-risk options. Within this framework, “hazard” denotes intrinsic toxicological or biological properties; “exposure” refers to pathways, dose, frequency, route, and receptor; and “risk” reflects their combination. Socioeconomic vulnerability is explicitly integrated as the structural determinant governing intervention accessibility, which subsequently configures realized hazard-exposure trajectories. Geographic emphasis is on Indonesia, with comparative evidence from Malaysia, India, the Philippines, and Pacific Island systems where smallholder structures are similar. The review process followed the general framework proposed by Fink (2014). Literature was retrieved from Scopus, Web of Science, Google Scholar, and CAB Abstracts using combinations of the search terms "Oryctes rhinoceros", "coconut rhinoceros beetle", "coconut", "Cocos nucifera", "integrated pest management", "biological invasion", "climate change", "nudivirus", "biosecurity", "pesticide pollution", "insecticide", "ecotoxicology", and "biopesticide", covering publications from 1976 to

2026. Records were screened for relevance to CRB biology, invasion ecology, control efficacy, or smallholder coconut socioeconomics; general insecticide environmental risk-assessment literature was included where CRB-specific ecotoxicological data were unavailable. Conformant with the stated narrative-review architecture, formal systematic screening protocols, including PRISMA guidelines, were not implemented in the article selection process. Of the 960 records identified, 363 remained after title screening, and 121 were retained following full-text assessment for relevance, availability, and language, as summarised in Fig. 1. The geographic scope of this review is illustrated in Fig. 2, which maps the five Indonesian smallholder case locations discussed in the "Case review synthesis" section: East Java (Prastowo *et al.*, 2022), Jepara in Central Java (Indriyanti *et al.*, 2018), Yogyakarta (Adi *et al.*, 2023, 2025), Bengkulu (Ginting *et al.*, 2025), and Rote-Ndao in East Nusa Tenggara (Nenotek *et al.*, 2024). Encompassing a broad spectrum of agroecological and socioeconomic gradients across four major islands—from the high-density smallholder configurations of Java to the dispersed, moisture-stressed coconut systems of eastern Indonesia, these cases illustrate that the environmental risk profiles analyzed in this review are structurally pervasive throughout the archipelago's smallholder agricultural landscape. The analytical framework used to structure this synthesis, mapping each guiding theme to its corresponding focus and extraction criteria, is presented in Table 1. Socioeconomic vulnerability is conceptualized within this structure not as a parallel risk dimension, but as the operational filter that dictates intervention accessibility for smallholders, thereby fundamentally conditioning the realized hazard-exposure trajectory. Where lower-risk biological or cultural options are technically available but inaccessible due to capital, extension, or institutional constraints, the higher-risk chemical alternative becomes the default realized exposure pathway, linking Table 2 (technical risk) and Table 3 (socioeconomic constraint) as a single integrated risk-management framework.

Hazard identification: CRB *as a persistent threat to smallholder coconut*

Adult *O. rhinoceros* bore into the unopened crown of the coconut palm to feed on sap, and the resulting V-shaped cuts in emerging fronds are the pest's most visible field sign. Persistent herbivory on immature or replanted palms frequently causes terminal destruction of the meristematic growing point, a damage dynamic well-documented throughout multiple invasion zones (Mansfield *et al.*, 2024). Larval development depends on decaying organic matter. Felled coconut trunks, sawdust, compost heaps, and other cellulose-rich debris common around smallholder plots and replanting sites function as breeding sites that are difficult to eliminate at the scale of an individual smallholding (Bedford, 1976; Zelazny and Alfiler, 1987; Manley *et al.*, 2018). Environmental conditions, including moisture and substrate composition, materially influence larval survival and breeding success. Hazard intensity is therefore partly determined by land-management practices within the smallholder's control, such as trunk disposal after felling or land clearing (Fauzana and Ustadi, 2020; Shen *et al.*, 2025). The severity of this hazard is structurally compounded by concurrent geographic dispersal and the proliferation of a genetically distinct haplotype impervious to standard biocontrol interventions. The CRB-G haplotype has spread across several Pacific islands where it was not historically established, evading suppression by OrNV isolates that had previously kept older haplotype populations in check (Marshall *et al.*, 2017; Tanaka *et al.*, 2021; Anggraini, 2023; Weston *et al.*, 2023). Its continued detection includes confirmation that it did not disperse to the Solomon Islands or Palau from Guam as initially suspected (Tay *et al.*, 2024). This illustrates how invasion pathways for this pest remain only partly understood. Independent confirmations of new or continuing incursions come from Papua New Guinea

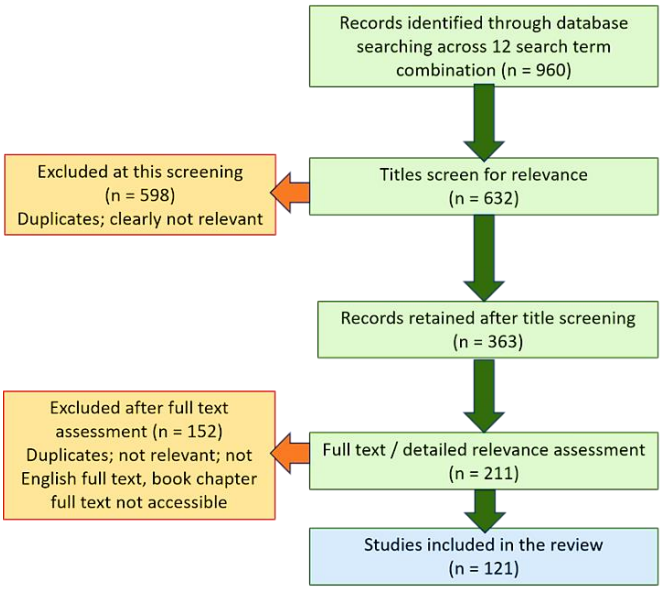

Fig. 1. Flow diagram of the literature search and selection process, showing the number of records identified, screened, and included at each stage, with reasons for exclusion



Fig. 2: Geographical location of the study area of the smallholder CRB infestation cases reviewed

Table 1: Analytical framework guiding the synthesis of literature

No	Analytical theme	Focus	Extraction criteria
1	Hazard and exposure identification	How CRB biology, invasion status, and smallholder management practices jointly determine exposure to different control options	Biological and damage records, documented chemical and biological control practices, application methods
2	Environmental and health risk characterization	Comparative environmental and health risk profile of chemical versus biological/cultural control components	Reported toxicity and ecotoxicological data, contamination indicators, mode of action, occupational exposure pathways
3	Risk management and adoption evidence	What socioeconomic and institutional evidence from Indonesian smallholder systems implies for adoption of lower-risk management	Field-scale case outcomes, adoption constraints, extension and financing evidence, institutional capacity indicators

Table 2: Comparative environmental and health risk profile of *O. rhinoceros* control options reported in smallholder and community plantation settings

Control agent	Active ingredients/ organism	Application route	Target stage	Evidence level	Principal environmental receptor	Occupational exposure pathway	Documented adverse effects	Confidence/ uncertainty	Source
Cypermethrin, dimethoate	Cypermethrin (pyrethroid); dimethoate (organophosphate)	Foliar/crown broadcast spray	Larvae/ adults	Laboratory	Non-target neurosecretory systems; soil/water (class-level)	Dermal/ inhalation during mixing/ application	Dimethoate: measurable neurosecretory changes at 0.125–0.5% concentration, 8–24h exposure	CRB-specific data limited to lab bioassay; broader risk drawn from comparative literature	Larval/adult treatment (Venkatarajappa, 2001; Padmasheela and Delvi, 2004)
Acephate (trunk injection)	Acephate (organophosphate)	Trunk injection/ implant	Adults (systemic)	Semi-field	Palm vascular tissue; feeding organisms	Reduced vs. broadcast spraying	Not specified beyond efficacy	Single study; long-term fate not evaluated	Tall palms via petiole bioassay (Rafie and Amit, 2024)
Marshal 5G / systemic (UAV/manual)	Carbosulfan 5% (carbamate)	Granular soil/leaf-axil; UAV aerial	Larvae/ adults	Laboratory + field	Soil/water (runoff, leaching)	Dermal/ inhalation during mixing/ application; reduced during UAV step	95–98% larval mortality (5–9g); 90% adult mortality (day 7), declining to 70–75% (10–15 days)	Efficacy well-documented; drift/deposition exposure not evaluated	Community oil palm, Riau (Tito *et al.*, 2026); O'ahu, Hawai'i (Russo *et al.*, 2026); UAV application (Roudhiyah *et al.*, 2024; Lan *et al.*, 2024)
Metarhizium anisopliae	Entomopathogenic fungus	Breeding-site inoculation	Larvae (3rd instar)	Laboratory bioassay (field-sourced isolates)	Non-target soil arthropods (broader host range)	Minimal; no chemical toxicant	None identified in literature; 90–100% mortality (day 13–15)	Field-scale/non-target/logistics less established	East Java (Prastowo *et al.*, 2022); compost-based "metankos" (Fauzana *et al.*, 2023)
Bacillus thuringiensis	Bacterium (Cry-toxin dependent)	Pot-based soil application	Larvae	Laboratory / pot trial	Non-target insects (strain-dependent)	Host-specific; non-target effects documented	None identified in literature	Strain-specific host range not fully characterized	Pot-based soil application trial (Pujiastuti *et al.*, 2020, 2021, 2023)
OrNV	Virus (host-specific)	Field release/ regional	Larvae/adults	Field/operational	None beyond target host	Minimal; no chemical toxicant	None identified	Long release history; limited by CRB-G resistance	Long-standing regional releases (Huger, 2005; Ramle *et al.*, 2005)
Pheromone trapping	Ethyl 4-methyloctanoate	Trap deployment	Adults	Field/ village-level	None (non-toxicant)	None	None	Suppression not demonstrated; non-target attraction and trap/lure disposal footprint untested	North Sulawesi (Hosang *et al.*, 2022); Jepara (Indriyanti *et al.*, 2018); Bengkulu (Ginting *et al.*, 2025)
Botanical larvicides	Plant-derived compounds	Lab/small-scale application	Larvae	Laboratory /small field trial	Non-target insects (compound-dependent)	Minimal; not established	Not established at scale	Limited evidence; non-target toxicity and application-frequency trade-offs untested	Laboratory/small field trials (Mohan and Padmanaban, 2013; Kumar *et al.*, 2018, 2019; Wandri *et al.*, 2024)

Table 3: Socioeconomic and institutional contexts of smallholder coconut production relevant to technology adoption

Constraint	Description	Supporting evidence
Capital/production economics	General coconut-sector studies document limited surplus capital among smallholders, which plausibly favors low-upfront-cost chemical sprays over the production/ monitoring infrastructure biological control requires	Godoy and Bennett, 1991; Omar and Fasleen, 2020, 2021;
Extension access	General studies document uneven extension access among Indonesian coconut smallholders, plausibly limiting farmer knowledge of and confidence in biological/cultural alternatives	Rusli and Isa, 2021
Replanting and financing schemes	General studies document historically low implementation of coordinated financing for smallholder long-term investment; sustained biocontrol production would plausibly face similar barriers	Sondakh and Hardaker, 1983; Wulandari and Alouw, 2021
Institutional/development strategy	General coconut-sector studies indicate sector-wide sustainability depends on coordinated strategy rather than farmer-level intervention alone, a principle plausibly relevant to CRB biocontrol adoption	Goltiano and Feliciano, 2022; Agus, 2025; Khopade *et al.*, 2025; Bahri *et al.*, 2026

(Jackson *et al.*, 2025a), Timor-Leste (Paudel *et al.*, 2025), Vanuatu (Paudel *et al.*, 2023), and the Americas (Jackson *et al.*, 2025b). Climatic scenario modeling for CRB indicates non-uniform distributional shifts, wherein regional assessments across China estimate an upward projection of highly suitable acreage by 5.48 percent (%) to 39.43% under different Representative Concentration Pathway scenarios by the 2050s and 2090s (Xu *et al.*, 2022), while global-scale modeling suggests responses vary by region and may include habitat contractions depending on localized environmental parameters (Hao *et al.*, 2022). These habitat suitability projections represent potential distribution rather than definitive predictions of actual presence or population abundance, with uncertainty arising from species occurrence data, predictor variables, climate scenarios, and modeling approach. Together with formal biosecurity interception records (Hoffmann *et al.*, 2024), these indicators reveal a pervasive hazard characterized by ongoing geographic expansion and insufficient containment under prevailing quarantine measures. In Indonesia specifically, field studies document CRB pressure across a wide range of smallholder coconut and oil palm growing areas: East Java (Prastowo *et al.*, 2022), Jepara in Central Java (Indriyanti, 2017; Indriyanti *et al.*, 2018), Rote-Ndao in East Nusa Tenggara (Nenotek *et al.*, 2024), and Yogyakarta (Adi *et al.*, 2023, 2025). The Yogyakarta studies also document co-occurrence with the Asiatic palm weevil (*Rhynchophorus vulneratus*). This spatial spread across islands with very different agroecological and socioeconomic contexts reinforces that CRB hazard identification in Indonesia cannot be reduced to a single regional problem. It must instead be understood as a recurring, archipelago-wide constraint on smallholder coconut production. As demonstrated in Fig. 3, the co-localization of diverse developmental cohorts within individual substrate matrices underscores the systemic difficulties of executing sanitation protocols at a localized smallholding scale. Concurrently, the characteristic foliar mutilation and bore-hole artifacts presented in Fig. 4 delineate the primary phenotypic symptoms upon which prevalent field-level surveillance continues to depend.

Exposure assessment: smallholder management practices and their exposure pathways

Chemical control practices

Chemical insecticides remain a common first response to CRB infestation in smallholder and community-managed plantations because they are locally available and provide a rapid, visible knockdown effect (Table 2). Documented applications within smallholder frameworks encompass the deployment of cypermethrin against CRB larvae, which yields significant and quantifiable residual toxicity profiles in the treated cohorts (Venkatarajappa, 2001). Dimethoate, an organophosphate, has been shown to produce neurosecretory damage in the brain of third-instar grubs, evidence that is itself indicative of the

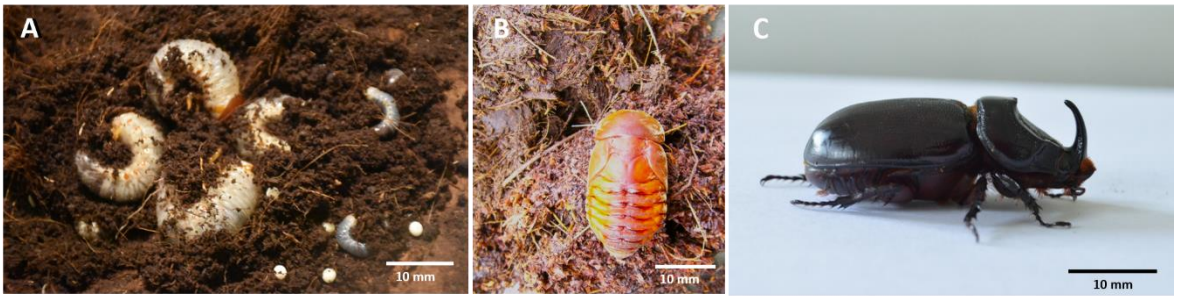

Fig. 3: Co-occurrence of multiple CRB life stages within a single decaying coconut trunk breeding site, illustrating why sanitation-based control is difficult to sustain at the scale of an individual smallholding: (A) eggs and larvae of different instars found together in the same breeding substrate, (B) pupa, (C) adult male poised for dispersal to the coconut palm crown. Scale bars = 10 millimeters (mm)



Fig. 4: Symptoms of CRB infestation on coconut palms: (A) characteristic triangular frond-cutting damage on a young palm, (B) adult *O. rhinoceros* feeding at the base of a young coconut frond, showing a bore hole that can extend toward the growing point, (C) infestation symptoms on a tall coconut palm (*Cocos nucifera* var. Tall) approximately 50 years (y) old

compound's neurotoxic mode of action in non-target contexts (Padmasheela and Delvi, 2004; Sadhu *et al.*, 2024). Other applications include acephate delivered via trunk injection or trunk-implanted controlled-release formulations, intended specifically to reduce broadcast exposure on tall palms (Rafie and Amit, 2024). The granular formulation Marshal 5G has also been tested against CRB larvae and adults in a community oil palm plantation in Riau, Indonesia (Tito *et al.*, 2026). To circumvent conventional canopy application routes, systemic insecticides have been assessed as an alternative control modality against CRB populations in Hawai'i (Russo *et al.*, 2026). UAV application has been trialed to reduce applicator exposure in immature oil palm (Roudhiyah *et al.*, 2024). Recent delivery methods—trunk injection, controlled-release implants, and UAV spraying—are framed as lower-exposure alternatives to conventional broadcast spraying, which remains the baseline practice for broad-spectrum products like cypermethrin and dimethoate. Operational constraints in smallholder frameworks—characterized by manual application protocols and deficient personal protective equipment availability—establish direct occupational exposure pathways to organophosphate and pyrethroid active ingredients during mixing and dispersion phases. These patterns reflect broader systemic trends wherein smallholder chemical management is governed by intrinsic risk appraisal and constrained health literacy, echoing documented exposure modalities across

organophosphate- and organochlorine-intensive agricultural landscapes. (Sulaiman *et al*., 2020). Repeated chemical pesticide use in smallholder coconut plantations can disrupt soil microbial communities and nutrient-cycling organisms, potentially reducing soil productivity and ecological resilience, with persistent residues compounding this pressure (Jeyaseelan *et al.,* 2024; Köninger *et al.,* 2026). Since CRB can also be controlled biologically via *Metarhizium* spp. and OrNV, routine chemical reliance risks undermining these ecological benefits unnecessarily (Paudel *et al.,* 2021; Villamizar *et al.,* 2024). Organophosphates, pyrethroids, and neonicotinoids used against CRB differ mechanistically-acetylcholinesterase inhibition, sodium-channel modulation, and nicotinic receptor modulation, respectively (IRAC, 2026)-with corresponding differences in environmental behavior. Organophosphates pose variable persistence and acute non-target toxicity depending on the active ingredient (Mali *et al.,* 2023; Rajan *et al.,* 2024); pyrethroids adsorb strongly to soil but remain toxic to aquatic organisms via rainfall runoff (Liu *et al.,* 2024); and neonicotinoids are more water-soluble and systemic, favoring leaching and prolonged non-target exposure (Fouad and Abdel-Raheem, 2024; Mandal *et al.,* 2025). Consequently, optimization of insecticide selection protocols for CRB mandates the comprehensive evaluation of chemical persistence, mobility, and ecotoxicological impacts alongside operational efficacy. Such strategies should favor judicious, threshold-driven interventions embedded within an integrated pest management (IPM) paradigm that prioritizes sanitation, pheromone trapping, and biological regulation (Paudel *et al.,* 2021; Villamizar *et al.,* 2024).

Biological and cultural control practices

A substantial body of field evidence documents biological and cultural alternatives already deployed against CRB in smallholder or near-smallholder settings. Entomopathogenic fungi, principally *Metarhizium anisopliae*, have long been used to control CRB larvae (Gopal *et al.*, 2006; Yapo *et al*., 2017). Recent Indonesian studies confirm continued local relevance: isolates recovered from infected larvae around coconut plantations in East Java (Prastowo *et al.*, 2022) (Fig. 5), a compost-based biopesticide formulation ("metankos") incorporating local *M. anisopliae* flour (Fauzana *et al.*, 2023), and virulence testing of *M. anisopliae* in liquid media against CRB larvae (Rozziansha *et al.*, 2025). Field-scale bio-formulation trials combining indigenous *Bacillus thuringiensis* and *Metarhizium* strains have also demonstrated management potential (Manjunatha *et al.*, 2023). Bt-based formulations isolated from Indonesian soils and evaluated in liquid and crude-extract forms have shown insecticidal activity against CRB larvae specifically in oil palm plantation contexts (Pujiastuti *et al.*, 2020, 2021, 2023; Anggraini *et al.*, 2021). OrNV persists as the historically dominant classical biological control agent against CRB, with a long record of field release and establishment across the Pacific and South Asia. This sustained efficacy stems from the agent's capacity for long-term persistence and self-dissemination once released-an ecological attribute that, while diminishing the need for repeated intervention, also means the agent cannot subsequently be withdrawn from the environment (Gorick, 1980; Bedford, 1986; Huger, 2005; Marshall *et al*., 2017; Tanaka *et al*., 2021; Anggraini *et al*., 2023). Documented use also spans Malaysian oil palm plantations (Ramle *et al.*, 2005) and the Andaman Islands (Prasad, 2008a; Prasad *et al.*, 2008b). Pheromone-based aggregation trapping protocols are broadly cited within Indonesian agricultural frameworks, including comparative assessments of pheromone variants conducted in North Sulawesi (Hosang *et al.*, 2022), alongside observational trap deployments in Jepara (Indriyanti *et al.*, 2018). Further studies cover attack-intensity and trapping-effectiveness studies in Bengkulu (Ginting *et al.*, 2025), and packaging-design work aimed at improving pheromone product usability



Fig. 5: *Oryctes rhinoceros* larvae: (A) healthy larva showing normal cuticle coloration and morphology, (B) larvae infected with the entomopathogenic fungus *Metarhizium anisopliae*, showing progressive mycosis symptoms including cuticle darkening and dense greenish conidial sporulation covering the body surface in advanced infection. Scale bars = 10 mm

for field application (Pradana *et al.*, 2023). Botanical control options with reported larvicidal or growth-disrupting activity include compounds isolated from *Adiantum latifolium* (Kumar *et al.*, 2018, 2019), various botanical formulations and neem-based products (Mohan and Padmanaban, 2013). *Senna multijuga* has recently been identified as a dual-action plant exhibiting both an attractant and bioinsecticide (Wandri *et al.*, 2024). Entomopathogenic nematodes have also demonstrated biocontrol potential under laboratory conditions (Zelazny, 1985; Sujithra *et al.*, 2022). Evidence shows that lower-risk biological and cultural alternatives to chemical control are viable for Indonesian smallholders. *Metarhizium*-based biopesticides and pheromone trapping have documented field trials in community plantations from East Java to Bengkulu. These regional OrNV programs build on earlier introduction trials in the Andaman Islands and biological suppression efforts against CRB in Andhra Pradesh, India. (Rao *et al.*, 2018). Empirical documentation from Malaysian oil palm plantations encompasses the quantification of pheromone-trapping dynamics, infestation gradients, and mortality outcomes (Kamarudin *et al.*, 2007), thereby corroborating concurrent molecular investigations into the genetic diversity of underlying genetic diversity of local CRB populations and regional derived via RAM marker profiling (Manjeri *et al.*, 2011).

Risk characterization: comparative environmental and health risk of control options

Chemical control risk

The active ingredients reported against CRB in smallholder and community plantation settings include, cypermethrin (a pyrethroid), dimethoate and acephate (organophosphates), and carbamate/ organochlorine adjacent formulations. These belong to chemical classes with well-characterized environmental and health risk profiles in the broader ecotoxicological literature, even where CRB-specific risk data are sparse. Pesticide movement pathways in coconut plantations are functionally dependent upon the operational application modality and the structural height of the target palms. For young/short palms, canopy application is used; synthetic pyrethroids (e.g., deltamethrin, cypermethrin, lambda-cyhalothrin) retain residual activity against CRB for at least 12 weeks, unlike organic pyrethrins, with residues potentially washed by rain into soil (Wei *et al.*, 2025). In tall palm management, trunk- and root-zone methods are operationally preferable despite distinct environmental pathways: soil drenching drives subsurface leaching toward groundwater, surface residues disperse into aquatic systems via runoff, and trunk injection minimizes direct soil loading, notwithstanding eventual environmental reentry through vegetative decay or root uptake. Flow magnitude depends on active-ingredient

properties, soil characteristics, rainfall, and application frequency (Araya *et al*., 2024; Sarker *et al*., 2024). Rainfall intensity, soil texture, and organic matter jointly determine pesticide mobility: heavy post-application rainfall and sandy soils increase leaching, fine soils increase runoff but permit rapid leaching through macropores, and organic matter enhances retention while potentially prolonging persistence (Sarker *et al*., 2024; Wendell *et al*., 2024). Organophosphates and other cholinesterase-inhibiting insecticides carry documented environmental risk through their shared mode of neurotoxic action, which is not restricted to target pests (Thetkathuek *et al*., 2017; Kori *et al.*, 2019). Empirical evidence directly couples occupational exposure to organochlorine and derivative insecticides with amplified health vulnerability profiles among agricultural workforces operating within smallholder frameworks (Carvalho, 1991). Pyrethroids, while generally less persistent than organochlorines, have been shown to pose environmental risk to aquatic systems following surface runoff, with transport modelling studies used specifically to characterize this pathway (Liu *et al.*, 2023). Chlorpyrifos, an organophosphate structurally related to compounds used against CRB, has documented ecotoxicological risk to aquatic indicator species (Marques *et al.*, 2021). Furthermore, neonicotinoid and associated systemic insecticides, frequently implemented to mitigate drift hazards inherent to broadcast dispersion, generate specialized environmental risk profile. This includes risk to pollinators and non-target invertebrates (Goulson, 2013; Hladik *et al.*, 2018; Longing *et al.* 2020), and human exposure through the food chain (Zhao *et al.*, 2020). Two features of smallholder application practice plausibly elevate this baseline risk profile. First, application techniques and dosage configurations characteristic of smallholder operations are infrequently calibrated against standardized risk-assessment frameworks. Frameworks such as the Pesticide Risk Tool and the Environmental Impact Quotient exist precisely to quantify comparative insecticide risk for decision-making (Meys *et al.*, 2024), but no evidence in the reviewed literature indicates that such tools are in routine use at the smallholder level for CRB management. Second, the manual and proximate nature of application routines renders established occupational exposure routes—such as dermal and inhalation contact during mixing and dispersion phases—directly relevant to smallholders conducting crown treatments or trunk injections absent consistent personal protective equipment. While direct ecotoxicological and occupational risk data specific to CRB-targeted chemical use remain limited, the broader insecticide environmental risk-assessment literature offers relevant contextual evidence for the same chemical classes. These studies were conducted in unrelated pest-management and public-health systems and are cited here for comparative context rather than as direct measurements of CRB-management risk: soil-insecticide risk in maize IPM (Furlan *et al.*, 2017), neonicotinoid substitution effects in U.S. maize (Perry and Moschini, 2020) and insecticide risk in tsetse and trypanosomiasis control. Further examples include neonicotinoid contamination of engineered waterways in China (Zhang *et al.*, 2024), metamidophos risk to non-target aquatic organisms (Iannacone, 2007), and fipronil and imidacloprid risk to river shrimp (Cáceres-Del Carpio and Iannacone, 2021). Extended case paradigms involve the analytical review of insecticide-treated bed-net safety in malaria mitigation initiatives, the systemic risks posed by sublethal mosquito control compounds, and comprehensive risk evaluation frameworks for acetamiprid. Other studies report insect movement responses used as environmental-risk indicators, an environmental risk index for insecticides used in Mato Grosso, Brazil, and a quantitative pollinator hazard model for sulfoxaflor. Further evidence covers insecticide contamination of tropical river systems in China regulatory risk considerations for herbicide-

tolerant crops, and honeybee toxicity of broflanilide. Moreover, empirical investigations utilizing rodent models indicate prospective neurobehavioral and psychiatric hazards linked to developmental insecticide exposure, running parallel to structured exposure-window management models intended for pollinator protection. This body of comparative literature indicates that the chemical classes used against CRB are not risk-free in principle; however, direct, CRB-specific exposure and ecotoxicological data would be needed to confirm the magnitude of risk under actual smallholder application conditions. These three classes differ mechanistically: organophosphates and carbamates share a cholinesterase-inhibiting mode of action, while pyrethroids act on nerve sodium channels. While carbamates such as carbosulfan demonstrate accelerated soil dissipation kinetics relative to organophosphates, corresponding comparative metrics regarding mobility and bioaccumulation under coconut plantation environments remain uncharacterized.

Biological and cultural control: a lower-risk but unevenly adopted alternative

CRB differ substantially in their host-range and mode of action. OrNV is highly host-specific to *Oryctes* species. *Metarhizium anisopliae*, an entomopathogenic fungus, has a comparatively broader host range among insect taxa, although its practical deployment at CRB breeding sites limits exposure of most non-target organisms. The host-range specificity of *Bacillus thuringiensis* is governed by the Cry-toxin profile of the respective strain used; the coleopteran-active strains detailed herein exhibit a more restricted host spectrum than Bt variants targeting other insect orders. Entomopathogenic nematodes have host ranges that vary by species and are generally broader than that of OrNV. Botanical products, unlike the biological agents above, act as natural chemical toxicants rather than host-specific organisms, and their non-target toxicity depends on the specific bioactive compounds involved rather than on host specificity by design. Their mode of biological control was itself modelled explicitly to assess population-level suppression rather than broad-spectrum toxicity (Hochberg and Waage, 1991). Although the reviewed biological control literature lacks the occupational exposure documentation characteristic of chemical-control studies, the broader Bacillus thuringiensis literature indicates that Bt applications can elicit direct or indirect effects on soil microorganisms, non-target invertebrates, and higher trophic (Belousova *et al*., 2021). Furthermore, assessments of the related subspecies *Bti* in mosquito control similarly documents non-target ecological impacts, though the long-term ecosystem-level consequences warrant further investigation (Brühl *et al*., 2020). This evidence is drawn from a different insect order (Diptera) than the coleopteran-active Bt strains discussed here and is therefore comparative rather than CRB-specific. The principal documented limitation of these agents is instead field performance, adoption logistics, and the practical burden of production and distribution at scale, echoed for CRB specifically in the integrated pest management synthesis of Alouw *et al.* (2020) and the applied IPM guidance of Hosang *et al.* (2025). Given its mechanism of action—which avoids broadcast toxicant application—pheromone trapping is not anticipated to entail substantial environmental or health risks; however, dedicated non-target or occupational exposure studies specific to this method were not uncovered in the surveyed literature. The Indonesian studies reviewed here measure trap-catch performance and attack intensity, factors addressed directly in packaging-design research (Pradana *et al*., 2023) and comparative trap-catch trials (Hosang *et al*., 2022; Ginting *et al*., 2025). Consequently, these deployments function primarily in surveillance and early detection rather than serving as mass-trapping control strategies or demonstrating population suppression, as neither of the latter two endpoints was assessed in the referenced

sources. Botanical larvicides similarly avoid the persistence and bioaccumulation concerns associated with synthetic insecticides. Their reported efficacy in the literature, however, is generally from laboratory or small field trials (Mohan and Padmanaban, 2013; Kumar *et al.*, 2018, 2019; Wandri *et al.*, 2024) rather than at the commercial scale reported for chemical alternatives. The overall risk contrast is therefore asymmetric. Chemical options carry a well-documented, non-trivial environmental and occupational risk burden but are readily available and provide fast, visible results; whereas biological and cultural options are not associated with the same documented risk pathways in the literature reviewed, though the extent to which these options have themselves been subject to comparable non-target or occupational risk testing remains limited. Nevertheless, the deployment of such methodologies necessitates advanced technical proficiencies regarding production, storage, and field management—capabilities that typically lie beyond the independent reach of individual smallholders. Broader Indonesian evidence on the gut microbiome of CRB, including its bacterial diversity and protease/lipase-producing potential (Aini *et al.*, 2023), points to further biologically-based management avenues under active investigation. This includes the biocontrol potential of CRB-associated gut bacteria against the oil-palm pathogen *Ganoderma boninense* (Surbakti and Marheni, 2025), alongside broader reviews of advances in rhinoceros beetle control in oil palm (Bedford, 2014).

Case review synthesis: Indonesian smallholder coconut systems

Field evidence from across Indonesia—encompassing East Java, Central Java, East Nusa Tenggara, Yogyakarta, and Bengkulu, demonstrates the previously discussed risk trade-offs within concrete, geographically dispersed settings rather than through abstract comparison. In East Java, *Metarhizium* isolates recovered directly from CRB-infested coconut plantations demonstrated laboratory-confirmed virulence against larvae (Prastowo *et al.*, 2022), providing a locally sourced biological alternative that does not depend on imported formulations. In Rote-Ndao, East Nusa Tenggara, damage intensity and geographic distribution mapping of CRB infestation (Nenotek *et al.*, 2024) illustrates the kind of spatial monitoring needed to target biological control deployment efficiently in a resource-constrained provincial setting. Furthermore, the execution of broad-spectrum chemical interventions across decentralized smallholder plots introduces substantial financial burdens and supervisory complexities within this operational framework. In Jepara, Central Java, pheromone trap monitoring has been implemented directly at village level (Indriyanti *et al.*, 2018), demonstrating that community-scale, low-toxicity monitoring infrastructure is technically feasible in a smallholder setting. Comparative pheromone trials conducted in Bengkulu systematically quantified both attack intensity and trap efficacy under conditions adjacent to oil palm and coconut cultivations (Ginting *et al.*, 2025). Packaging-design research has also addressed a genuinely practical barrier-product usability and shelf stability to pheromone adoption in the field (Pradana *et al.*, 2023). A summary of these Indonesian smallholder CRB case studies, including their locations, intervention types, principal findings, management relevance, and scale of evidence, is provided in Table 4. These cases share a common pattern: the lower-risk biological or cultural intervention was not merely tested under laboratory conditions but taken into the field in the same smallholder landscapes where CRB damage was documented. This indicates that the technical feasibility barrier to implementing safer management practices in Indonesia is less pronounced than commonly presumed. What the case evidence does not show, however, is systematic scale-up: each of these studies documents a localized trial or monitoring program

Table 4: Summary of Indonesian smallholder coconut rhinoceros beetle case evidence reviewed

Location	Study Type	Approach documented	Key finding	Source
Jember East Java	Control efficacy trial (laboratory)	*Metarhizium* anisopliae isolation from field cadavers	Locally-sourced isolates show laboratory-demonstrated virulence against larvae	Prastowo *et al.*, 2022
Jepara Central Java	Operational implementation study	Pheromone aggregation trapping	Village-level monitoring infrastructure technically feasible at community scale	Indriyanti *et al.*, 2018
Rote-Ndao East Nusa Tenggara	Hazard/damage surveillance	Damage/distribution mapping	Mild average damage intensity [8.89%) spread across 10 sub-districts	Nenotek *et al.*, 2024
Yogyakarta D.I. Yogyakarta	Diagnostic/distribution study	GIS-based distribution mapping	Co-occurrence with Asiatic palm weevil documented	Adi *et al.*, 2023, 2025
Bengkulu Bengkulu	Hazard surveillance + control efficacy trial	Pheromone trapping efficacy trial	Attack intensity and trap effectiveness quantified under oil palm/coconut-adjacent conditions	Ginting *et al.*, 2025

rather than province- or nation-wide deployment. This is consistent with the broader observation that historical coconut replanting and support initiatives in Indonesia have necessitated dedicated, scheme-level coordination to effectively reach smallholders at scale (Heriyanto *et al*., 2019; Wulandari and Alouw, 2021). These capital and institutional constraints sit within a much longer history of smallholder-dominated coconut and oil-palm production. Smallholder involvement in tree-crop cultivation in Malaya, including coconut and oil palm in Johor, has been documented back to the 1860s (Pakiam, 2020). Historically, smallholder coconut plantation management practices, such as canopy-level pasture composition in Malaita, Solomon Islands, have been dictated by the identical land- and labor-constrained mechanics that currently restrict the uptake of biological control (Manaros and Gurbuz, 2020).

RECOMMENDATION

Drawing upon the risk asymmetry and adoption gaps established across review, subsequent recommendations are categorized into practical management implications for smallholders and extension personnel, policy-level directives for institutional and financial stakeholders, and prioritized research agendas aimed at resolving remaining critical empirical and operational knowledge and implementation gaps.

Management implications

Routine pheromone-trap surveillance should form the baseline activity for smallholder CRB management, escalating to sanitation once a locally defined action threshold is exceeded, then to intensified pheromone trapping combined with biological control (OrNV, *Metarhizium*, or *B. thuringiensis*) where infestation persists. Targeted chemical intervention ought to be designated as a final recourse, preferably administered via trunk injection or controlled-release implants rather than broadcast spraying, with implementation proving more viable at a cooperative or program level than at the individual farmer scale.

Policy implications

Closing the adoption gap for lower-risk controls depends on the same institutional and financing mechanisms that support Indonesian coconut smallholders more broadly: extension access (Rusli and Isa, 2021), coordinated replanting and financing schemes (Sondakh and Hardaker, 1983; Wulandari and Alouw, 2021), and sector-wide development strategy (Agus, 2025; Khopade *et al*., 2025; Bahri *et al*., 2026). The continued spread of the OrNV-tolerant CRB-G haplotype (Jackson *et al*., 2025a, 2025b) requires actively maintained regionally coordinated capacity. Incorporating CRB risk mitigation strategies within overarching coconut-sector sustainability and climate-resilience paradigms would harmonize capital

allocation with pre-existing financial architectures designed to address alternative smallholder limitations.

Research priorities

Structured risk-quantification tools such as the pesticide risktool (Meys *et al*., 2024), alongside life-cycle assessment or comparative environmental footprint approaches, have not yet been applied to CRB management and warrant evaluation. Capital allocations directed toward locally manufactured, economically viable biological agents—exemplified by liquid-media *Metarhizium* cultivation systems (Rozziansha *et al*., 2025), would effectively attenuate the cost disparities relative to conventional chemical alternatives. Farm-scale intervention studies directly measuring pesticide-use reduction, environmental contamination, and non-target exposure following integrated CRB management deployment would address a gap not filled by the individual-component evidence reviewed here. More broadly, the evidence base and policy frameworks presented here would be significantly enhanced by future research that applies standardized risk-assessment methodologies and CRB-specific exposure data, tracks environmental and occupational outcomes longitudinally, and identifies which combinations of financing, extension services, and institutional arrangement most effectively bridge the adoption gap.

LIMITATIONS

This review has several limitations. First, as a narrative rather than a systematic review, no formal PRISMA-style screening protocol with tracked exclusion reasons at each stage was applied; a simplified literature-flow diagram (Fig. 1) is provided based on global rather than per-database search records. Second, because the individual studies synthesized here utilize non-standardized toxicological and exposure endpoints, constructing a harmonized quantitative risk index across all control strategies proved unfeasible; consequently, the risk comparisons presented in Table 2 remain qualitative in nature. Third, the apparent absence of non-target or occupational risk findings for biological and cultural control options should not be interpreted as confirmed evidence of environmental safety; it more likely reflects limited investigation of these agents relative to chemical insecticides. Fourth, evidentiary strength varies substantially, ranging from controlled laboratory bioassays to replicated field trials and village-level monitoring, with these distinctions noted explicitly where they materially influence interpretation. Fifth, a substantial proportion of the chemical, biopesticide, and pheromone-trapping evidence derives from oil-palm rather than coconut systems (Ramle *et al*., 2005; Kamarudin *et al*., 2007; Tito *et al*., 2026; Roudhiyah *et al*., 2024); differences in canopy structure, planting density, and exposure pathways mean such findings are comparative rather than directly equivalent for coconut. Sixth, no systematic dataset comparing farmer adoption, cost, extension access, and institutional support was identified, limiting the institutional-capacity interpretation offered in the Conclusion. Several gaps remain unaddressed within the reviewed literature: the cumulative ecological consequences of recurring *Metarhizium* application over multiple seasons; systematic cross-regional comparison of environmental risk profiles; localized non-target impacts on beneficial insects, pollinators, and soil or aquatic microorganisms within coconut agroecosystems; the pesticide handling life-cycle (including storage, transportation, container disposal and equipment washing) and associated household and livestock spillover risks in smallholder environments; and the adequacy of pesticide regulatory frameworks and monitoring mechanisms in Indonesia. Finally, the evidence base is geographically concentrated in a small number of Indonesian provinces and source countries, and publication bias toward positive efficacy findings cannot be excluded, as is common in the pest-management literature more broadly generally.

CONCLUSION

Oryctes rhinoceros remains a persistent and geographically expanding hazard to smallholder coconut plantations. Ultimately, the environmental and health hazards associated with its management are dictated less by the intrinsic biology of the pest than by the specific control option that smallholder can practically access and afford. Chemical control, while effective and widely available, carries a documented risk burden spanning ecotoxicological, occupational, and environmental-contamination pathways, a burden that is plausibly amplified under typical smallholder application conditions. Biological and cultural alternatives, by contrast, carry a substantially lower risk profile, with laboratory bioassays using field-sourced *Metarhizium* isolates in East Java and field-deployed pheromone monitoring in Jepara and Bengkulu illustrating that the technical feasibility barrier to safer management in Indonesia is smaller than is sometimes assumed. The evidence assembled here suggests that limited adoption, despite documented technical efficacy of several lower-risk options, is more consistent with institutional and economic capacity constraints than with a simple lack of viable technology. Although the narrative design of this synthesis precludes causal inferences, future *CRB* risk-management interventions must nevertheless be conceptualized and appraised through a dual lens—balancing biological efficacy against their practical compatibility with smallholder economic structures and pre-existing extension and replanting frameworks. Closing this gap is, in the authors' assessment, as much an institutional priority as a technical one; the specific surveillance, financing, and technology priorities this implies are set out in the Recommendation above. Subsequent investigations employing standardized risk-assessment methodologies and CRB-specific exposure metrics, coupled with longitudinal monitoring of farm-level environmental and occupational consequences, would substantially reinforce the evidentiary foundation supporting these priorities. This review also did not identify CRB-specific evidence on insecticide resistance or its potential role in driving escalating application frequency and dose; given the established role of such feedback loops in other insect pest systems, this represents a further gap warranting dedicated monitoring in Indonesian smallholder contexts.

AUTHOR CONTRIBUTIONS

M.L.A. Hosang developed the review concept, prepared the visualizations, and reviewed and edited the manuscript. S. Susilawati wrote the original draft, conducted the literature search, and reviewed and edited the manuscript. N. Nurindah performed the analysis and synthesis and reviewed and edited the manuscript. J.C. Alouw wrote the original draft and reviewed and edited the manuscript. M. Puspitasari reviewed and edited the manuscript. R. Semewe reviewed and edited the manuscript. R. Rohimatun reviewed and edited the manuscript. R.T. Hutasoit reviewed and edited the manuscript. S. Subiyakto reviewed and edited the manuscript. S. Sujak reviewed and edited the manuscript. D.A. Sunarto reviewed and edited the manuscript. R.G.U.I. Meththananda reviewed and edited the manuscript. B.A.N. Pinaria reviewed and edited the manuscript. All authors reviewed and approved the final version of the manuscript carefully and jointly before formal submission.

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CONFLICT OF INTEREST

The authors declare no conflicting interests in relation to the publication of this manuscript. Furthermore, all ethical standards of scholarly publishing that include encompassing plagiarism, informed consent, research misconduct, data fabrication and/or falsification, duplicate publication and/or submission, and redundant publication, have been fully adhered to by the authors throughout the research and publication process.

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ABBREVIATIONS

%	Per cent
CRB	Coconut rhinoceros beetle
CRB-G	Coconut rhinoceros beetle-Guam biotype
E4-MO	Ethyl 4-methyloctanoate
GIS	Geographic information system
IPM	Integrated pest management
mm	Millimeter
OrNV	*Oryctes rhinoceros* nudivirus
PCR	Polymerase chain reaction
RPA	Recombinase polymerase amplification
SNP	Single nucleotide polymorphism
UAV	Unmanned aerial vehicle
y	Year

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