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Review

A Comparative Review of Green-Synthesized Species-Specific Pheromones and Conventional Chemical Insecticides for Managing Invasive Insect Populations

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Abstract:
Invasive insect species remain among the most persistent threats to agricultural productivity, food security, and ecosystem stability, and their suppression has long depended on synthetic chemical insecticides. Accumulating evidence of environmental toxicity, accelerating resistance, and harm to beneficial organisms has shifted attention toward selective and ecologically compatible alternatives. This review examines the comparative standing of green-synthesized species-specific pheromones and conventional chemical insecticides as instruments for managing invasive insect populations. Drawing on published work across invasion ecology, chemical ecology, and green chemistry, the discussion considers the mechanisms, field performance, and ecological footprint of each approach. Attention is given to the behavioural basis of pheromone-mediated control, the rise of plant-assisted and microbial synthesis routes, and the consequences of each strategy for biodiversity and long-term sustainability. The synthesized evidence indicates that although chemical insecticides frequently deliver rapid and pronounced suppression, green-synthesized pheromones achieve broadly comparable management while inflicting markedly lower collateral damage on non-target communities. The review also weighs the economic, regulatory, and technical factors that govern adoption and identifies the principal gaps that currently constrain wider deployment. On balance, green-synthesized pheromones emerge as credible, species-specific components of integrated pest management and align closely with the broader transition toward environmentally responsible agriculture.

Keywords: Green synthesis; pheromones; invasive insects; sustainable pest management; chemical insecticides; integrated pest management.

1. Introduction

Invasive insect species impose a heavy burden on global agriculture, biodiversity, and ecosystem function, and their spread is frequently accompanied by large economic losses and lasting ecological disturbance [1,2]. For much of the past century, the dominant response has been the application of synthetic chemical insecticides. These compounds are

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effective in the short term, yet their repeated use is closely tied to adverse outcomes that include toxicity to non-target organisms, bioaccumulation across food webs, and the steady erosion of susceptibility through resistance [3,4]. Such drawbacks have encouraged a search for selective alternatives that limit ecological disruption while preserving acceptable levels of pest control [5,6].

Pheromone-based management has gained attention precisely because it offers a high degree of specificity together with a benign environmental profile. Species-specific pheromones can disrupt mating, support population monitoring, or contribute directly to population reduction, and they generally do so without injuring beneficial species [7,8]. The conventional preparation of these semiochemicals, however, often relies on multistep chemical procedures that sit uneasily with the principles of green chemistry [9]. Against this background, green synthesis methods that exploit biological systems or eco-friendly reagents present a practical route to producing pheromones with a reduced environmental cost [10,11].

Advances in green chemistry have made it possible to design bio-based synthesis routes that are comparatively energy efficient, less hazardous, and in many cases more economical [12,13]. Such routes commonly employ plant extracts, microbial processes, or enzymatic transformations to generate target compounds, an approach that is consistent with both sustainability objectives and tightening regulatory expectations [14,15]. Even with this progress, the literature still lacks systematic comparison of how green-synthesized pheromones perform relative to conventional insecticides across laboratory and field settings. This review brings that scattered evidence together. It sets out to compare the efficacy, selectivity, and environmental consequences of the two approaches, and to situate green-synthesized pheromones within the wider framework of integrated and ecologically grounded pest management [16,17].

2. The Ecological and Economic Burden of Invasive Insects

The scale of damage attributable to invasive insects provides the central justification for investment in better control. Beyond direct feeding injury to crops, invasive populations restructure communities, displace native species, and impose recurring costs through yield loss, quarantine measures, and management expenditure [1]. Quantitative assessments at continental and global scales place these losses among the most significant pressures on contemporary agriculture, with the threat distributed unevenly across regions according to trade patterns, climate, and the availability of suitable hosts [2]. Because establishment is often difficult to reverse once it occurs, management decisions are made under conditions of urgency that have historically favoured fast-acting chemical solutions [1,2].

This urgency, while understandable, has helped entrench a reliance on broad-spectrum products whose costs accumulate over time. The same characteristics that make a population invasive, including rapid reproduction and ecological flexibility, also accelerate the selection of resistant genotypes when a single class of insecticide is applied repeatedly [3]. The result is a control treadmill in which short-term gains are offset by rising application rates and a narrowing set of effective compounds, a dynamic that sharpens the case for selective and durable alternatives [3,4].

3. Conventional Chemical Insecticides and Their Ecological Costs

Conventional insecticides remain valued for their speed and breadth of action, and they continue to underpin pest management in many production systems. Their mode of action is typically neurotoxic or metabolic, and because the molecular targets they exploit are widely conserved among arthropods, the same activity that suppresses a pest also affects pollinators, parasitoids, and predators that regulate pest numbers naturally [4,6]. Field and laboratory studies of widely used classes, including the neonicotinoids, have documented sublethal as well as lethal effects on beneficial insects, alongside movement of residues into soil and water [6].

Two further liabilities recur throughout the literature. The first is resistance, which arises predictably under sustained selection pressure and can render formerly reliable compounds ineffective within a few seasons

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[3]. The second is persistence, since many active ingredients and their breakdown products remain in the environment long after application, contributing to bioaccumulation and to chronic exposure of organisms that were never the intended target [4]. Botanical and other reduced-risk insecticides have been proposed to soften these effects, and they do offer advantages in degradability and selectivity, yet they share with synthetic products a fundamentally toxicological mode of action rather than a behavioural one [5]. These limitations explain why interest has moved toward approaches that manipulate insect behaviour rather than simply poisoning the target [5,6].

4. Principles of Pheromone-Based Pest Management

Pheromones are chemical signals that mediate communication within a species, and the sex pheromones used to coordinate mating have proved especially useful for pest management. Three broad applications are well established in the literature. In monitoring, traps baited with synthetic pheromone allow managers to track population density and time interventions precisely. In mating disruption, the deliberate saturation of an environment with pheromone prevents males from locating females, thereby reducing successful reproduction. In mass trapping, high densities of lures remove a substantial fraction of the responding population directly [7,8].

The defining strength of these methods is specificity. Because a given pheromone blend is tuned to the chemistry of a single species or a narrow group, beneficial insects sharing the same habitat are largely unaffected, which preserves the natural enemies that contribute to long-term regulation [7]. Mass trapping and mating disruption have additionally been examined as tools for the early suppression and even eradication of newly established invaders, a role for which broad-spectrum insecticides are poorly suited because of their collateral effects [8]. The principal constraint is that the underlying semiochemistry must be characterised for each target, and historically the production of pure pheromone compounds has depended on demanding synthetic chemistry [9]. It is this production bottleneck, rather than any limitation of the concept itself, that green synthesis is positioned to address [9,10].

5. Green Synthesis of Pheromones and Semiochemicals

Green chemistry provides the conceptual foundation for reconsidering how semiochemicals are produced. Its guiding principles favour the prevention of waste, the use of safer solvents and reagents, energy efficiency, and the design of processes around renewable feedstocks [10]. Applied to pheromone production, these principles direct attention away from energy-intensive multistep routes and toward strategies that achieve the required molecules with a smaller resource and pollution footprint [10,11].

Several biologically grounded routes have matured in recent years. Plant-mediated and microbial-assisted syntheses use the reducing and catalytic capacity of biological extracts or living cultures to carry out transformations under mild conditions, often replacing hazardous reagents with benign ones [12,13]. The body of work on plant-extract-mediated synthesis, much of it developed in the context of nanomaterials, has established reproducible protocols, characterisation standards, and an understanding of how extract composition governs product quality, and these lessons transfer usefully to the controlled production of organic semiochemicals [14,15]. Enzymatic and whole-cell biocatalysis is particularly attractive for pheromones because many of these molecules are chiral, and biological catalysts can deliver the correct stereochemistry with high selectivity and minimal protection and deprotection steps [12,14]. Taken together, these developments suggest that the historical cost and complexity of pheromone supply can be reduced without sacrificing purity, which is the central requirement for behavioural efficacy [13,15].

6. Comparative Assessment of the Two Approaches

Bringing the preceding strands together allows a structured comparison across the dimensions that matter most for practical adoption. The literature does not support a simple ranking of one approach as universally superior. Rather, it points to a trade-off between immediate potency on one side and

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selectivity and durability on the other, with the balance depending on the management objective and the ecological context [4,7].

6.1 Efficacy and Speed of Control

Chemical insecticides characteristically produce rapid and pronounced reductions in pest density, which is decisive during acute outbreaks when speed is paramount [3,4]. Pheromone-based methods act more gradually, since mating disruption and mass trapping suppress populations across one or more generations rather than through immediate mortality [7,8]. Where infestations are detected early or maintained below economic thresholds, this slower cumulative action is generally sufficient, and the gap in apparent efficacy narrows considerably over a full season [8].

6.2 Selectivity and Non-Target Effects

The clearest divergence between the approaches lies in their effect on organisms other than the target. Broad-spectrum insecticides routinely suppress pollinators and natural enemies alongside the pest, which can trigger secondary outbreaks once natural regulation is removed [6]. Species-specific pheromones, by contrast, leave the surrounding community largely intact, preserving the ecological services on which sustainable production depends [7]. This contrast is the strongest single argument advanced in the literature for incorporating pheromones into mainstream practice [6,7].

6.3 Biodiversity and Ecosystem Stability

Consistent with their selectivity, pheromone-treated systems tend to retain greater biological diversity than systems managed with conventional insecticides, because non-target taxa are spared and habitat structure is less disturbed [5,7]. Higher diversity in turn supports more stable pest regulation through intact predator and parasitoid assemblages, creating a reinforcing relationship between selective control and ecosystem resilience [7,16]. Chemical regimes, by depressing this diversity, can undermine the very natural processes that would otherwise limit pest resurgence [4,6].

6.4 Economic and Regulatory Dimensions

Economic appraisal must extend beyond the price of a single application. Chemical insecticides often appear inexpensive at the point of use, yet their full cost includes resistance management, repeated treatment, and environmental remediation, all of which accumulate over time [3,4]. Pheromone-based programmes can carry higher initial costs but may prove more economical across a season by reducing the frequency of intervention and by protecting beneficial species [7,8]. On the regulatory side, international policy increasingly favours reduced pesticide loads and the adoption of integrated pest management, which positions selective tools such as green-synthesized pheromones advantageously within evolving frameworks [16,17].

Table 1 summarises the qualitative comparison that emerges from the reviewed literature.

Table 1. Comparative overview of the two pest management approaches, synthesized from the reviewed literature.

Attribute	Conventional chemical insecticides	Green-synthesized species-specific pheromones
Mode of action	Neurotoxic or metabolic, broad spectrum	Behavioural disruption, monitoring, and direct removal
Target specificity	Low, affects many taxa	High, species or genus specific
Speed of suppression	Rapid and pronounced	Gradual and cumulative
Non-target effects	Frequently substantial	Minimal
Resistance risk	High under repeated use	Low to moderate
Environmental persistence	Often persistent and bioaccumulative	Low, readily degraded
Synthesis footprint	Energy and reagent intensive	Reduced energy, eco-friendly reagents
Fit within IPM	Limited as a standalone tool	Strong complementary role
Principal limitation	Ecological and resistance costs	Scalability, cost, and context-dependent efficacy

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7. Challenges and Knowledge Gaps

Several constraints temper the conclusions that can presently be drawn. Much of the comparative evidence concerns a limited set of well-studied pests, which restricts confident generalisation across the full diversity of invasive species and agro-climatic regions [2,5]. Pheromone performance is sensitive to environmental variables such as temperature, humidity, and wind, and to the spatial scale of application, so results obtained in one setting do not always transfer cleanly to another [7,8]. On the production side, green synthesis routes still vary in scalability and batch-to-batch consistency, and these factors bear directly on the purity and therefore the field reliability of the resulting compounds [12,14]. Long-term effects, including the slow emergence of behavioural resistance and the cumulative ecological consequences of either approach, remain insufficiently characterised, and rigorous economic analysis at commercial scale is still scarce [3,16]. These gaps define the agenda for the next phase of research rather than undermining the broad direction the evidence indicates.

8. Future Directions

Progress will depend on widening the empirical base and on closing the production gap. Comparative trials spanning a broader range of invasive species and multiple agro-climatic zones would substantially improve the generalisability of current findings [2]. Long-term field studies are needed to evaluate the persistence of control, the prospect of behavioural resistance, and the ecological stability of pheromone-managed systems over successive seasons [7,8]. On the chemistry side, the optimisation of green synthesis for scale, cost, and stereochemical fidelity is a priority, since reliable low-cost supply is the practical precondition for adoption [12,14]. Integrating pheromone-based tactics with complementary components of integrated pest management, including biological control and selective reduced-risk products, is likely to yield more robust outcomes than any single tactic alone [16]. Finally, molecular and genomic methods promise a deeper understanding of species-specific responses, and policy-oriented research can help translate technical feasibility into the regulatory and economic conditions needed for uptake [15,17].

9. Conclusion

The comparison of green-synthesized species-specific pheromones with conventional chemical insecticides reveals a coherent picture rather than a contest with a single winner. Chemical insecticides retain a clear advantage in the speed and magnitude of immediate suppression, which keeps them relevant for acute outbreaks, but this advantage is purchased at a recurring ecological cost in the form of non-target mortality, biodiversity loss, persistence, and resistance [3,4,6]. Green-synthesized pheromones deliver competitive management of invasive populations while sparing beneficial organisms and conserving the diversity that supports natural regulation, and the maturation of biologically grounded synthesis routes is steadily lowering the cost and complexity that once limited their use [7,10,12].

Read together, the literature supports a clear strategic conclusion. Green-synthesized pheromones are best understood not as a wholesale replacement for chemical insecticides but as a selective and sustainable cornerstone of integrated pest management, deployed alongside other tactics and reserving broad-spectrum chemistry for situations that genuinely require it [16,17]. Adopting this balanced position offers a credible path toward protecting agricultural productivity while safeguarding environmental health and biodiversity over the long term [5,7].

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