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Semiochemical-Driven Strategies for Sustainable Pest Management in Indian Agriculture

NATIONAL ACADEMY OF AGRICULTURAL SCIENCES, NEW DELHI
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Preface

Semiochemicals, including pheromones, kairomones, allomones and plant volatile cues, represent a promising class of tools for transforming pest management in Indian agriculture. Their species-specific mode of action, environmental safety, and compatibility with integrated and ecological farming systems make them important for reducing dependence on conventional insecticides, lowering pesticide residues in food, and enhancing the competitiveness of Indian agricultural produce in domestic and export markets.

Despite proven research outputs and emerging field successes, the large-scale deployment of semiochemical-based interventions in India remains limited. Gaps in focused R&D, regulatory clarity, product quality assurance, standardized deployment protocols, manufacturing capacity, and extension support continue to constrain wider adoption. A coordinated national strategy is therefore needed to address these challenges and position semiochemicals as a mainstream component of sustainable pest management.

In this context, the brainstorming session on ***"Semiochemical-Driven Strategies for Sustainable Pest Management in Indian Agriculture"*** organized by the Academy was timely and highly relevant. The session brought together leading scientists, industry representatives, regulatory authorities, and developmental agencies, and generated valuable insights on dedicated R&D platforms, regulatory reforms, quality assurance mechanisms, infrastructure development, farmer adoption models, and commercialization pathways.

I appreciate the efforts of the Convener, Reviewer and Editors for bringing out the Policy Paper. I am confident that this document will provide useful guidance to policymakers, researchers, industry, extension personnel and other stakeholders in accelerating the adoption of semiochemical-based pest management strategies in India.

July 2026 **(M.L. Jat)**
New Delhi *President, NAAS*

Semiochemical-Driven Strategies for Sustainable Pest Management in Indian Agriculture

1. INTRODUCTION

Semiochemicals operate within complex agro-ecological networks, mediating interactions among plants, herbivores, natural enemies, pollinators, and associated microorganisms. These chemical signals regulate essential behaviours such as host location, feeding, mating, oviposition, and natural enemy recruitment, thereby enabling pest regulation through ecological processes rather than direct lethal action (Kamala Jayanthi *et al.*, 2015; 2020; Thomas *et al.*, 2023). While this functional diversity underpins the effectiveness and environmental compatibility of semiochemical-based interventions, their successful translation into field-scale pest management depends not only on ecological understanding but also on enabling policy frameworks, regulatory clarity, quality assurance systems, and standardised deployment mechanisms. Recognising and strengthening this science-policy interface is essential for transforming semiochemicals from context-specific research tools into scalable, reliable, and farmer-trusted components of sustainable pest management in Indian agriculture.

Globally, semiochemical-based technologies have gained prominence as a core component of integrated pest management (IPM), enabling effective pest surveillance, early detection, mass trapping, mating disruption, & attract-and-kill strategies. Commercial adoption has been most pronounced in high-value horticultural crops and niche production systems, including organic agriculture, protected cultivation, and geographically certified produce. Recent advances in formulation chemistry, dispenser technologies, controlled-release systems, and digital monitoring platforms have further expanded the scope and reliability of semiochemical applications.

India has made significant contributions to semiochemical research, particularly in the synthesis, and field validation of pheromones for major pests of rice, cotton, fruits, vegetables, and plantation crops. Proven technologies, such as those developed for yellow stem borer in rice, pink bollworm in cotton, and red palm weevil in palms, demonstrate clear potential for scale-up and commercial deployment. However, the translation of these technologies into widespread field adoption remains fragmented. Constraints related to regulatory bottlenecks, variability in product quality, uneven field implementation, limited extension support, and the absence of standardised deployment and operational protocols continue to limit their broader adoption, despite India's growing manufacturing capability.

As India aims to strengthen sustainable pest management and expand ecological, export-oriented, and residue-sensitive production systems, semiochemicals offer a strategic opportunity to enhance productivity, market access, and environmental stewardship. Realising this potential will require coordinated action across research & development, regulatory & standardisation frameworks, manufacturing & industry engagement, extension systems, and farmer networks.

This policy paper examines the current status, opportunities, challenges, and strategic priorities for advancing semiochemical-based pest management in India. It draws upon the deliberations of the brainstorming session organised by the Academy and presents policy recommendations to guide national efforts towards improved adoption, innovation, and institutional support for semiochemicals in Indian agriculture. In this context, semiochemical-based pest management is considered in a broad sense, encompassing both molecule-based interventions and agro-ecological practices that manipulate semiochemical cues within cropping systems (Box 1).

BOX 1. Semiochemical-Based Pest Management: An Integrated Framework

Semiochemical-based pest management refers to a spectrum of approaches that exploit chemical cues governing plant-insect, insect-insect and plant-insect-microbe interactions. These approaches include both the application of formulated semiochemicals and the use of agro-ecological practices that manipulate semiochemical signals within cropping systems.

Molecule-based approaches involve the use of identified semiochemicals including pheromones, kairomones, allomones, synomones, and herbivore-induced plant volatiles (HIPVs) through traps, dispensers, or formulated delivery systems for monitoring, behavioural manipulation, and suppression of pest populations.

Practice-based approaches rely on cropping and habitat-management practices that enhance, disrupt, or redirect naturally occurring semiochemical cues without isolating individual compounds, including push-pull strategies, companion planting, trap cropping, and attract-and-reward systems.

Together, these complementary approaches position semiochemical-based pest management as a flexible and scalable component of integrated pest management across diverse agro-ecological conditions and farming systems.

2. GLOBAL & NATIONAL CONTEXT OF SEMIOCHEMICALS

Semiochemicals have emerged globally as a strategic component of sustainable pest management, driven by increasing demand for residue-free production, ecological farming, and precision pest monitoring. Semiochemical-based technologies are increasingly deployed across diverse cropping systems for monitoring, mass trapping, mating disruption, attract-and-kill, and push-pull strategies, with commercial adoption particularly evident in fruit, vegetable, plantation, protected-cultivation, and organic production systems. The global semiochemical market is also expanding rapidly, with recent analyses projecting growth from USD 6.29 billion in 2025 to USD 17.51 billion by 2032, representing a compound annual growth rate (CAGR) of 15.75% (Fortune Business Insights, 2025). This expansion reflects growing confidence in species-specific and environmentally compatible tools for precision pest management.

Several countries, including the United States, member states of the European Union, Japan, Brazil, and Australia, have established enabling regulatory and technical frameworks to accelerate semiochemical adoption. These include proportionate registration pathways for low-risk behavioural modifiers, harmonised quality standards, and standardised deployment protocols that have facilitated commercialisation and wider field adoption. These international experiences demonstrate that successful mainstreaming of semiochemical-based pest management depends not only on scientific advances but also on enabling regulatory systems, quality assurance, coordinated extension, and sustained institutional support.

India has made notable progress in semiochemical synthesis over the last decade, transitioning from a predominantly import-dependent market to an emerging exporter of pheromone-based products. Indian industries currently manufacture and export semiochemical products targeting >40 economically important pest species, reflecting the country's growing capabilities in synthesis, formulation, and quality assurance. These products are supplied to international markets, contributing to export earnings and supporting IPM programmes worldwide (Renee *et al.*, 2025), thereby positioning India as an emerging global supplier and innovation hub for semiochemical technologies.

This apparent contrast between India's strong export capability and relatively limited domestic adoption reflects systemic rather than technological constraints. While the country possesses well-established expertise in semiochemical synthesis, formulation, and manufacturing, widespread field deployment has been constrained by regulatory bottlenecks, inconsistent product quality, the absence of standardised deployment protocols, limited extension support, inadequate institutional coordination, and the limited availability of validated semiochemical technologies for many economically important pests. Furthermore, the absence of a coordinated national platform integrating research, regulation, quality assurance, extension, and industry participation continues to constrain wider adoption despite the country's strong scientific and industrial capacity.

Aligning semiochemical deployment with national priorities such as the National Mission on Sustainable Agriculture and broader sustainability and export-oriented production goals presents a timely opportunity to mainstream chemical ecology-based interventions in Indian agriculture. Building on existing research strengths, manufacturing capability, expanding industrial participation, and growing stakeholder awareness, a coordinated national approach can enable semiochemicals to become a mainstream component of sustainable crop protection in India.

3. EXISTING TECHNOLOGIES & DEPLOYMENT EXPERIENCE IN INDIA

India has developed a diverse and mature portfolio of semiochemical-based technologies across multiple cropping systems, reflecting strong national capabilities in semiochemical synthesis, formulation, and field validation. Proven applications are available for major pests of rice, cotton, sugarcane, vegetables, fruits and plantation crops, demonstrating the technical readiness and versatility of semiochemical approaches for large-scale deployment.

Validated semiochemical-based interventions are available for several important crop-pest systems, including:

- **Yellow stem borer in rice**, using pheromone-based monitoring and mass trapping, with standardised trap densities and lure replacement intervals validated through long-term research, and supported by a sustained-release patent filed by ICAR-Indian Institute of Rice Research.
- **Pink bollworm in cotton**, where pheromone-based mating disruption and mass trapping have demonstrated compatibility with IPM programmes and potential for area-wide deployment.
- **Fruit flies in mango and other horticultural crops**, through para-pheromone-based male annihilation and attract-and-kill strategies.
- **Brinjal shoot and fruit borer**, using pheromone-based mass trapping approaches.
- **Sugarcane borers and early shoot borer**, through semiochemical-assisted monitoring systems.
- **Red palm weevil in coconut and date palm plantations**, using aggregation pheromone trapping.
- **Tomato fruit borer and other lepidopteran pests in vegetables**, through dispenser-based systems.

A notable Indian example is the 300-acre area-wide deployment of pheromone-based mating disruption against pink bollworm in cotton under Project Bandhan in Maharashtra. PBKnot™ deployment reduced flower, boll, and locule damage by 49.2%, 58.3%, and 51.8%, respectively, achieved more than 93% mating disruption after approximately three months, and increased average seed cotton yield by 550 kg ha^{-1}, demonstrating the effectiveness and scalability of cluster-based mating disruption under Indian farming conditions (Mayee *et al.*, 2023).

In addition to these established applications, mating disruption has emerged globally as one of the most effective semiochemical-based strategies for area-wide management of several lepidopteran pests. Advances in dispenser technologies, controlled-release formulations, aerosol systems, SPLAT-based delivery platforms, and other long-lasting delivery systems have significantly improved the operational feasibility of mating disruption programmes. These developments offer considerable opportunities for adaptation and deployment in Indian cropping systems, particularly for pests where conventional monitoring and mass trapping have already demonstrated success.

International field evidence further demonstrates the potential environmental benefits of semiochemical-based interventions through reduced dependence on conventional insecticides. In codling moth management, pheromone-based mating disruption reduced the number of codling-moth-targeted insecticide applications by approximately 44-45%

over two successive seasons compared with the conventionally managed orchard, while maintaining substantially lower fruit infestation (Kutalmış and Ögür, 2025). Reduced reliance on broad-spectrum insecticides may lower exposure pressure on non-target organisms, while chemical ecology approaches that conserve or manipulate semiochemical cues can support predators, parasitoids, and associated ecosystem services; however, the magnitude of these benefits remains context dependent (Sharma *et al.*, 2019; Kansman *et al.*, 2023; Wyckhuys *et al.*, 2024).

India's semiochemical manufacturing sector has expanded significantly over the last decade, with domestic industries capable of synthesising a wide range of pheromone actives at bulk scale and supplying both research-grade and field-ready products for mass trapping and mating disruption programmes. In addition to domestic use, Indian manufacturers currently supplying high-quality semiochemical products to international markets and supporting global IPM programmes. These developments reflect growing national strengths in synthesis, formulation, and quality assurance, and reinforce India's potential to emerge as a significant global hub for semiochemical technologies.

Despite these achievements, commercial deployment within India remains concentrated in a relatively limited number of validated crop-pest systems compared with the country's agricultural diversity. Considerable opportunities therefore exist to expand semiochemical discovery, characterisation, validation, and deployment for economically important pests across field crops, horticultural crops, plantation crops, stored products, and emerging invasive species.

Taken together, these experiences demonstrate that India possesses a strong scientific, technological, and industrial foundation for semiochemical-based pest management. This foundation provides a credible basis for scaling deployment under appropriate regulatory, institutional, and implementation frameworks, which are examined in the following section.

4. KEY CHALLENGES & SYSTEMIC GAPS IN SCALING SEMIOCHEMICALS

Despite significant scientific achievements and industrial capability in semiochemical synthesis and formulation, mainstream deployment in India remains limited. Multiple interlinked challenges spanning semiochemical isolation and identification, regulatory systems, product quality, deployment practices, institutional coordination, capacity development, and field-level implementation have been identified. Collectively, these interconnected constraints limit the ability of semiochemical-based interventions to contribute fully to sustainable pest management in India. These challenges are closely interrelated and therefore require coordinated policy, regulatory, scientific, and institutional responses rather than isolated interventions.

In addition to deployment-related constraints, a major gap exists in the coverage of semiochemical tools across the full spectrum of economically important pests in Indian agriculture. While validated semiochemical interventions are available for several major crop-pest systems, many pests across field crops, horticulture, plantation crops, stored products, and emerging invasive species remain without identified, characterised, or standardised semiochemical solutions. This gap is particularly relevant for invasive and rapidly expanding pests, where early detection, surveillance, and behaviour-based management could provide critical advantages. Strengthening research on semiochemical-mediated surveillance and management of invasive and emerging pests, including fall armyworm (*Spodoptera frugiperda*), tomato pinworm (*Phthorimaea absoluta*), and other emerging threats, is therefore needed to expand technology coverage and support rapid pest-response systems.

Another major limiting factor is the regulatory environment, which currently treats semiochemicals within the same approval framework as conventional insecticides. The absence of a simplified, low-risk registration pathway has resulted in high compliance costs, prolonged approval timelines, and unclear data requirements for semiochemical products. This situation persists even for compounds already approved in other regulatory jurisdictions such as the European Union and North America. Streamlined approval processes, including fast-track pathways and recognition of relevant international safety and efficacy data, are therefore needed to facilitate timely market access.

Closely associated with regulatory constraints is the lack of standardised national deployment protocols. Current field practices vary widely across crops, regions, and implementing agencies, particularly in relation to trap densities, placement strategies, installation patterns, lure replacement schedules, and monitoring thresholds. This variability contributes to inconsistent field performance and undermines confidence in semiochemical-based interventions among farmers and extension agencies. Stakeholders emphasised the need for nationally harmonised technical sheets and guidelines to ensure uniform and effective deployment.

Product quality variability emerged as a critical concern, with reports of inconsistent formulations, incomplete pheromone blends, and products of uncertain quality entering the market through conventional as well as digital commercial channels. Multiple visually similar products are currently available without transparent disclosure of pheromone composition, blend ratios, release characteristics, dispenser performance, or validated field longevity. In the absence of nationally enforced quality standards, traceability mechanisms, and independent verification systems, farmers and extension agencies are unable to distinguish validated products from substandard formulations. Such variability contributes to inconsistent field performance, undermines farmer confidence, and threatens the credibility of semiochemical-based pest management interventions. Accordingly, the need for robust quality assurance frameworks and effective mechanisms to prevent the manufacture and distribution of low-quality products was strongly emphasised.

Climate variability presents an additional challenge to the reliable deployment of semiochemical-based interventions across India's diverse agro-climatic regions. Temperature, humidity, rainfall, and wind regimes can influence semiochemical volatility, release rates, atmospheric dispersion, and dispenser longevity, while changing climatic conditions may alter insect phenology, behaviour, seasonal activity, and geographic distribution. Consequently, deployment parameters validated under one set of environmental conditions may not perform consistently across regions or seasons. Climate-responsive validation of formulations, dispenser systems, trap densities, lure replacement schedules, and monitoring thresholds will therefore be essential to ensure reliable field performance under current and future climatic scenarios.

In addition, stakeholders pointed to limited seasonal availability and distribution challenges, even for well-established technologies such as yellow stem borer pheromone traps. Farmers in regions with strong awareness and demand frequently experience difficulties in accessing quality-assured traps and lures during critical crop stages, highlighting weaknesses in production planning, supply-chain management, and last-mile distribution.

Farmer adoption is further constrained by socio-economic, behavioural, and awareness-related barriers, particularly in smallholder-dominated production systems. Upfront costs of traps, lures, dispensers, and their periodic replacement can discourage adoption where benefits are not immediately visible or where farmers compare these investments with familiar, rapidly acting insecticide applications. Limited awareness of pest behaviour and the preventive mode of action of semiochemical-based interventions may also lead to unrealistic expectations of immediate pest mortality and premature discontinuation. Adoption is further influenced by fragmented landholdings, dependence on neighbouring-farm participation for area-wide approaches such as mating disruption, uncertainty regarding product quality and efficacy, limited access to timely technical support, and seasonal availability of reliable inputs. These constraints highlight the need for locally adapted extension, demonstration-based learning, collective deployment models, and affordable access mechanisms tailored to smallholder farming systems.

The brainstorming session also revealed significant human resource and capacity constraints in semiochemical identification and deployment. Effective deployment of semiochemicals requires specialised knowledge in behavioural ecology, formulation science, and field implementation practices. However, trained personnel in these domains remain limited across ICAR institutes, State Agricultural Universities (SAUs), Krishi Vigyan Kendras (KVKs), and extension networks. Inadequate training contributes to improper installation, inconsistent deployment, and reduced field performance, thereby limiting farmer confidence and wider adoption of semiochemical-based technologies.

Institutionally, the sector suffers from a policy-research-implementation gap, wherein national research capacity and manufacturing capability have not translated into coordinated field deployment. While India possesses strong scientific expertise and industrial synthesis infrastructure, the absence of a national platform to align research institutions, regulatory agencies, extension systems, and industry stakeholders has limited large-scale adoption. The need to formally integrate chemical ecology into national pest management frameworks and extension programmes emerged as a strategic priority.

Further, the business and implementation models for semiochemicals are still evolving in India. Most deployments remain product-centric rather than service-oriented, with limited emphasis on trap maintenance, lure replacement schedules, and analytical decision support. The absence of service-based or cluster-based implementation models limits adoption, particularly in smallholder production systems. Stakeholders highlighted the potential of subscription-based services and season-long IPM packages to improve adoption, ensure timely maintenance, and enhance field outcomes.

Overall, the constraints facing semiochemical deployment are not solely technical but systemic. Addressing regulatory clarity, quality assurance, deployment protocols, institutional coordination, capacity development, and technology coverage through an integrated policy framework will be essential to unlock the full potential of semiochemical-based interventions as a mainstream strategy for sustainable pest management in India.

5. OPPORTUNITIES & STRATEGIC PRIORITIES

Following the challenges outlined above, India is well positioned to strengthen the role of semiochemical-based pest management within sustainable agricultural systems. The country possesses a strong scientific base in chemical ecology, expanding manufacturing capability, and increasing industrial participation, providing a solid foundation for translating research into scalable field applications. Coupled with growing demand for residue-safe food production, ecological intensification, and export-oriented agriculture, these strengths present significant opportunities to mainstream semiochemical-based interventions as an integral component of national pest management strategies.

India's expanding manufacturing ecosystem offers a particularly important strategic advantage. Domestic industries have developed capabilities in semiochemical synthesis, formulation, dispenser technologies, and commercial production, enabling the manufacture of both research-grade and field-ready products. Continued growth of this ecosystem, supported by closer collaboration among research institutions, industry, and extension agencies, can accelerate technology transfer, improve product availability, strengthen supply chains, and enhance India's competitiveness in the rapidly growing global semiochemical market.

These opportunities are closely aligned with national priorities promoting sustainable agriculture, ecological farming, reduced pesticide dependence, climate resilience, and export competitiveness. Integrating semiochemical-based approaches within ongoing national programmes on sustainable agriculture, integrated pest management, natural farming, and residue-safe production can significantly strengthen environmentally compatible crop protection while improving market access for Indian agricultural commodities.

Semiochemical-based interventions should be viewed as complementary to, rather than replacements for, other emerging sustainable pest management technologies such as biopesticides, microbial biological control, RNA interference (RNAi), sterile insect technique (SIT), host-plant resistance, and precision agriculture. Each technology possesses distinct strengths and operational limitations. Semiochemicals provide highly species-specific behavioural manipulation for surveillance, monitoring, mass trapping, mating disruption, attract-and-kill, and habitat-mediated pest regulation with minimal environmental residues. In contrast, RNAi technologies require effective delivery systems and stable gene silencing under field conditions; SIT depends on large-scale insect mass rearing and coordinated area-wide implementation; while microbial biocontrol agents may be influenced by environmental conditions and often require repeated applications. Rather than competing approaches, these technologies offer complementary components of integrated pest management, with semiochemicals serving as an important platform for surveillance, behavioural manipulation, decision support, and integration with other sustainable interventions.

Beyond direct pest suppression, wider deployment of semiochemical-based interventions offers important environmental opportunities through reduced reliance on broad-spectrum insecticides and lower chemical exposure of non-target organisms. Their high biological specificity can minimise disturbance to pollinators, predators, parasitoids, and other beneficial arthropods while strengthening conservation biological control and associated ecosystem services. Practice-based approaches that manipulate naturally occurring semiochemical cues within cropping systems including push-pull strategies, companion planting, trap cropping, and attract-and-reward systems offer additional opportunities to enhance ecological regulation and improve the resilience of agroecosystems. Although the magnitude of these benefits will vary among crop-pest systems and production environments, they reinforce the role of semiochemicals as an important component of environmentally compatible pest management.

Expanding the national research ecosystem presents another major opportunity for advancing semiochemical-based pest management. Although India has established strong scientific capability in chemical ecology, semiochemical synthesis, behavioural studies, and field validation, substantial opportunities remain to broaden technology coverage across economically important crop-pest systems. In particular, semiochemical discovery, characterisation, surveillance, and validation for invasive and emerging pests represent an important frontier for strengthening national preparedness and expanding behaviour-based pest management options. Greater integration of multidisciplinary expertise in chemical ecology, analytical chemistry, molecular biology, behavioural ecology, formulation science, and digital agriculture can further accelerate innovation and translation of research into field-ready technologies.

Emerging technologies are rapidly expanding the scope and effectiveness of semiochemical-based interventions. Continued advances in semiochemical isolation, identification, synthesis, and formulation science, together with improvements in controlled-release matrices, nano-formulations, dispenser technologies, aerosol systems, SPLAT-based formulations, biodegradable delivery platforms, and other long-lasting release systems, are enhancing the stability, precision, and field longevity of semiochemical delivery systems (An *et al.*, 2022). These developments create new opportunities for area-wide pest suppression, particularly through mating disruption, while reducing dependence on conventional insecticides in suitable crop-pest systems.

Climate change further highlights the importance of continued innovation in semiochemical technologies. Rising temperatures, altered rainfall patterns, and changing pest distributions are likely to influence semiochemical release characteristics, insect behaviour, and field performance. Consequently, development of climate-resilient formulations, dispenser systems, and deployment strategies adapted to diverse agro-climatic conditions represents an important opportunity to improve the reliability and scalability of semiochemical-based interventions across India's varied production environments.

The ongoing digital transformation of agriculture provides additional opportunities to enhance the effectiveness of semiochemical-based pest management. Integration of semiochemical tools with AI-enabled decision-support systems, IoT-based smart traps, automated sensors, remote sensing, GIS platforms, weather-based forecasting, and precision agriculture technologies can substantially improve pest surveillance, real-time monitoring, and evidence-based decision-making. Such digital integration can enable more precise deployment of semiochemical interventions, improve resource-use efficiency, strengthen early-warning systems, and facilitate area-wide implementation, particularly in geographically dispersed smallholder production systems.

Service-oriented deployment models also present significant opportunities for improving adoption and long-term sustainability. Beyond the supply of traps and lures, integrated service models incorporating installation, monitoring, lure replacement, advisory support, and digital decision-making can improve implementation quality and consistency. Cluster-based deployment approaches, particularly for mating disruption, mass trapping, and surveillance programmes, are well suited to India's predominantly smallholder farming systems and can generate greater collective benefits than isolated farm-level interventions.

From an economic perspective, semiochemical-based pest management offers considerable potential to improve farm profitability while reducing environmental costs associated with excessive insecticide use. Reduced pesticide inputs, lower residue risks, improved marketable yields, and enhanced export opportunities collectively strengthen the economic case for wider adoption. At the national level, expansion of domestic manufacturing, innovation, technology transfer, and export of semiochemical products can contribute to rural entrepreneurship, industrial growth, and India's position as a global supplier of sustainable pest management technologies.

Finally, closer integration among research institutions, regulatory agencies, industry, extension systems, and farming communities represents a significant opportunity to strengthen the overall semiochemical ecosystem. Improved coordination across these stakeholders can accelerate technology validation, regulatory harmonisation, quality assurance, manufacturing, extension, and field deployment, thereby creating a more enabling environment for widespread adoption of semiochemical-based pest management.

Given the diversity of India's cropping systems and pest complexes, prioritisation of semiochemical research and deployment should follow a structured, need-based framework rather than a fixed national list of crop-pest systems. Priority may be guided by economic importance, crop losses, pesticide burden and resistance risk, technology readiness, suitability for area-wide or cluster-based deployment, residue and export-market concerns, invasive or emerging pest status, and compatibility with existing integrated pest management programmes. Crop- and pest-specific priorities may subsequently be refined through coordinated national programmes, with participating ICAR Institutes, State Agricultural Universities, and other research organizations addressing systems aligned with their respective crop, commodity, regional, and institutional mandates. Such a flexible framework will enable strategic investment while allowing timely responses to emerging pest threats, regional priorities, and future advances in semiochemical science and technology.

Collectively, these opportunities demonstrate that India possesses the scientific capability, manufacturing capacity, and institutional foundation necessary to substantially expand the role of semiochemical-based pest management in sustainable agriculture. Strategic investments, coordinated institutional mechanisms, and alignment with national agricultural priorities can enable the systematic translation of scientific advances and industrial capacity into effective field deployment.

Accordingly, the brainstorming session identified the following strategic priorities (see Box 2), which form the basis for the detailed policy recommendations presented in Section 6.

6. RECOMMENDATIONS

The strategic priorities outlined in Box 2 provide the broad direction for strengthening India's semiochemical ecosystem. Building on these priorities, the following policy

BOX 2. Strategic Priorities Identified

- **Establish a coordinated national programme** on semiochemical-based pest management to strengthen research, innovation, multi-location validation, technology deployment, and institutional coordination.
- **Develop a proportionate and science-based regulatory framework** for semiochemicals, including simplified approval pathways for low-risk behavioural modifiers and greater harmonisation with international regulatory practices.
- **Strengthen national quality assurance systems** through harmonised standards, traceability mechanisms, referral laboratories, and standardised deployment protocols to ensure product quality and field performance.
- **Expand semiochemical discovery, characterisation, validation, and deployment** across economically important, invasive, and emerging pest systems while strengthening climate-resilient formulations, advanced delivery systems, and area-wide technologies such as mating disruption.
- **Promote integration of semiochemicals with digital and precision agriculture technologies**, including AI, IoT-enabled smart traps, and decision-support systems.
- **Strengthen manufacturing ecosystems, technology transfer, public–private partnerships, and service-oriented deployment models** to improve commercialisation, seasonal availability, and farmer access to quality-assured products.
- **Promote farmer-centred adoption strategies** through targeted incentives, extension, demonstration programmes, cluster-based implementation, and specialised human resource development.
- **Foster investment, entrepreneurship, international collaboration, and export competitiveness** to position India as a global leader in semiochemical technologies.

recommendations and phased action plan present a coordinated national framework to advance scientific innovation, regulatory clarity, quality assurance, institutional capacity, and effective field deployment of semiochemical-based interventions. Implementation should be supported through phased resource mobilisation involving public research funding, competitive grants, industry co-investment, and public-private partnership mechanisms, with detailed financial requirements determined through programme-specific costing.

The proposed policy actions are organised within a phased implementation roadmap comprising short- (1-2 years), medium- (> 2-5 years), and long-term (> 5-10 years) priorities. Short term actions focus on regulatory clarity, quality standards, and enabling mechanisms; medium term actions emphasise research infrastructure, coordinated validation, capacity building, and scalable deployment models; and long term actions aim to institutionalise innovation ecosystems, sustained market development, and integration of semiochemical-based pest management within national agricultural programmes. Implementing agencies and expected outcomes are indicated under each recommendation area to support coordinated and accountable implementation.

The recommendations are designed to be complementary and mutually reinforcing, recognising that regulatory reforms, quality assurance, research, manufacturing, extension, and farmer adoption must progress in parallel to achieve large-scale deployment of semiochemical-based pest management.

6.1. Regulatory and Policy Reforms (Short Term: 1-2 years)

- Establish a fast-track approval pathway for low-risk semiochemicals, recognising international safety and efficacy data where applicable
- Develop a regulatory sandbox within CIB&RC for proven semiochemical technologies to enable conditional approvals and monitored field deployment
- Clarify regulatory exemptions or simplified pathways for monitoring and mating disruption applications, where toxicological risk is minimal
- Streamline dossier formats and data requirements for semiochemical products, including blends and formulations
- Harmonise national regulatory guidelines with relevant international frameworks, including OECD (Organization for Economic Co-operation and Development) guidance, and facilitate domestic registration and export

Implementing Agencies: Ministry of Agriculture & Farmers Welfare (MoA&FW), Central Insecticides Board and Registration Committee (CIB&RC) and Industry

6.2. Quality Assurance and Standards (Short Term: 1-2 years)

- Develop national quality standards for semiochemicals, specifying minimum requirements for active ingredient purity, isomeric composition, release rates, dispenser performance, packaging, storage, and shelf life to ensure product consistency, reliability, and field performance

- Establish a network of designated referral laboratories across regions for independent verification of semiochemical quality, release characteristics, and dispenser functionality
- Implement regulatory surveillance and enforcement mechanisms to prevent the manufacture, import, distribution, and sale of low-quality, adulterated, or incomplete semiochemical products that undermine field performance and farmer confidence
- Create a national traceability and quality control portal, modelled on the NAS seed portal[1], to enable batch-wise traceability, transparency, and regulatory oversight throughout the semiochemical supply chain (see Figure 1)

Implementing Agencies: ICAR/CSIR Institutes, CIB&RC and Industry partners

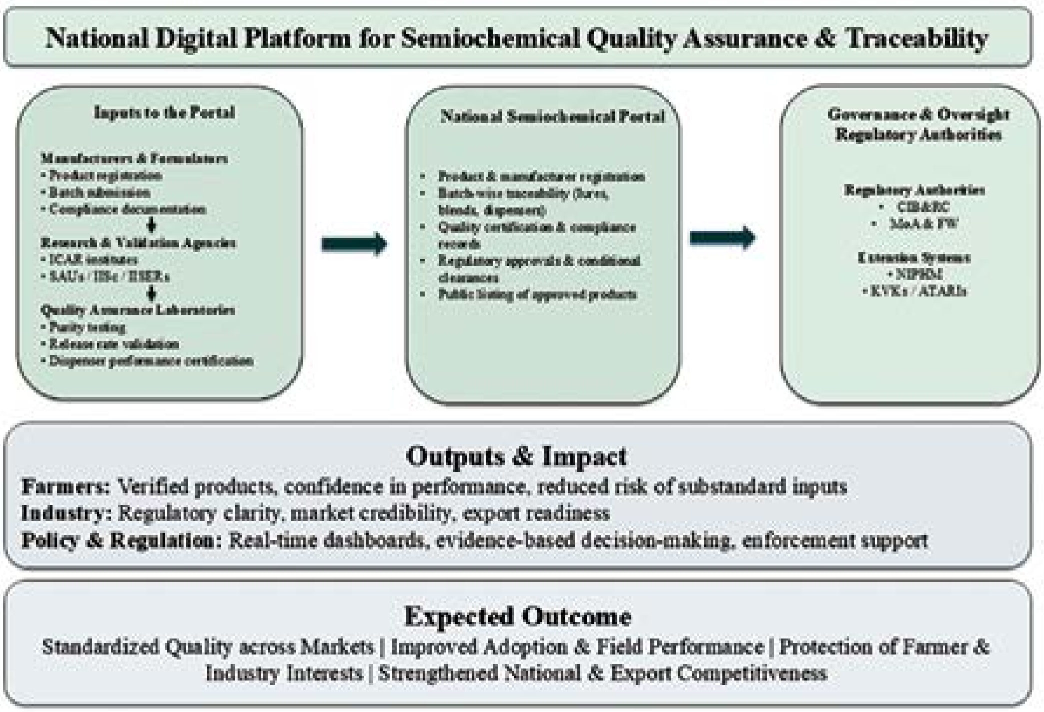

Figure 1. Conceptual framework for a national semiochemical quality assurance & traceability in India agriculture, modelled on the NAS Seed Portal.

[1]The proposed semiochemical quality assurance and traceability portal may be modelled on the NAS Seed Portal, which demonstrates how a national digital platform can strengthen product traceability, regulatory oversight, quality compliance, and farmer confidence for agricultural inputs.

6.3. Research and Innovation Infrastructure (Medium Term: > 2-5 years)

- Establish a **'National Centre of Excellence for Semiochemical Science and Innovation'**, with dedicated facilities and expertise focused on semiochemical isolation and identification, GC-EAD and behavioural assays, and formulation and delivery system development
- Create a national research consortium linking ICAR institutes, SAUs, IISc, IISERs, CSIR laboratories, and industry partners to promote coordinated, interdisciplinary research and translational outcomes
- Establish dedicated funding streams for semiochemical research through ICAR, ANRF, and other national competitive funding mechanisms to support discovery, validation, and scale-up of promising technologies
- Support innovation in advanced and climate-resilient delivery systems, including controlled-release matrices, nano-formulations, and smart trap technologies, and validate their performance across representative agro-climatic conditions to enhance efficacy, stability, and field reliability

Implementing Agencies: ICAR, ANRF, SAUs, IISc, IISERs, CSIR laboratories, and Industry partners

6.4. Deployment Models and Extension Capacity (Medium Term: > 2-5 years)

- Develop nationally harmonised deployment protocols and pest-specific technical sheets to standardise trap density, placement, lure replacement schedules, and threshold-based decision criteria across crops and regions
- Introduce mandatory training and certification for KVK and extension personnel prior to recommending semiochemical interventions, ensuring correct installation, maintenance, and interpretation of field data
- Establish demonstration clusters in high-value crops and representative agro-climatic regions to demonstrate and refine deployment models, build farmer confidence, and facilitate scaling through peer learning
- Promote subscription-based or service-oriented deployment models incorporating trap installation, maintenance, timely lure replacement, pest monitoring, and data-driven advisory services

Implementing Agencies: ICAR, SAUs, NIPHM, ATARIs, KVKs, State Departments of Agriculture, FPOs, and Industry partners

6.5. Incentives, Market Development, and Enabling Policies (Long Term: > 5-10 years)

- Reduce GST on semiochemical-based products from 18% to 5% to improve affordability and encourage wider adoption, particularly among small and marginal farmers

- Include semiochemical-based pest management under ecological farming, sustainable agriculture, and integrated pest management incentive schemes to promote wider adoption of environmentally compatible pest management practices
- Enable financial incentives or subsidies for farmer clusters adopting semiochemical-based IPM approaches, particularly high-value and export-oriented cropping systems.
- Provide targeted support for industry through export facilitation, regulatory harmonisation, and dossier alignment enabling smoother access to international markets, and reducing compliance-related barriers

Implementing Agencies: MoA&FW, Ministry of Finance (MoF), Agricultural and Processed Food Products Export Development Authority (APEDA), CIB&RC, State Departments of Agriculture, FPOs and Industry Associations

Successful implementation of the proposed policy actions will require a coordinated Monitoring, Evaluation and Learning (MEL) framework integrated across the immediate, medium-, and long-term implementation phases. Baseline values should be established at programme initiation, followed by periodic assessment using a nationally harmonised set of indicators to track implementation progress, identify gaps, and evaluate outcomes against defined policy objectives. Regular review of monitoring results should inform adaptive policy refinement, resource allocation, and prioritisation of interventions in response to emerging scientific, regulatory, and field-level developments. By embedding evidence-based monitoring and adaptive learning within the implementation process, the proposed policy framework can ensure greater accountability, improve programme effectiveness, and support the continuous refinement of India's national semiochemical strategy.

Collectively, the proposed policy framework provides a phased and coordinated pathway to strengthen India's semiochemical ecosystem through regulatory reform, quality assurance, scientific innovation, institutional capacity, and farmer-centred deployment. Supported by sustained investment, strategic partnerships, effective implementation, and continuous monitoring and adaptive learning, these measures can enable semiochemical-based pest management to contribute significantly to sustainable agricultural intensification, residue-safe production, and export competitiveness, while positioning India as a global leader in the development, manufacture, and deployment of semiochemical technologies.

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