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Climate-smart entomology extension: A review of tools for sustainable agriculture

¹Amandeep and ²Krishna Kant

¹Technical Assistant (Group C), Department of Agriculture, NDUAT, Kumarganj, Ayodhya, Uttar Pradesh, India

²Ph.D. Scholar, Agricultural Economics, Acharya Narendra Deva University of Agriculture and Technology (NDUAT), Kumarganj, Ayodhya, Uttar Pradesh, India

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Corresponding Author: Amandeep

Abstract

Climate change is reshaping the distribution, phenology, and outbreak intensity of insect pests, placing new demands on the agricultural extension systems that connect research to farmer decision-making. This review synthesizes recent peer-reviewed and institutional literature on tools available for climate-smart entomology extension, organized into seven functional categories: mobile and digital advisory platforms, remote-sensing and UAV/satellite surveillance, artificial-intelligence-based decision-support and forecasting systems, biological and conservation-biocontrol extension, climate-resilient varieties bundled with integrated pest management (IPM) training, blended climate-smart agriculture (CSA) extension packages, and transboundary early-warning networks for migratory pests such as fall armyworm and desert locust. Evidence from field evaluations in Nepal, Zambia, Ethiopia, Kenya, India, and other contexts indicates that digitally supported extension is associated with measurable gains in technology adoption and yield, although effect sizes vary widely by intervention design, crop, and socio-economic setting. Because access to these tools is not gender-neutral, the review also examines documented disparities in women's access to extension and climate information services, and considers the economic and environmental trade-offs of different pest-management pathways. The review presents two comparative summary tables, a conceptual framework diagram, and a synthesis figure of reported outcomes, and concludes with a discussion of persistent barriers - including connectivity gaps, data quality, cost, gender inequity, and extension-workforce capacity - that constrain the scaling of climate-smart entomology tools in resource-limited farming systems.

Keywords: Climate-smart agriculture, integrated pest management, agricultural extension, digital advisory services, remote sensing, biological control, gender and extension, transboundary pests

Introduction

Insect pests already account for a substantial share of global crop losses - estimates place pest-related losses at up to 40% of the world's potential food supply - and climate change is altering pest ranges, generation times, and outbreak thresholds in ways that outpace the knowledge base of many farming communities. Warmer temperatures shorten insect development times and can add additional generations per season for many species, while shifting precipitation patterns alter the synchrony between pests, host crops, and natural enemies. These dynamics are compounded by the accelerating spread of invasive species, which move into new territories as climatic suitability expands and as global trade and travel create new introduction pathways.

Climate-smart pest management (CSPM) has emerged as a cross-sectoral framework that integrates climate adaptation and mitigation with pest control, requiring coordinated action among researchers, extension services, and policymakers to remain effective as conditions change. Unlike conventional pest management, which often assumes relatively stable pest calendars and thresholds, CSPM treats those calendars and thresholds as moving targets that must be continuously monitored, modelled, and communicated to farmers in near-real time.

Agricultural extension - the set of institutions and channels

through which agronomic and entomological knowledge reaches farmers - is the practical mechanism through which climate-smart pest management is translated into field-level practice. Historically dependent on in-person visits and printed material, extension is increasingly delivered through a growing toolkit of mobile applications, remote-sensing platforms, artificial-intelligence-based forecasting systems, and blended digital-plus-in-person programmes. This review examines that toolkit specifically through an entomological lens, asking which categories of tools are being used, what evidence exists for their effectiveness, who is able to access them, and what barriers continue to limit their reach in sustainable agriculture systems.

The changing landscape of pest pressure under climate change

The entomological literature reviewed here converges on several recurring climate-pest interactions relevant to extension design. First, temperature-driven shifts in insect phenology change when pests emerge relative to crop growth stages, which can render fixed, calendar-based spray or scouting recommendations obsolete. Second, climate variability interacts with natural enemies, pathogens, and abiotic stressors such as drought and heat in ways that complicate single-pest management advice, since a control

measure effective under one set of conditions may underperform under another. Third, the establishment of invasive species in new regions - most visibly the spread of fall armyworm across more than 45 African countries since 2016, and recurrent desert locust upsurges in the Horn of Africa - illustrates how quickly extension systems can be confronted with pests for which local knowledge and control infrastructure do not yet exist.

These dynamics disproportionately affect smallholder and climate-vulnerable farming systems, where the capacity to absorb an unanticipated outbreak is lowest and where extension coverage is often thinnest. Reviewed sources emphasize that international frameworks led by the Food and Agriculture Organization (FAO), the International Plant Protection Convention (IPPC), and regional plant-protection organizations play an increasingly important coordinating role in quarantine, biosecurity, and cross-border data sharing, but that significant gaps persist in long-term monitoring datasets and in predictive modelling capable of handling compound climate scenarios.

The Evolution of agricultural extension delivery

Agricultural extension has moved through several overlapping generations of delivery models. The earliest model relied almost entirely on in-person contact between government extension officers and farmers, typically through scheduled field visits, demonstration plots, and farmer-training days. This model provided rich, contextualized advice but scaled poorly: extension-to-farmer ratios in many low- and middle-income countries remained far below recommended levels, leaving large numbers of farmers with infrequent or no direct contact.

A second generation introduced mass media - radio broadcasts, printed bulletins, and later television programming - to extend the reach of centrally produced advice, though these channels offered little ability to tailor recommendations to local pest pressure or farm conditions. The current, still-unfolding generation layers mobile telephony, the internet, and increasingly artificial intelligence onto these earlier channels, enabling two-way, geographically targeted, and near-real-time communication. Reviewed evidence suggests that this digital layer performs best not as a replacement for earlier generations of extension but as a complement: the strongest documented outcomes in this review come from programmes that combine digital messaging with continued in-person training and locally present extension agents, rather than programmes that substitute technology for human contact entirely.

Review approach

This is a narrative review drawing on peer-reviewed journal articles, institutional reports, and practice briefs published primarily between 2019 and 2026, identified through targeted searches on climate-smart pest management, digital agricultural extension, remote-sensing pest surveillance, transboundary pest early-warning systems, gender and extension access, and climate-smart agriculture adoption. Sources were selected for direct relevance to entomological extension tools and for reporting quantifiable outcomes where available. The review does not follow a systematic PRISMA protocol; where a cited source is itself a systematic or scoping review, this is noted explicitly. Given the pace of

publication in this field, the review should be read as a synthesis of illustrative, well-documented cases rather than an exhaustive inventory of every available tool.

Tool categories in climate-smart entomology extension

Mobile and digital advisory platforms

Mobile-phone-based advisory services, including SMS, interactive voice response (IVR), and smartphone applications, have become one of the most widely deployed extension channels because mobile penetration in rural areas now exceeds that of most other infrastructure. Platforms such as CABI's PlantwisePlus toolkit and Digital Green's FarmStack data-sharing system deliver pest identification guides, life-cycle information, and IPM recommendations directly to advisory workers and farmers. A cluster-randomized evaluation in Nepal's Western Terai found that combining agricultural training with real-time digital extension raised adoption of a recommended fertilizer-and-pest-relevant practice by 11.4-15.7 percentage points and increased rice yields by 35-56% relative to training alone, underscoring that digital tools tend to perform best as a complement to, rather than a replacement for, human advisory contact.

A broader review in Science of digital agricultural advisory concluded that GPS-linked smartphones could in principle deliver locally relevant weather and pest information at low marginal cost, but that realizing this potential depends on content quality, farmer trust, and last-mile design rather than on smartphone availability alone. In Southern India, a cluster-randomized trial of the FarmStack platform delivered orchard-management advisories, weather alerts, and soil-based recommendations to cashew growers through a mix of in-person video sessions, SMS, and IVR messaging, illustrating how digital and analogue channels are increasingly blended within a single programme rather than treated as substitutes.

Remote sensing and UAV/satellite surveillance

Satellite platforms (Sentinel-2, Landsat-8, MODIS) and unmanned aerial vehicles (UAVs) equipped with multispectral or hyperspectral sensors are increasingly used to detect crop stress and pest pressure before symptoms are visible to the naked eye. A systematic review of 147 studies applying remote sensing and artificial intelligence to crop pest and disease monitoring found that deep-learning object-detection models (e.g., YOLO, Faster R-CNN variants) typically achieved mean average precision and F1-scores in the 0.75-0.90 range for insect and lesion detection tasks, while satellite time series offered broader spatial and temporal coverage than UAV imagery at the cost of coarser resolution and sensitivity to cloud cover.

For extension purposes, the practical value of these tools lies less in raw imagery and more in their integration into simplified alerts that extension agents or automated systems can relay to farmers, since few smallholders can interpret spectral data directly. Satellite-based biomass-anomaly detection using Sentinel-2 imagery has also been explored specifically for fall armyworm monitoring in East Africa, where NDVI time-series analysis was validated against field data from the FAO's FAMEWS mobile application, though the reviewed evidence found that confounding factors such as intercropping, weeds, and cloud cover produced mixed

validation results, suggesting that satellite detection currently works best as a complement to, rather than a replacement for, ground-based scouting networks.

Artificial-intelligence-based decision-support and forecasting

Machine-learning models are being layered onto sensor and climate data to forecast pest population dynamics and outbreak risk. Reviewed applications include convolutional and recurrent neural network models for early-warning forecasting, and decision-support systems (DSS) that couple pest population models with environmental data to recommend intervention timing; one cited DSS application in tomato thrips management was linked to a direct reduction in insecticide use. These systems still face constraints around data availability, model generalization across regions and cultivars, and computational requirements that can put them out of reach of extension services with limited technical capacity.

Beyond outbreak forecasting, AI-based image recognition is also being applied to taxonomic and behavioural entomology tasks that traditionally required specialist expertise, such as distinguishing fruit-fly species by wing pattern or tracking pollinator activity. While these applications remain largely at the research stage, they point toward a future in which routine pest-identification tasks currently bottlenecked by the scarcity of trained taxonomists could be partially automated and pushed out to extension workers or farmers through smartphone-based tools.

Biological control and conservation-biocontrol extension

Extension programmes that promote biological control agents - such as field releases of *Trichogramma* parasitoids against lepidopteran pests, or habitat manipulation to conserve natural enemies - form a core pillar of climate-smart pest management because non-chemical control options can lower the greenhouse-gas intensity of crop protection relative to synthetic pesticide use, while also reducing input costs for farmers. Climate change complicates this category by shifting the synchrony between pests and their natural enemies, meaning that conservation-biocontrol extension increasingly requires locally updated guidance rather than static recommendations.

A related, climate-adapted push-pull system - which combines a repellent intercrop with an attractive trap crop to manage cereal stemborers and, more recently, fall armyworm - illustrates how ecologically based control methods can be adapted for changing conditions while remaining accessible to resource-constrained farmers, since the method relies on locally available plant material rather than purchased inputs. Extension of push-pull and similar agroecological methods has also been the subject of explicit gender-focused adoption research, discussed further in Section 8.

Climate-resilient varieties bundled with IPM Training

Pairing drought- or heat-tolerant crop varieties with participatory IPM training through farmer field schools addresses both abiotic and biotic stress simultaneously. A scoping review of 202 studies on climate-resilient crop adoption across low- and middle-income countries found that the availability and effectiveness of extension services and outreach was the single most important determinant of

adoption, ahead of education levels, input access, and socio-economic status, reinforcing that variety-level innovation depends heavily on the extension channel through which it is delivered. The same review found that seed and information access, together with social networks such as farmer cooperatives, were consistently reported as key facilitators, while dis-adoption was most often linked to a variety's underperformance under real field stress rather than to extension failure per se.

Blended climate-smart agriculture (CSA) extension packages

Some extension programmes bundle pest management with irrigation, fertilizer, and agronomic advice into a single climate-smart agriculture package. In Nyimba District, Zambia, a study of 194 smallholder households found that adopters of bundled CSA practices recorded a 20.2% increase in overall crop yield and a 21.5% increase in maize yield relative to non-adopters, with education, access to climate information, and extension contact identified as significant adoption determinants. Similarly, in North Wollo, Ethiopia, joint adoption of climate-smart crop-intensification strategies was associated with a 90.5% increase in dietary variety and a 69.9% reduction in household food insecurity relative to non-adoption. These bundled packages illustrate a broader pattern in the literature: interventions that combine multiple climate-smart practices tend to report larger effect sizes than single-practice interventions, but they are also harder to attribute to any one component, including the entomological one, since yield and food-security outcomes reflect the joint effect of pest management, irrigation, variety choice, and fertilizer use together.

Transboundary early-warning networks for migratory pests

Highly mobile, invasive pests such as fall armyworm and desert locust require extension tools that operate above the level of an individual farm or district. The FAO's Fall Armyworm Monitoring and Early Warning System (FAMEWS) mobile application anchors a community-based monitoring network in which trained Community Focal Persons operate pheromone traps and report data used to characterize pest bioecology and guide the timing of IPM interventions; one implementation across six East African countries trained more than 650 focal persons and generated data credited with improving community-level pest awareness. A separate study of desert locust dynamics in eastern Africa has focused on estimating the timing of hatching from climate and vegetation data to enable earlier response before hopper bands form and swarming begins.

Research on the design of these warning systems emphasizes that technical accuracy alone does not guarantee use: a study surveying professional input distributors, agronomists, and researchers in East Africa found that the timing and spatial precision of warnings - not merely the existence of predictive models - determined whether recipients could act on the information, pointing to a persistent gap between the technical sophistication of forecasting models and their translation into farmer- and distributor-relevant guidance.

Comparative summary of tool categories

Table 1 summarizes the seven tool categories discussed

above, their representative technologies, primary extension function, and the reported evidence from the studies reviewed.

Table 1: Comparative overview of climate-smart entomology extension tool categories, drawn from the sources cited in Section 5 and the reference list.

Tool Category	Representative Technologies	Primary Extension Function	Reported Evidence / Impact	Key Source
Mobile & digital advisory platforms	SMS/IVR alerts, smartphone apps, Digital Green FarmStack, PlantwisePlus toolkit	Deliver real-time pest, weather, and management advisories directly to farmers and extension agents	Digital extension combined with training raised technology adoption by 11.4-15.7 percentage points and rice yields by 35-56% in Nepal	Karki Nepal <i>et al.</i> (2025) ^[8] ; Fabregas <i>et al.</i> (2019) ^[6]
Remote sensing & UAV/satellite surveillance	Sentinel-2, Landsat-8, UAV multispectral imagery, IoT field sensors	Early detection and spatial mapping of pest outbreaks and crop stress across large areas	Deep-learning detection models report average precision/F1 of 0.75-0.90 across 147 reviewed studies	Aziz <i>et al.</i> (2025) ^[2]
AI/ML decision-support & forecasting systems	Machine-learning population models, threshold-based warning systems, cloud-linked DSS	Predict pest emergence and outbreak risk to guide timing of interventions	ML-based decision-support tools linked to measurable reductions in insecticide applications	Aziz <i>et al.</i> (2025) ^[2]
Biological control & conservation-biocontrol extension	Trichogramma and other parasitoid releases, habitat manipulation, natural-enemy conservation	Reduce reliance on synthetic pesticides while supporting ecosystem services	Non-chemical control options associated with lower greenhouse-gas intensity per unit of food produced	Heeb <i>et al.</i> (2019) ^[7] ; Bouri <i>et al.</i> (2023) ^[3]
Climate-resilient varieties bundled with IPM training	Drought/heat-tolerant cultivars, farmer field schools, participatory IPM curricula	Combine genetic and behavioural tools to reduce pest and climate-related yield loss	Extension access identified as the leading determinant of adoption across 202 reviewed studies	Acevedo <i>et al.</i> (2020) ^[1]
Blended CSA/extension packages	Combined agronomic, irrigation, and pest-management advisory bundles delivered through extension services	Integrate multiple climate-smart practices into a single farmer-facing programme	CSA adopters recorded a 20.2% increase in overall crop yield and 21.5% in maize yield versus non-adopters	Petros <i>et al.</i> (2024) ^[11]
Transboundary pest early-warning networks	FAO FAMEWS mobile app, community focal-person trap networks, desert-locust hatching models	Coordinate cross-border monitoring and rapid alerts for migratory, invasive pests	Community-based monitoring network of over 650 focal persons deployed across six East African countries	Niassy <i>et al.</i> (2021) ^[10] ; Brown <i>et al.</i> (2022) ^[4]

Regional case studies

The six cases summarized in Table 2 span East Africa, South Asia, and Southern Africa and illustrate how the tool categories described in Section 5 have been combined in practice. Two broad patterns emerge across these cases. First, programmes targeting a single, well-defined threat - such as fall armyworm surveillance in East Africa - tend to build dedicated, purpose-specific infrastructure (a standardized mobile app, a trained focal-person network), whereas

programmes targeting general climate-smart intensification bundle pest management alongside irrigation, variety choice, and fertilizer advice within a single extension package. Second, across nearly every case, extension contact and information access are reported as significant, and often the single strongest, determinants of adoption, ahead of purely technical factors such as which sensing or forecasting technology was used.

Table 2: Regional case studies of climate-smart entomology and CSA extension programmes referenced in this review.

Region / Country	Pest / Focus	Extension Approach	Key Outcome
East Africa (Ethiopia, Kenya, Tanzania, Uganda, Rwanda, Burundi)	Fall armyworm (<i>Spodoptera frugiperda</i>)	Community-based monitoring using the FAO FAMEWS mobile app and trained Community Focal Persons operating pheromone traps	Over 650 focal persons trained; data used to characterize FAW bioecology and guide IPM deployment timing (Niassy <i>et al.</i> , 2021) ^[10]
East Africa (regional)	Fall armyworm and desert locust	Predictive modelling and outbreak warning systems combining geospatial data with input-distributor and agronomist feedback	User-centred warning design found timing and spatial precision more decisive for uptake than raw data availability (Brown <i>et al.</i> , 2022) ^[4]
Western Terai, Nepal	Rice production constraints (fertilizer/pest-relevant practice adoption)	Sequential agricultural training paired with real-time digital extension messaging	11.4-15.7 percentage-point higher adoption and 35-56% higher rice yield versus training alone (Karki Nepal <i>et al.</i> , 2025) ^[8]
Nyimba District, Zambia	General climate and pest stress on maize-based systems	Bundled climate-smart agriculture package delivered through household-level extension contact	20.2% increase in overall crop yield; 21.5% increase in maize yield among adopters (Petros <i>et al.</i> , 2024) ^[11]
North Wollo Zone, Ethiopia	Crop-intensification under drought and pest stress	Combined use of maturing varieties, small-scale irrigation, and efficient fertilizer use	90.5% increase in dietary variety and 69.9% reduction in food insecurity among joint adopters
Southern India (Andhra Pradesh)	Cashew orchard management advisories	Digital Green's FarmStack platform delivering video, SMS, and IVR advisories on orchard and pest management	Cluster-randomized evaluation associated with improved orchard management practice adoption (Singh <i>et al.</i> , 2023) ^[12]

Synthesis of reported outcomes and conceptual framework

To illustrate the range of outcomes reported across field studies, Figure 1 compares four independently reported percentage changes associated with climate-smart extension interventions: overall crop-yield gain in Zambia, the range of rice-yield gain in Nepal, and the gains in dietary variety and

reduction in food insecurity reported in Ethiopia. These figures come from different study designs (propensity-score matching, quasi-experimental treatment-effects models, and household surveys) and different outcome metrics, so the comparison is illustrative of the scale of reported benefits rather than a pooled or statistically combined estimate.

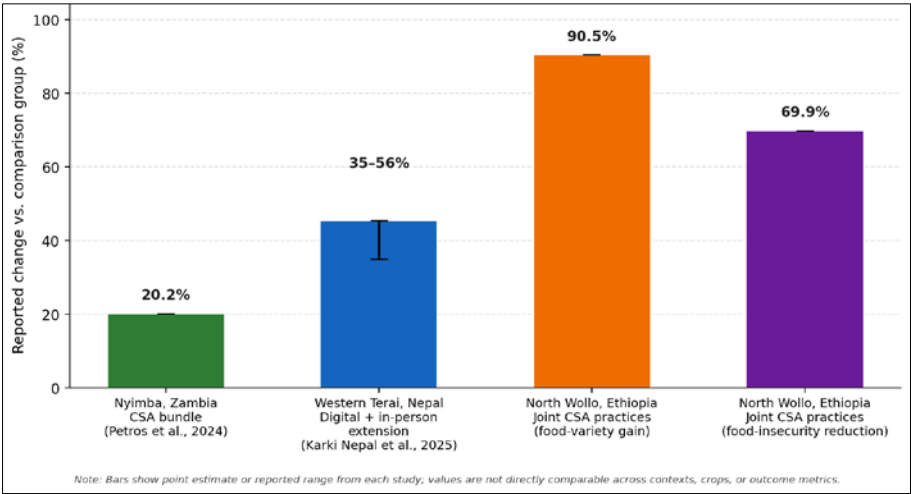


Fig 1: Reported outcomes of climate-smart extension interventions across selected field studies

Figure 1. Reported percentage change in yield, technology adoption, food-security, or dietary-diversity outcomes associated with climate-smart extension interventions in four field studies. Values are drawn from independent studies using different designs, crops, and metrics and are not directly comparable; bars show point estimates or reported ranges (error bars) as published by each source. Figure 2 synthesizes the tool categories from Section 5 into a single conceptual pipeline: climate and pest data flow into sensing and analysis tools, which feed extension delivery

channels, which in turn inform farmer decisions and action. A feedback loop returns field-level outcomes to refine future data collection and models, while an underlying enabling-environment layer - extension-workforce capacity, connectivity, financing, gender-inclusive design, and monitoring and evaluation systems - determines whether the pipeline functions as intended. The barriers discussed in Section 9 map directly onto weaknesses in this enabling layer.

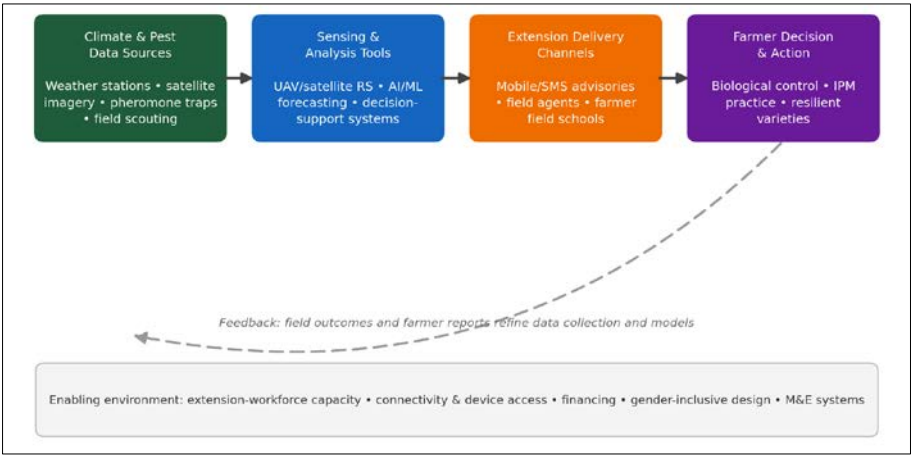


Fig 2: Conceptual framework of the climate-smart entomology extension pipeline

Figure 2. Conceptual framework linking climate and pest data sources through sensing and analysis tools, extension delivery channels, and farmer decision-making, with a feedback loop returning field outcomes to refine data collection, and an enabling-environment layer of capacity, connectivity, financing, and equity conditions that determine whether the pipeline functions in practice.

Gender and equity considerations in extension delivery
A recurring finding across the reviewed literature is that access to climate-smart entomology tools is not gender-neutral. A systematic review of gender dynamics in climate information services across Sub-Saharan Africa found that women frequently face greater barriers to accessing the mobile phones, radios, and extension contact through which

pest and weather information travels, compounded by financial constraints and restricted land ownership that limit investment in complementary inputs. An intra-household survey of 156 married couples in Kenya found that husbands had significantly more access to early-warning systems and adaptation advisory services, while wives had comparatively better access to weather forecasts, with the two spouses also reporting different preferred information channels - husbands favouring extension officers, print media, and television, and wives favouring radio and social groups.

These patterns matter for entomology extension specifically because pest advisories are often time-sensitive: if a household's female members, who frequently carry out day-to-day field monitoring and pest scouting, have systematically weaker access to the channel carrying an early warning, the practical value of that warning is reduced regardless of its technical accuracy. Reviewed literature on extension-workforce composition also finds that women farmers report greater comfort learning from female extension workers, yet women remain under-represented in many extension services, suggesting that workforce diversification is itself a lever for improving the reach of climate-smart entomology tools. Programme-design responses documented in the literature include women-to-women extension models, joint invitation of both spouses to household-level advisory sessions where female extension staff are scarce, and deliberate use of local languages and lower-literacy formats to reduce participation barriers.

Economic and environmental considerations

Beyond yield and adoption metrics, several reviewed sources point to economic and environmental trade-offs that extension programmes must weigh when recommending among pest-management pathways. Non-chemical control options - biological control, habitat manipulation, and conservation biocontrol - are associated in the literature with lower greenhouse-gas emissions intensity per unit of food produced than broad-spectrum chemical control, reinforcing the case for extension systems to actively promote these options as part of climate mitigation, not just adaptation. At the same time, the upfront and recurring costs of digital and remote-sensing infrastructure - satellite subscriptions, UAV hardware, sensor networks, and the connectivity required to use them - fall disproportionately on extension services and development partners rather than on individual farmers, raising questions about the long-term financial sustainability of tool-intensive extension models once donor or project funding ends.

Economic evaluations of digital advisory services more broadly report positive but context-dependent returns: SMS-based weather-forecast programmes in West Africa have been linked to meaningful annual income gains for participating farmers over multi-year studies, and text-based soil-information services have been associated with favourable benefit-cost ratios for input uptake. These findings suggest that, where digital advisory tools are well targeted and consistently delivered, the economic case for extension investment can be strong, even though the specific entomological component of a bundled programme is rarely evaluated in isolation from its agronomic and irrigation components.

Barriers to adoption and scaling

- Connectivity and device gaps: mobile and remote-sensing tools depend on network coverage and smartphone access that remain uneven in rural, climate-vulnerable regions.
- Data quality and local calibration: AI/ML forecasting models trained on data from one region or cultivar often generalize poorly to new contexts, requiring costly local recalibration.
- Cost and financing: satellite subscriptions, UAV hardware, and DSS platforms carry upfront and maintenance costs that can be prohibitive for extension services in low-income settings.
- Extension-workforce capacity: interpreting sensor and model outputs into actionable, farmer-relevant advice requires technical skills that many extension systems have not yet built at scale.
- Gender and social inclusion: unequal access to phones, extension contact, and preferred information channels reduces the practical reach of otherwise well-designed advisories.
- Trust, timing, and last-mile design: digital advisories are most effective when paired with in-person contact and delivered at agronomically relevant moments, as shown by the Nepal and Zambia evaluations, rather than deployed as a stand-alone substitute for extension staff.
- Cross-border coordination: migratory pests such as fall armyworm and desert locust require data sharing and warning systems that function across national boundaries, which existing institutional arrangements do not always support smoothly.

Several reviewed sources also note that the determinants of adoption are as much social as technical: household education, gender, farm size, and access to credit repeatedly emerge as significant predictors of whether a climate-smart tool is taken up and sustained, independent of the tool's technical performance.

Future directions and emerging technologies

The literature points to several emerging directions likely to shape the next generation of climate-smart entomology extension. Genomics, RNA interference (RNAi), and microbiome research are opening new, more targeted avenues for pest control that may reduce reliance on broad-spectrum chemical inputs, though these approaches remain largely at the research or early field-trial stage and are not yet routinely part of extension advisory content. Citizen-science smartphone tools that combine AI-based image recognition with crowd-sourced reporting are being piloted for plant-disease and insect-pest detection in horticulture and viticulture, potentially offering a lower-cost complement to formal remote-sensing infrastructure by turning farmers themselves into a distributed sensor network.

IoT-linked sensor networks paired with edge or cloud computing are also reducing the latency between pest detection and advisory delivery, an important development given that reviewed warning-system research consistently identifies timing precision as a key determinant of whether farmers and input distributors can act on an alert. Finally, growing attention to the socio-economic determinants of adoption - gender, literacy, extension-workforce

composition, and financing - suggests that future tool development is likely to be judged less on raw technical performance and more on whether it can be delivered equitably and sustainably within existing extension systems rather than alongside them.

Conclusion and recommendations

Climate-smart entomology extension now draws on a diverse toolkit spanning mobile advisories, remote sensing, AI-based forecasting, biological control, resilient varieties, blended CSA packages, and transboundary early-warning networks. The evidence reviewed here suggests that digital and remote-sensing tools amplify rather than replace the value of human extension contact, with the strongest documented outcomes arising from programmes that combine technology with in-person training and locally calibrated advice. Evidence also shows that access to these tools is uneven along gender and socio-economic lines, meaning that technical performance alone does not determine a tool's real-world impact.

For practitioners and policymakers, this points toward five priorities: (1) investing in extension-workforce capacity, including gender-diverse staffing, to interpret and localize AI- and sensor-derived pest information; (2) designing digital tools around low-connectivity, low-literacy contexts rather than assuming smartphone-level access; (3) building longer-term monitoring and evaluation into climate-smart pest management programmes so that reported gains in yield, adoption, and food security can be compared across contexts on a consistent basis; (4) strengthening cross-border data-sharing arrangements for migratory pests, building on models such as FAMEWS; and (5) explicitly budgeting for the recurring costs of digital and remote-sensing infrastructure beyond the lifespan of individual donor-funded projects, so that gains documented during pilot phases are not lost once external funding ends.

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