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From Pest Identification to Management Decisions: Evidence and Priorities for Monitoring Banana Arthropod Pests

Jhih-Rong Liao*

Taiwan Banana Research Institute, Pingtung, Taiwan
Department of Biological Sciences, Tokyo Metropolitan University, Hachioji, Tokyo, Japan
* Corresponding author. Email: jrliao1378@mail.banana.org.tw

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ABSTRACT

Effective monitoring of banana arthropod pests depends on knowing what a field signal represents and whether it supports action. This review evaluates evidence linking identification, measurement, repeated monitoring, and management decisions for banana weevils, thrips, spider mites, and the banana aphid, with additional coverage of lepidopteran defoliators and other sap feeders. Direct banana studies support acoustic larval detection, relationships between thrips abundance and fruit injury, repeated pest surveys, spectral screening, and standardized corm-injury assessment. Lepidopteran trials also provide field comparisons of biological and chemical control. Recent aphid research shows why trap captures and plant counts require separate interpretation. These measurements provide a basis for surveillance, while their links to marketable loss, virus transmission, and management outcomes need further development. Methods from other crops offer transferable equipment and procedures, with biological calibration required for local species and production conditions. Direct-injury pests require economic injury levels and economic thresholds; vectors and quarantine pests require criteria based on infection, transmission, or spread risk. For Taiwan, four priorities are thrips counts linked to fruit injury, pseudostem-weevil acoustics, mite counts combined with spectral screening, and spatial surveillance of aphids and Banana bunchy top virus. A shared three-stage sequence connects voucher-based identification and paired reference observations, independent validation across farms and seasons, and prospective comparison of an action rule with current practice. Sampling should represent southern, central, and eastern production regions, nurseries and production fields, and contrasting management and weather conditions. Operational readiness requires acceptable missed-detection rates and demonstrated gains in warning time, inspection effort, injury, or infection control.

Key words: banana, arthropod pest, pest identification, population monitoring, action threshold

Introduction

Field observations are useful for pest management only when their biological source and management relevance are known. Plant damage, a trapped insect, an internal sound, and a positive molecular assay represent different types of evidence. Identification establishes the organism and life stage; sampling defines what is measured and with what effort; repeated measurements show whether abundance, activity, injury, or transmission risk is changing. Management decisions should be based on this linked evidence rather than on detection alone.

The economic injury level (EIL) and economic threshold (ET) are the classical decision tools for direct-injury pests. The EIL is the lowest pest density at which the expected economic loss equals the cost of control. The ET is the density or injury indicator at which control is initiated to prevent the population from reaching the EIL (Stern *et al*., 1959; Pedigo *et al*., 1986; Onstad, 1987). The distinction is important. The EIL defines an economic boundary, whereas the ET also allows time for confirmation and intervention. Both require a demonstrated relationship among pest density, injury, yield or quality loss, control efficacy, and production cost. A sensor reading or trap catch has no threshold value on its own.

Banana arthropod pests differ in where they occur and what can be observed, so no single monitoring unit suits all groups. Larvae of the banana pseudostem weevil, *Odoiporus longicollis*, and banana weevil, *Cosmopolites sordidus*, feed within the pseudostem and corm, respectively (Gold *et al*., 2001; Borah *et al*., 2020). External signs may appear after feeding has begun, while adult trap catches combine local abundance with movement and attraction (Gold *et al*., 2001; Delaplace *et al*., 2024). Banana-infesting thrips occupy different plant strata and reproductive tissues, whereas spider-mite eggs and mobile stages require close examination of leaf undersides (Carval *et al*., 2015; Manrique-Silupú *et al*., 2021; Singh *et al*., 2024; Topakcı, 2026). Lepidopteran larvae also produce visible injury: *Spodoptera litura* damages young banana plants, and *Erionota torus* feeds within rolled leaves (Tsai *et al*., 1990; Chiang and Hwang, 1991; Chen and Chao, 2008). The banana aphid, *Pentalonia nigronervosa*, is managed chiefly because it transmits Banana bunchy top virus (BBTV), rather than because of direct feeding injury (Anhalt and Almeida, 2008; Hooks *et al*., 2011). Detection therefore has different biological and management meanings among these pests.

Direct banana studies have established several measurable signals and sampling designs. Acoustic recordings detected *Cosmopolites sordidus* larval activity (Vinatier and Vinatier, 2013). Counts of *Elixothrips brevisetis* on banana plants were related to fruit injury, weather-based models described thrips incidence, and long-term surveillance identified recurrent periods of rusty thrips damage (Carval *et al*., 2015; Manrique-Silupú *et al*., 2021; Campos *et al*., 2022; Singh *et al*., 2024). A two-year greenhouse survey used visual inspection, sticky traps, and plant sampling to describe banana pest densities (Topakcı, 2026). Spectroscopy distinguished mite-infested from uninfested plants, unmanned aerial vehicle (UAV) imagery enabled repeated tracking of individual plants and field-anomaly mapping, and digital image analysis made destructive corm-damage assessment more repeatable (Aeberli *et al*., 2022, 2023; Choosumrong *et al*., 2023; Mwanje *et al*., 2026). These studies provide useful measurements, but the reviewed banana literature rarely links them to marketable loss, virus transmission, or a prospectively tested management rule.

Studies in other crops describe or evaluate procedures for insect imaging, camera-equipped traps, DNA-based identification, environmental DNA (eDNA), acoustic detection, spectral and thermal sensing, and continuous field recording (Preti *et al*., 2021; van Klink *et al*., 2022; Cavazzoni *et al*., 2025; De Cesaro Júnior *et al*., 2026). Camera geometry, illumination, sensor placement, primer development, time-series evaluation, and device maintenance can be adopted or adapted. Species labels, within-plant distribution, trap attractiveness, acoustic signatures, spectral responses, relationships between assay output and living abundance, and action criteria still need to be measured in the target pest and production system.

Liao (2025) reviewed computational models and sensing platforms for banana pest and

disease management at the broader crop-health level. Here, the focus is the entomological evidence required to move from detection and identification to a valid field measurement and, ultimately, a management decision. Specifically, this review (1) distinguishes identification, sampling, monitoring, forecasting, EIL, ET, and other action criteria; (2) evaluates direct evidence for major banana arthropod pests; (3) examines which methods from other crops can be transferred and which biological relationships must be re-established; (4) defines the validation needed between a sensor output and a management rule; and (5) identifies priorities for Taiwanese banana production.

Review scope and decision framework

This narrative review was initially based on literature available up to 23 July 2026 and was supplemented by targeted searches through 11 October 2026. Searches covered banana arthropod identification, sampling, trapping, monitoring, forecasting, and action thresholds, using banana or *Musa* and the four core pest groups as initial terms. Supplementary searches included Lepidoptera, *Spodoptera*, *Erionota*, *Chrysodeixis*, defoliation, mealybugs, scale insects, whiteflies, natural enemies, and surveillance guidance. Searches for transferable methods added imaging, molecular assays and eDNA, acoustic and vibration sensing, spectral and thermal sensing, UAVs, environmental time series, and decision support. Relevant publications were also identified from cited references. Authors, titles, sources, and years were checked against journal, DOI, or originating institutional records. Institutional guides were retained for survey procedures and implementation context and were distinguished from experimental evidence of monitoring performance or management benefit. Unresolved bibliographic conflicts, conference abstracts without a full paper, and unconfirmed forthcoming articles were excluded. The aim was a critical narrative synthesis, not a systematic or bibliometric census.

The four core groups represent different monitoring problems in banana production: concealed borers, small insects that damage flowers or young fruit, leaf-surface colonizers, and a virus vector. Lepidopteran defoliators and other sap feeders extend the comparison to nursery injury, leaf-area loss, and the role of natural enemies. Broader inventories document substantially more taxa: Krishnan *et al*. (2020) compiled 93 pest species and 25 non-pest species associated with *Musa* in the Indo-Pacific region, while Topakcı (2026) surveyed pest composition and natural enemies in greenhouse banana. These inventories establish the breadth of the fauna; the examples here were selected to compare measurement and decision problems. Evidence was grouped into four types—direct evidence involved banana and a specified arthropod, injury class, or monitoring setting. Biological analogs involved another species with a similar size, habitat, feeding site, or vector role. Platform evidence came from another crop or pest but used a comparable sensor, trap, assay, or longitudinal design. Conceptual sources provided definitions and decision theory. Transfer to banana requires testing the target organism, sampling unit, and management endpoint.

This review distinguishes six functions because they answer different questions. Identification assigns a specimen or signal to a taxon, life stage, or vector class. Detection establishes presence within a defined sample and detection limit. Counting quantifies organisms, activity, or injury under a stated sampling effort. Monitoring repeats the measurement through time or space. Forecasting estimates future abundance, injury, infection risk, or threshold crossing. Decision support links the result to a specified field response. A count from one image remains an image-level value until sampling effort and its relationship to field abundance are established. Likewise, identity does not establish abundance, and environmental risk does not establish pest presence. Table 1 lists the evidence and performance measures required for each function.

Figure 1 links the identity-to-decision chain to three shared validation stages: local calibration, independent field validation, and prospective evaluation of the management rule. Misidentification assigns the wrong injury mechanism, biased sampling gives unrepresentative counts, trap capture can reflect device response rather than population

Table 1. Functions, evidence, and validation endpoints in the identity-to-decision chain

Stage	Purpose	Required evidence and measures	Valid output and common misinterpretation
Identification	Assign organism, life stage, or vector class	Voucher or diagnostic characters; blinded morphological identification or validated molecular confirmation; cross-reaction testing	Verified identity; do not report a group-level label as species identity
Detection	Establish target presence in a defined sample	Sensitivity by abundance; specificity; detection limit; field blanks or negative controls; false alerts	Presence or absence with uncertainty; overall accuracy does not describe early-detection performance
Counting	Quantify targets, activity, or injury per sampling unit	Defined unit and effort; expert or destructive reference; mean absolute error; bias; agreement by density	Count, catch, activity, or injury estimate; correlation alone does not show count agreement
Monitoring	Measure change across time or space	Repeated standardized sampling; device uptime and missing intervals; complete farm-season test units; production-region and team evaluation	Abundance, distribution, or trend; random splits within one field do not show transfer to new fields
Forecasting	Estimate future risk or criterion crossing	Held-out farm, season, or year; calibration; lead time; threshold-crossing sensitivity; false alerts	Risk or expected time to criterion crossing; retrospective classification is not forecasting
Decision support	Specify and evaluate the field response	Prespecified rule and response time; prospective comparison with current practice; marketable loss or infection, labor, cost, and benefit	Confirm, scout, contain, remove, or treat; a functioning dashboard does not by itself improve management

change (Preti *et al*., 2021; Rydhmer *et al*., 2022), and canopy stress can have several causes (Aeberli *et al*., 2022; Choosumrong *et al*., 2023). Each stage therefore has a reference observation, a performance requirement, and an explicit progression condition. The same sequence applies across pest groups, with the final endpoint determined by direct injury or transmission and spread risk.

Direct-injury pests and vectors require different interpretations. A threshold for a direct-injury pest must relate pest density to injury, marketable loss, control efficacy, and cost (Stern *et al*., 1959; Pedigo *et al*., 1986; Onstad, 1987). For *Pentalonia nigronervosa*, feeding density alone does not describe transmission risk because vector life stage, acquisition and inoculation conditions, movement, and the distribution of infected hosts also affect epidemic development (Madden *et al*., 2000; Anhalt and Almeida, 2008). The low aphid thresholds developed for potato leafroll virus illustrate this epidemiological basis for action (Mowry, 2001).

Figure 2 evaluates evidence on two

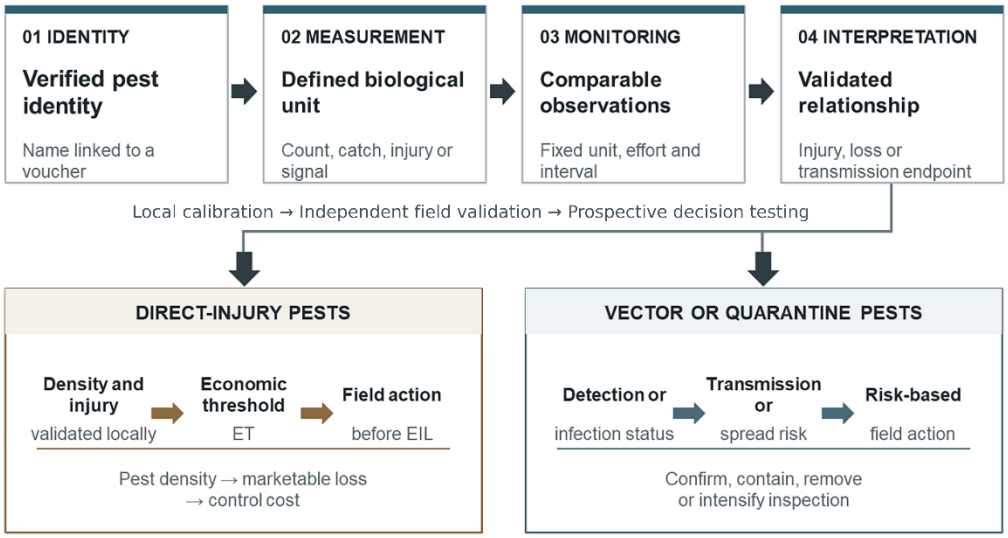


Fig. 1. Identity-to-decision chain and shared validation sequence for banana arthropod monitoring and management. Identification, measurement, monitoring, and interpretation support two action pathways. The central annotation summarizes local calibration of identity, sampling units, and paired reference measurements; independent validation across farms, production settings, and seasons; and prospective testing of an action rule against current practice. Prespecified performance criteria determine progression between stages. Direct-injury pests require locally validated injury-loss relationships and thresholds; vectors and quarantine pests use infection, transmission, or spread-risk criteria. ET, economic threshold; EIL, economic injury level.

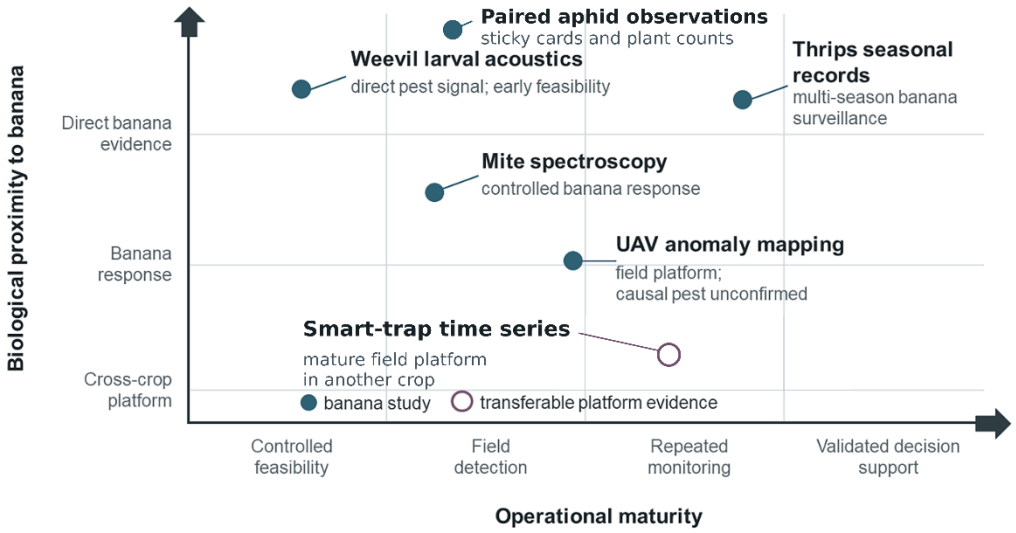


Fig. 2. Evidence map for banana arthropod monitoring. Biological proximity ranges from cross-crop platform evidence to banana plant-response evidence and direct banana-pest evidence. Operational maturity ranges from controlled feasibility to field detection, repeated monitoring, and prospectively validated decision support. Examples include weevil larval acoustics (Vinatier and Vinatier, 2013), mite spectroscopy (Aeberli *et al.*, 2022), UAV anomaly mapping (Choosumrong *et al.*, 2023), multi-season thrips surveillance (Singh *et al.*, 2024), paired aphid trapping and plant observations (Ogwal *et al.*, 2026), and smart-trap time series in mango (Rustia *et al.*, 2023). Filled circles denote banana studies; the open circle denotes another-crop platform. Positions are qualitative. Repeated monitoring alone does not establish management benefit.

independent axes: biological proximity to banana and operational maturity. Acoustic detection of banana-weevil larvae is direct evidence from banana but remains an early feasibility study (Vinatier and Vinatier, 2013). By contrast, a multi-year camera-trap network

in mango is operationally more mature but remains platform evidence for banana (Rustia *et al*., 2023). The two axes prevent technical maturity in another crop from being mistaken for biological validation in banana.

Pest-specific measurement pathways and direct evidence in banana

The four core groups and the additional pest examples require different sampling units and management endpoints (Table 2). Figure 3 illustrates four field observations: an aphid colony counted on a plant, a yellow water pan used as a candidate index of alate activity, pseudostem surface injury that still requires causal confirmation, and corm dissection exposing larvae and internal feeding injury. Stating both the observation unit and the basis for pest attribution is essential before these records are interpreted as abundance, activity, or injury.

Pseudostem and corm weevils. *Odoiporus longicollis* larvae develop mainly within the pseudostem, and their seasonal occurrence varies among banana cultivars (Borah *et al*., 2020). *Cosmopolites sordidus* larvae damage the corm, while adults are commonly sampled with pseudostem or pheromone traps (Gold *et al*., 2001). External holes and frass indicate possible infestation, whereas dissection of the pseudostem or corm provides direct evidence of larvae and internal feeding loss. For *C. sordidus*, corm damage has been associated with production effects. In a three-year Ugandan field study, plants in the highest damage class produced bunches that were 40 to 55% smaller, and plot-level yield loss was 14 to 20% (Rukazambuga *et al*., 2002).

Adult-trap catch reflects movement, attraction, and local abundance. Intensive pseudostem trapping reduced corm damage after one year, but population responses differed among 27 farms and were not significant overall (Gold *et al*., 2002). Increasing pheromone-trap density from four to eight traps per hectare likewise produced low catches and no consistent reduction in population or plant damage in a 42-farm trial (Tinzaara *et al*., 2005). Placement, aggregation, field management, lure response, and weather also affect capture (Rhino *et al*., 2010; Maldonado *et al*., 2016; Delaplace *et al*., 2024). Until local calibration is available, results should be reported as weevils per trap per exposure period rather than as field density.

Acoustic sensing is intended to detect concealed larvae before dissection or obvious external damage. Vinatier and Vinatier (2013) detected *C. sordidus* larvae from internal sound without opening the plant. Field validation now requires blinded comparison of infested and uninfested plants, followed by dissection to record larval number, stage, depth, and tissue condition. Rain, wind, and the interval between acoustic detection and visible symptoms should also be measured. In a separate study, image analysis of 370 cut corms improved the repeatability of *C. sordidus* damage assessment for resistance phenotyping, but still required destructive sampling (Mwanje *et al*., 2026). Acoustics and corm imaging therefore address different tasks: early detection and standardized injury assessment, respectively.

Thrips. Counts from a defined plant stratum, flower, young fruit, or bunch describe local colonization; sticky-card captures describe flight and trap response; and fruit scars describe accumulated fruit injury. Whether that injury becomes marketable loss depends on grading and price (Pedigo *et al*., 1986). A calibration study should collect these measurements on the same dates. Trap exposure, crop stage, bagging, weather, and species composition should also be recorded because they can change both captures and injury.

The direct banana literature provides some evidence linking thrips abundance to injury, but not a complete economic threshold. In Martinique, *Elixothrips brevisetis* abundance was measured on suckers, mother plants, and bunches. Covered bunches had 98% fewer thrips than uncovered bunches, and fruit damage increased linearly with the number of thrips present during the second to fourth week after flowering (Carval *et al*., 2015). In Peruvian organic banana, Manrique-Silupú *et al*. (2021) modeled manually classified thrips incidence from atmospheric variables, and Campos *et al*. (2022) combined field observations with expert rules. Ten seasons of surveillance in India identified a recurrent period of rusty thrips damage (Singh *et al*., 2024). These studies identify useful sampling periods and show that

Table 2. Pest-specific measurements, evidence gaps, and priority endpoints for Taiwanese banana production, including complementary defoliator and sap-feeder pathways

Pest group	Primary field unit or signal	Evidence in banana systems	Main uncertainty	Priority endpoint for Taiwan
Pseudostem and corm weevils	Pseudostem or corm dissection; adult catch per trap per exposure period; internal sound; tissue injury	Injury-yield relation; mixed trapping outcomes; non-destructive larval acoustic detection; repeatable digital corm injury	Adult catch versus density or injury; field sensitivity of acoustics; transfer from *C. sordidus* to *O. longicollis*	Earlier inspection or sanitation; validated activity or injury unit; locally tested ET where feasible
Thrips	Plant-stratum or bunch count; sticky-card catch; fruit scarring	Within-plant abundance and fruit-injury relation; environmental incidence models; expert rules; ten-season timing of damage	Local species composition; relation among sticky-trap catch, plant infestation, injury, marketable loss, control cost, and efficacy	Verified complete-trap counts paired with plant counts and fruit injury; prospective injury-based ET
Spider mites	Eggs and mobile stages per defined leaf area; injury score; spectral hotspot	Two-year greenhouse density survey; controlled spectral discrimination of mite-infested banana; individual-plant UAV tracking; field anomaly mapping	Species specificity; relation between spectral response, mite density, and competing stresses	Leaf-underside count agreement; hotspot sensitivity; reduction in inspection area
Banana aphid and BBTV	Direct plant-site count; wing morph; separately calibrated sticky-card or water-pan catch; BBTV and spatial records	Plant-stage and within-plant sampling; transmission biology; short-term sticky-card/plant comparison; linked image and molecular diagnostics	Water-pan calibration; arrival versus colony density; viruliferous status; infection latency; regional transfer and management benefit	Earlier confirmation and infected-plant removal; lower secondary infection; prospectively tested risk criterion
Lepidopteran defoliators	*S. litura* egg masses and larvae per seedling; *E. torus* occupied leaf rolls; fresh defoliation; adult catches	Taiwan nursery record; skipper surveys and barcodes; natural enemies; Canary Island biocontrol comparison	Adult catch versus larval injury; occupied versus abandoned rolls; plant-stage effects; natural-enemy mortality	Nursery survival and planting quality; functional leaf area and bunch performance; locally calibrated injury criterion
Other sap feeders	Live mealybugs or scales per plant site; whitefly nymphs per leaf area; parasitism and injury	Broader pest inventories; farm and greenhouse surveys with natural enemies; experimental mealybug virus transmission	Local importance and injury-loss relation; biological-control effects; pathogen occurrence and vector competence	Standardized pest and natural-enemy counts; intervention effects; separate direct-injury or confirmed vector-risk criteria



Fig. 3. Four banana-pest field observations with different measurement units. (A) A banana aphid colony on young tissue, suitable for direct plant counts and records of within-plant colonization. (B) A yellow water pan used as a candidate index of alate flight or arrival. Its performance requires independent calibration; results from yellow sticky cards do not validate water pans. (C) Pseudostem surface injury. Attribution to a weevil requires dissection or recovery and identification of the insect. (D) Corm dissection revealing banana corm weevil (*Cosmopolites sordidus*) larvae and internal feeding injury.

plant counts can relate to fruit injury. They do not provide the marketable-loss, control-cost, and efficacy estimates needed for an economic threshold in Taiwan.

The density-injury relationship required for a threshold has been quantified in other crops. In greenhouse cucumber, Shipp *et al*. (2000) related western flower thrips counts to fruit injury, yield, control cost, and EILs; Wang and Shipp (2001) then developed sequential sampling plans using the same biological units. In greenhouse pepper, flower counts and four-day yellow-sticky-card catches predicted fruit scarring and supported economic thresholds (Park *et al*., 2007). Banana research can adopt this paired design, but not the numerical thresholds. Voucher specimens and periodic molecular checks are also needed when damaged or mixed thrips cannot be identified morphologically (Brunner *et al*., 2002; Sánchez-Luna *et al*., 2024; Boonmee *et al*., 2025; Zeira *et al*., 2026).

Spider mites. Because eggs and mobile stages occur mainly on leaf undersides, counts should refer to a defined leaf area, leaf position, and life stage. A two-year greenhouse study sampled banana pests every 15 days. Spider mites were the most abundant pest group, but the study reported pest densities rather than a density-injury or action threshold (Topakcı, 2026). Automated microscopy may reduce counting effort, but researchers must first test its bias across banana leaf backgrounds and mite-density classes (Wiseman *et al*., 2025). Slide-mounted morphology or a validated molecular assay is still needed when species identity affects interpretation. Existing *Tetranychus* assays also show why local sequence variation and cross-reaction among related species must be tested (Chen *et al*., 2020; Matsuda *et al*., 2025).

Spectral and UAV measurements primarily record plant response, not the mite itself. Aeberli *et al*. (2022) distinguished mite-infested from uninfested banana plants spectrally under controlled conditions, but did not establish field specificity or a mite-density threshold. Aeberli *et al*. (2023) showed that individual banana plants

could be followed through repeated UAV surveys, and Choosumrong *et al*. (2023) mapped multi-spectral anomalies in banana fields. In field use, these signals should first rank plants for inspection. Leaf-underside counts and records of leaf age, water status, nutrition, and disease should be collected on the same day. The relevant test is whether hotspot screening reduces the area inspected without missing infestations of management concern.

Lepidopteran defoliators. *Spodoptera litura* and *Erionota torus* add two distinct monitoring problems relevant to Taiwan. The Taiwanese banana-protection guide records *S. litura* injury to young plants, making nurseries and the establishment period relevant surveillance settings (Chen and Chao, 2008). Useful candidate units are egg masses, larvae by instar, and fresh leaf-area loss per seedling or plant. Counts should relate to survival, growth, and planting suitability because the consequences of defoliation change with plant stage. The guide establishes local pest relevance, but does not provide a validated density-injury function for banana seedlings. *Spodoptera litura* pheromone trapping provides a technical starting point for repeated adult monitoring. Kawakita and Sato (2023) tested camera-equipped traps in two Japanese soybean fields; images were transmitted daily and visually counted, revealing changes that were less apparent in five-day conventional observations. It is same-species platform evidence from another crop. Male moth catches need to be paired with egg deposition, larval infestation, and subsequent banana injury before they can support a nursery action rule. Record lure replacement, exposure, nearby host crops, and trap saturation along with the counts.

Erionota torus larvae feed within leaf rolls, so that an occupied roll can be used as a sampling unit only after the occupant and life stage have been confirmed. Taiwanese studies documented establishment, distribution, seasonal occurrence, and natural enemies (Tsai *et al*., 1990; Chiang and Hwang, 1991). The earlier survey reported seasonal peaks in March-May and October-November, providing hypotheses for contemporary sampling rather than fixed calendar rules (Tsai *et al*., 1990). A recent barcode study includes Taiwanese populations and provides reference information for identification and invasion surveillance (Cock *et al*., 2025). Field assessment should distinguish occupied rolls, feeding larvae, parasitized stages, and abandoned rolls and should pair them with remaining functional leaf area, plant stage, and subsequent growth or bunch performance. These units connect defoliator monitoring with biological control and injury assessment.

Another direct banana example is *Chrysodeixis chalcites* in the Canary Islands. Dionisio and Calvo (2022) compared *Trichogramma achaeae* releases with conventional chemical control in randomized pairs of commercial banana greenhouses over two seasons. Repeated egg and larval counts, parasitism, leaf and fruit injury, and pesticide use were recorded. The study connects standardized observations with a field comparison of management strategies. Its species, production environment, and operational criteria differ from those in Taiwan; local injury relationships and action rules require separate validation.

Banana aphids and BBTV. Field studies indicate where to count aphids on the plant. *Pentalonia nigronervosa* occurred most often near the plant base and the newest unfurled leaf, supporting binomial presence-absence sampling (Robson *et al*., 2006). Surveys of Hawaiian banana mats later found the largest populations on suckers no taller than 1.5 m and few aphids in the upper canopy (Hooks *et al*., 2011). Recent Ugandan observations also found more aphids in concealed sites, including leaf sheaths and lower or middle pseudostem sections (Ogwal *et al*., 2026). Aphid density differs among *Musa* genotypes, and BBTV acquisition can reverse the vector's preference for infected and healthy plants (Ngatat *et al*., 2022; Murhububa *et al*., 2024). Plant stage, within-plant position, wing morph, and infection status should therefore accompany each count.

Yellow sticky cards and yellow water pans sample alate activity and require separate calibration. In a short study in two Ugandan banana fields, sticky-card captures were not significantly associated with aphid counts on the nearest plant (Ogwal *et al*., 2026). This finding cautions against treating flight captures as a

proxy for colony density; it does not establish water pans' performance. A six-year potato study likewise found that yellow-water catches, suction-trap catches, and plant recruitment could diverge (Kocourek *et al*., 2025). No banana water-pan study establishing a catch-colonization or transmission relationship was located. A Taiwan trial should pair each trap interval with species confirmation, direct counts on selected suckers, nearby BBTV assays, weather, and subsequent infection records.

For BBTV management, the relevant outcome is interrupting transmission rather than preventing feeding loss. Temperature, vector life stage, and plant access period alter transmission efficiency (Anhalt and Almeida, 2008); acquisition, inoculation, vector movement, latency, and the distribution of infected hosts also affect epidemic development (Madden *et al*., 2000). Suitable endpoints include first confirmed alate arrival, viruliferous status, distance from an infected plant, time to plant removal, and the number of secondary cases. Aphid density alone cannot define the action rule. Evaluate surveillance by whether it shortens confirmation and removal and reduces new infections.

Linked plant and diagnostic records can connect vector surveillance with infection confirmation. Ouedraogo *et al*. (2026) combined mobile-image screening, loop-mediated isothermal amplification (LAMP) testing of field-collected banana tissues, and sample identifiers linking phenotypic and molecular records. The study compared LAMP with PCR and real-time PCR, providing a banana-specific example of a screening-to-confirmation workflow. Regional and seasonal transfer, detection of low-prevalence infection, and the effect of surveillance on transmission remain additional validation tasks. IPPC field-survey guidance and a recent banana bunchy top disease (BBTD) management manual provide complementary procedures for sampling, diagnosis, infected-plant removal, vector management, and healthy planting material (IPPC Secretariat, 2025; Omondi *et al*., 2026). These documents support implementation but do not provide a locally validated aphid-density threshold.

Other sap feeders and natural enemies. Mealybugs, scale insects, and whiteflies are represented in broader banana-pest inventories (Krishnan *et al*., 2020). Their monitoring should use a defined leaf, leaf area, fruit surface, or other occupied plant site, with separate records for live pests, injury, and natural enemies. In Costa Rican banana plantations, a study across ten farms followed spiralling whitefly, *Aleurodicus dispersus*, and parasitized nymphs for a year and also evaluated management effects on natural enemies (Blanco-Metzler *et al*., 2018). It provides direct evidence from banana sampling of pests and parasitoids together. A greenhouse banana survey likewise recorded pest composition and natural enemies, extending surveillance beyond the four core groups (Topakcı, 2026).

Some sap feeders also require a vector-risk pathway. *Dysmicoccus brevipes*, *Planococcus citri*, and *P. ficus* transmitted episomal Banana streak OL virus in experimental banana transmission tests (Meyer *et al*., 2008). Such results establish vector competence under the tested conditions; local pathogen occurrence, vector identity, and infection status determine their relevance to Taiwanese surveillance. Counts of natural enemies, parasitism, and recent management should therefore accompany sap-feeder records, while direct injury and confirmed vector risk retain separate action criteria.

The expanded evidence provides complementary parts of the measurement-to-decision chain. Pest inventories establish scope, sampling studies define observation units, and biological-control studies describe natural-enemy and management effects. Sensor-assisted decisions additionally require calibration against abundance or injury, independent validation across farms and seasons, estimation of injury or transmission relationships, and prospective comparison of the proposed rule with current practice (Table 2). The distinction is between evidence that a measurement works and evidence that acting on it improves management.

Transferable approaches from other crops and pest systems

1. Organism identification and standardized counting

Taxonomic identification should remain anchored to a retained specimen. Imaging can increase throughput when magnification, illumination, background, orientation, and field of view are standardized. Camera traps can also extend observation beyond manual survey periods, but the image labels still require expert-identified specimens and a defined sampling design (Høye *et al*., 2021; Bjerge *et al*., 2023, 2024). Sticky-trap imaging provides the closest platform evidence for automated surveillance of thrips and alate aphids. Kalfas *et al*. (2023) analyzed 731 field-exposed plates containing 74,616 annotations and evaluated complete unseen plates rather than randomly separated image crops. Other systems have automated detection, localization, and counting of small insects on sticky cards under greenhouse or outdoor conditions (Böckmann *et al*., 2021; Li *et al*., 2022; Ciampi *et al*., 2023; Rustia *et al*., 2023; Fotouhi *et al*., 2024; He *et al*., 2025; Okole *et al*., 2026). Species-level classification and long-exposure counting are technically possible, but performance changes with trap color, device, overlap, debris, and image source (Fujisawa *et al*., 2023; Laekeman *et al*., 2025; Ong and Høye, 2025; Ueki *et al*., 2026). Evaluation in banana should therefore use complete traps from several density classes and report count bias, absolute error, and false species assignments.

Molecular methods are useful when damaged specimens, immature stages, or cryptic species cannot be resolved from images. DNA barcoding provides a general identification framework, while thrips keys, *Tetranychus* assays, microarrays, and metabarcoding offer more targeted or higher-throughput options (Brunner *et al*., 2002; Hebert *et al*., 2003; Chen *et al*., 2020; Boonmee *et al*., 2025; Matsuda *et al*., 2025; Zeira *et al*., 2026). A local reference library should link morphology and sequence from the same voucher whenever possible and retain the specimen, collection record, image, and sequence accession.

Environmental DNA can detect arthropod material on plant surfaces, in flowers, in air, or in trap residue. Whitefly and spider-mite DNA has been recovered from greenhouse tomato plants, and studies comparing flower eDNA, video, and airborne DNA have detected partly different components of arthropod occurrence (Roger *et al*., 2022; Kestel *et al*., 2024; Lee-Rodriguez *et al*., 2024; Mikko *et al*., 2025; Zeira *et al*., 2026). DNA quantity is affected by shedding, transport, degradation, inhibition, and contamination, so it cannot be interpreted as living abundance without calibration. Initial banana applications should be limited to detection or taxonomic confirmation and should include field blanks, retained specimens, and direct plant inspection.

2. Concealed activity and plant-response sensing

Feeding and movement by concealed insects generate substrate-borne sounds and vibrations that can be recorded through plant tissue. Studies in soil, stems, trunks, and stored products have described both biological signals and common noise sources (Mankin *et al*., 2000, 2011, 2021). Red palm weevil studies have included probe recordings, field classifiers, and optical-fiber distributed sensing (Hetzroni *et al*., 2016; Ashry *et al*., 2022; Boulila *et al*., 2023; Saranya and Martin, 2025). Thermal imaging has also been tested for palm-weevil infestation, although a thermal anomaly cannot identify the causal organism without independent confirmation (Martin *et al*., 2026). Banana trials should pair blinded recordings with dissection and test larval number, species, depth, pseudostem structure, wind, rain, irrigation, and other borers. The primary outcome is the gain in detection time over visible symptoms or routine inspection.

Spectral, thermal, and UAV systems generally measure plant response because mites, thrips, and aphids are below the practical resolution of routine aerial imagery. Cross-crop studies have detected spider-mite injury in pepper, bean, and cucumber, as well as spectral changes associated with leafminers, stem borers, and aphid infestation classes (Herrmann *et al*., 2017; Nguyen and Nansen, 2020; Wan *et al*., 2022; Mandrapa *et al*., 2024; Skendžić *et al*., 2025). These methods may identify plants that need inspection, but they do not establish pest identity in bananas. Each spectral or thermal acquisition in banana should therefore be paired with same-day arthropod counts and records of life stage, injury, crop stage, leaf age, water status, nutrition, and disease. A model trained only to separate healthy and visibly stressed

plants should be described as an anomaly screen. Its field value can be measured as warning lead time, sensitivity for confirmed infestations at a prespecified hotspot area, and labor saved during ground inspection.

3. Longitudinal monitoring and forecasting

Continuous imaging, acoustic recording, and environmental sensors can fill the intervals between manual surveys, but only if the observation unit and recording effort remain explicit. Each record should include date, time, location, plant or trap identity, exposure or recording effort, device settings, crop stage, recent management, and the corresponding reference count. Device downtime and missing intervals should be reported as part of the time series. Weather variables improve inference only when paired with observed abundance or injury. Direct banana thrips studies used atmospheric records with field incidence, and a tropical mango network demonstrated more than two years of outdoor imaging (Manrique-Silupú *et al*., 2021; Campos *et al*., 2022; Rustia *et al*., 2023). Rydhmer *et al*. (2022) recorded many more insect events with near-infrared flight sensors than with water traps, but the devices agreed only moderately. The measurements represented related components of activity rather than interchangeable counts.

The validity of a time series depends on the sampling unit. The best unit for aphids and thrips varies with crop, pest, and plant stratum (Tomaz *et al*., 2026). Banana studies have identified preferred aphid locations, and the aggregated distribution of *C. sordidus* affects sample numbers and placement (Robson *et al*., 2006; Hooks *et al*., 2011; Maldonado *et al*., 2016). Candidate sampling units should therefore be compared in a pilot study before developing an automated time series. Forecast models should be evaluated on a complete farm, season, year, or device that was not used for development. Randomly splitting records from one season can place nearly identical weather, background, and management conditions in both datasets. Calibration, sensitivity to a future threshold crossing, false-alert rate, warning lead time, and missing-data rate are more informative than retrospective classification accuracy (Kalfas *et al*., 2023; Fotouhi *et al*., 2024; De Cesaro Júnior *et al*., 2026). Table 3 distinguishes transferable technical components from relationships that must be rebuilt for banana.

From monitoring measurements to action thresholds

1. Direct-injury pests: EIL and ET

For direct-injury pests, an EIL requires estimates of injury per pest, crop loss per unit injury, crop value, control cost, and control efficacy (Pedigo *et al*., 1986). The ET must allow enough time to confirm the problem and apply control before the EIL is reached (Onstad, 1987). Both values must use a locally defined biological unit, such as mites per leaf area, thrips per flower, damaged fruit per bunch, or corm tissue consumed. Species and life stage affect injury and control response. A shared threshold for several species therefore needs an equivalence function. Huang *et al*. (2013) quantified injury equivalence among three rice planthoppers in Taiwan before deriving a common threshold. A pooled banana thrips or mite class can serve as a screening alert, but treatment decisions require evidence that its members produce comparable injury or retained specimens for confirmation.

Threshold development requires a sequence of linked studies: define the sampling unit, calibrate a sensor or trap against a reference count, relate pest density to injury and injury to marketable loss, and then incorporate crop value, control cost, and efficacy. Studies of thrips in cucumber and pepper follow this sequence, linking flower or trap counts to fruit injury and economic thresholds (Shipp *et al*., 2000; Wang and Shipp, 2001; Park *et al*., 2007). Any ET developed for banana should then be compared prospectively with current practice. Trap catches need separate calibration because adult movement, lure strength, color, height, weather, and vegetation affect capture. Inconsistent population and damage responses in banana-weevil trials show why catch must be paired with direct counts or subsequent injury over a defined interval (Gold *et al*., 2002; Tinzaara *et al*., 2005). Sequential sampling becomes defensible only after estimating pest aggregation and a compatible decision boundary (Maldonado *et al*., 2016).

Table 3. Transferable technical components and banana-specific validation requirements

Pathway	Transferable components	Information requiring local reconstruction	Banana validation endpoint
Trap imaging	Camera geometry, illumination, small-object annotation, exposure and device monitoring	Target classes, trap response and density range; field background; sex or life-stage bias; catch versus plant infestation	Complete-trap count bias and low-density sensitivity; retained specimens; paired plant and injury observations; egg and larval checks for moth traps
Molecular identification and eDNA	Voucher workflow, primer design, blanks, sequencing, contamination control	Local sequence variation, primer specificity, DNA persistence, relation to living abundance	Morphology-sequence agreement; cross-reaction; inhibition; field blanks; paired direct survey
Acoustic and vibration sensing	Sensor coupling, repeated recording, event extraction, noise library	Species signal, larval-number relation, tissue transmission, activity period	Paired dissection; stage and depth; other borers; wind and rain; blinded plants; warning lead time
Spectral, thermal, and UAV sensing	Calibration, individual-plant mapping, hotspot ranking	Pest specificity, density and injury relation, competing stress response	Same-day arthropod counts; water, nutrition, leaf age, and disease controls; hotspot sensitivity
Environmental time series	Continuous logging, metadata, missing-data handling, remote diagnostics	Pest-weather relation, crop-stage effect, management effect, local action rule	Multi-region and multi-season paired records; complete farm-season test units; calibrated warning time; prospective rule comparison

2. Vector and quarantine pests: risk-based action criteria

For vectors and quarantine pests, action may be justified before a classical EIL is reached. In the BBTV system, secondary spread depends on virus acquisition and inoculation, aphid life stage, temperature, host access, movement, and the distribution of infected plants (Madden *et al*., 2000; Anhalt and Almeida, 2008). Candidate criteria include confirmed alate arrival, a viruliferous aphid, a newly confirmed BBTV-positive plant, or a spatial risk score. The response should match the evidence: an arrival alert can trigger intensified plant inspection and testing, while confirmed plant infection supports containment and infected-plant removal. The rule should specify the surveillance area, sampling interval, assay detection limit, confirmation procedure, response, and maximum response time. Survey guidance provides practical procedures for detection, sample collection, diagnosis, and spatial records

(IPPC Secretariat, 2025); management guidance connects surveillance with vector management, infected-plant removal, and virus-free planting material (Omondi *et al*., 2026). Their application should be evaluated using time to confirmation and removal, cases detected before symptoms, secondary infection, false alerts, and operational cost. EIL should be reserved for a demonstrated density-loss relationship.

Evaluation in both pathways should preserve independent sampling units. Images from the same trap or plant should remain in one data partition, and at least one complete farm, season, or device should be reserved for testing. The evaluation should report low-density sensitivity, blinded identification, count error, forecast calibration, warning lead time, and the result of a prospective management trial under variation in cultivar, crop stage, trap condition, weather, debris, and equipment (Kalfas *et al*., 2023; Ong and Høye, 2025; De Cesaro Júnior *et al*., 2026). Failures at low density should be retained because they define the conditions under which the method cannot be relied upon.

An alert system should distinguish data-quality failure, suspected occurrence, confirmed occurrence, intensified scouting, and management action. For each level, the required evidence, responsible person, and response time should be specified in advance. Automated alerts should not bypass verification; specimens, source records, uncertainty, and expert review must remain available for decisions that lead to treatment, plant removal, or quarantine action.

Priorities for Taiwanese banana production

The four priorities below share the validation sequence in Figure 1. Their endpoints differ: fruit injury and marketable loss for thrips; concealed larval activity and tissue injury for weevils; mite counts and inspection coverage for spectral screening; and BBTV transmission or containment for aphids. The additional defoliator and sap-feeder pathways in Table 2 use the same sequence when local occurrence or injury warrants further study. Common sample identifiers, paired reference observations, and explicit progression criteria allow these studies to contribute to one monitoring and decision framework.

Stage 1 establishes local calibration. A pilot study defines the taxon, life stage, plant or trap unit, sampling effort, and reference method. Each sensor or trap record is paired in time and space with expert counts, dissection, injury assessment, or an appropriate diagnostic assay. The pilot should span low and high target abundance and common non-target signals and should estimate count agreement, detection limits, and uncertainty. Progression requires a reproducible sampling procedure and a biologically interpretable signal, with tolerable missed-detection and bias limits specified for the intended use before external testing.

Stage 2 tests performance across independent farms and seasons. The procedure and model developed in Stage 1 should be fixed before testing complete farm-season combinations reserved from development. Images, plants, traps, and repeated observations remain nested within their original field units. Region, cultivar, crop stage, canopy structure, irrigation, bagging, recent treatments, weather, and device downtime should be recorded so that performance can be assessed under contrasting conditions. Sample size should be based on pilot variability, the required precision of low-density sensitivity, and the independence of field replicates. Progression requires meeting the prespecified detection and bias limits and establishing a warning interval that permits the intended response.

Stage 3 tests the action rule prospectively. The calibrated signal is linked to a stated confirmation procedure, response, and maximum response time and compared with current practice. Farms or independent field blocks should be assigned at the scale of the intervention and pest movement, with repeated plant measurements treated as subsamples when treatment is applied to the whole block. Direct-injury trials measure marketable loss or seedling performance, control efficacy, labor, and cost. BBTV trials compare surveillance and response procedures while retaining required containment of confirmed infections; outcomes include confirmation and removal time and new infections. An operational rule should improve a relevant outcome while maintaining the detection performance established in Stage 2.

Validation in Taiwan should include

southern banana-growing areas such as Pingtung and Kaohsiung, central areas such as Nantou, and eastern production settings where transfer is intended. Within these regions, sampling should represent nurseries and production fields, lowland and hillside environments, contrasting cultivars and management systems, and wet and dry periods. Strong wind or rain and changes in canopy or bagging should be represented when they affect the signal or inspection access. Replication within region and production setting is needed to distinguish regional effects from a single farm's conditions. A coordinated protocol can use the same core metadata and progression criteria while retaining pest-specific units and seasonal sampling schedules.

For thrips, pair standardized trap photographs with microscopic identification, voucher specimens, counts from a defined plant stratum or bunch, fruit injury, crop stage, bagging, rainfall, and management. The banana study by Carval *et al*. (2015) provides a direct design for linking plant counts to fruit injury, but local species and production practices still require calibration. Complete-trap counts should first be compared with expert counts across densities and seasons, and trap catch should then be tested against plant infestation and marketable injury. An ET trial is justified only after both relationships are established. Molecular checks can resolve mixed or damaged samples (Boonmee *et al*., 2025; Zeira *et al*., 2026).

For pseudostem weevils, blinded recordings should be followed by dissection across cultivars, larval stages, depths, and weather conditions. For the proposed use, acoustic detection should precede holes, frass, or routine scouting by enough time to change inspection or sanitation. Direct work on banana weevil provides the biological precedent, while studies of concealed red palm weevils provide field procedures for sensor placement and noise control (Vinatier and Vinatier, 2013; Hetzroni *et al*., 2016; Ashry *et al*., 2022).

For mites, a fixed leaf-underside imaging unit, counts by life stage, and periodic taxonomic or molecular confirmation should be established before spectral screening is added. Proximal or UAV hotspots should then be checked against same-day mite counts and records of leaf age, water status, nutrition, and disease. The proposed screening method should be judged by whether it reduces the number of plants inspected while meeting a prespecified sensitivity target for confirmed infestations.

For aphids, records should include species, wing morph, plant stage, within-plant position, date, and coordinates. These data should be linked to BBTV assays, locations of infected plants, removal dates, and subsequent cases. Sticky-card results in banana and yellow-water results in potato show why a trap index must be tested separately from direct plant infestation (Kocourek *et al*., 2025; Ogwal *et al*., 2026). Taiwan trials should retain direct counts on selected suckers and test whether adding trap and spatial information improves confirmation timing and response. Plant photographs, sampled tissues, test results, and response dates should remain traceable to the same plant, following the principle of linked phenotypic and molecular records illustrated by Ouedraogo *et al*. (2026).

For *S. litura*, the initial study should focus on nurseries and recently planted bananas, pairing moth records with egg masses, larval stages, leaf-area loss, seedling survival, and planting suitability. For *E. torus*, occupied leaf rolls, larval counts, parasitoid emergence, and retained functional leaf area provide the corresponding field units. Routine inspections can be expanded to include other sap feeders through standardized plant-site counts and natural-enemy observations. These extensions broaden surveillance while retaining separate injury functions and decision criteria for each pest and production stage.

Samples and records from these studies should form a reusable reference collection. Specimens, sequences, trap and leaf images, acoustic recordings, and BBTV records should have stable identifiers and complete acquisition metadata. Test sets should retain non-target arthropods, debris, overlapping specimens, damaged leaves, wind, rain, and equipment variation. An independent field team should apply the finalized procedure to new farm-season combinations. Recording failed detections and the conditions under which they occur will define where additional inspection or recalibration is needed.

Conclusions

Banana studies support acoustic detection of concealed weevil larvae, links between thrips abundance and fruit injury, weather- and season-based surveillance, spectral screening, and standardized digital assessment of corm injury. Recent aphid work adds direct evidence that trap activity and plant colonization require separate interpretation. Lepidopteran studies broaden the framework to nursery injury, leaf-area loss, and field comparisons of biological control, while other sap-feeder studies add natural-enemy observations and vector risks. Together, these findings provide reference measurements and practical sampling units for integrated surveillance. The next step is to establish how the measurements improve warning time, inspection effort, marketable yield, or infection control under field conditions.

For direct-injury pests, locally valid EILs and ETs require density-injury and injury-loss relationships, together with control cost and efficacy. Defoliation criteria should account for plant stage, nursery survival or planting quality, and functional leaf area. For banana aphids and other confirmed virus vectors, decisions should be based on infection, transmission, or containment risk. Methods from other crops can supply equipment, assay design, sampling procedures, and evaluation methods; local species labels, sampling units, injury functions, and action criteria require biological calibration.

The immediate priorities proposed for Taiwan remain verified thrips counts linked to fruit injury, pseudostem-weevil acoustics, mite counting combined with spectral screening, and spatial surveillance of aphids and BBTV. A common three-stage sequence links local calibration to independent farm and seasonal validation and prospective comparison with current practice. Validation should represent different production regions, nurseries and production fields, management systems, and weather conditions. A method is ready to support the specified decision when it meets the prespecified sensitivity and bias requirements and improves a relevant field outcome. This sequence also provides a practical route for incorporating additional pests as their local management importance becomes clear.

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從害蟲鑑定到管理決策：香蕉節肢動物害蟲監測的證據與研究重點

廖治榮*

財團法人台灣香蕉研究所　屏東，臺灣
東京都立大學生命科學系訪問學者　八王子，東京，日本
* 通訊作者 email: jrliao1378@mail.banana.org.tw

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摘　要

香蕉節肢動物害蟲監測須確認田間訊號的生物意義及其支持管理行動的能力。本綜合論述以象鼻蟲、薊馬、葉蟎與香蕉蚜蟲為核心，並納入鱗翅目食葉害蟲及其他吸汁害蟲，檢視鑑定、量測、持續監測與管理決策間的證據。香蕉研究支持聲學偵測、蟲量與危害的關聯、重複調查、光譜篩選及數位危害評估；鱗翅目研究亦提供田間管理比較的實例。蚜蟲誘捕量與植株定殖量須分別校準，監測資料仍需連結商品損失、病毒傳播及管理成效。直接危害型害蟲須建立經濟危害水平與經濟閾值，媒介及檢疫害蟲則依感染、傳播或擴散風險訂定行動準則。臺灣四項優先方向為薊馬計數與果實危害之連結、假莖象鼻蟲聲學偵測、葉蟎計數結合光譜篩選，以及香蕉蚜蟲與香蕉萎縮病毒的空間監測。共同流程依序為本地校準、跨蕉園與季節的獨立驗證，以及行動準則與現行作法的前瞻性比較。驗證應涵蓋不同產區、苗圃與生產田、管理及氣候條件；實際應用須符合預設漏檢率標準，並改善預警時間、巡查效率、危害或感染控制。

關鍵詞：香蕉、節肢動物害蟲、害蟲鑑定、族群監測、行動閾值