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Designing Resistance-Resilient IPM Programmes through Deliberate Sequencing of Chemical, Biological, Behavioural, and Cultural Interventions

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ABSTRACT

Resistance-resilient crop protection depends not simply on increasing the number of available interventions, but on controlling how, when, and under what biological conditions those interventions are deployed. Integrated pest-management programmes frequently contain chemical, biological, behavioural, and cultural components without specifying their temporal relationships, compatibility requirements, escalation triggers, or responses to declining susceptibility. This article addresses that design gap by developing an original strategic framework for deliberate intervention sequencing. The approach integrates programme-level resistance management, chemical timing, functional mode-of-action diversity, biological and behavioural suppression, cultural prevention, monitoring, and adaptive adjustment. The principal synthesis is that resistance resilience emerges from a state-dependent exposure programme: preventive measures reduce initial pest pressure; surveillance identifies pest, damage, susceptibility, and natural-enemy states; ecological interventions are protected where their preconditions are met; and selective chemical interventions are reserved for explicit escalation points. Rotation and mixtures remain conditional tools rather than automatic safeguards because cross-resistance, residual overlap, unequal efficacy, pest movement, and implementation inconsistency can undermine their intended functions. Biological, behavioural, and cultural components can reduce dependence on chemical mortality, but component-level efficacy cannot establish whole-programme performance. The proposed structure therefore separates intervention availability from sequencing quality and requires post-intervention feedback, compatibility assessment, and locally relevant validation. Important limitations include sparse direct comparisons of complete intervention sequences, context dependence across pest–crop systems, uncertainty in susceptibility and natural-enemy monitoring, and differences between recommended and implemented practice. The central implication is that resistance management should be evaluated as an adaptive, multi-season programme architecture rather than as a product-rotation rule or a static collection of control tactics.

Keywords: Integrated pest management, Resistance management, Ecological intensification, Pest suppression, Crop diversification.

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INTRODUCTION

Integrated pest management (IPM) is commonly described as the coordinated use of preventive, biological, behavioural, cultural, and chemical tactics. In practice, however, programmes may remain chemically centred while nonchemical elements are included as peripheral recommendations rather than functioning parts of a decision sequence. This implementation gap matters because a list of diverse interventions does not indicate which tactic should act first, what evidence should trigger escalation, or how previous exposures constrain later choices. The persistence of implementation gaps means that IPM should be treated as a designed programme rather than a nominal bundle of tactics [1]. Resistance resilience therefore concerns the architecture of repeated management decisions, not simply the presence of multiple control categories.

Programme-level experience demonstrates that coordination is possible but highly dependent on production history and institutional capacity. The Australian cotton system progressively combined surveillance, economic thresholds, selective insecticides, biological control, transgenic crops, and resistance-management arrangements. Its development illustrates how disruptive interventions can be reduced when chemical decisions are connected to pest monitoring and natural-enemy conservation. The Australian cotton experience shows that thresholds, selective chemistry, biological control and resistance management can be combined at industry scale, although the resulting programme remains system specific [2]. Such experience provides design principles rather than a universally transferable sequence, because pest complexes, climatic conditions, available technologies, advisory systems, and grower incentives differ among production systems.

Resistance also develops through interactions extending beyond the biological response of an isolated pest population. Individual growers may obtain an immediate benefit from an intervention even when repeated regional use reduces its future effectiveness. Manufacturers, advisers, regulators, researchers, and producers may also interpret early control failure differently or act over different time horizons. Pesticide resistance is a sociobiological problem because biological adaptation, individual incentives and collective action interact [3]. A resistance-resilient programme must consequently connect evolutionary reasoning with diagnostics, communication, coordinated implementation, and rules for revising recommendations when susceptibility or control performance changes.

The central problem addressed here is the absence of an explicit design logic connecting intervention timing, ecological compatibility, selection pressure, monitoring, and feedback. Intervention diversity is not equivalent to resistance-resilient sequencing, because the same components can create different exposure patterns when applied in different orders. Evidence from transgenic crops further shows that nominal technological diversity cannot compensate for unsuitable deployment, inadequate refuges, cross-resistance, or favourable inheritance conditions. The emergence of practical resistance to Bt crops shows that deployment pattern, refuge design and inheritance can override the mere availability of diverse technologies [4]. This article therefore develops a proposed, non-validated strategic structure in which each intervention has a defined purpose, entry condition, sequence position, compatibility requirement, failure mode, and validation need.

Why resistance management requires programme-level design

The appropriate unit of resistance-management design is the exposure programme experienced by pest populations across generations, fields, and seasons. Product labels or written recommendations cannot produce resilience unless growers can identify thresholds, distinguish modes of action, obtain suitable alternatives, and implement decisions at the required time. An extension-based programme increased adoption of threshold and rotation practices, indicating that resistance management depends on decision support as well as technical content [5]. Nevertheless, increased adoption should not be interpreted as direct evidence that resistance evolution was slowed. Programme evaluation must separately examine implementation, pest suppression, exposure histories, susceptibility change, and the durability of management options.

Biological starting conditions further prevent a universal sequence from producing uniform outcomes. Resistance may originate from pre-existing variation, new mutation, migration, altered dominance, metabolic mechanisms, target-site changes, or combinations of these processes. Selection intensity is then shaped by dose, coverage, residual activity, pest phenology, untreated hosts, immigration, and the proportion of the population exposed. Resistance trajectories depend on standing variation, mutation, gene flow and selection, so identical intervention lists can generate different evolutionary outcomes [6]. Programme design must therefore specify assumptions about pest biology and exposure rather than treating rotation, mixtures, or intervention diversity as context-free principles.

Monitoring must also represent resistance as a changing state rather than a binary label. Global Bt evidence distinguishes early warning, statistically detected susceptibility change, and practical resistance associated with diminished field performance, underscoring the need for explicit programme states [7]. These states require different responses: intensified sampling may be appropriate for uncertain signals, whereas confirmed operational failure may require withdrawal, containment, or substantial programme redesign. Australian grain systems illustrate how biological, economic and institutional factors can combine to intensify resistance despite the availability of management recommendations [8]. Thus, programme architecture must join diagnostics and intervention rules with extension, access to alternatives, regional communication, and authority for timely adjustment.

The evidence dimensions and interpretive boundaries for resistance management requires programme-level design are summarized in **Table 1**.

Table 1. Why Resistance Management Requires Programme-Level Design: Pest Targets, Ecological Mechanisms, Intervention Timing, Context Dependence, Trade-Offs, and Adaptive Management Requirements

IPM component	Target pest or guild	Ecological or behavioural mechanism	Timing and sequence	Expected contribution	Context dependency	Trade-off or failure risk	Monitoring or adaptation need
Programme-level coordination	Mobile and multi-generational pests	Aligns thresholds, advice, access, and collective action	Established before seasonal interventions	Improves consistency of resistance-management practice	Extension capacity and grower participation	Recommendation uptake may remain incomplete	Audit implementation separately from resistance outcomes
Exposure-history design	Pests exposed across successive generations	Limits repeated selection on the same genetic background	Planned across applications, crops, and seasons	Makes cumulative selection visible	Pest phenology, migration, and residual exposure	Unrecorded exposures obscure causal interpretation	Maintain field and regional exposure records
Resistance-state classification	Bt-target and comparable pest populations	Distinguishes susceptibility change from practical failure	Applied before escalation or technology replacement	Supports proportionate management responses	Sampling design and operational definitions	Binary classifications may delay intervention	Repeat susceptibility and field-performance assessment
Regional resistance coordination	Grain and other landscape-level pest complexes	Links movement, shared selection, and stakeholder decisions	Coordinated before and during regional outbreaks	Reduces fragmented or contradictory action	Market structure and availability of alternatives	Individual incentives may undermine collective durability	Regional diagnostics and communication
Threshold-based selective chemistry	Pest complexes regulated partly by natural enemies	Concentrates chemical mortality when ecological control is insufficient	Used after surveillance and ecological assessment	Reduces avoidable disruptive exposure	Threshold validity and natural-enemy activity	Poorly timed application may remove beneficial organisms	Monitor pests, damage, and natural enemies
Deployment and refuge architecture	Target pests exposed to transgenic traits	Maintains susceptible genotypes and modifies mating opportunities	Designed before exposure begins	Can delay resistance under suitable assumptions	Inheritance, refuge compliance, and cross-resistance	Technology diversity may create false reassurance	Track compliance, susceptibility, and practical failure

Chemical intervention timing and mode-of-action diversity

Chemical timing should be treated as the deliberate placement of selection within a wider suppression programme. A resistance-resilient sequence must specify the pest state that justifies treatment, the life stage targeted, the expected residual window, and the conditions under which another intervention may follow. Rotation is therefore a temporal selection strategy rather than an intrinsically protective practice. The resistance-management value of rotation is conditional on exposure and genetic assumptions rather than inherent in alternation itself [9]. Alternating compounds may provide little benefit when each treatment exposes most of the same population, when resistance alleles carry limited fitness costs, or when surviving individuals reproduce before susceptibility is restored through immigration or untreated refuges.

Mixtures require a different set of conditions. Their intended resistance-management function depends on each component being independently effective against individuals resistant to the other component, sufficiently similar exposure and persistence, low initial resistance frequencies, and the absence of pharmacological or operational antagonism. Mixtures can contribute to resistance management only when both components remain effective and their exposure and genetic assumptions are satisfied [10]. Applying two compounds together after resistance has become common, using unequal doses, or combining components with mismatched residual periods may increase chemical load without creating the mortality structure assumed by mixture theory. Consequently, mixtures should pass an explicit efficacy and independence gate before being assigned a resistance-management role.

Mode-of-action labels are useful for organizing chemical choices, but they do not directly reveal the genetic independence of resistance. Diamide experience shows that target-site and metabolic mechanisms can create cross-resistance that a label-based rotation scheme may fail to detect [11]. Metabolic detoxification, reduced penetration, transport processes, behavioural avoidance, and multiple target-site mutations can connect responses across compounds that appear distinct in classification schemes. Multiple-insecticide resistance in *Tuta absoluta* demonstrates that alternating product labels can still select a shared multi-resistance background [12]. Mode-of-action rotation is therefore not equivalent to absence of cross-resistance. Functional diversity must be supported by susceptibility data, mechanistic evidence, exposure history, and continued effectiveness under locally relevant use conditions.

Biological and behavioural control contributions

Biological and behavioural interventions can diversify the sources of pest mortality and reduce the frequency with which chemical escalation is required. Their programme roles nevertheless differ substantially. Microbial agents, predators, parasitoids, semiochemicals, repellents, trap crops, attract-and-kill systems, and habitat manipulations operate through different spatial and temporal mechanisms. Alternatives to neonicotinoids differ in mechanism, operational maturity and crop fit, so their sequencing role cannot be inferred from the label "nonchemical" alone [13]. The proposed synthesis therefore assigns each nonchemical component a defined target, activation condition, expected duration, compatibility constraint, and failure indicator rather than treating nonchemical diversity as a single interchangeable layer.

Biological control should enter the programme as an observable ecological process, not merely as the release or presence of a beneficial organism. Its contribution depends on establishment, synchrony with susceptible pest stages, environmental suitability, dispersal, food resources, intraguild interactions, and compatibility with previous and subsequent pesticide residues. Biological control can reduce the suppression burden assigned to insecticides, but its programme value depends on timing, environmental fit and compatibility with chemical residues [14]. A decision sequence must therefore examine natural-enemy activity before chemical escalation, protect effective populations through selective chemistry or residue-free windows, and define a contingency response when establishment or suppression is inadequate. Biological-control efficacy in isolation remains insufficient evidence of programme-level resistance benefit.

Natural-enemy diversity may improve suppression when predators or parasitoids attack different pest stages, forage in complementary microhabitats, or remain active under different environmental conditions. Predator diversity can strengthen biological control through functional complementarity, but diversity alone does not guarantee suppression and may introduce antagonistic interactions [15]. Behavioural manipulation can complement this ecological layer by attracting natural enemies, repelling pests, redirecting movement, or concentrating targets where mortality is greater. Combining synthetic plant volatiles with companion plants shows how behavioural and habitat tactics can be sequenced, while also illustrating the need to verify attraction, retention and net suppression [16]. Within the proposed design, these interventions precede chemical escalation only when local monitoring confirms their functional preconditions. Required validation includes comparative whole-programme trials, compatibility measurements, pest and natural-enemy trajectories, crop-damage outcomes, susceptibility monitoring, and documentation of failure-driven escalation. A proposed sequence is not equivalent to locally validated implementation.

Cultural practices and pest-pressure reduction

Cultural control is most useful when decomposed into mechanisms that alter pest establishment, reproduction, survival, or movement before reactive treatment becomes necessary. Crop rotation, temporal diversification, intercropping, altered planting schedules, sanitation, resistant cultivars, and habitat management act at different biological and spatial scales; they should not be grouped as a single generic "diversification" input. Agricultural research documents multiple forms of crop diversification whose functions and constraints differ substantially [17]. A resistance-resilient programme must therefore map each practice to the target pest's host range, life cycle, dispersal behaviour, and seasonal bottlenecks.

Rotation can affect pest pressure beyond the treated field because mobile insects respond to the regional distribution and continuity of host crops. Regional crop-rotation patterns were associated with differing autumn pest pressures in winter oilseed rape, although responses varied among pest taxa and landscape conditions [18]. Behavioural–cultural combinations may also redirect colonization. A push–pull strategy tested against *Drosophila suzukii* in raspberry illustrates that repellents, attractants, crop arrangement, and trap placement must operate together to change pest distribution [19]. Movement responses alone, however, cannot establish reduced crop damage or delayed resistance.

Similar interpretive limits apply when companion crops, attractive plants, repellents, and pathogen-management objectives are combined. A tomato push–pull system targeting *Frankliniella* species demonstrated the practical integration of spatial and behavioural elements, while also showing that pest abundance, plant infection, and crop protection remain separate outcomes [20]. Cultural and behavioural practices can consequently occupy the preventive or early-intervention portion of a sequence, but monitoring must continue because delayed threshold crossing is not equivalent to permanent suppression. Their resistance-management contribution remains a plausible reduction in chemical exposure that requires direct multi-season validation.

Sequencing, rotation, mixtures, and adaptive adjustment

Adaptive sequencing begins with reliable observation. Camera-equipped traps can increase temporal resolution and reduce some labour demands, but image quality, species identification, trap selectivity, maintenance, and analytical error determine whether the resulting information can support intervention decisions [21]. Monitoring frequency is therefore not equivalent to monitoring validity. Each decision should record sampling effort, detection uncertainty, pest stage, crop injury, natural-enemy activity, recent exposures, and the time available before an intervention loses biological relevance.

Risk prediction can help determine where surveillance or preventive action should be intensified. A selection-pressure proxy has been proposed to extend predictions of resistance risk across arthropod pests, but such estimates cannot replace local susceptibility testing or verified exposure histories [22]. Spatially explicit evolutionary models can also compare candidate rotations, mixtures, refuges, migration patterns, and intervention sequences under stated assumptions [23]. These models are valuable for identifying failure conditions, yet they produce scenario evidence rather than proof that a programme will perform similarly in a commercial production system.

Experimental–theoretical systems provide another bridge between mechanism and programme design. A proof-of-concept model linking evolving genomes with pesticide exposure can test hypotheses about resistance trajectories, but model-organism results should not be presented as validation for a particular crop–pest programme [24]. The defensible sequence is therefore conditional: preventive pressure reduction, documented surveillance, compatible biological or behavioural action, selective chemical escalation, and post-intervention reassessment. Rotation and mixtures enter only after checks for efficacy, cross-resistance, persistence, and exposure overlap. The evidence dimensions and interpretive boundaries for sequencing rotation mixtures and adaptive adjustment are summarized in **Table 2**.

Table 2. Sequencing, Rotation, Mixtures, and Adaptive Adjustment: Pest Targets, Ecological Mechanisms, Intervention Timing, Context Dependence, Trade-Offs, and Adaptive Management Requirements

IPM component	Target pest or guild	Ecological or behavioural mechanism	Timing and sequence	Expected contribution	Context dependency	Trade-off or failure risk	Monitoring or adaptation need
Preventive cultural layer	Host-associated pests with identifiable seasonal bottlenecks	Disrupts host continuity, colonization, or reproduction	Before expected establishment and throughout crop planning	Lowers initial pressure and may delay escalation	Pest mobility, host range, crop system, landscape composition	Diversification may not affect the target mechanism	Track pest arrival, damage, agronomic effects, and later resurgence
Repeated surveillance	Trappable or visually identifiable pests	Detects changes in abundance, phenology, and intervention response	Before and after every decision point	Supports state-dependent rather than calendar-based action	Trap selectivity, identification accuracy, weather, sampling effort	Automated records may create false precision	Document effort, error, missed detections, and decision latency
Behavioural manipulation	Pests responsive to attractive or repellent cues	Redirects movement or concentrates targets	Before colonization or alongside low-disruption controls	Reduces crop contact or increases targeted mortality	Cue range, spatial configuration, crop attractiveness	Attraction without retention or crop protection	Measure movement, crop injury, pest density, and persistence
Mode-of-action rotation	Multi-generational pests receiving repeated chemical exposure	Alternates selection among functionally independent targets	Only after susceptibility and residual-window checks	May reduce repeated selection on one mechanism	Cross-resistance, fitness costs, migration, exposure coverage	Label rotation may preserve the same resistance background	Repeat bioassays and review complete exposure histories
Insecticide mixtures	Pests susceptible to both independently active components	Exposes resistant individuals to an effective partner compound	Only while both components retain high independent efficacy	Can reduce survival of rare resistant genotypes under restrictive assumptions	Starting resistance frequency, dose, persistence, antagonism	Unequal decay or existing resistance undermines redundant mortality	Confirm efficacy, persistence alignment, and resistance frequency
Cross-resistance gate	Pests with metabolic or target-site resistance	Tests whether nominally different compounds share resistance mechanisms	Before rotation, mixture, or replacement decisions	Prevents false classification of functional diversity	Diagnostic availability and unknown mechanisms	Undetected metabolic resistance may connect multiple classes	Combine phenotypic bioassays with mechanistic diagnostics
Adaptive feedback	Pest populations under changing selection and environmental conditions	Revises future actions from observed response and resistance risk	Immediately after intervention and at cycle review	Converts a static plan into a learning programme	Observation error, weather, immigration, external exposures	Data collection without decision change is not adaptation	Define stop, escalate, withdraw, and redesign rules in advance

Proposed resistance-resilient IPM design logic

The proposed design begins with four state inputs: pest pressure and life stage, crop injury and economic context, natural-enemy function, and resistance or exposure history. Preventive cultural measures form the first layer; surveillance then determines whether biological or behavioural suppression has suitable preconditions. Chemical intervention is considered only after ecological control and threshold states are assessed. This ordering is supported by evidence that pesticides may add little pest suppression where effective natural enemies are already operating, while potentially disrupting those enemies [25]. **Figure 1** presents the sequencing logic of chemical, biological, behavioural, and cultural intervention portfolios within the analytical logic developed in this section.

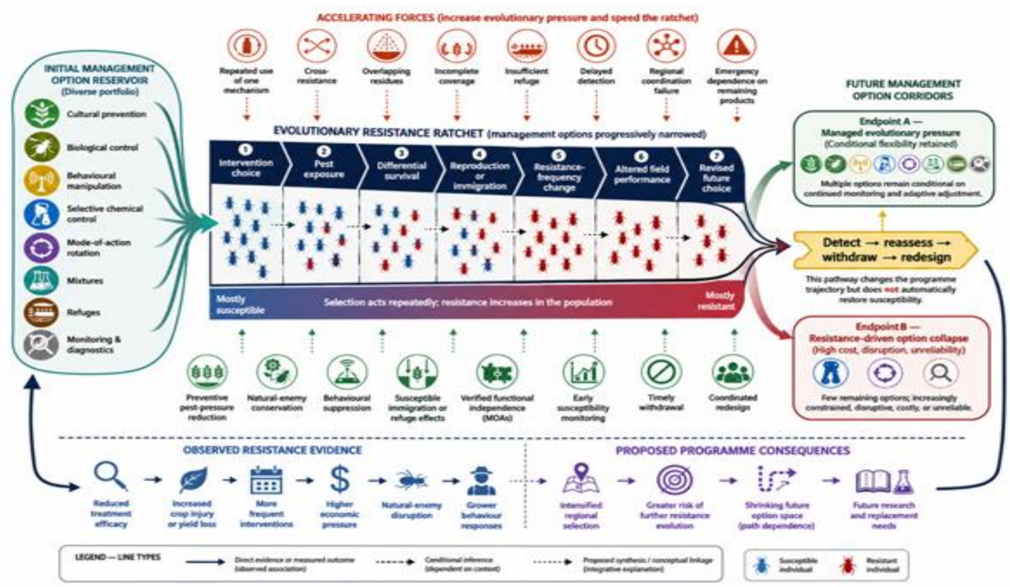

Figure 1. The sequencing logic of chemical, biological, behavioural, and cultural intervention portfolios

Alt text

A structured conceptual diagram that presents the sequencing logic of chemical, biological, behavioural, and cultural intervention portfolios, with labelled components, directional relations, contextual modifiers, uncertainty points, and a clear boundary between observed evidence and proposed synthesis.

Chemical escalation passes through compatibility and functional-independence gates. Selective technologies may preserve natural-enemy functions more effectively than broad-spectrum alternatives, but they retain their own resistance-management requirements [26]. Habitat interventions such as flower strips and hedgerows enter as preventive infrastructure because their effects on pest control and crop outcomes vary with landscape, design, and ecological context [27]. After any intervention, pest density, damage, natural enemies, susceptibility, and operational feasibility are reassessed. Resistance can narrow the future option set by removing effective compounds, increasing reliance on remaining mechanisms, and intensifying selection on those mechanisms. **Figure 2** shows the feedback pathways through which resistance alters future management options within the analytical logic developed in this section.

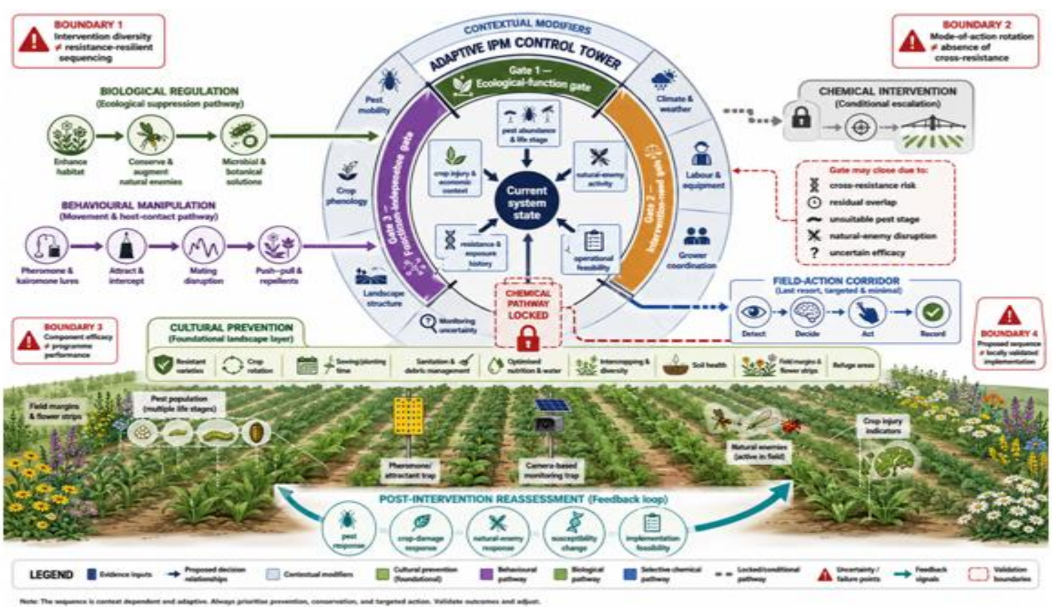

Figure 2. The feedback pathways through which resistance alters future management options

Alt text

A structured conceptual diagram that shows the feedback pathways through which resistance alters future management options, with labelled components, directional relations, contextual modifiers, uncertainty points, and a clear boundary between observed evidence and proposed synthesis.

The resulting logic is a closed loop rather than a fixed ladder. Diversification can provide a preventive base and support several ecosystem services without necessarily reducing yield on average, but aggregate benefits do not validate a particular local intervention order [28]. Every component therefore requires an input condition, intended function, stop rule, failure indicator, and validation endpoint. Intervention diversity is not equivalent to resistance-resilient sequencing; component efficacy is not equivalent to programme performance; and the proposed sequence is not equivalent to locally validated implementation. The proposed components, evidence bases, boundary conditions, failure modes, and validation requirements are organized in **Table 3**.

Table 3. Proposed Resistance-Resilient IPM Design Logic: Components, Evidence Basis, Relations, Boundary Conditions, Failure Modes, and Validation Requirements

Proposed component	Purpose	Evidence basis	Relation or mechanism	Input or precondition	Expected output	Boundary condition or failure mode	Validation requirement
Baseline state characterization	Establish the programme's biological starting point	Evolutionary and programme-level resistance evidence	Defines pest, exposure, susceptibility, and natural-enemy states	Reliable baseline sampling and exposure records	Explicit initial decision state	Incomplete histories or unrepresentative samples	Repeated local diagnostics across relevant populations
Preventive pressure-reduction layer	Delay or reduce threshold crossing	Crop and landscape diversification evidence	Disrupts host continuity and supports ecological regulation	Pest-specific agronomic and landscape fit	Lower initial pest pressure	Practice may not affect the target pest mechanism	Multi-season agronomic, pest, and damage assessment
Surveillance and uncertainty record	Trigger interventions from observed states	Monitoring and risk-prediction evidence	Links documented observations to decision rules	Defined effort, identification quality, and response time	Traceable intervention trigger	False precision, delayed detection, or unmeasured uncertainty	Compare monitoring outputs with independent field observations
Natural-enemy state gate	Protect effective ecological mortality	Biological-control synthesis	Tests whether enemies are active before chemical escalation	Adequate enemy abundance, synchrony, and residue compatibility	Preserved biological suppression	Climate mismatch, intraguild effects, or disruptive residues	Measure enemy function and pest suppression together
Behavioural-control gate	Modify pest colonization or movement	Push–pull and semiochemical evidence	Redirects pests or concentrates them for targeted mortality	Valid cues and spatial configuration	Reduced crop contact or improved targeted control	Attraction without retention or reduced damage	Assess movement, abundance, damage, and persistence
Selective chemical escalation	Restore control when earlier layers are insufficient	Threshold and selective-intervention evidence	Applies chemical mortality at an explicit decision point	Verified need, suitable pest stage, effective option	Short-term suppression with reduced avoidable disruption	Calendar application, poor timing, or broad ecological harm	Compare threshold, damage, natural-enemy, and resistance outcomes
Functional mode-of-action gate	Prevent false assumptions of chemical diversity	Cross-resistance and resistance-mechanism evidence	Tests independence of candidate chemical options	Current phenotypic and mechanistic susceptibility evidence	Defensible rotation or mixture choice	Shared metabolic or target-site resistance	Local bioassays and diagnostic confirmation
Conditional rotation or mixture branch	Manage repeated chemical selection	Evolutionary theory and mixture analysis	Alternates or combines independently effective mechanisms	Low resistance, adequate dose, and compatible persistence	Reduced avoidable selection under stated assumptions	Pre-existing resistance, unequal decay, or antagonism	Longitudinal susceptibility and exposure tracking
Post-intervention feedback	Revise the next action from observed outcomes	Monitoring and adaptive-management evidence	Returns pest, damage, enemy, and susceptibility data to the decision process	Timely reassessment and predefined response rules	Stop, continue, escalate, withdraw, or redesign decision	Monitoring that does not change decisions	Evaluate whether feedback alters actions and outcomes

End-of-cycle programme review	Preserve future management options	Programme and sociobiological evidence	Examines cumulative exposure, failure, feasibility, and coordination	Shared records and decision authority	Revised next-cycle sequence	Fragmented actors or unreported exposures	Multi-season programme and implementation evaluation

Practical trade-offs and implementation conditions

Biologically defensible strategies may be used for different reasons in operational practice. Evidence from Arizona cotton indicates that insecticide mixtures can be selected for pest-spectrum coverage, convenience, or immediate control rather than because the assumptions of resistance-management theory have been verified [29]. Programme documentation should therefore distinguish the operational purpose of a mixture from its proposed evolutionary function. The same distinction applies to rotations: changing products may solve logistical or efficacy problems without generating functionally independent selection.

Implementation also depends on institutions, communication, trust, product access, and coordination among growers, advisers, researchers, manufacturers, and public agencies. Embedding social science in resistance research can expose differences in incentives, risk perception, decision authority, and outreach effectiveness that biological optimization alone cannot resolve [30]. More ambitious reductions in pesticide dependence may require redesign of farming systems, markets, technologies, advisory structures, and research priorities rather than substitution of isolated field inputs [31]. These wider changes are relevant boundary conditions, not evidence that a particular resistance-resilient sequence has already been achieved.

Farm work imposes a final feasibility gate. A biologically preferred intervention may be unavailable during a narrow weather window, conflict with labour demands, require information that arrives too late, or depend on equipment and skills that are not locally accessible. Research on transitions toward sustainable cropping practices shows that farmers require work-related information about timing, organization, equipment, labour, and coordination, not only evidence of technical efficacy [32]. Validation should therefore compare complete candidate sequences over multiple seasons and assess pest suppression, crop damage, susceptibility, natural enemies, workload, cost, adherence, and regional coordination without collapsing these distinct outcomes into a single performance claim.

CONCLUSION

Resistance-resilient IPM is best understood as the deliberate design of changing exposure pathways rather than the accumulation of diverse interventions. Preventive cultural measures, biological regulation, behavioural manipulation, chemical timing, rotation, mixtures, and monitoring acquire resistance-management value only through their order, compatibility, biological preconditions, and feedback effects. Rotation cannot establish the absence of cross-resistance, and successful components cannot establish whole-programme durability. The strongest defensible synthesis is therefore a state-dependent, closed-loop programme in which interventions are triggered by documented pest, crop, natural-enemy, susceptibility, and feasibility conditions; chemical options pass functional-independence and compatibility gates; and every action changes the information used to select the next one. Its major boundary conditions are pest biology, landscape movement, diagnostic quality, ecological context, access to alternatives, labour, incentives, and regional coordination. The highest-priority research implication is prospective comparison of complete sequences under locally relevant, multi-season conditions while preserving separate measures of biological effectiveness, resistance trajectories, ecological effects, implementation fidelity, and operational feasibility.

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