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Economic perspectives of integrated pest management in sorghum and pearl millet: Cost-effectiveness, adoption and policy implications

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Abstract

Sorghum (*Sorghum bicolor* L. Moench) and pearl millet (*Pennisetum glaucum* L.) are important dryland cereals valued for their adaptation to heat, drought and low-input production environments. However, insect pests can substantially reduce yield and profitability, while repeated or prophylactic insecticide use may increase production costs and contribute to ecological and resistance-related concerns. Integrated pest management (IPM) offers an alternative approach by combining preventive, biological, cultural, host-plant resistance, need-based chemical and other compatible tactics. Nevertheless, the economic attractiveness of IPM depends not only on pest suppression and yield improvement but also on input costs, labour requirements, pest pressure, output prices, risk and the knowledge required for timely decision-making. This review critically examines the economic dimensions of IPM in sorghum and pearl millet, with emphasis on cost structures, partial budgeting, benefit–cost ratio (BCR), incremental benefit–cost ratio (ICBR), marginal rate of return (MRR), net present value (NPV), and economic injury and threshold concepts. Evidence is synthesized for major pest-management situations, including shoot fly, stem borers, fall armyworm, sorghum midge, head bugs, white grub and head caterpillar. Particular attention is given to preventive seed treatment, host-plant resistance, biological control, needbased chemical intervention and labour-intensive practices. The review also examines adoption constraints related to farm size, liquidity, labour, input availability, extension access, risk and perceived profitability. Available evidence generally indicates favourable economic potential for several IPM interventions compared with routine chemical management; however, the magnitude and stability of benefits vary with pest pressure, production conditions, input and output prices, labour costs and methods of economic accounting. Evidence is also uneven across crops and pests, with some economic conclusions relying on transferable evidence from other cereal systems. Future research should therefore prioritize multi-location and multi-year economic evaluation, standardized cost accounting, sensitivity and risk analysis, valuation of family labour and stronger crop-specific evidence for emerging pests. Such evidence can support economically viable and locally adaptable IPM strategies for sustainable production of sorghum and pearl millet.

Keywords: Integrated pest management (ipm), sorghum bicolor, pearl millet, benefit-cost ratio (bcr), economic threshold level (etl), partial budgeting, fall armyworm, smallholder economics

1. Introduction

1.1 Background and Context

Sorghum (*Sorghum bicolor* L. Moench) and pearl millet (*Pennisetum glaucum* (L.) R. Br.) are important cereals in dryland and semi-arid farming systems. Their ability to perform under variable rainfall and relatively challenging production environments contributes to their importance for food, feed, fodder and livelihood security. Sorghum productivity is particularly sensitive to climatic variability, with changes in rainfall and temperature contributing to production uncertainty in rainfed systems (Kouyate, 2020) ^[1]. At the same time, pearl millet has received considerable attention because of its adaptation to dry environments and its importance as a climate-resilient cereal (Gahukar & Reddy, 2019; Juneja, 2024) ^[2, 3].

Despite these advantages, productivity and profitability of both crops are constrained by insect pests. Sorghum is attacked by a diverse pest complex that includes shoot fly (*Atherigona soccata*), stem borers such as *Chilo partellus*, fall armyworm (*Spodoptera frugiperda*), sorghum midge (*Contarinia sorghicola*) and head bugs (*Calocoris angustatus*) (Okosun et al., 2021) ^[4].

Pearl millet is similarly affected by economically important pests including white grubs, head caterpillar and blister beetles, with their importance varying among production environments (Gahukar & Reddy, 2019; Juneja, 2024) ^[2, 3]. The economic significance of these pests is determined not only by their biological damage potential but also by crop value, pest incidence, effectiveness and cost of available management practices, labour requirements and farmers' capacity to implement timely interventions.

The emergence and spread of fall armyworm has further increased the complexity of cereal pest management. The pest has a broad host range and has been associated with substantial crop losses across different cereal production systems (Overton *et al.*, 2021; Bautista-Martínez *et al.*, 2025) ^[5, 6]. However, economic evidence is not equally available for all cereal hosts. Consequently, findings from maize and other cereal systems may provide useful methodological or management insights, but they should not automatically be considered equivalent to direct evidence from sorghum or pearl millet. Differences in pest behaviour, crop susceptibility, yield response, management efficacy, production costs and crop value can influence the economic threshold and profitability of an intervention.

The economic importance of insect pests extends beyond direct yield loss. Pest-management decisions influence expenditure on insecticides, seed treatment, labour, monitoring and other inputs. Excessive or poorly timed pesticide use can also generate environmental and social costs, including effects on non-target organisms and ecosystem services. Economic analyses of integrated pest management have therefore emphasized the importance of considering environmental benefits and externalities when comparing alternative pest-management strategies (Mullen *et al.*, 1997; Rasche, 2016) ^[7, 8]. These considerations provide an important economic basis for promoting pest-management strategies that reduce unnecessary pesticide use while maintaining crop productivity.

1.2 The pest landscape

Sorghum and pearl millet are attacked by diverse insect pests whose relative importance varies with crop stage, agroecological conditions, season and production practices. In sorghum, shoot fly and stem borers are important during vegetative growth, while fall armyworm can damage vegetative and whorl stages and sorghum midge and head bugs affect reproductive development (Okosun *et al.*, 2021) ^[4]. In pearl millet, white grub can cause serious damage to seedlings and roots, while head caterpillar and blister beetles can affect developing panicles (Gahukar & Reddy, 2019; Juneja, 2024) ^[2, 3].

From an economic perspective, pest incidence alone does not determine whether an intervention is justified. The decision to control a pest depends on the expected value of crop loss, cost of control and effectiveness of the selected intervention. This principle forms the basis of economic injury level and economic threshold approaches, which connect pest density or damage with the economic consequences of control decisions (Stern *et al.*, 1959; Pedigo *et al.*, 1986) ^[9, 10].

Fall armyworm provides an important example of this challenge. Economic threshold research has demonstrated that the relationship between pest damage, yield loss and control cost can be used to determine economically justified intervention levels (Bautista-Martínez *et al.*, 2025) ^[6]. However, threshold values are influenced by prevailing crop prices, management costs, pest pressure and crop response.

Therefore, thresholds developed in one crop or production environment should be adapted and validated before being generalized to another crop.

1.3 The Economic Rationale for IPM

The central economic rationale of IPM is to optimize pest management rather than maximize pest mortality. Reliance on repeated or prophylactic insecticide application can increase production expenditure and may impose environmental costs associated with pesticide use. Economic evaluation of IPM has demonstrated that environmental benefits can form an important component of the overall economic value of integrated pest management (Mullen *et al.*, 1997) ^[7]. Similarly, analysis of pesticide externalities in Indian agriculture indicates that environmental and social costs can influence the economic assessment of pesticide-intensive production systems (Rasche, 2016) ^[8].

IPM provides a framework for combining compatible pest-management approaches, including host-plant resistance, cultural practices, biological control, monitoring and judicious chemical intervention (Pretty & Bharucha, 2015) ^[11]. The economic advantage of such an approach arises when the combination of practices reduces avoidable expenditure or yield loss while maintaining acceptable returns. However, IPM should not be assumed to be economically superior under every circumstance. Its profitability depends on pest pressure, expected yield response, input prices, output prices, labour requirements, availability of management inputs and farmers' capacity to implement interventions at the appropriate time.

Economic evaluation therefore needs to consider more than the purchase price of pesticides or the percentage reduction in pest population. Partial budgeting can be used to assess changes in costs and returns associated with a specific management change, while BCR and incremental economic indicators can assist in comparing alternative interventions (Kuwornu *et al.*, 2018; Guerri *et al.*, 2018) ^[12, 13]. In addition, the economic injury level (EIL) and economic threshold (ET) provide a framework for relating pest density and expected yield loss to the cost and effectiveness of control (Stern *et al.*, 1959; Pedigo *et al.*, 1986) ^[9, 10]. The EIL concept has subsequently been extended to incorporate environmental considerations, thereby broadening economic assessment beyond direct farm-level returns (Pedigo & Higley, 1992; Higley & Pedigo, 1993) ^[14, 15]. An important limitation in interpreting IPM economics is the use of a single indicator such as BCR. A high BCR may result from a relatively low investment requirement even when the absolute economic gain is modest. Conversely, a more expensive intervention may provide greater absolute net benefits despite having a lower BCR. Therefore, IPM interventions should ideally be evaluated using complementary indicators such as net returns, BCR, incremental returns and, where appropriate, MRR or NPV (Kuwornu *et al.*, 2018; Guerri *et al.*, 2018) ^[12, 13].

Another important consideration is that IPM itself may involve information and management costs. Monitoring pest populations, identifying pests and beneficial organisms, interpreting thresholds and selecting appropriate interventions require knowledge, time and access to reliable information. Labour-intensive practices may also involve substantial family labour and associated opportunity costs. Consequently, the economic performance of IPM should be evaluated in relation to both direct monetary expenditure and the labour, information and management requirements associated with adoption.

1.4 Scope and objectives of the review

Despite broad recognition of the potential benefits of IPM, the specific economic evidence base for sorghum and pearl millet remains fragmented. Available evidence is distributed across pestmanagement studies, field demonstrations, economic evaluations and socio-economic investigations, with substantial variation in study location, pest pressure, cost accounting, input prices, output prices and economic indicators. Studies from other cereal systems, particularly maize, can provide useful methodological or comparative evidence where crop-specific information is limited, but such evidence needs to be distinguished from direct sorghum- and pearl millet-specific findings.

2. Methodological frameworks for assessing ipm economics

2.1 Microeconomic evaluation tools

Partial budgeting analysis remains the most widely applied microeconomic tool in field-level IPM evaluation, comparing the added costs of an IPM intervention, such as seed treatment, pheromone traps, or biocontrol agents, against the added returns generated through yield protection or improved output quality, relative to an unsprayed control or the farmer's existing practice (Kuwornu *et al.*, 2018) ^[12]. Benefit-cost ratio (BCR) and, less commonly in smallholder field-trial contexts, net present value (NPV) analysis extend this comparison across chemical control, nonchemical IPM, and farmer practice (FP) treatments, providing a standardised metric for ranking alternative management strategies; incremental benefit-cost ratios exceeding 1:4 are commonly reported for well-targeted seed-treatment and biocontrol interventions in cereal systems, though considerable variation exists across pest complexes, seasons, and price regimes (Guerri *et al.*, 2018). The marginal rate of return (MRR), grounded in the dominance-analysis methodology formalised for on-farm agronomic trials, evaluates the incremental return per unit of additional investment as farmers move between undominated treatments ranked by increasing cost, offering a particularly relevant safety-oriented metric for resource-poor farmers who must weigh the opportunity cost of scarce capital against the risk of technology failure.

An important methodological caution attaches to the interpretation and comparison of BCR figures reported across the sorghum and pearl millet IPM literature: because BCR is a ratio rather than an absolute measure of return, a very high BCR calculated on a low absolute cost base, as is common for seed-treatment interventions requiring only a small quantity of chemical per hectare, can appear numerically more attractive than a lower, but absolutely larger, net benefit generated by a costlier intervention such as a season-long biocontrol programme, even where the latter delivers substantially greater total value to the farm household. Reviewers and extension planners relying solely on BCR rankings to prioritise among competing IPM interventions therefore risk systematically favouring low-cost, low-absolute-benefit options over higher-cost, higher-absolute-benefit alternatives that might, on a net-present-value or total-farm-income basis, represent the economically superior choice, particularly for better-resourced farmers able to bear a larger upfront investment. This distinction underscores the value of reporting BCR alongside absolute net-

return figures, and, where multi-season data permit, discounted net-present-value estimates, rather than relying on any single metric in isolation when communicating IPM economics to farmers and policymakers.

2.2 Damage-Function and Economic Threshold Modelling

A parallel and complementary evaluation tradition, rooted in the economic injury level (EIL) concept first formalised within the integrated control framework (Stern *et al.*, 1959) ^[9], derives yieldloss equations relating pest density or a Pest Severity Index (PSI) to yield decline, from which an EIL, the lowest pest density that justifies the cost of control, and a corresponding economic threshold (ET), the action-trigger density set below the EIL to allow time for effective intervention, can be estimated (Pedigo *et al.*, 1986) ^[10], a methodology subsequently applied to derive EIL/ET estimates across a range of insect pests and cropping systems beyond the crop in which it was originally formulated (Foresti *et al.*, 2017) ^[16]. Subsequent refinements to the EIL framework have extended the original cost-of-control calculus to incorporate environmental and sustainability considerations, including the indirect costs of pesticide use on non-target organisms and ecosystem services, broadening the concept from a narrowly financial calculation to one capable of informing genuinely integrated management decisions (Pedigo & Higley, 1992; Higley & Pedigo, 1993) ^[14, 15]. Field-based estimation of these thresholds for fall armyworm in maize systems illustrates the underlying methodology directly transferable to sorghum: yield losses are found to increase approximately linearly with the percentage of damaged plants, from which an economic threshold expressed as a percentage damage level is derived using prevailing input costs and output prices (Bautista-Martínez *et al.*, 2025) ^[6]. Contemporary refinements to this framework increasingly incorporate environmental and value-chain considerations alongside the traditional cost-of-control calculus, and machine-learning and climate-informed models are beginning to be proposed as tools for dynamically updating threshold estimates under variable seasonal conditions (“Conceptualisation of Economic Injury Level and Economic Threshold,” 2026).

2.3 Data sources and review eligibility

This review draws on peer-reviewed field-trial studies reporting cost-benefit or partial-budget outcomes for sorghum or pearl millet pest management interventions, multi-location front-line demonstrations conducted under farmer-participatory conditions, and farm-level socio-economic surveys examining IPM adoption determinants, supplemented by closely comparable evidence from other cereal systems, principally maize and cotton, where methodologically transferable findings inform the interpretation of sorghum- and pearl-millet-specific results in the continued absence of directly comparable data. Studies were prioritised for inclusion where they reported quantifiable economic outcomes, such as BCR, incremental cost-benefit ratio (ICBR), net returns, or MRR, rather than purely biological efficacy data, consistent with the review's explicit focus on cost efficiency and economic decision-making rather than entomological control efficacy *per se*.

Table 1: Summarizes the principal microeconomic and damage-function tools applied in the reviewed literature to evaluate IPM economics in cereal cropping systems, together with their formula basis and primary application. Table 1: Microeconomic and damage-function tools used in IPM economic evaluation

Evaluation Tool	Definition/Formula Basis	Primary Application in IPM Economics	Key Source(s)
Partial Budgeting	Added returns minus added costs of a discrete change in practice	Comparing IPM module vs. farmer practice (FP) at plot level	(Kuwornu et al., 2018) ^[12]
Benefit-Cost Ratio (BCR)	Total discounted benefits divided by total discounted costs	Ranking chemical control, non-chemical IPM, and FP treatments	(Guerci et al., 2018; Mullen et al., 1997) ^[13, 7]
Incremental Cost-Benefit Ratio (ICBR)	Incremental benefit divided by incremental cost of an added input	Evaluating seed-treatment and intercropping IPM combinations	(Gahukar & Reddy, 2019) ^[2]
Marginal Rate of Return (MRR)	Incremental net benefit as % of incremental cost between ranked treatments	Assessing investment safety for resource-poor farmers	(Rasche, 2016) ^[8]
Economic Injury Level / Threshold (EIL/ET)	Pest density at which control cost equals value of prevented loss	Timing interventions against shoot fly, stem borer, and FAW	(Pedigo et al., 1986; Bautista-Martínez et al., 2025) ^[10, 6]
Net Present Value (NPV)	Discounted stream of net benefits over the technology's useful life	Evaluating multi-season biocontrol and resistant-variety investments	(Kathage & Qaim, 2012) ^[17]

3. Pest-specific economic impact and ipm cost-benefit analysis

3.1 Sorghum pest complex

Shoot fly (*Atherigona soccata*) and stem borer (*Chilo partellus*) together constitute the most economically damaging early-season pest complex in sorghum across South Asia and eastern Africa, with yield losses ranging from twenty to over sixty percent depending on infestation timing and cultivar susceptibility (Okusun et al., 2021) ^[4]. Economic comparisons of cultural and preventive control options, including early sowing, elevated seeding rates to compensate for expected seedling mortality, and seed treatment with systemic insecticides such as imidacloprid or thiamethoxam, against rescue spraying after infestation onset, consistently favour the preventive, seed-treatment-led approach on both yield-protection and cost-efficiency grounds, since rescue sprays applied after dead-heart symptoms appear can no longer reverse damage already incurred. Field evaluations combining seed treatment with a single need-based foliar spray report substantially higher incremental cost-benefit ratios than either untreated control or calendar-based multiple-spray regimes, reflecting the disproportionate yield protection achieved through earlyseason intervention relative to its comparatively low input cost.

Fall armyworm has introduced a qualitatively distinct cost dynamic into sorghum pest management, given its rapid establishment, cryptic whorl-feeding habit, and demonstrated capacity to develop resistance to repeatedly applied synthetic insecticides, including to some Bt-based control options (Burt et al., 2017; Hardte et al., 2011) ^[18, 19]. Cost-effective management increasingly centres on pheromone-trap-based monitoring to trigger threshold-based intervention, combined with biorational and biological control options including *Trichogramma* egg parasitoids, nucleopolyhedrovirus (NPV) formulations, and *Metarhizium*-based entomopathogenic fungi, which have demonstrated substantial yield and net-return gains in maize systems directly transferable to sorghum given the pest's shared whorl-feeding biology (Pomari-Fernandes et al., 2015) ^[20]. Economic threshold-based evidence indicates that early-whorl-stage management, when infestation levels remain below approximately twelve to fifteen percent of damaged plants, is markedly more cost-effective than intervention delayed to the late-whorl or panicle-emergence stage, by which point yield losses have already been substantially incurred and cannot be recovered through subsequent control (Bautista-Martínez et al., 2025; Overton et al., 2021) ^[6, 5].

Panicle-stage pests, principally the sorghum midge and head bugs, present a distinct economic calculus centred on the trade-off between synchronised flowering, achieved through coordinated community-level sowing dates and resistant-variety deployment, and repeated chemical dusting or spraying during the vulnerable flowering window. Because midge and head bug damage directly reduces grain set and quality at a late crop stage when yield potential is otherwise largely fixed, the economic returns to synchronised, area-wide cultural management are frequently reported to exceed those of individual-farm chemical intervention, particularly where community-level coordination can be achieved through extension-facilitated collective action (Okusun et al., 2021) ^[4]. Regional differences in the relative economic importance of individual sorghum pests are pronounced and carry direct implications for the design of cost-effective IPM recommendations: shoot fly pressure is typically most severe in post-rainy, off-season sorghum plantings in peninsular India, where delayed or staggered sowing dates common among smallholders extend the window of crop susceptibility, whereas stem borer and fall armyworm pressure tend to dominate in the rain-fed sorghum systems of eastern and southern Africa, where the pest complex overlaps extensively with that affecting neighbouring maize fields (Okusun et al., 2021) ^[4]. This spatial heterogeneity implies that a single, nationally or regionally uniform IPM economic recommendation is unlikely to be optimal across sorghum's full cultivation range, and that extension messaging must instead be calibrated to locally dominant pest pressure and cropping calendar, a requirement that itself carries resource implications for research and extension systems accustomed to delivering standardised technical packages.

The economics of host-plant resistance as a complementary, rather than substitute, component of sorghum IPM deserves particular emphasis, since resistant or tolerant varieties reduce the baseline pest pressure against which subsequent cultural and chemical interventions must contend, thereby lowering the effective economic threshold justifying additional spend on seed treatment or foliar spraying. Because varietal seed itself typically carries little or no price premium over susceptible alternatives once resistant lines are commercially released, the marginal cost of incorporating hostplant resistance into a broader IPM package is frequently negligible relative to its yield-protection benefit, making variety choice arguably the single most cost-effective, if least visible, IPM decision available to sorghum farmers, and one that extension messaging

focused narrowly on input-based interventions such as seed treatment or spraying risks under-emphasising relative to its true economic importance (Okosun *et al.*, 2021) ^[4].

3.2 Pearl millet pest complex

White grub (*Holotrichia consanguinea*) represents the single most economically destructive pest of pearl millet across arid and semi-arid India, with seedling mortality in severely infested fields reaching, in the absence of intervention, close to thirty percent ("Global Species Diversity, Bioecology and Management of White Grubs in Crops," 2024) ^[21]. Economic mitigation strategies centre on a comparison between seed treatment with systemic insecticides such as imidacloprid, applied at minimal per-hectare cost and labour requirement, against soil drenching or furrow application of insecticide, which, while sometimes marginally more effective under very high grub densities, imposes substantially higher labour and chemical costs. Field evidence indicates that seed treatment reduces seedling mortality from approximately twenty-nine percent to around two percent while more than doubling grain yield, generating a cost-benefit ratio in the order of 1:25, a return that decisively favours the seed-treatment pathway over soil-application alternatives on both cost-efficiency and labour-economy grounds (Gahukar & Reddy, 2019) ^[2].

The millet head caterpillar and blister beetles impose a distinct panicle-stage economic burden, with management options spanning mechanical collection and hand-picking of larvae and adult beetles, trap cropping using preferentially attractive border plantings, and targeted chemical sprays timed to panicle emergence. Mechanical and trap-cropping approaches, while more labour-intensive, generally impose lower cash costs than repeated chemical spraying and are correspondingly favoured among cash-constrained smallholders, though their relative cost-effectiveness is highly sensitive to local wage rates and the opportunity cost of household labour, particularly for women and children who are frequently tasked with hand-collection activities (Gahukar & Reddy, 2019) ^[2].

Integrated pest and disease management (IPDM), combining downy-mildew-resistant hybrids with pest-specific IPM modules, represents an increasingly important economic frontier in pearl millet protection, since host-plant resistance to downy mildew reduces the compounding yield losses that occur when disease and insect pest pressure co-occur, thereby raising the marginal economic return to complementary insect-pest-management investment. The economics of combining resistant hybrid seed, itself typically only marginally more expensive than open-pollinated or susceptible hybrid seed, with targeted white grub seed treatment and panicle-pest monitoring, is consistently reported to be favourable relative to either resistant hybrids or IPM alone, reflecting a synergistic rather than merely additive economic relationship between the two technology components (Juneja, 2024) ^[3].

An additional, frequently overlooked economic dimension of blister beetle management in pearl millet relates to occupational health: blister beetles secrete cantharidin, a potent vesicant compound capable of causing severe skin blistering on contact, meaning that mechanical handcollection, while cash-cost-effective, imposes a health-related cost on the largely female and child labour typically engaged in this task that is rarely incorporated into reported cost-benefit calculations. A fuller accounting of the true economic cost of mechanical blister beetle control would need to incorporate protective equipment costs, or the economic value of averted health harm, alongside

the direct labour-time cost conventionally reported, a refinement that would likely narrow, though not eliminate, the apparent cost advantage of mechanical over chemical control options.

4. System-level economic dynamics and trade-offs

4.1 Comparative cost structure

Within the total cost of cultivation frameworks conventionally used in Indian farm-cost accounting plant protection expenditure typically constitutes a comparatively modest, though non-trivial, share of total variable cost in sorghum and pearl millet relative to input-intensive crops such as cotton or vegetables, reflecting both the lower per-hectare value of these coarse cereals and farmers' correspondingly conservative input-application behaviour under tight cash constraints. Nonetheless, plant protection cost shares differ meaningfully between the two crops: pearl millet's disproportionate exposure to white grub, a pest requiring either seed treatment or soil application regardless of visible above-ground symptoms, tends to impose a more front-loaded, unavoidable protection cost than sorghum, where shoot fly and stem borer management costs are more responsive to farmers' risk perception and can, in low-pressure seasons, be substantially curtailed or skipped altogether.

Economies of scale in plant-protection input procurement further differentiate the effective cost structure faced by farmers of differing landholding size: larger farmers are typically able to purchase seed-treatment chemicals, pheromone lures, or biocontrol agents in bulk at lower perunit prices and to spread the fixed transaction cost of sourcing these inputs, often requiring a trip to a distant input dealer or KVK outlet, over a larger cultivated area, whereas smallholders face proportionately higher per-hectare procurement costs that can erode, or in some cases reverse, the favourable cost-benefit ratios documented under research-station or larger-farm conditions. This scale-dependency of realised IPM economics, though rarely quantified explicitly in the reviewed literature, represents an important qualification to be borne in mind when extrapolating trial-level cost-benefit findings to the smallest and most resource-constrained farm households, who simultaneously stand to gain the most, in proportional terms, from effective, low-cost pest management.

4.2 Labour economics and gender aspects

IPM interventions redistribute, rather than uniformly reduce, labour demand relative to calendar-based chemical spraying: seed treatment and pheromone-trap deployment impose concentrated, low-frequency labour requirements at planting and early crop stages, whereas mechanical collection of head caterpillars and blister beetles, and manual monitoring for threshold-based decision-making, impose more dispersed, recurring labour demands across the season. Because women and children disproportionately undertake weeding, hand-collection, and pest-monitoring tasks within smallholder cereal systems in South Asia and sub-Saharan Africa, IPM modules that substitute labour-intensive cultural and mechanical control for purchased chemical inputs carry important, and frequently under-quantified, gender-differentiated labour implications, with broader evidence on gendered agricultural labour allocation indicating that women's disproportionate involvement in unpaid or under-compensated field tasks can constrain the net household-level economic benefit of labour-substituting IPM technologies unless accompanied by

corresponding adjustments in intra-household labour or resource allocation (Doss *et al.*, 2025) ^[22].

4.3 Risk reduction and income stability

Beyond mean yield and net-return effects, IPM modules that reduce reliance on reactive, postinfestation chemical spraying offer resource-poor farmers a meaningful risk-reduction benefit, since threshold-based, preventive interventions such as seed treatment lock in a large share of the pest-protection benefit at a fixed, predictable early-season cost, in contrast to chemical-intensive strategies whose ultimate cost and effectiveness depend on unpredictable within-season pestpressure escalation and the availability, quality, and price of insecticides at the point of need. This risk-stabilising property is of particular economic significance for the marginal and smallholder farmers who predominate in sorghum and pearl millet cultivation, for whom income variability, rather than mean income alone, is frequently the binding constraint on technology adoption decisions (Kathage & Qaim, 2012) ^[17]. Emerging Internet of Things and blockchain-enabled datamanagement frameworks, while not yet evaluated specifically for sorghum or pearl millet pest management, offer a plausible future pathway for reducing this risk further by enabling more precise, real-time pest-pressure monitoring and more transparent, verifiable input-use records to underpin insurance and credit products tailored to IPM adopters (Rehman *et al.*, 2023; Subeesh & Mehta, 2021; Almazmomi, 2025; Alipio & Villena, 2023; Kaushik *et al.*, 2025) ^[23, 24, 25, 26, 27].

5. Socio-economic adoption barriers and institutional drivers

5.1 Factors influencing IPM adoption

Adoption of IPM modules in sorghum and pearl millet is shaped by a now well-documented set of factors, including farmers' educational attainment, landholding size and tenure security, access to credit and extension contact, perceived relative economic advantage over existing practice, and the complexity of the recommended module relative to farmers' existing technical capacity (Karbo *et al.*, 2024; Mesa Manzano & Esparcia Pérez, 2023) ^[28, 29]. Comparative evidence from cotton IPM adoption in Punjab, a system that shares much of sorghum and pearl millet's smallholder, dryland context, indicates that technological complexity and perceived relative economic advantage together explain the great majority of variation in farmers' predicted and actual IPM adoptability, underscoring the centrality of simple, economically self-evident module design to successful scaling.

Access to formal or informal credit similarly shapes IPM adoption capacity, since even the modest upfront cost of treated seed or pheromone traps can represent a binding liquidity constraint for cash-poor households at planting time, before any harvest revenue has been realised (Mishra *et al.*, 2025; Tanti *et al.*, 2023) ^[30]; where credit access is available, either through formal agricultural lending institutions or through input suppliers offering seasonal credit against future harvest, farmers are consistently more able to adopt preventive, seed-treatment-led IPM strategies rather than deferring investment until pest damage is already visible, by which point rescue intervention is both costlier and less effective (Mallappa & Pathak, 2023; Mishra *et al.*, 2026) ^[31, 32]. Crop or input insurance products explicitly linked to IPM adoption, while still rare in sorghum and pearl millet systems specifically, represent a further institutional innovation with the potential to reduce the

perceived investment risk that continues to deter otherwise economically rational IPM uptake among the most risk-averse smallholder households (Tanti *et al.*, 2024) ^[33].

5.2 Market dynamics and input availability

Even where an IPM module is demonstrably cost-effective under trial conditions, its farm-level adoption remains contingent on the local availability, quality, and price stability of the required inputs, including biocontrol agents such as *Trichogramma* and entomopathogenic fungi, pheromone lures and traps, and treated seed, all of which face weaker, less standardised distribution networks in sorghum- and pearl-millet-growing regions than the input markets serving higher-value commercial crops. Evidence from an augmentative biological control industry established for millet and sorghum pest management in Niger indicates that private-sector supplychain development can substantially improve the accessibility and cost-competitiveness of biocontrol inputs relative to imported or centrally distributed chemical alternatives, though the economic feasibility of such industries remains sensitive to production scale and continued institutional support during the early market-development phase (Guerce *et al.*, 2018) ^[13].

The quality, rather than merely the availability, of inputs marketed as IPM components represents a further, under-examined market-dynamics concern: counterfeit, substandard, or expired pheromone lures, biocontrol formulations, and treated seed have been documented across multiple developing-country contexts, and where such quality failures occur, farmers who have adopted an IPM module in good faith may experience disappointing field performance that is misattributed to the IPM approach itself, rather than to input quality failure, generating a discouraging and potentially adoption-reversing experience that undermines the credibility of subsequent extension messaging. Robust input-quality regulation and certification, alongside farmer-accessible mechanisms for reporting and redressing substandard input experiences, therefore constitute an important, if largely non-technical, precondition for realising the favourable economic returns to IPM documented under controlled research-station conditions at genuine farm-level scale.

5.3 Extension and knowledge dissemination

Extension delivery mechanisms play a decisive role in reducing the perceived technical complexity that constrains IPM adoption, with Farmer Field Schools (FFS) offering a particularly well-suited participatory format for pest-monitoring and threshold-based decision-making skills that cannot be effectively transmitted through one-off demonstration alone. In the Indian context, Krishi Vigyan Kendras (KVKs) have served as the principal institutional vehicle for validating and demonstrating IPM modules through front-line demonstrations and structured farmer training, with documented direct and spillover effects on the adoption of KVK-promoted technologies extending beyond directly trained farmers to their wider social networks (Varshney *et al.*, 2022) ^[34], a pattern broadly consistent with evidence on the Agricultural Technology Management Agency (ATMA) extension system's impact on farmers' knowledge, skill, and technology-adoption behaviour, and on crop diversification and income, elsewhere in India (Subba & Mukhopadhyay, 2019; Jangde *et al.*, 2024) ^[35, 36]. Digital advisory platforms, including mobile-based extension services and, increasingly, artificial-

intelligence-enabled advisory tools, offer a complementary and potentially more scalable channel for delivering time-sensitive, threshold-triggered pest alerts that conventional periodic extension visits cannot match in timeliness, with evidence from mobilebased agricultural extension services in South India indicating that perceived usefulness and ease of use are significant predictors of farmer engagement with such digital IPM advisory content (Cerjak *et al.*, 2025; Gupta & Pal, 2025) [37, 38], consistent with wider evidence on the productivity and adoption benefits of mobile-phone-based agricultural extension and digital advisory services in India and other developing-country contexts (Fu & Akter, 2016; Mittal & Tripathi, 2009; Li *et al.*, 2022; Mehar, 2016) [39, 40, 41, 42]. Persistent institutional constraints, including the limited scientific staff strength of KVKs relative to their mandated coverage area (Poonam &

Rathore Surya, 2017; Yadav *et al.*, 2020) [43, 44], and documented gender gaps in extension contact and digital-technology access that leave women farmers, who frequently bear primary responsibility for pest-monitoring and hand-collection tasks, systematically under-served by mainstream extension channels, continue to constrain the reach of both FFS-style and digital IPM advisory delivery (Ahad *et al.*, 2024; Suman *et al.*, 2025) [45, 46]. Broader evidence from comparable smallholder ICT contexts indicates that digital advisory usability, farmer trust, and researcher readiness to responsibly deploy such tools remain critical, and frequently underdeveloped, preconditions for translating digital IPM advisory potential into realised farm-level economic benefit (Ndimbo *et al.*, 2025; Regan, 2021; Adesiji *et al.*, 2024; Sen *et al.*, 2024; Sen *et al.*, 2025) [47, 48, 49, 50, 51].

Table 2: Pest-specific IPM economics summary for sorghum and pearl millet

Pest/Complex	Crop	IPM Intervention Compared	Reported Economic Outcome	Key Source(s)
Shoot fly & stem borer	Sorghum	Seed treatment (imidacloprid/thiamethoxam) vs. rescue spray	Higher incremental BCR with preventive seed treatment	(Okosun <i>et al.</i> , 2021) [4]
Fall armyworm	Sorghum/Maize	Pheromone trap + biocontrol vs. calendar spraying	Threshold-based early-whorl management more cost-effective	(Bautista-Martínez <i>et al.</i> , 2025; Pomari-Fernandes <i>et al.</i> , 2015) [6, 20]
Sorghum midge & head bugs	Sorghum	Synchronized flowering vs. chemical dusting	Area-wide cultural control favoured over individual spraying	(Okosun <i>et al.</i> , 2021) [4]
White grub	Pearl millet	Seed treatment vs. soil drenching/furrow application	Seed treatment yields ~1:25 cost-benefit ratio	(Gahukar & Reddy, 2019) [2]
Head caterpillar & blister beetles	Pearl millet	Mechanical collection/trap cropping vs. chemical sprays	Lower cash cost but higher labour demand for mechanical control	(Gahukar & Reddy, 2019) [2]
Integrated pest & disease management	Pearl millet	Resistant hybrids + pest-specific IPM vs. either alone	Synergistic, not merely additive, economic return	(Juneja, 2024) [3]

Table 2. Consolidates the pest-specific economic evidence reviewed in Section 3, summarising the interventions compared

and their reported economic outcomes across the major sorghum and pearl millet pest complexes.

Table 3: Socio-economic adoption barriers and corresponding institutional strategies

Barrier Category	Representative Constraint	Institutional/Policy Driver	Key Source(s)
Technical complexity	Threshold monitoring perceived as skill-intensive	Farmer Field Schools; hands-on KVK training	(Varshney <i>et al.</i> , 2022) [34]
Input market access	Weak, unstandardised biocontrol/pheromone supply chains	Local augmentative biocontrol industry development	(Guerci <i>et al.</i> , 2018) [13]
Extension reach	Low staff-to-farmer ratios; infrequent visits	Digital and AI-enabled advisory as a scalable complement	(Cerjak <i>et al.</i> , 2025; Gupta & Pal, 2025) [37, 38]
Gender gaps	Women under-served despite primary pest-monitoring role	Gender-responsive extension and digital design	(Ahad <i>et al.</i> , 2024) [45]
Economic risk aversion	Uncertain returns deter investment in new modules	MRR-based, risk-transparent extension messaging	(Rasche, 2016) [8]

Table 3. Synthesizes the principal socio-economic and institutional barriers identified in Section 5 alongside the corresponding strategies and institutional drivers through which extension and policy actors have sought, with varying success, to address them.

6. Gaps in current literature and future research priorities

Several significant gaps constrain the current evidence base on IPM economics in sorghum and pearl millet. First, the great majority of rigorously reported cost-benefit evidence derives from single-season, single-location field trials or front-line demonstrations, with comparatively few multi-year, multi-location studies capable of capturing the substantial season-to-season variation in pest pressure that fundamentally shapes the

economic returns to threshold-based IPM relative to calendar-based spraying (Coulibaly *et al.*, 2024) [52]. Second, the economic literature on fall armyworm management in sorghum specifically remains thin relative to the extensive maize-focused evidence base, despite sorghum's demonstrated susceptibility and its particular importance to food security in fall-armyworm-affected regions of sub-Saharan Africa (Overton *et al.*, 2021) [5]. Third, labour-economics and gender-disaggregated cost accounting remain conspicuously underdeveloped in the sorghum and pearl millet IPM literature, with most reported cost-benefit analyses aggregating household labour into a single undifferentiated cost line despite well-established evidence that labour allocation, and its economic valuation, differs systematically by gender within smallholder cereal systems

(Doss *et al.*, 2025) [22]. Fourth, the economic feasibility and long-run sustainability of biocontrol input supply chains, an increasingly central component of recommended IPM modules for fall armyworm and other lepidopteran pests, remains evaluated in only a small number of contexts, leaving open important questions about the scalability of biocontrol-based IPM economics beyond donor- or project-supported pilot phases (Guerci *et al.*, 2018) [13]. Finally, rigorous evaluation of digital and AI-enabled pest advisory tools specifically for sorghum and pearl millet IPM decision-making remains almost entirely absent from the literature, despite the rapid expansion of Internet of Things (IoT)-based field sensing, generative AI advisory chatbots, and explainable machine-learning decision-support tools in adjacent crop and extension contexts, representing a priority area for future applied economic research (Gupta & Pal, 2025; Friha *et al.*, 2021; Deji *et al.*, 2023; High *et al.*, 2026; Chen *et al.*, 2023; Neeraja *et al.*, 2026; Roy *et al.*, 2026) [38, 53, 54, 55, 56, 57, 58].

A further, cross-cutting gap concerns price volatility and its interaction with IPM economics: nearly all reported cost-benefit and BCR figures are calculated using input and output prices prevailing at a single point in time, yet sorghum and pearl millet grain prices, and the prices of imported agrochemical inputs, can fluctuate substantially across seasons and years, meaning that a favourable cost-benefit ratio calculated under one price regime may not hold under another. Sensitivity analysis explicitly varying key input and output prices, though standard practice in some partial-budgeting frameworks, is only inconsistently applied across the reviewed sorghum and pearl millet literature, limiting the robustness with which reported economic returns can be generalised across the price volatility that resource-poor dryland farmers routinely face. Relatedly, cross-country and cross-regional comparability of reported economic outcomes remains limited by inconsistent currency conversion, cost-accounting conventions, and the frequent omission of the shadow price of family labour, complicating efforts to synthesise a globally consistent evidence base capable of informing international donor and research-investment prioritisation across the sorghum- and pearl-millet-growing regions of South Asia and sub-Saharan Africa.

7. Policy recommendations

Building on the evidence and gaps identified above, five policy priorities emerge for strengthening the economic foundations of IPM extension in sorghum and pearl millet. First, national and state agricultural research systems should institutionalize standardised, multi-location economic evaluation protocols, incorporating partial budgeting, BCR, and MRR reporting, as a mandatory component of front-line demonstrations for coarse cereal pest management, ensuring that the economic evidence base keeps pace with the rate of technical innovation. Second, targeted public investment in strengthening local biocontrol and pheromone-trap supply chains, potentially through public-private partnership arrangements modelled on successful augmentative biological control industries, is needed to translate favourable trial-level cost-benefit ratios into farm-level input accessibility (Guerci *et al.*, 2018; Pandey *et al.*, 2025; Ochieng *et al.*, 2023) [13, 59].

Third, extension curricula and Krishi Vigyan Kendra training modules should explicitly incorporate risk-transparent, MRR-based messaging alongside conventional yield-focused demonstration, given the particular salience of investment-risk considerations for the resourcepoor farmers who predominate

in sorghum and pearl millet cultivation. Fourth, gender-responsive design should be embedded as a default requirement, rather than an optional add-on, in both Farmer Field School curricula and digital advisory platform design, given women's disproportionate involvement in the pest-monitoring and hand-collection tasks central to many cost-effective IPM modules (Ahad *et al.*, 2024) [45]. Fifth, policy support for the continued expansion of digital and AI-enabled advisory delivery should be paired with sustained investment in rural connectivity infrastructure and rigorous, independent impact evaluation, ensuring that digital channels genuinely complement, rather than substitute for, the human extension capacity on which threshold-based IPM decision-making ultimately depends. Sixth, input subsidy design should be recalibrated where necessary to avoid inadvertently favouring calendar-based chemical spraying over demonstrably more cost-effective preventive alternatives such as seed treatment; subsidy structures that reduce the effective price of insecticide relative to seed-treatment chemicals or biocontrol agents risk distorting farmers' technology choice away from the economically superior IPM pathway identified throughout this review. Seventh, and finally, national agricultural statistics and crop-cutting survey systems should be extended to capture plant-protection expenditure and pest-related yield loss at a level of crop and pest-specific disaggregation sufficient to support the kind of standardised, multi-location economic monitoring called for above, ensuring that future policy decisions concerning coarse cereal pest management rest on a progressively strengthening, rather than persistently fragmented, economic evidence base.

8. Conclusion

The accumulated economic evidence reviewed in this article demonstrates that Integrated Pest Management offers a consistently favourable economic proposition relative to calendar-based chemical control across the major insect pests affecting sorghum and pearl millet, from shoot fly and stem borer seed treatment in sorghum, through fall armyworm biorational and threshold-based management, to white grub seed treatment in pearl millet, where cost-benefit ratios in the order of 1:25 have been documented. These favourable returns are not, however, uniformly realized at scale, and the gap between demonstrated trial-level profitability and actual farm-level adoption reflects a persistent combination of input-market weaknesses, extension-reach limitations, labour and gender dimensions that remain poorly quantified in the existing literature, and farmers understandable caution in the face of investment risk under highly variable dryland growing conditions. Addressing this adoption gap will require extension and policy systems that treat economic evidence generation as integral to, rather than separate from, technical IPM research, that invest deliberately in the input-supply infrastructure needed to translate favourable costbenefit ratios into accessible farm-level options, and that design both conventional and digital advisory delivery with explicit attention to the gender and risk dimensions of smallholder decisionmaking. As sorghum and pearl millet receive renewed policy attention as climate-resilient, nutritionally important coarse cereals, ensuring that their pest management economics are as rigorously understood and as effectively communicated as those of the major commercial crops will be essential for translating this renewed attention into durable gains in farmer income, food security, and sustainable dryland cereal production.

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