Strengthening Integrated Pest Management through Eco-Friendly Technologies

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Integrated Pest Management (IPM) has emerged as a critical approach for ensuring sustainable crop protection while minimizing environmental and health risks associated with indiscriminate pesticide use. Increasing concerns over pesticide residues, resistance development, ecological toxicity, and regulatory restrictions have created an urgent need for validated bio-based alternatives, safer pesticide selection tools, and scientifically tested low-risk pest management strategies. At the same time, large volumes of Indigenous Technical Knowledge (ITKs) and natural resources remain underutilized due to lack of scientific validation and standardization. Addressing these gaps requires translational research that combines traditional knowledge systems, toxicological science, bioassay validation, and field-scale testing to develop practical, scalable IPM solutions.

The research contributions have been developed under the broader mandate of IPM with the objective of reducing chemical risk, validating bio-based alternatives, improving pesticide safety decisions, and developing scalable eco-compatible technologies for crop and post-harvest protection. The work integrates indigenous knowledge (ITK) validation, pesticide risk assessment, toxicological modelling, post-harvest pest control, and natural product innovation, leading to patents and commercialization.

1. ITK in plant protection

A major milestone was the scientific validation of Indigenous Technical Knowledge (ITKs) through the development and standardization of a cow urine based formulation (CBF) within the IPM framework. The formulation was evaluated under laboratory and it could effectively inhibit *Rhizoctonia bataticola*, *Sclerotinia sclerotiorum* and *Pythium aphanidermatum* compared to untreated control. It was tested on tomato crop under field studies for two consecutive years, and two sprays of this formulation @ 3% at nursery stage and four sprays @ 10% at flowering, fruiting and maturing stage, gave promising results in controlling tomato fruit borer, leaf miner, mites and whitefly giving good yield of the produce. The observed yield in CBF treated tomato fields with zero inputs (no fertilizers or any other inputs used in the soil) was 36 t/ha as compared to 15 t/ha in check plots and 17 t/ha in organically treated plots during 2006-08. Detailed compositional analysis of the CBF revealed the presence of essential macro and micronutrients at levels adequate to support crop growth, indicating that the formulation could contribute to plant nutrition without requiring additional nutrient supplementation under tested conditions. The CBF demonstrated dual functionality as a plant growth regulator and pest management input.

Its consistent performance as a bio-based IPM tool resulted in granting a patent *Biopesticide formulation for controlling insect pests and fungal pathogens and process for preparation there of*" from Indian Patent House in 2018 followed by its commercialization through three Indian companies, enabling farmer-level adoption of a validated traditional technology. The CBF has been registered under the trade name "Coneem" as a plant growth regulator, and the trademark was granted in 2019 under Application No. 3896650 in accordance with the Trade Marks Act, 1999, Government of India. This innovation was highlighted in ICAR news in 2018 under the title, '*An indigenous biopesticide enhances tomato yield*'. In continuation of ITK-based bioresource validation under the IPM framework, systematic studies were conducted on plant-derived compounds through solvent extraction and chromatographic fractionation. One such investigation involving *Ailanthus longifolia* led to the isolation of an active column fraction that demonstrated highly promising insecticidal activity at very low concentrations (as low as 10 ppm). The fraction showed significant efficacy against both sucking and chewing pests, including mustard aphid (*Lipaphis erysimi*) and the lepidopteran pest *Helicoverpa armigera*. This work highlighted the strong potential of plant-based bioactive fractions as low-dose, eco-compatible pest management tools and reinforced the scientific value of Indigenous Technical Knowledge–based plant resources within modern IPM strategies.

Effective visibility of the indigenous formulation with Zero inputs

2. Pesticides with reduced risk to environment

To promote safer pesticide use within IPM programs, the Environmental Impact Quotient (EIQ) model was applied to pesticide usage patterns in the rice cropping system of Sitapur district, Uttar Pradesh. Rice is among the highest pesticide-consuming crops in India, and indiscriminate pesticide application remains a major constraint to sustainable agricultural development. Field surveys indicated widespread non-IPM pesticide use practices among farmers, leading to elevated environmental risk and avoidable input costs.

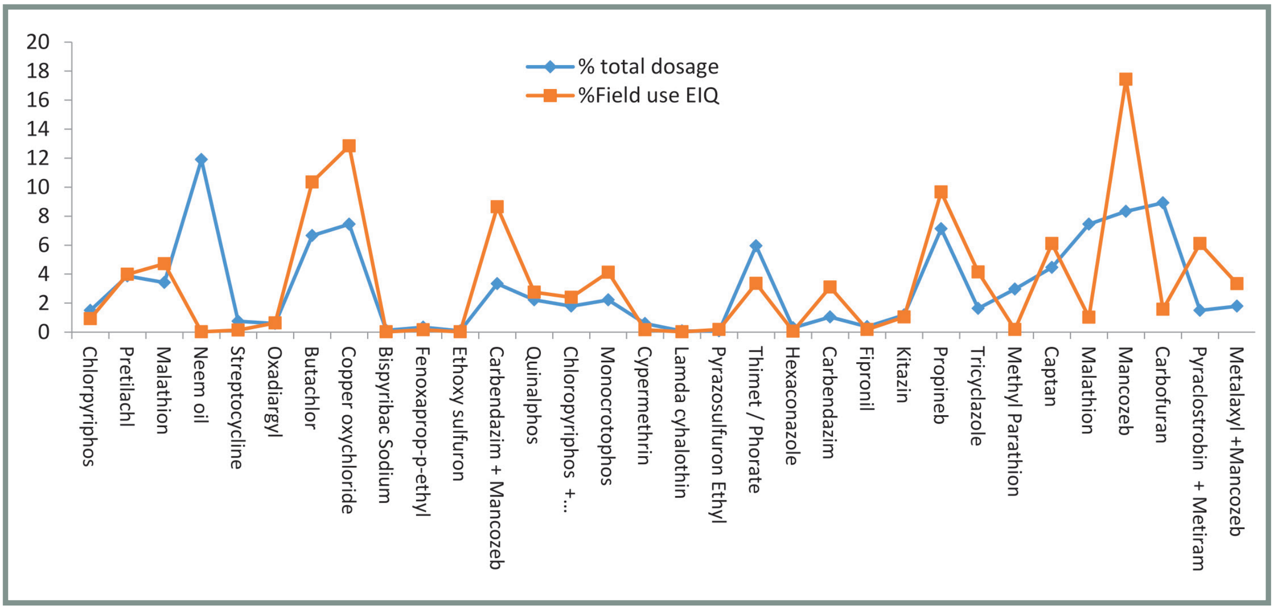

Fig. 1. EIQ Product Profile ranked by % formulated dose

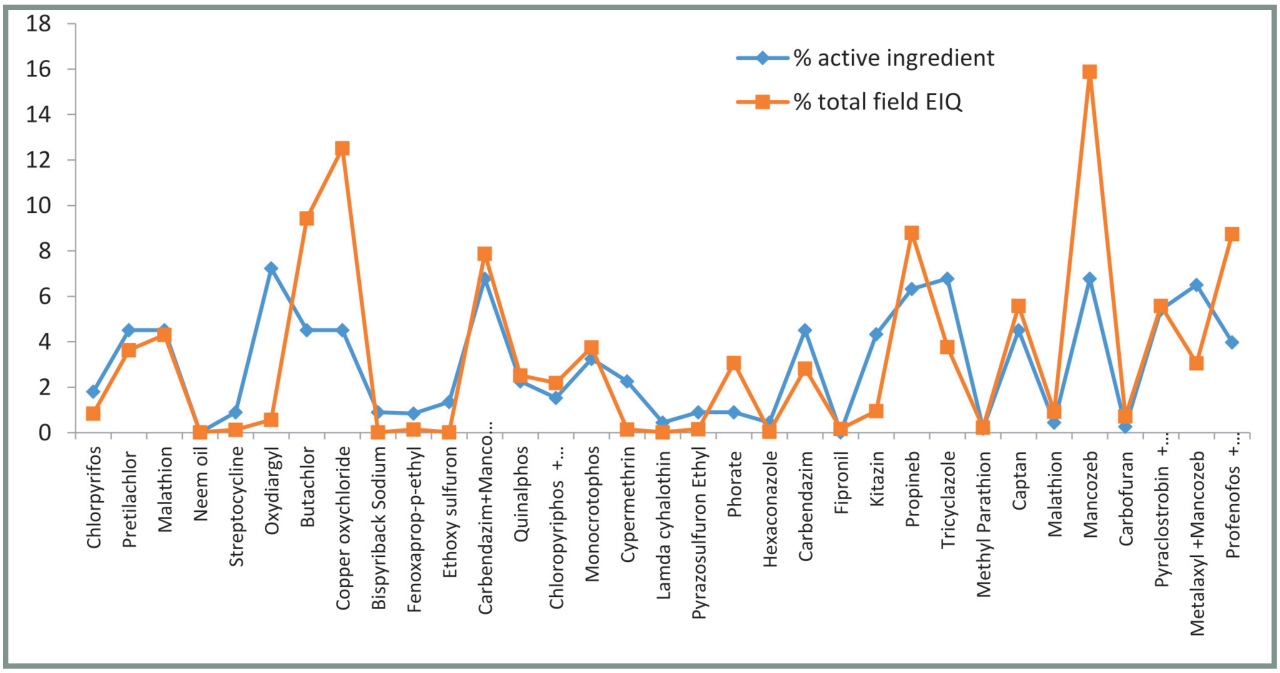

Fig. 2. EIQ Product Profile ranked by % active ingredient

The EIQ, a science-based decision-support tool developed for evaluating the inherent toxicity and environmental impact potential of pesticide molecules, was adapted and applied under local field conditions to guide safer pesticide selection. Soil samples were analyzed for impacts on soil flora and fauna, including both beneficial and harmful organisms. Comparative analysis of percentage dosage, percentage of active ingredient applied, and percentage contribution to total field EIQ revealed that certain fungicides (mancozeb and copper oxychloride) and the herbicide butachlor contributed disproportionately to environmental risk and were identified as high-risk inputs (Fig 1 & 2).

In contrast, some insecticides categorized under WHO Class I hazard category, such as carbofuran and phorate, contributed relatively small proportions to the total field EIQ (1.6% and 3%, respectively), demonstrating that hazard classification alone may not reflect field-level environmental impact. Mixture effects further highlighted the importance of EIQ-based evaluation: cypermethrin alone showed limited impact, but when combined with profenofos, it emerged as a major contributor to total field EIQ, indicating synergistic risk behavior. Conversely, mancozeb alone showed the highest contribution to total field EIQ, whereas its combination with metalaxyl resulted in substantially lower impact, indicating antagonistic interaction. This analytical approach enabled identification of pesticide products and combinations that contributed disproportionately to environmental risk relative to their application rate, thereby supporting their avoidance or substitution within IPM programs.

Field comparisons of management strategies showed that IPM modules had the least ecological impact, with 30–40% increase in natural enemy populations and weed levels were maintained below 10%. In contrast, prevailing farmer practice resulted in approximately 20% reduction in crop yield, 50% reduction in biodiversity and nearly 150% increase in weed population relative to untreated control fields. Total field EIQ values further indicated that farmer practice posed about 56% greater environmental risk compared to IPM-based management (EIQ rating was 141 under farmer practice and was 62 under IPM conditions). These findings demonstrate that the EIQ model is a practical and effective tool for pesticide risk assessment and can be readily adopted by pesticide managers and IPM planners to support environmentally responsible pest management decisions.

3. Toxicity assessment of pesticides for IPM strategies

A technology platform was also developed for assessing pesticide toxicity in binary mixtures relevant to real-world IPM spray practices and environmental exposure scenarios. Since pesticides frequently occur in the environment as mixtures through agricultural runoff and effluent discharge, their combined risk cannot be reliably predicted from individual compound assessments alone. The developed approach utilized dose responsive modelling to characterize mixture effects and determine whether interactions were additive, antagonistic or synergistic across pesticides with similar or different modes of action, particularly in aquatic ecosystems containing living organisms.

The methodology combined biochemical and organism level indicators to strengthen environmental risk assessment. *In-vitro* enzyme inhibition studies were conducted using a scaled-down assay based on purified acetylcholinesterase (AChE) from housefly head enzyme systems as a sensitive bioindicator. A total of nine commonly co-occurring pesticides, including organophosphates, carbamates, and synthetic pyrethroids, along with their binary combinations, were evaluated. *In-vivo* biomarker studies were conducted using fingerlings of *Bidyanus bidyanus* fish as aquatic bioindicator organisms to capture sub-lethal and behavioral toxicity responses that are not detected through residue analysis alone.

The approach demonstrated very high analytical sensitivity, detecting enzyme inhibition and toxic effects at environmentally safer concentrations (IC_{10}), with sensitivity levels 50–100 times greater than conventional toxicity endpoints. Results showed that several pesticide mixtures, even at low concentrations that did not produce immediate lethal effects, caused significant impairment in fish behavior and physiological activity. Importantly, findings indicated that pesticide residues present at or below maximum residue limits (MRLs) may still pose substantial ecological risk when present in mixtures.

Mixture dose calculations at IC_{10} levels, generally considered environmentally safe, frequently produced toxicity comparable to or greater than the recommended doses of individual pesticides, demonstrating strong synergistic behavior. In several cases, combining pesticides at as little as 1/50th of their standard application rates resulted in toxicity levels many times higher than those observed for single compounds. The technology proved capable of detecting pesticide effects at parts-per-trillion (ppt) levels and effectively capturing synergistic amplification in combined exposures.

This mixture-toxicity assessment framework provides a highly sensitive and practical tool for screening environmental samples and strengthening pesticide risk analysis by integrating chemical residue measurement with biomarker-based early warning indicators. The approach supports improved ecological risk evaluation and safer pesticide use strategies within IPM programs by emphasizing mixture effects rather than single-compound toxicity alone.

4. Post-harvest pest management

Effective post-harvest pest management is essential for safeguarding the quantity, quality, and market value of agricultural produce across commodities such as food grains, pulses, dry fruits, spices, and perishable fruits, vegetables, and flowers. Significant losses occur after harvest due to insect infestation, contamination, and quality deterioration during storage, transport, and marketing. These losses not only reduce food availability and farmer returns but also affect seed viability, nutritional quality, trade standards, and export potential.

In the post-harvest IPM, multi-locational laboratory and field trials were undertaken to evaluate phosphine (PH_3) fumigation against stored-grain insects under quarantine and pre-shipment (QPS) as well as long-term storage conditions. Methyl bromide (MBr), widely used for QPS treatments and grain storage pest control, is being phased out globally under the Montreal Protocol due to its ozone-depleting potential. In addition, international trade restrictions on MBr-treated consignments have created economic and regulatory challenges, highlighting the urgent need for an effective and compliant alternative.

Phosphine, that is already registered for domestic use and is internationally accepted, was systematically evaluated across diverse agro-ecological regions to standardize dosage and exposure protocols for reliable insect control in cereals and pulses. This work gained particular importance during periods of surplus pulse production, when safe and effective long-term storage solutions were urgently required. A phosphine-based fumigation protocol was developed and validated based on extensive field trials for QPS and bulk storage applications using 1.5 g/m^3 phosphine delivered through 56% aluminium phosphide tablets and 77.5% granule formulations. The standardized treatment achieved effective control of major storage insect pests within a 7-day exposure period, with no insect emergence recorded up to 60 days after treatment. The terminal concentrations of PH_3 gas for different dosages, under field trials, were observed in the range of 250-800 ppm. The residues of PH_3 in all fumigated food grains, from different locations, were observed below MRL. The observations based recommendations were submitted to DAC, ministry of agriculture for implementation for trading of food grains treated with phosphine. *This developed protocol has been certified by ICAR under certificate number ICAR-CS-NRIIPM-Process-2025-030.*

The fumigation approach was successfully extended and validated for use on a wide range of perishable commodities, including fruits, vegetables, and cut flowers, thereby substantially broadening the scope of IPM-based post-harvest protection strategies. Phosphine fumigation demonstrated high efficacy in managing economically important insect pests across multiple commodities, such as aphids (*Macrosiphoniella sanbornii*) in chrysanthemum flowers, thrips (*Rhipiphorothrips cruentatus*) in rose flowers, thrips (*Scirtothrips dorsalis*) in chilli fruits, fruit fly larvae (*Bactrocera dorsalis*) in mango, and fruit fly (*Bactrocera cucurbitae*) in bitter gourd during storage. Effective control was achieved under varying exposure periods ranging from 4 to 15 hours, depending on the commodity and pest load (Table 1). Detailed post-treatment evaluation of treated produce included assessment of physical as well as biochemical quality parameters, which confirmed that commodity quality and nutritional attributes were not adversely affected by phosphine treatment. In addition, systematic analysis of phosphine residues and sorption behavior showed only trace-level residues in all treated commodities, consistently remaining below the MRLs prescribed by the Codex Alimentarius Commission (CAC), thereby establishing both the safety and practical applicability of the protocol for perishable produce systems.

This validated phosphine fumigation technology supports regulatory compliance, reduces dependence on methyl bromide, minimizes trade-related losses, and provides a practical, scalable solution for researchers, storage managers and policymakers involved in post-harvest pest management.

Phosphine is currently the only single-molecule fumigant registered with Central Insecticides Board and Registration Committee (CIBRC) for stored-product protection, and resistance to phosphine has been widely reported in several major storage insect pests. Following the phase-out of MBr, there is an urgent need to identify and register additional fumigant molecules for effective storage pest management. Under post-harvest pest management programs, newer fumigants, namely e-fume (a mixture of 83.3% CO_2 and 16.7% ethyl formate) for stored insects of food grains and dry fruits and EDN (ethanedinitrile) for timber insects, were evaluated under laboratory and multi-location field conditions to generate data required for CIBRC registration in India. The study was supported by Draslovka Services India (DSI) Pvt Ltd.

Field trials were conducted in fumigation cocoons at multiple locations including Jaipur, Kandla (Gujarat), and Mumbai/Pune to assess the efficacy of e-fume fumigant at three dosage levels (340, 420, and 525 g/m^3) with a 24-hour exposure period. Target pests included major stored-grain insects, *Trogoderma granarium* (khapra beetle larvae), *Tribolium castaneum* (red flour beetle adults and larvae), *Sitophilus oryzae* (rice weevil adults), and *Rhyzopertha dominica* (lesser grain borer adults), as well as dry fruit pests *Ephestia cautella* (almond moth) and *Lasioderma serricorne* (cigarette beetle). EDN was separately evaluated against timber insects at Bengaluru, Mumbai, and CAFRI, Jhansi. The experiments were laid out with five treatments comprising three dosages of e-fume, one positive control (MBr @ 32 g/m^3), and one untreated control, each with four replicates.

Laboratory-reared target insects were placed in perforated plastic containers and distributed at different positions within the commodity stacks inside the cocoons. Gas concentration levels were monitored at multiple time intervals viz. 30 minutes, 1 hour, 6 hours, 12 hours and 24 hours for each treatment replicate. Observations recorded after fumigation showed that e-fume and EDN achieved 95–100% mortality of stored-product and timber insects across treatments. The reports based on laboratory and field have been submitted along with application for registration of these molecules have been submitted to CIBRC by DSI.

stored food grain insect management using e-fume (83.3% CO_2 + 16.7% ethyl formate) by fumigating wheat grain stacks at Jaipur.

Timber insect management using EDN (ethane dinitrile) by fumigating stacks of wooden logs at Jhansi.

Table 1. Impact on quality of phosphine treated perishable commodities

Commodity	Name of commodity	Exposure period	Effective concentration	Quality parameters		Residues (ppm)	Remarks
				Physical	Biochemical		
Vegetables	Bitter gourd	4	1400	Moisture Content, Colour, Texture	Chlorophyll content, Ascorbic Acid (AA), and Total Soluble Solids (TSS)	0.1	No significant difference was observed in any quality parameter of treated and untreated control samples
		6	1200			0.09	
		8	1100			0.1	
		10	800			0.1	
		15	600			0.07	
	Chillies	4	60	Moisture Content, colour and Texture	Chlorophyll content, Ascorbic Acid, TSS, and Antioxidants	0.01	
		6	50			0.01	
		8	40			0.015	
		10	30			0.02	
Fruits	Mango	4	1500	Texture, and Physiological loss in weight (PLW)	Titratable Acidity (TA), Carotenoids	0.03	-do-
		6	1200			0.019	
		8	1000			0.03	
		10	800			0.024	
	Pomegranate	10	0, 500, 1000, and 2000	PLW, Juice Yield, and Juice pH	TSS, AA, phenols, TA, Antioxidants, Anthocyanins		-do- Infested samples could not be arranged
		24	0, 500, 1000, and 2000	PLW, Juice Yield, and Juice pH,	-do-		
Flowers	Chrysanthemum	4	2400	Water uptake, vase life, Initial & final Dry weight	Anthocyanins content	0.24	No significant difference was observed in quality parameter of treated and control samples
		6	2200			0.21	
		8	1400			0.21	
		10	1200			0.17	
	Roses	4	65	-do-	-do-	0.02	-do-
		6	55			0.003	
		8	50			0.004	
		10	40			0.008	