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Stored-Product Entomology in the Digital Era: Smart Monitoring, Semiochemicals and Precision Protection of Stored Grains

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INTRODUCTION

Stored grains—rice, wheat, maize, sorghum, millets, pulses, oilseeds—may remain in storage for months, exposed to insects, mites, microorganisms and deterioration. Stored-product insects multiply rapidly, turning small infestations into serious problems. Key pests include rice weevil, maize weevil, lesser grain borer, khapra beetle, red and confused flour beetles, cigarette beetle and Indian meal moth. Effects include broken kernels, powder, frass, webbing, odours, heating, and conditions favouring secondary microbial deterioration. Traditional management—sanitation, drying, aeration, insecticides, fumigation, periodic inspection—remains essential but lacks precision about pest location, intensity and development. Digital technologies can shift pest management from periodic observation to near-continuous surveillance.

Stored-Product Insects and the Storage Ecosystem

Insects differ in feeding habits, mobility, reproduction and environmental needs. Primary pests attack intact kernels; secondary pests exploit damaged grain. Temperature and moisture strongly influence development—warmth accelerates reproduction, excess moisture increases both insect and microbial activity. Bulk storage is a three-dimensional ecosystem where infestations spread from localized points through grain masses, walls and equipment, so a single inspection point rarely represents the whole facility. Spatially distributed monitoring is increasingly important.

Limitations of Conventional Monitoring

Visual inspection, sampling, sieving and probing are inexpensive but limited when infestations are concealed, localized or low-density. Insects may hide inside kernels or structural areas, and manual inspection depends on labour and observer experience, often producing fragmented data. Delayed detection—once damage is already visible—loses opportunities for cheap preventive action. Smart monitoring addresses this by providing early warnings from insect activity and environmental changes.

Smart Monitoring and Digital Transformation

Smart monitoring combines sensors, automated data collection, communication and analytics to identify species, location and population trends alongside environmental conditions. Digital pheromone traps use cameras or optical sensors to detect and count insects automatically, transmitting data to a central dashboard and reducing manual inspection. Environmental sensors continuously track temperature, humidity and grain moisture; combined with insect data, this gives a fuller risk picture. Wireless sensor networks across warehouses and silos provide location-specific information, letting managers prioritize zones with rising insect activity.

Semiochemicals in Stored-Product Pest Management

Semiochemicals—chemical behavioural signals—are valuable because pheromones attract specific species, enabling selective monitoring even at low insect numbers. Beyond detection, they support mass trapping, attract-and-kill systems and behavioural manipulation. Food-derived attractants and controlled-release formulations extend lure effectiveness, which is especially useful for automated traps needing minimal intervention. Semiochemicals also integrate with biological, physical and chemical control, expanding their role from detection to broader behavioural management.

Automated Image-Based Detection

Computer vision increasingly identifies and counts trapped insects via cameras and image processing. Machine-learning and deep-learning models classify insects by shape, size and colour when trained on sufficiently large datasets. This reduces labour and standardizes observation, but dust, poor lighting, overlapping or damaged specimens, and orientation differences complicate deployment—requiring training data from real storage environments, not just lab images.

Acoustic, Vibrational and Volatile Detection

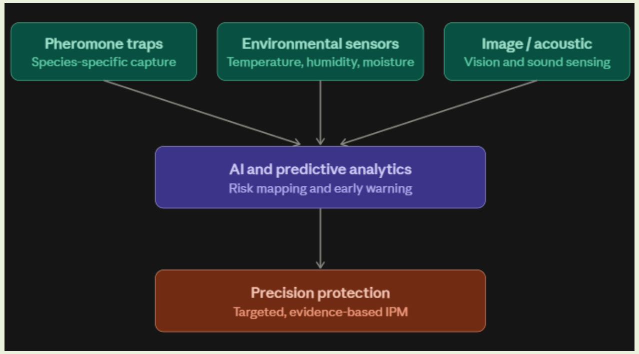
Acoustic and vibrational sensors can detect larval feeding or movement inside kernels without extensive sampling, though machinery and environmental noise can interfere. Volatile detection via electronic-nose systems can sense chemical changes from insect activity or grain deterioration, complementing pheromone-based monitoring.

Artificial Intelligence and Predictive Pest Management

AI's greatest value comes from combining monitoring data—captures, temperature, humidity, moisture, storage duration, commodity type, history—into predictive risk models rather than just present-population reports. Rising temperature with increasing trap captures might signal conditions for rapid growth, triggering early warnings. AI can also flag abnormal spatial patterns, such as one zone showing rising activity while others stay stable. However, models need careful validation, since performance under controlled conditions may not translate to commercial storage, and the trap-capture-to-infestation relationship varies by species, trap design and structure.

Precision Protection of Stored Grains

Precision protection directs resources by actual risk rather than treating facilities uniformly, since pest activity often concentrates in specific locations. Digital mapping of trap captures across a facility reveals hotspots, movement pathways and risk-prone areas, enabling targeted sanitation, grain removal, moisture correction, aeration adjustment or selective chemical treatment—reducing unnecessary treatment and making management more evidence-based.



Integration with Integrated Pest Management

Digital monitoring should strengthen, not replace, IPM principles: sanitation, drying, moisture management, and aeration remain fundamental. Where insecticides or fumigants are needed, monitoring can improve treatment timing and target problem areas, and post-treatment activity changes can indicate effectiveness. Physical, biological and behavioural methods integrate similarly, aiming for a continuous cycle of prevention, monitoring, decision-making, intervention and reassessment.

Challenges and Future Prospects

Adoption barriers include high costs of sensors, cameras and communication systems, especially for small facilities, making affordable, robust technology essential. Data quality is critical—sensors need calibration, traps need standardized placement, and AI needs reliable training data. Interoperability across devices with incompatible data formats is another hurdle; future platforms should unify pheromone traps, sensors, image recognition, acoustic monitoring and management software. Establishing reliable action thresholds is also needed, since detecting insects doesn't automatically justify treatment—research must better link captures, infestation levels, damage and economic loss. The most practical systems will likely combine automation with human expertise: AI generating alerts and patterns, entomologists interpreting unusual cases.

CONCLUSION

Stored-product entomology is moving from manual inspection toward continuous, connected, predictive pest management. Smart sensors, automated traps, image recognition, acoustic and volatile detection, AI and spatial analysis can significantly improve detection and management of stored-grain insects. Semiochemicals offer biologically informed, species-specific tools that, combined with digital monitoring, create responsive early-detection systems. The goal is not technological sophistication for its own sake, but more effective protection, earlier detection, efficient resource use and reduced reliance on unnecessary chemical intervention. Future research should prioritize affordable sensors, standardized protocols, robust AI models, reliable economic thresholds, and integration with physical, biological, behavioural and chemical management—positioning the convergence of entomology, sensor technology, data science and precision agriculture as a foundation for next-generation stored-grain protection.