

Smart Crop Protection in the Digital Era: Emerging Technologies for Integrated Pest Management

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ABSTRACT

Agriculture is undergoing a new era in which digital technologies are becoming more prevalent in the crop production and pest management practices of traditional farmers. Although insect pests are still considered as a major problem to agricultural productivity there is a concern over excessive and indiscriminate use of pesticides which can pose environmental, economic and ecological issues. Integrated Pest Management (IPM) is a sustainable framework and is based on monitoring pest populations and making decisions about action on pests using a combination of biological, cultural, mechanical, physical and chemical methods. Digital agriculture can support this framework with artificial intelligence (AI), machine learning, Internet of Things (IoT), remote sensing, unmanned aerial vehicles (UAVs), computer vision, geographic information systems (GIS) and digital decision-support systems. These technologies provide the ability to identify pests quickly, monitor them automatically, estimate population levels, provide early warning, map their location and take targeted action. The fusion of AI, field sensors and remote sensing may also have the potential to bring about a paradigm change in pest control, transitioning from reactive and

calendar-driven approaches to timely, site-specific and information-driven interventions. Some constraint issues with data quality, model accuracy, infrastructure, cost, connectivity and field validation still exist, however. Finally, the smart crop protection of the future relies on the combination of digital technologies, pest ecology, economic thresholds, use of biological control, and farmer knowledge. Well-validated digital tools can be an important component of sustainable and precision-based IPM. This will be useful for anyone involved in digital agriculture or precision crop protection, as well as those interested in integrated pest management and AI in precision agriculture.

INTRODUCTION:

Insect pests, disease, climate variability, labour shortfalls and the need to produce more food on less environmental resources are increasingly threatening agricultural production. Insect pests may be a source of significant losses in crop productivity and quality and frequent or inappropriate pesticide use can lead to insecticide resistance, undesirable changes of beneficial organisms and environmental contamination. Integrated Pest Management (IPM): an ecological approach that incorporates multiple pest management practices and uses different tactics based on the abundance of pest and/or damage to the crop and economic factors. Digital agriculture is growing and offers the potential to enhance this strategy. Artificial intelligence, machine learning, sensors, smartphones, drones, and satellite imagery and cloud computing can produce and analyse information at a rate never before known. These technologies can be used in conjunction with conventional field scouting to give more information relating to pest occurrence, crop stress and environment.

The recent developments of AI, Internet of Things (IoT), computer vision, UAVs and sensor technologies have attracted attention to their growing potential in smart pest monitoring, forecasting and management (Rameash, 2025). The new idea of smart crop protection thus seeks to link observation from the field and scientific decision options.

Digital technologies do not aim to replace IPM; they can enhance the monitoring and decision-making aspects of IPM, potentially making them quicker, more accurate and more reactive.

Digital Technologies for Smart Pest Management

Artificial Intelligence and Machine Learning: Artificial intelligence (AI) is an emerging and useful technology in crop protection today. Machine learning (ML) and deep learning algorithms can detect patterns in images, environmental observations and historical pest data. Images of insects on mobile phones, camera or automatic traps can be used for identification of pest species, abundance estimation or crop damage assessment.

Deep-learning techniques, especially image-based ones, can identify intricate visual characteristics and categorize insects or symptoms. AI can also be employed to interpret environmental data like temperature, humidity and rainfall in conjunction with pest observations to inform pest forecasting.

One of the great things about AI is its ability to analyse massive amounts of data in a short amount of time. But an AI model shouldn't be thought of just as an automated insect-identification tool. It has a higher level of value in IPM when data from identification and monitoring is linked to pest threshold

limits and management decisions. However, recent studies underscore the need to integrate AI-driven sensing into operational IPM, not for detection alone, but as a means to achieve effective management (Amiri & Bandani, 2026).

Internet of Things and Smart Sensors: The Internet of Things (IoT) is a new paradigm of the Internet where everything is connected to share, collect and exchange information. In the field of agriculture, IoT sensors can be used to continuously track the condition of the crops, soil moisture, rainfall, humidity, and temperature of the microclimate. Pest traps that utilize a camera or a sensor can give you information about pest activity without having to manually inspect the traps often. AI algorithm analysis of images and observations can be sent to a central platform. These systems may be able to offer near real-time information on pest population changes. The pairing of IoT and AI is especially intriguing due to the ability of sensors to capture real-time data from the field and the potential for AI to process that data and uncover patterns that are important for pest management. This integration has been recognized as a significant pathway towards smart pest monitoring and forecasting (Rameash, 2025).

UAVs and Remote Sensing: High resolution observations of agricultural fields are obtained through the use of Unmanned Aerial Vehicles (UAVs), also known as drones. Depending on the application, cameras on UAVs may be able to capture RGB, multispectral, hyperspectral or thermal data. Using remote sensing, it is possible to detect the spatial variability of the crop condition and to detect abnormal stress areas. Observations can be repeated to track change over time and GIS can transform observations into spatial maps of pest risk.

The potential of UAVs with AI is significant. Machine-learning and deep-learning techniques can be used to analyse large

datasets of images and detect patterns that are correlated with crop stress or pest infestation. In the last few years, remote sensing using UAVs in combination with AI has been reported to be used more and more for crop pest and disease monitoring, and field validation and transferability of models and methodologies were highlighted (Aziz *et al.*, 2025).

From Pest Detection to Pest Decision

The real strength of digital agriculture lies in connecting detection with decision-making. A smart IPM system can be represented as:

Field observation → Digital sensing → AI-based identification → Population estimation → Forecasting → Economic/action threshold → Management decision → Precision intervention → post-treatment monitoring.

This sequence is important because the presence of an insect does not automatically mean that pesticide application is required. IPM decisions depend on pest density, crop growth stage, potential economic damage, natural-enemy populations, weather conditions and management thresholds.

The process of decision making for IPM should be reinforced by digital agriculture and not be the basis for automatic use of pesticides. An AI-based system can offer information for decision-making on the timing, place and why intervention might be justified. This aligns with recent works on the development of IPM decision support systems and AI based pest identification and prediction (Amiri & Bandani, 2026).

Precision Pest Management

Digital technologies can also help to control spatial precision in pest-management operations. The traditional field spraying method has the tendency to apply the same spray to the entire field, even if pests are

localized in certain areas of the field. UAV imagery, GIS-based maps and observations using sensors can assist in identification of potential pest hotspots. Precision equipment can then pin-point certain areas for treatment, which may minimize unnecessary treatment of pest-free areas within a field.

However, technological precision does not automatically result in sustainable pest management. The accuracy of the underlying pest detection, appropriate threshold selection and correct interpretation of field information remain essential. Therefore, digital tools should operate within an established IPM framework rather than functioning independently.

Digital Agriculture in Rice Pest Management

Rice is an important crop in which digital pest-management approaches have considerable potential. Major insect pests include yellow stem borer, *Scirpophaga incertulas*; rice leaf folder, *Cnaphalocrocis medinalis*; brown planthopper, *Nilaparvata lugens*; rice gall midge, *Orseolia oryzae*; and rice hispa, *Dicladispa armigera*.

A digital rice IPM platform could integrate several technologies:

- Smartphone-based pest identification
- Automated or smart traps to monitor insects
- Crop surveys utilizing UAVs and Weather sensors for microclimate monitoring
- The automated translation of plant species names from foreign language
- Historical data and information on population projections
- Risk assessment and management based on GIS

- Mobile-based farmer advisories.

For example, automated monitoring of adult yellow stem borer populations could provide information about pest activity, while crop-stage information and weather data could be incorporated into forecasting systems. Similarly, image-based systems could assist in recognizing characteristic damage symptoms such as dead hearts and white ears caused by stem borer infestation or folded and damaged leaves associated with leaf folder attack.

Such systems could be particularly useful when integrated with conventional entomological surveillance rather than used as a complete replacement for field expertise.

Digital Tools and Sustainable IPM

The major opportunity provided by digital agriculture is a shift from calendar to information-based pest management. Rather than having a set schedule for pesticide application, farmers would be provided with management information based on the occurrence of a pest, the stage of the crop and environmental conditions. If the pests are not at an economically important level, it may not be necessary to intervene. If a pest hotspot is identified, appropriate control measures can, if necessary, be targeted to the affected area. The efficiency and sustainability of crop protection (Aziz *et al.*, 2025; Amiri & Bandani, 2026) are being investigated with the help of AI enabled crop protection systems, with the aim of early detection, prediction and precision intervention.

Digital tools can also be used to complement non-chemical aspects of IPM. Knowledge of pest occurrence can provide information to help direct biological control programmes, deployment of resistant varieties, cultural control, and conservation of natural enemies. Thus, the ultimate goal should be better pest-

management decisions, rather than simply greater automation.

Major Challenges

Despite considerable technological progress, several limitations must be addressed.

Data quality and availability: AI systems require large, representative and accurately labelled datasets. Models developed under controlled conditions may not perform equally well under diverse field environments.

Field variability: Lighting, background vegetation, insect developmental stages, crop varieties and weather conditions can influence image-based detection. Recent research has identified limited external validation and variability among field conditions as important barriers to practical deployment (Aziz *et al.*, 2025).

Infrastructure and cost: Sensors, UAVs, high-performance computing and reliable internet connectivity may not be equally accessible to all farmers.

Model reliability: A high accuracy reported under experimental conditions does not necessarily guarantee reliable performance across different geographical regions, crops or seasons.

Farmer usability: Digital systems must provide simple, understandable and actionable information. A technically sophisticated system may have limited value if farmers cannot operate it or interpret its recommendations.

Future Perspectives

In the future, combinations of different technologies will become ever more important than their individual application in the field of smart crop protection. Digital decision-support platforms can integrate AI, IoT, UAVs,

satellite imagery, GIS, and mobile Apps and field sensors.

A promising future is the multimodal data fusion, that is, analysis of pest images, weather observations, crop phenology, historical pest data and remote sensing data. This kind of systems could have potential to enhance pest forecasting and offer more context-specific recommendations.

Future research should also emphasize explainable AI, low-cost sensors, edge computing, standardized pest-image databases and multi-location field validation. Recent research has particularly highlighted the need to overcome dataset bias, limited generalizability, infrastructure constraints and insufficient validation before AI-based crop-protection systems can be widely deployed (Amiri & Bandani, 2026).

For developing agricultural systems, including those dominated by small and medium-scale farmers, affordability and accessibility will be as important as technological sophistication.

CONCLUSION

Digital agriculture is creating a new route to modernizing integrated pest management. AI, machine learning, IoT sensors, UAVs, remote sensing, computer vision and GIS can support increased efficiency of pest surveillance, identification, forecasting, risk mapping and precision intervention. The future of crop protection, however, is not to be decided by the substitution of farmer or entomologists by machines.

The true promise is the blending of digital intelligence and ecological knowledge and human expertise. Smart technologies can facilitate more timely, precise and sustainable crop protection by combining digital observations with pest biology, economic thresholds and biological control and appropriate management practices.

So, digital IPM is not a paradigm shift, it is an augmentation of the existing concepts of conventional IPM. Digital agriculture can be a key element of sustainable crop protection in the future if it is designed with the farmer and is implemented in a responsible manner.

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