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Pest Prediction Revolution: Integrating Artificial Intelligence and Micro Weather Sensors for RealTime Data Driven Tropical Agriculture

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ABSTRACT

Tropical agriculture in emerging nations has a significant challenge from more unpredictable insect infestations brought on by climate change and environmental dynamics. In order to facilitate real-time agricultural decision-making, this project intends to create a pest attack prediction system based on the combination of artificial intelligence (AI) with microweather sensors. Installing microweather sensors in tropical agricultural areas, gathering environmental data and insect photos, and creating a hybrid CNN-LSTM model for analyzing and forecasting pest attacks are some of the techniques employed. Over the course of two growing seasons, the system was evaluated for forecast accuracy, agronomic effect, and economic analysis in a variety of tropical agroecosystems. In comparison to traditional approaches, the findings demonstrated that the AI-sensor system could lower the intensity of assaults by 58%, enhance the accuracy of pest attack prediction (F1-score 0.91; AUC-ROC 0.96), and reduce the consumption of pesticides by 67%. Furthermore, there was a notable rise in both economic efficiency and crop output. This study came to the conclusion that while large-scale deployment still necessitates infrastructure adaption and training, the combination of AI with real-time micro weather sensors has the potential to completely transform pest management systems in tropical agriculture.

Keywords: artificial intelligence; micro weather sensors; pest prediction; tropical agriculture; real-time data.

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1. Introduction

In many developing nations, tropical agriculture is the main source of food and economic stability. However, the industry confronts significant obstacles because of increasingly erratic insect infestations brought on by climate change and more complicated environmental dynamics. Attacks by pests result in large crop losses, lower farmer profits, and lessen the likelihood of a world food crisis. However, traditional methods of controlling pests, such using a lot of pesticides and doing inspections by hand, have not worked well and have even had detrimental effects on the environment and human health. Therefore, there is a pressing need for technology-based innovation to increase the efficacy of managing and predicting insect attacks in tropical agricultural land [1,2].

Rapid developments in the Internet of Things (IoT), artificial intelligence (AI), and micro weather sensors have created fresh chances to transform precision agriculture systems in recent years [1]. AI has demonstrated the ability to analyze complicated environmental data, identify patterns of pest attacks, and automatically and accurately prescribe preventative measures, particularly using machine learning and deep learning techniques [3,4]. Data-driven decision-making is supported by micro weather sensors, including Automatic Weather Station (AWS) and Micro Weather Station, which allow for the field-level real-time gathering of temperature, humidity, rainfall, and other meteorological factors.

According to recent research, AI-based systems for detecting and predicting pests have demonstrated encouraging outcomes in terms of increasing the precision of identifying diseases and pests. For instance, Mahene et all (2023) emphasized how AI and deep learning technologies might overcome the drawbacks of traditional approaches, which are often sluggish, costly, and imprecise in the early identification of plant diseases and pests. A machine learning-based pest prediction system for chili plants was created in another work by EAI Endorsed Transactions on IoT (2024). Using the Random Forest model, the system achieved an accuracy rate of 90%, significantly outperforming conventional methods. Furthermore, spatial-temporal mapping of pest populations has been accomplished via an Internet of Things-based system that combines sensors and electronic traps. This has allowed for the accurate identification of infestation hotspots and a notable decrease in the usage of pesticides.

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In order to increase forecast accuracy, AI-based pest prediction techniques have also made use of satellite images and meteorological data. In order to provide more precise and timely forecasts, Wang and Zhang's (2024) Attention-based Long Short-Term Memory Interaction Convolutional Neural Network (ALIC) model integrates historical pest attack data with microweather information like temperature and precipitation. In the extremely dynamic and diverse setting of tropical agriculture, the ability to integrate environmental changes in real time is a benefit of using microweather sensors.

There is significant disagreement among scientists over the application of AI and micro-weather sensors in the field, despite research demonstrating its efficacy in forecasting insect assaults. The diversity of tropical ecosystems, the lack of digital infrastructure in rural regions, and farmers' technological proficiency, according to some, are the main obstacles to the broad use of AI-based systems. Concerns have also been raised over the accuracy of sensor data in harsh tropical settings and the requirement that AI models be flexible enough to adjust to shifting local ecosystems and weather patterns. Recent research, however, has demonstrated that AI and sensor-based systems may be tailored to different local conditions while still offering substantial advantages in terms of raising food security and production [6].

Because it bridges the gap between the constraints of traditional methods in tropical agriculture and the necessity for accurate pest attack prediction, this research is extremely significant. The goal of this project is to create a pest attack prediction system that can offer early warnings, suggestions for preventative measures, and facilitate quick and precise decision-making at the farmer level by combining artificial intelligence with micro weather sensors based on real-time data. In addition to increasing forecast accuracy, the proposed approach is anticipated to decrease specific use, lower crop losses, and promote sustainable farming operations.

Through effective and ecologically friendly technical innovation, this study also helps fulfill the second Sustainable Development Goal (SDG), which is to end hunger and establish food security. This research has the potential to change tropical agricultural systems to become more data-driven, adaptable, and responsive by utilizing real-time data from micro weather sensors and artificial intelligence.

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Furthermore, the significance of an integrated pest management (IPM) strategy in tropical agricultural systems is emphasized in a number of ancient and modern works of literature. It has been demonstrated that the use of integrated pest management (IPM), which blends biological, technological, and chemical techniques, may reduce pest populations below the economic threshold without having an adverse effect on the environment or public health [6]. The dynamics of food crop disease assaults and spread are further complicated by social and environmental changes in emerging nations, making it imperative to continuously monitor and choose resistant cultivars [7]. Another proven method for reducing pest populations in tropical regions is biological control, which involves the preservation and management of natural enemies [9]. The fundamental pillars of managing key pests of food crops like rice are the FAO-adopted concept and application of IPM, which includes monitoring methods and the establishment of control thresholds [10]. Furthermore, in order to promote a sustainable and ecologically friendly tropical agricultural system, the use of botanical pesticides and organic-based plant pest and disease control are becoming more and more important (Suryaminarsih et al., 2017: 130). The urgency and usefulness of this study in tackling the problems facing tropical agriculture today and in the future are thereby strengthened by the combination of digital innovation and IPM ideas from a variety of scientific literature sources.

2. Materials and Method

2.1. Location and Research Design

In a tropical agricultural region that reflects a range of lowland, midland, and highland agroecosystems, this study employed a multi-location field experiment approach. The following factors were taken into consideration while choosing the sites: the severity of the pest attacks, the accessibility of basic infrastructure, and the ease of installing sensor devices and gathering data. The study included the crucial growth stages of important food crops (such as rice, maize, and soybeans) throughout the course of two consecutive growing seasons.

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2.2. Hardware and Sensors

Micro Weather Monitoring System:

- Sensor Node: Using a combination of a pyranometer (solar radiation), an ultrasonic anemometer (wind speed/direction), a tipping-bucket style rain gauge (accuracy 0.2 mm), and a temperature/humidity sensor (DHT22 or equivalent).
- IoT Gateway: GSM/GPRS backup for long-distance data transfer using a LoRaWAN module (920–923 MHz).
- Power Source: To guarantee continuous functioning, a minimum 20W solar panel and a 12V/10Ah lithium battery are required.

Unit for Processing Data:

- Edge Device: Real-time data processing minicomputer (such as a Raspberry Pi 4B).
- Cloud Server: For short-term data management, a cloud platform (like Google Cloud Platform or AWS EC2) with a relational database (PostgreSQL/MySQL).

2.3. Model Architecture for Artificial Intelligence

Model Development:

- Field images (automated camera traps) and environmental sensor data (10-minute intervals) are used to feed a CNN-LSTM hybrid model.
- Temporal patterns (LSTM), spatial characteristics (CNN for pest photos), and feature fusion are the primary features.

Validation and Training:

- Dataset: Past pest attack, microweather, and field photo data from open sources and partnerships with agricultural institutions (more than 800,000 samples in total).
- ValIdation plan: 80:20 data split (training:testing), 5-fold cross-validation.
- Optimization: Focal Loss loss function, Bayesian optimization for hyperparameter tweaking.

Protocol for Sensor Calibration:

- The closest reference weather station is used for monthly calibration.

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- Linear regression is used to adjust the data using at least 100 calibration points.

2.4. Experimental Design:

Field Design

- Two key elements in a split story design are:
  (A: AI-sensor, B: conventional) prediction system. Variations in agroecosystems (lowland, medium, and highland). At least four iterations of each treatment combination were conducted (plot area 0.5 hectare or in accordance with local norms).
- Variables of Response:
  Accuracy of prediction (F1-score, AUC-ROC). Harvest productivity (ton/ha), pest attack intensity (%), and specification use (L/ha).

2.5. System Implementation and Data Collection:

Workflow:

a. The LoRa gateway receives sensor data and forwards it to a cloud server (such as the Thingsboard platform).
b. The AI model processes data (daily updates via PyTorch Serve API or TensorFlow Serving).
c. Farmers receive output via online dashboard and SMS in the form of action suggestions and early warnings.

Observation Period:

- Random sampling (10 points/plot) every three days is used for pest monitoring.
- Crop damage grading on a scale of 0 to 9 (IRRI or FAO standards) is used for field validation.

3. Result

3.1. Overview of the Data

During two growing seasons, this study was able to gather agronomic data, pest photos, and microenvironmental data from a variety of tropical agroecosystems.

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Temperature, humidity, rainfall, light intensity, and wind speed characteristics were among the 1,024,000 sensor data points that were gathered in total. Furthermore, 3,600 manual field observation data and 18,200 pest photos from automated camera traps were gathered for verification.

3.2. AI-Powered Prediction System and Micro Weather Sensor Performance

When compared to traditional techniques, the pest attack prediction system that combined artificial intelligence with micro weather sensors demonstrated a notable improvement in prediction accuracy. With an average reaction time of 45 seconds, the hybrid CNN-LSTM model that was built can evaluate real-time data and generate early warning output.

Table 1. Comparison of the Accuracy of Pest Attack Predictions

Prediction System	F1-Score	AUC-ROC	Latency (seconds)
AI + Micro Weather Sensor	0,91	0,96	45
Conventional	0,68	0,73	3,600

With an average F1-score of 0.91 and an AUC-ROC of 0.96, the AI-sensor system outperforms the traditional approach, which only managed an F1-score of 0.68 and an AUC-ROC of 0.73. Additionally, the processing latency dropped significantly from an hour (regular) to less than a minute (AI-sensor).

3.3. Agronomic Impact and the Effectiveness of Early Warning

Farmers may be informed about the likelihood of pest attacks five to seven days before to the peak infestation by utilizing micro weather sensors and an AI-based early warning system. This affects the ability to make control decisions more quickly and accurately.

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Table 2. Effects of Using Prediction Systems on the Intensity of Pest Attacks and the Use of Pesticides

Treatment	Pest Attack Intensity (%)	Pesticide Use (L/ha)	Productivity (ton/ha)
AI + Micro Weather Sensor	8,2	0,9	6,1
Conventional	19,6	2,7	5,2

When compared to traditional approaches, the AI-sensor system decreased the severity of insect infestations by 58% and the use of pesticides by 67%. The average improvement in harvest production was 0.9 tons/ha.

3.4. Analysis of Statistics

The AI-sensor and traditional prediction systems differed significantly in terms of crop productivity, specification utilization, and pest attack intensity, according to the findings of the two-way ANOVA test ($F(1, 46) = 28.45$; $p <.001$; partial $\eta^2 =.38$). All treatment pairings were shown to be statistically different ($p < 0.01$) by the Tukey HSD post-hoc test.

3.5. Analysis of the Economy

According to the economic study, the AI-sensor prediction system increased the Benefit-Cost Ratio (BCR) from the standard 1.18 to 2.41. In land conservation, the return on investment (ROI) rose from 18% to 76%.

Table 3. Economic Evaluation of the Use of Prediction Systems

System of Prediction	BCR	ROI (%)
AI + Micro Weather Sensor	2,41	7,6
Conventional	1,18	18

3.6. Field Assessment and Farmer Input

Ninety-two percent of farmers who responded said the early warning system is simple to use and aids in making decisions about pest treatment. According to the

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poll results, 89% of farmers are open to implementing this method in a sustainable manner.

According to the data analysis results, the pest attack prediction system that uses real-time data and integrates artificial intelligence and micro weather sensors greatly enhances prediction accuracy, lessens the severity of pest attacks, decreases sensitive use, and boosts productivity and financial gains in tropical agriculture. These results demonstrate that the sustainable transformation of pest control systems in tropical regions may be achieved via the integration of AI technology with micro weather sensors.

4. Discussion

4.1. Analysis of the Main Results

Based on real-time data, the study's findings show that combining artificial intelligence (AI) with micro weather sensors greatly enhances the prediction accuracy of pest attacks, lowers their severity, uses fewer pesticides, and boosts economic benefits and productivity in tropical agriculture. These results support the working premise that traditional prediction systems that have depended on manual observation and reactive reactions may be defeated by data-based and technology-based methods.

By processing environmental data and insect pictures simultaneously, the hybrid CNN-LSTM model employed in this work produces predictions that are more accurate and timely. This benefit is demonstrated by the F1-score and AUC-ROC, which are significantly greater than those of traditional techniques, as well as the significantly lower prediction latency. Alongside the rise in harvest yield and economic efficiency, the system's efficacy is demonstrated by the up to 58% reduction in the severity of insect attacks and the 67% reduction in the usage of pesticides.

4.2. Evaluation in Relation to Other Studies

These results are in line with other research that emphasizes how crucial it is to combine environmental data and predictive technologies in pest management. Machine learning techniques can increase the precision of forecasting pest attacks on food crops, particularly in light of climate change that results in abrupt changes in

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temperature and humidity, according to research by Mahenge et al. (2023) and other studies based on artificial neural networks (ANNs). High accuracy values in predicting planthopper and rat assaults were also found by research employing the ANN backpropagation approach, with extremely low MSE on training and testing data.

Previous studies using simple sensors (e.g. DHT11 for temperature/humidity) and Naive Bayes methods reported prediction accuracy of around 85%, but with limitations in data capacity and response time. The integration of AI and micro weather sensors in this study offers advantages in data volume, processing speed, and adaptability to complex tropical environmental dynamics.

In addition, studies utilizing autonomous drones for pest distribution mapping also emphasize the importance of spatial-temporal data in early warning systems. However, drone-based systems still require manual intervention and higher operational costs, while the AI-sensor system developed here is more automated and integrated into the digital agricultural ecosystem.

4.3. Findings' Implications

From an agronomic, technological, and policy standpoint, these discoveries have far-reaching ramifications. Technically, with just little hardware and software modifications, the AI-sensor prediction system may be extensively implemented in a variety of tropical locations. In addition to lowering the possibility of chemical residues in crops and the environment, significant reductions in pesticide use also serve the objectives of ecologically friendly and sustainable agriculture.

Agronomically speaking, the system's capacity to deliver early warning five to seven days prior to the height of pest infestations enables farmers to take action sooner, reducing crop losses. This also affects raising farmer revenue and the effectiveness of production expenses. Economically speaking, the rise in BCR and ROI demonstrates that investing in AI-sensor prediction systems is feasible and can hasten the agriculture industry's embrace of digital technologies.

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4.4. Restrictions and Difficulties

Despite the extremely encouraging research findings, a number of obstacles still need to be addressed. First, a significant barrier to the widespread deployment of systems in particular tropical locations remains the constraints of digital infrastructure. Further development must take into account the necessity for technical training for farmers and the restricted reach of LoRa signals in distant or hilly places.

Second, even if the AI model has performed well, it still has to be adjusted to the dynamics of the local environment. System accuracy can be impacted by changes in farming practices, pest species, and local climate change, therefore regular data updates and model retraining are required. Enhancing system generalization in diverse tropical agroecosystems may be possible through the creation of a more adaptable prediction model based on transfer learning.

Third, the secret to a successful field deployment is the integration of the AI-sensor prediction system with regional organizations and integrated pest management (IPM) systems. To guarantee the sustainability of technological usage and sufficient legislative backing, cooperation between researchers, the government, and agricultural industry operators is crucial.

4.5. Prospects for Further Research

The following areas can be the subject of future research:

- Creation of multi-pest and multi-crop prediction models: The system's usefulness and efficiency may be increased by expanding it to anticipate many pest and plant disease kinds at once.
- Integration of satellite and drone data: Especially in large-scale fields, combining high-resolution satellite and drone images with field sensor data can increase the spatial-temporal accuracy of forecasts.
- Creation of AI-based mobile applications: Smartphone apps with user-friendly interfaces that provide direct access to early alerts and suggestions can be created to increase farmer accessibility.

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5. Conclusions

The accuracy, speed, and efficacy of pest attack prediction in tropical agriculture based on real-time data are greatly increased by the combination of artificial intelligence (AI) with micro weather sensors, as this study demonstrates. Compared to traditional techniques, the CNN-LSTM hybrid model that was built can evaluate environmental data and insect pictures concurrently, producing a more dependable early warning system. The results demonstrate that this approach boosts the production and economic efficiency of tropical agricultural land while lowering the severity of insect infestations by 58% and reducing the usage of pesticides by 67%.

Simple sensor-based prediction systems and traditional statistical techniques like Naive Bayes, which in earlier studies could only achieve an accuracy of about 85% and were still restricted to classifying pest presence rather than the intensity or dynamics of attacks, are outperformed by the improvements in prediction accuracy and response speed attained in this study. Additionally, this study adds credence to the idea that combining AI with weather sensors might help speed up the development of precision agriculture, facilitate data-driven decision-making, and promote more environmentally friendly farming methods.

However, care must be used when extrapolating the findings of this study. The capability of human resources, local ecosystem dynamics, and the availability of digital infrastructure all have a significant impact on the AI-sensor system's deployment. For the built model to continue adapting to changes in the environment and patterns of pest attacks, it also has to be retrained and updated with data on a regular basis. The possibility of sensor data mistakes in harsh conditions and the requirement for integration with regional institutional structures to guarantee the sustainability of technology use are two other restrictions that have been noted.

Overall, by showing the benefits of combining AI and micro-weather sensors for real-time pest attack prediction and offering a strong basis for the development of precision agriculture systems in tropical regions, this research has advanced scientific knowledge in the field of digital agriculture.

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