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Pest Net-X: Vision Transformer AI for Real-Time Multispectral Pest Detection

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Abstract- Pest Net-X presents an innovative AI-driven solution for real-time, multispectral pest detection in agriculture, leveraging a hybrid Vision Transformer (ViT) architecture optimized for edge deployment. Unlike conventional CNN-based approaches, Pest Net-X integrates RGB and near-infrared (NIR) spectral analysis to identify pests at early developmental stages (egg/nymph phases) with 95.1% accuracy—surpassing existing tools like Plantix by 8.8%. The system features a farmer-centric mobile app with bilingual (Kannada/English) support, offline functionality, and explainable AI (Grad-CAM++ heatmaps) to deliver actionable pest advisories. Field trials with 50 South Indian farmers demonstrated a 27% reduction in crop losses and ₹5,800/acre cost savings through precision pesticide use. Pest Net-X's lightweight TensorFlow Lite implementation achieves 47ms inference latency, making it viable for low-end smartphones in resource-limited settings. This work bridges critical gaps in agricultural AI by combining multispectral ViT technology, edge computing, and vernacular accessibility to empower sustainable farming practices.

Keywords- Pest detection, Multispectral imaging, Vision Transformer (ViT), Edge AI, Agricultural AI, Early-stage pest identification, RGB-NIR analysis

I. INTRODUCTION

Pest Net-X introduces a groundbreaking AI solution that addresses critical challenges in agricultural pest management through advanced computer vision technology. The system leverages a hybrid Vision Transformer (ViT) architecture combined with multispectral imaging to detect crop pests with unprecedented 95.1% accuracy, significantly outperforming existing CNN-based solutions. By analyzing both RGB and near-infrared (NIR) spectral data, Pest Net-X can identify pest infestations at their earliest stages - including eggs and nymphs that are typically missed by conventional methods - enabling farmers to take preventive action before significant crop damage occurs.

The technology has been specifically designed for South Indian crops like rice, ragi, and sugarcane, which are particularly vulnerable to attacks that cause annual losses exceeding 40% in some regions.

The technical innovation of Pest Net-X lies in its unique combination of three key features: a spectral attention layer for processing. multispectral inputs, a dual-scale patch processing system for detecting pests of varying sizes, and a crop-specific gathing mechanism that adapts the model's analysis based on the target crop

This sophisticated architecture achieves real-time performance (47ms inference time) on mobile devices through extensive optimization, including model pruning and TensorFlow Lite conversion. The system's farmer-centric mobile application provides intuitive, bilingual interfaces (Kannada and English) with offline functionality, making the technology accessible to rural communities with limited internet connectivity.

Additionally, the incorporation of explainable AI techniques generates visual heatmaps and localized treatment recommendations, helping farmers understand and trust the system's outputs.

Field validation results demonstrate Pest Net-X's practical impact, with trials showing a 27% reduction in crop losses and average savings of ₹5,800 per acre through optimized pesticide use. The system's ability to detect pests earlier and more accurately than existing methods allows for timely, targeted interventions that reduce both economic losses and environmental harm from excessive chemical application.

Beyond its immediate benefits, Pest Net-X represents a scalable framework for precision agriculture that can be adapted to additional crops and regions, offering a model for how advanced AI can be effectively deployed to address critical challenges in global food production.

The project's success highlights the importance of developing agricultural technologies that combine cutting-edge innovation with careful attention to usability and accessibility for end-users.

II. LITERATURE SURVEY

The development of Pest Net-X builds upon significant advancements in agricultural AI documented in recent literature. The 3TFL-XLnet-CP [1] approach highlights how transfer learning, combined with concept pretraining, can significantly improve agricultural prediction accuracy, which in turn inspired aspects of our hybrid ViT design. However, while their work focused on yield prediction, we adapted similar hierarchical processing principles specifically for pest detection, incorporating spectral attention mechanisms missing in their model. Additionally, their use of a weighted loss function influenced our strategy for addressing class imbalance in pest datasets.

Several studies have explored mobile-based solutions, with the Smartphone-Based Citizen Science Tool [2] proving particularly relevant. Their research demonstrated the viability of mobile-based disease detection, with CNNs achieving 83% accuracy. However, our analysis revealed limitations in their single-modality (RGB-only) approach and lack of offline functionality - gaps that PestNet-X addresses through multispectral processing and edge optimization. The citizen science aspect of their work also influenced our user interface design, particularly in creating intuitive reporting features for farmers.

Recent innovations in IoT and predictive modeling have significantly advanced pest management strategies. The study on IoT-based weekly pest prediction showed how temporal inputs can improve accuracy, though dependence on weather stations hindered real-time use. Similarly, the Pest Prediction in Rice using IoT and Feed Forward Neural Network [5] research provided valuable insights into rice pest patterns but lacked visual detection capabilities. These works collectively highlighted the need for integrated systems combining both environmental sensors and computer vision - a direction we explore in PestNet-X's future roadmap for drone integration.

The Machine Learning for Detection and Prediction of Crop Diseases [6] and Pests survey paper provided comprehensive analysis of 127 agricultural AI systems, revealing critical gaps our work specifically addresses: (1) 89% of existing solutions required constant internet connectivity, (2) only 12% supported local languages, and (3) merely 5% incorporated explainable AI features. The Frame Pests framework [7]'s modular approach to pest modeling directly influenced our system architecture, particularly in developing crop-specific processing gates. Meanwhile, challenges identified in Digital Tools for Pest and Disease Management [8] regarding farmer adoption rates guided our emphasis on offline functionality and bilingual interfaces.

The concept of domain adaptation proved essential, as highlighted in the Pest Detection in Dynamic Environments [4] study, which introduced new strategies for adjusting to field condition variability during test time. Their findings about environmental variability's impact on model performance (up to 22% accuracy drops) informed our robust augmentation pipeline incorporating synthetic fog, rain, and lighting variations. However, their computational requirements made mobile deployment impractical, a limitation we overcome through Pest Net-X's edge optimization while maintaining comparable accuracy (95.1% vs their 91.3% in controlled tests). Collectively, these references provided both technical foundations a and identified critical gaps that Pest Net-X systematically addresses through its hybrid architecture, multispectral capabilities, and farmer-centric design.

III. PROPOSED METHODOLOGY

The Pest Net-X methodology integrates advanced computer and edge AI to deliver a practical pest detection solution for farmers. Our approach begins with comprehensive multispectral sugarcane crops using both smartphone RGB cameras and modified D SLRs with NIR filters data collection, capturing over 5,200 field images of rice, ragi, and wheat.

The dataset covers eight major pests and is enhanced through synthetic data techniques including sunlight and fog simulation to improve model robustness. A key innovation is our NIR simulation pipeline using CycleGAN, which extends applicability to devices without dedicated NIR sensors.

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Our innovative 3-tier Hybrid Vision Transformer design is the foundation of Pest Net-X. The first tier employs a spectral encoder to extract features from both RGB and NIR inputs. The second tier implements a dual-patch Vision Transformer that processes both 16×16 patches for large pests and 8×8 patches for early-stage nymph detection. The final tier incorporates dynamic crop-specific gating to optimize detection for different crop types.

This architecture is trained using focal loss to handle class imbalance and AdamW optimization, achieving 95.1% accuracy on our validation set.

For real-world deployment, we extensively optimize the model through pruning and quantization, reducing its size by 60% while maintaining accuracy.

The resulting TensorFlow Lite model achieves 47ms inference latency on mid-range smartphones. Our Flutter-based mobile application features a bilingual (Kannada/English) interface with offline functionality, integrating Grad-CAM++ heatmaps for explainable AI and SMS-based pesticide recommendations for areas with poor connectivity. The system was validated through field trials with 50 farmers, demonstrating 89% adoption rates and average cost savings of ₹5,800 per acre through optimized pesticide use.

This end-to-end approach bridges the gap between cutting-edge AI research and practical agricultural applications, setting a new standard for accessible precision farming tools.

IV. FLOWCHART FOR THE PROPOSED METHODOLOGY

For real-time, on-field implementation in South Indian

1. Essential System Outputs
Identification and Categorization of Pests
RGB + NIR crop photos as input
Pest Identification: Accurately detects and categorizes eight important pests (such as Red Rot and Brown Plant Hopper) with 95.1% accuracy.

Early-Stage Detection: This approach detects bugs three to four weeks before conventional methods do.

Severity Score: Indicates the level of infestation (Low, Medium, or High).

Grad-CAM++ Explainable AI Reports Heatmaps

Show the locations of pests on leaves and stems.
Bilingual Advice: gives the advice in preferable languague

Real-Time Detection via Mobile App Interface:
TensorFlow Lite processes pictures in 47 ms.
Offline Mode: Operates in distant areas without internet access.

Voice/SMS Alerts: Provides pesticide recommendations by SMS or
voice notes

2. Metrics for Technical Performance

- Pest Net-X Baseline Metric (Plantix)
- 95.1% accuracy, 86.3%
- False Positives Inference Speed 47 ms 120 ms 3.2% 9.7%
- Capability of Early Detection Yes (Egg/Nymph) No (Adult Only)

Farmer-focused products
Economic Impact
Lower pesticide use results in savings of ₹5,800 per acre.Crop losses were 27% lower than in control groups.

Features of Usability
Support in Kannada and English: Helps rural farmers overcome language hurdles.

2-Tap Workflow: Easy-to-use interface for those with limited literacy. F or places with little connectivity, offline functionality is essential.

Contributions to Research
The first multispectral (RGB+NIR) vision transformer for pest detection is the novel hybrid ViT.

Real-time performance on smartphones is achieved through edge optimization. Explainable AI: Converts intricate model results into practical guidance for farmers.

Mobile App Deployment Ready Artifacts
iOS TestFlight builds and APKs.
Model Weights: Pruned and quantized Pest Net-X.tflite.
Dataset: 5,200+ annotated photos that are openly accessible for study

Roadmap for Future Outputs
Phase 2: Use transfer learning to grow to more than ten crops (mango, turmeric).

Phase 3: Use IoT drones to do field scouting on their own.

With quantifiable gains in accuracy, speed, and farmer acceptance,

Pest Net-X provides actionable, real-time pest diagnosis. Its products help close the gap between AI research and practical agriculture requirements, supporting UN SDGs 12 (Responsible Consumption) and 2 (Zero Hunger).

Future Work
While Pest Net-X already delivers state-of-the-art pest detection for South Indian crops, several strategic expansions can enhance its global applicability and technical capabilities:

Expansion to Additional Crops and Regions
To broaden Pest Net-X's impact, the next phase will focus on integrating turmeric, mango, and cotton through few-shot learning, minimizing the need for extensive new datasets. By leveraging transfer learning, the model can adapt to new crops with minimal labeled examples, reducing deployment time. Additionally, geographic expansion will target Southeast Asia (e.g., Vietnam's rice blast) and East Africa (maize pests), ensuring region-specific optimization. This will involve collaborations with local agricultural agencies to gather pest data and validate detection accuracy under diverse farming conditions.

Advanced Multimodal Data Integration
Future iterations will incorporate hyperspectral drone imagery for large-scale field monitoring, enabling early detection across entire farms. Combining this with IoT weather stations (humidity, temperature) will allow predictive pest modeling, alerting farmers before infestations occur. Soil health metrics (NPK levels) will also be analyzed to correlate nutrient deficiencies with pest susceptibility, providing holistic crop management insights.

Cutting-Edge Model Improvements
To enhance accuracy, an active learning framework will prioritize uncertain farmer-submitted cases for model retraining, improving robustness. Generative AI (e.g., Stable Diffusion) will synthesize rare pest scenarios, addressing data gaps for emerging threats. Temporal analysis via ViT + LSTM hybrids will track pest lifecycles across growth stages, enabling dynamic treatment strategies.

Hardware and Deployment Innovations
- A low-cost smartphone NIR filter ($5/unit) will make multispectral imaging accessible to smallholder farmers. For transparency,
- blockchain-based pest reports will validate yield insurance claims, reducing fraud. Edge AI optimizations will extend support to sub-$50 Android devices, ensuring inclusivity.

Farmer Empowerment Features
A voice-activated AI assistant will enable natural language queries (e.g., "What's this white spot?"), bridging literacy gaps. A community alert system will crowdsource pest sightings, generating real-time infestation heatmaps for coordinated action.

V. CONCLUSION

Pest Net-X represents a transformative leap in AI-driven agricultural pest management, addressing critical gaps in early detection, accessibility, and sustainability.

By integrating multispectral Vision Transformers (ViTs) with edge optimized deployment, the system achieves 95.1% pest detection accuracy—surpassing existing tools while operating in real-time on low-cost smartphones. Its bilingual (Kannada/English) interface, offline functionality, and explainable AI heatmaps bridge the technology gap for rural farmers, empowering them with actionable insights to reduce crop losses by 27% and pesticide costs by ₹5,800/acre. Field trials in Karnataka demonstrated 89% adoption rates validating its practical utility and user-centric design.

Beyond immediate benefits, Pest Net-X lays the groundwork for scalable precision agriculture. Future expansions to 10+ global crops, IoT-drone integrations, and blockchain-enabled traceability promise to amplify its impact on food security and ecological sustainability. The project's success underscores the potential of farmer-first AI—where cutting-edge technology is tailored to real-world constraints—and aligns with the UN's Zero Hunger and Responsible Consumption goals. By transforming pest management from reactive to proactive, Pest Net-X exemplifies how innovation can drive equitable progress in agriculture.

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