A proposed CPS system for managing *S. incertulas* populations in Assam.

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Abstract

Rice sustains food security across Assam and India, yet outbreaks of the *Scirpophaga incertulas* are rising with warmer conditions and input-intensive monoculture. Group discussion with farmers in Nagaon district confirm literature that present integrated pest management relies on periodic scouting and broad insecticide use, which delays action and drives repeated spraying. Here we propose a human- cyber-physical system that can predict plot-level risk and coordinate responses. The architecture couples heterogeneous sensing, with edge hubs, and a KDSS interface. RGB imaging is proposed for detecting adults and egg masses; infrared and microclimate sensors for tracking crop stress and conditions favourable for oviposition and larval development; and acoustic sensing to identify larval feeding inside stems. Data streams are geo-located, hashed and time-stamped on a blockchain system and archived for provenance and audit. A fusion pipeline integrates these modalities with weather and planting calendars; a YOLOv8 model trained on curated images is proposed for detecting adult moths Predictive alerts trigger early interventions before economic thresholds are crossed. Linking observations to Assam's BhuNaksha enables traceable recommendations, compliance reporting, and aggregation for district-level surveillance. The proposed solution furthers India's Agristack initiative, and the solution's modular design supports extension to other rice pests and neighbouring agro-ecologies.

Keywords
YSB, H-CPS, Agritech, Agristack, Assam.

1. Introduction

Rice cultivation is significant for the Assamese society and economy because it supports the livelihoods of over 75 % of Assam's inhabitants, directly employing more than 53 percent of the total workforce[1]. In the year 2022-23, Assam produced approximately 1,19,750 tonnes of autumn rice, 48,05,794 tonnes of winter rice, and 11,19,355 tonnes of summer rice, aggregating to a total of 60,44,899 metric tonnes of rice. The provisional forecast for 2023-24 expects an overall decrease of 8.37% in rice production, with autumn rice expected to decrease by nearly 35%, winter rice by about 11%, while summer rice is projected to increase by 4%[2].

Today, the production of this rice is under threat from a host of biotic and abiotic stressors. Our focus has been one such biotic stressor, particularly the *Scirpophaga incertulas (the* yellow rice stem borer, "**YSB**"), a lepidopteran pest that has co-evolved with rice cultivation across monsoonal Asia for millennia[3]. Unfortunately, the current methods of YSB management relies heavily on reactive, labor-intensive approaches that depend primarily on visual detection methods and indiscriminate pesticide applications. This methodology has created a cascade of negative consequences, including pest resurgence, ecosystemic degradation, health hazards from chemical residues, and the development of pesticide resistance[4]. Contemporary Integrated Pest Management (IPM) strategies, while scientifically sound, face significant implementation challenges in smallholder farming systems due to technical complexity, resource requirements, and the need for precise timing of interventions[5].

Statement of the Problem:

Despite decades of IPM practices, the Yellow Stem Borer continues to be a persistent biotic threat to rice cultivation in Assam and across Asia, often resulting in 25–60% yield loss due to a variety of factors, including YSB incidences increasing as the climate change hastens YSB life cycles as a direct result of increased growing degree days[6]; lack of ecologically sound pest management practices [7]; There is a pressing need for proactive, real-time surveillance systems that empower farmers with data-driven, localized, and timely interventions to effectively mitigate YSB infestations without causing environmental degradation.

1.1 Objectives

- Find out if the farmers are willing to adopt pest detection (HCPS) systems.
- Are they willing to use a chatbot for their queries on pests and policies.
- Identify methods to do pest (YSB) detection and management.

2. Literature Review

A host of biotic and abiotic factors threaten rice yields, necessitating the study of both factors to reliably predict insect population. To identify the most optimal solutions for predicting and managing the population of YSB, we conducted a syntonical review of 23 primary studies and 11 policy/technical notes and press releases. Duplicates, opinion pieces and studies outside the rice–YSB–technology nexus were excluded. Reliability was assured through double coding and cross-checking of quantitative claims against original tables/figures. The themes, key papers studied and the salient findings have been tabulated below for ease of reference.

Authors	Study Focus	Key Contributions	Relevant to the Study	Citation Count
Litsinger, J. A., et al. (2011)	Philippine Rice Stemborers: A Review	Comprehensive taxonomic classification of rice stemborer species; documented prevalence and distribution patterns of Scirpophaga spp. across ecosystems	Foundational taxonomic and ecological data on yellow stem borer (S. incertulas); establishes baseline for stemborer biology and management	77
Dutta, S. & Roy, N. (2022)	Review on Bionomics and Management of Rice Stem Borer	Synthesis of stemborer life cycle, bionomics, and management strategies including ETLs (Economic Thresholds); integrated management approaches	Core reference on rice stem borer biology and conventional management practices; critical for comparison with digital approaches	8
Parsa, S., et al. (2014)	Obstacles to Integrated Pest Management Adoption in Developing Countries	Identification of 51 unique obstacles to IPM adoption; concept mapping analysis of barriers across 96 countries	Addresses institutional and socioeconomic barriers to technology adoption relevant to developing context adoption of digital pest management systems	389
Roy, S., et al. (2022)	Review on Bionomics and Management of Rice Stem Borers	ETLs by crop stage (5% dead-hearts; 6% white-ears); integrated management module development	Provides standardized thresholds for pest management decision-making critical for KDSS implementation	8

Authors	Study Focus	Key Contributions	Relevant to the Study	Citation Count
Wang, X., et al. (2025)	Blockchain-Empowered H-CPS Architecture for Smart Agriculture	Integration of blockchain with cyber-physical systems; semantic-based framework for data management and AI model integration in agriculture	Relevant for system architecture design combining blockchain, IoT, and AI for transparent, secure agricultural decision support	5
Singh, A. K., et al. (2024)	Smart Connected Farms and Networked Farmers to Improve Crop Production, Sustainability and Profitability	Framework for integrating technology with farmer networks; comprehensive review of precision agriculture advancements; data analytics and decision-making optimization	Addresses networked farmer coordination and data-driven decision support essential for coordinated pest management implementation	18
Mankin, R., et al. (2021)	Automated Applications of Acoustics for Stored Product Insect Detection, Monitoring, and Management	Development and validation of acoustic sensors for automated insect detection; methodologies for field deployment and signal processing	Relevant for non-invasive pest detection technologies that could complement visual imaging in field monitoring systems	77
Deka, M. K., et al. (2006)	Traditional Pest Management Practices of Assam	Documentation of indigenous pest management practices in Assam; ethnobotanical knowledge of local farmers; validation of traditional methods	Essential background on locally available, cost-effective pest management alternatives; relevant for integrated approach combining traditional and modern methods	28
Sanyal, S., et al. (2025)	The Global Invasion Risk of Rice Yellow Stem Borer Scirpophaga Incertulas Under Current and Future Climate Scenarios	MaxEnt modeling of S. incertulas geographic distribution; climate suitability assessment; prediction of future range expansion under climate change	Critical for understanding potential range expansion of target pest; relevant for geographic prioritization of system deployment areas	1
Singh, A. K., et al. (2024)	Smart Connected Farms and Networked Farmers to Improve Crop Production, Sustainability and Profitability	Smart farm architecture design; farmer networking strategies; technology adoption frameworks; sustainability metrics integration	Addresses farmer engagement and technology adoption mechanisms essential for successful deployment and user acceptance of digital systems	18
Melesse, T. Y. (2025)	Digital Twin-Based Applications in Crop Monitoring	Digital twin modeling methodologies for crop management; real-time crop health monitoring; integration of IoT and simulation for decision support	Directly relevant for digital twin architecture design; provides framework for virtual crop models integrated with real-time sensor data for predictive analytics	20

Synthesis of the Literature Review

Rice cultivation remains central to Assam's food security and livelihoods, sustaining over 75% of the population. However, the persistent threat of YSB consistently reduces yields by 25-60%, exacerbated by climate change accelerating pest lifecycles through increased growing degree days. Current management approaches, heavily reliant on reactive, labor-intensive visual detection and indiscriminate pesticide applications, have generated pesticide resistance, ecosystem degradation, and health hazards, necessitating paradigm innovation.

Our systematic review of 23 primary studies reveals that while foundational taxonomic and ecological understanding of YSB is well-established (Litsinger et al., 2011; Dutta & Roy, 2022), significant implementation barriers persist in developing economies (Parsa et al., 2014). Traditional indigenous practices like manual stem cutting, bird perches, and botanical controls—are documented as scientifically rational and cost-effective (Deka et al., 2006; Barman et al., 2024), yet require integration with emerging technologies for scalable deployment.

Recent technological advancements offer transformative potential: blockchain-empowered cyber-physical systems (Wang et al., 2025), real-time pest detection via YOLO-driven computer vision (On & Abubacker, 2024), acoustic sensing for larval identification (Mankin et al., 2021), and UAV-based remote sensing for predictive zoning (Kharim et al., 2022). Federated learning frameworks enable privacy-preserving model deployment across multiple farms (Li et al., 2025), while digital twin architectures integrate IoT and simulation for predictive crop management (Melesse, 2025).

Critical research gaps identified include inadequate multimodal data fusion, limited economic evaluation of technology adoption, and insufficient policy-technology alignment. India's emerging agritech policies, Digital Agriculture Mission, National Pest Surveillance System, Agristack, Namo Drone Didi, provide institutional scaffolding for deployment.

Our proposed H-CPS directly addresses these gaps by integrating heterogeneous sensing, blockchain provenance, AI-driven decision support, human-in-the-loop, and indigenous knowledge, positioned to deliver predictive YSB management while advancing yield sustainability and rural resilience in Assam.

2.6 Research Gap:

Despite these advances, several critical gaps persist in the scholarly corpus:

1. *Absence of Predictive Digital Twins.*
2. *Economic Evaluation of Technology Adoption.*
3. *Policy-Technology Alignment.*
4. *Enhanced Multimodal Data Fusion.*
5. *Holistic Stress Integration*.

2.7 Hypothesis:

H1: Farmers are willing to adopt technology-based pest detection systems if they demonstrate clear yield benefits.
H2: Simple, multilingual interfaces increase farmer adoption of digital agricultural tools.
H3: Blockchain-empowered cyber-physical systems can significantly reduce pesticide dependency while maintaining crop yield.

3. Methods

3.1 Research Type:

Exploratory and Descriptive Research with a focus group discussion with a qualitative approach and output, resulting in a recorded transcript of the discussions in Assamese, subsequently translated into English ("***Video Script***").

3.2 Sample Design and Size:

A total of 15 farmers were included in the Focus Group discussion led by the team at Herbarium Labs. The farmers had to be located in Assam as we are focusing on implementing within the local region first.

3.3 Scope of the Study:

Geographic Scope:

- Rural Assam, India (Upper Assam region specifically)
- Agro-climatic homogeneity and cultural consistency
- Technology infrastructure and policy implementation uniformity

Technological Scope:

- AI/ML for pest detection and prediction
- Multilingual chatbot interfaces via Bhashini AI platform

Agricultural Scope:

- YSB as target pest
- Rice cultivation systems (monsoon-fed and irrigated)
- IPM practices
- Smallholder farming contexts

Temporal Scope:

- April 2025 to August 2025

4. Data Collection

4.1 Sources of Data:

Primary Data:
- Focus group discussions with farmers in rural Assam.
- Expert interviews with agriculture professionals.
- Field observations and farmer testimonials.

Secondary Data:
- Literature review of 23 primary studies and 11 policy/technical notes and press releases.
- Government policy documents and agricultural reports.

4.2 Tools used in data collection:

- Audio and video recorded focus group discussions
- Structured interviews
- Online video calls
- Transcription and thematic analysis

5. Results and Discussion

5.1 Interview and focus group interpretation

Below is an interpretive analysis of the Video Script (Appendix) transcript mapped against the Research Report's stated Objectives (3.3). Key farmer quotes are cited to show how the field data speak to each objective.

Objective 1: Find out if the farmers are willing to adopt pest detection (HCPS) systems

Strong openness, conditional on yield benefit.
"If you people are bringing us some useful advice, why wouldn't we take it? Everyone will adopt it." *Video Script*
Willingness tied to simplicity.
"We're not proficient with complex apps… but if it helps production, we'll use it." *Video Script*
Interpretation: Farmers are open to using any technology and adopt them as long as it is gives them clear actionable outcomes such as increase yield, reduce losses and improve pest management. However, they did emphasize on having low-complexity, low-cost systems that delivers clear communication and alerts.

Objective 2: Are they willing to use a chatbot for their queries on pests and policies

Positive attitude toward conversational tools.
"If you gave us a tool… where you could share information or get help using voice or photos—would you use it? Of course! Absolutely!" *Video Script*
Interpretation: Farmers are receptive to a simple, multilingual chatbot—especially one that accepts voice or images. However, building trust will require in-field demonstrations and local endorsements to overcome scepticism.

Objective 3: Identify methods to do pest (YSB) detection and management

Traditional ecological controls.
Manual stem-cutting and burying ("If I cut and throw away the pomelo plants, the stem borer just disappears.") *Video Script*
Bird perches and grain scattering to attract predators ("When the moths hatch… the birds eat them right away.") *Video Script*

Chemical controls:
Weekly pesticide sprays (₹1,500–2,000 per bigha seasonally) *Video Script*
Reliance on shop-bought insecticides ("Rogor, Thymol… 1 mg can kill you.") *Video Script*

Experimental/organic alternatives:
Fermented cow-dung sprays: too time-consuming and socially repellent to farmers *Video Script*

Interpretation:

The survey confirms that YSB causes significant yield losses in Assam's rice farms under current measures taken. Traditional methods used are low-cost but labour intensive and not always successful, and weekly insecticide sprays cost ₹1,500–2,000/bigha and raises environmental concerns. Using non-invasive sensor alerts through hyperspectral radiometry can detect early infestation.

The focus group discussion with the farmers shows both the pain points and clear farmer demands for simple, yield enhancing technology. Mapping these insights underscores the critical need for a transparent blockchain backed, IoT phygital system paired with a low-barrier multi lingual chatbot that can help farmers find immediate alerts and solutions.

5.2 Proposed Solution

To address these enduring agricultural challenges, we propose a three pronged CPS solution, that strategically integrates emerging technologies, policy incentives and indigenous technical knowledge resulting in a sophisticated blockchain powered H-CPS as the back end, which can be interfaced as a policy maker or administrative dashboard and as a gamified KDSS for the rice farmers of Assam.

Emergence of Technologies

Emerging technologies like artificial intelligence, machine learning, blockchain, Internet of Things ("**IoT**"), combined as cyber-physical systems ("**CPS**") unlock novel methods for managing YSB populations in a manner not possible earlier[8], including creating data-driven, proactive pest management systems[9], smart networked farms with integrated physical and digital components to improve crop production, sustainability and profitability[10].

Human-Cyber-Physical Systems ("**H-CPS**") are an extension of traditional CPS concept by explicitly embedding human knowledge, judgment, and decision-making into cyber-physical operations enables real-time crop management, pest spotting, data-driven decision-making, and transparent trading of agricultural products while anchoring actions keeping humans in the loop, which, when integrated with Blockchain technology, enhances data integrity, traceability, and trust[9].

However, the successful implementation of blockchain-empowered H-CPS for pest management faces several critical challenges that must be addressed through comprehensive research and development efforts. Technical challenges include the reliability of acoustic sensors in detecting minute larval feeding sounds in noisy field environments[11], the accuracy of data fusion across spectral, acoustic, and environmental domains, and the development of machine learning models that can generalize across different agro-ecological zones[12].

AgriTech Policy Alignment

There is a need for collaboration between different stakeholders in the agricultural ecosystem, including farmers, technology companies, researchers, and policymakers if the problems facing rice farmers in Assam are to be sustainable addressed 13]. Relevantly, policy makers in India recognize the need for upgrading India's agricultural system to become future ready, and towards this, provide varied support for technological innovations through comprehensive digital initiatives. These policy interventions can be leveraged to build H-CPS solutions to manage YSB populations in Assam, with these solutions then extended to other pests in other crops:

- the Digital Agriculture Mission ("**DAM**")[14] whose core element, AgriStack, is an integrated digital public infrastructure designed to create a comprehensive registry of India's farmers, geo-referenced village maps, and crop-sown databases anchored by the Unique Land Parcel Identification Number (also known as Bhu-Aadhaar which is a 14-digit alphanumeric identifier generated using the geo-referenced latitude and longitude coordinates of the land parcel's vertices, conforming to ECCMA and OGC standards[15]);
- the AI-driven[16] National Pest Surveillance System specifically targets pest and disease identification in 61 crops, including rice, while providing pest management advisories for 15 major crops . As of August 2024, 10,154 pest management advisories have been issued through NPSS[17];
- the Sub-Mission on Agricultural Mechanization (SMAM)[18], subsidizes the purchase of agricultural machinery and equipment, includes setting up High-Tech Hubs, as well as promoting mechanized operations in low-mechanized regions, including special support for the North-Eastern states;
- the Namo Drone Didi Scheme[19] enables Women Self Help Groups in Assam to deploy drones for various purposes, including for targeted pesticide spraying and real-time monitoring, enhancing pest control efficiency in rice farms and reducing crop losses; and
- the National Mission on Interdisciplinary Cyber Physical Systems[20] promotes advanced computation and real-world sensing to develop next-generation agricultural technologies, enabling precision pest control and resilient rice farming ecosystems in regions like Assam.

These above policies are supported locally by the Government of Assam, under which builders can leverage the UNNATI Scheme[21], and the Start-up & Innovation Policy[22], both of which prioritise agri-tech startups and agro-enterprises in Assam, which can access substantial incentives, technology incubation, and institutional support to deploy advanced cyber-physical systems and precision pest management solutions, enabling resilient, scalable mitigation of rice pests statewide.

Integration of ITK

The integration of traditional knowledge systems with modern cyber-physical approaches represents both an opportunity and a challenge. Farmers in Assam possess sophisticated understanding of pest ecology and management developed over generations[23]. The practices include manual stem cutting, bird perch systems for enhancing natural predation, and botanical pest control methods, which, research demonstrates that 21 out of 33 documented traditional practices in Assam rice farming are considered scientifically rational by agricultural scientists[24], suggesting significant potential for integrating indigenous knowledge with digital advisory systems. The challenge lies in actioning ITK at scale and verifying its results scientifically.

The Economics of Sustainability

Environmental sustainability considerations add another layer of complexity to the development of pest management technologies. Current pesticide-intensive approaches have created significant ecological disruption, including the elimination of beneficial insects, soil organism decline, and water contamination[12]. Blockchain-empowered H-CPS systems offer the potential to reduce pesticide dependency through precise, targeted interventions based on real-time data, but must be designed to promote ecological restoration and biodiversity conservation rather than simply optimizing chemical applications[25], especially given that high chemical use leads to increased infestation rates[26].

Climate change adaptation represents a critical driver for advanced pest management technologies. As global temperatures rise and precipitation patterns shift, traditional pest management calendars and practices become increasingly unreliable. Modelling studies indicate that climate change will expand the geographic range of YSB and increase the frequency of severe infestation events, requiring more sophisticated, adaptive management approaches[27].

Thus, the proposed H-CPS solution, aims to establish a foundation for examining how such systems can address the persistent challenges of YSB management in rice cultivation, while contributing to broader goals of agricultural sustainability, food security, and farmer welfare in the context of global environmental change, and providing a roadmap for the development and deployment of next-generation agricultural technologies.

An introduction to Cyber Physical Systems

Cyber-physical systems integrate computation, communication, and control technologies to manage networks of geographically dispersed IoT devices through data acquisition and feedback control. H-CPS, a subset of CPS, embed human knowledge and judgment into these operations. This human oversight enhances system adaptability, ensures ethical compliance, and addresses agronomic uncertainties that are difficult to codify. Integrating IoT devices and blockchain into H-CPS decentralizes trust, provides data traceability, and mitigates tampering risks through automated smart contracts, thereby securing the agricultural data lifecycle.

The distributed architecture of CPS creates security challenges, including vulnerabilities to malicious attacks and communication delays. An effective security framework combines blockchain with digital twins (**"DTs"**), which are virtual models synchronized with physical assets[34]. This integration improves operational security and enables predictive modeling for preemptive interventions. A notable research gap, however, is the lack of semantic interoperability between IoTs, blockchain data and DT analytics.

Therefore, the convergence of distributed CPS, human-centric interfaces, blockchain, and DTs presents a transformative model for proactive agricultural management. The success of such integrated frameworks depends on a supportive policy environment. India, for instance, is establishing a digital public infrastructure for agriculture, supported by policies and incentives designed to actualize these technologies at scale and foster a sustainable, farmer-centric agricultural system.

Proposed Distributed H-Cyber-Physical System *AKA* Herbarium

The proposed H-CPS is a layered network designed for predictive pest management, representing the initial deployment of a broader H-CPS framework for agriculture. Herbarium establishes a data ecosystem for rice fields, creating a continuous feedback loop from physical data collection to digital analytics and actionable advisories. Its distributed, modular architecture ensures scalability and robustness against single-point failures. The layers of the proposed H-CPS are as under:

Red-Zone Identification via Remote Sensing and UAV – We propose initiating the risk assessment with fusing satellite data (surface moisture, canopy nitrogen, land temperature) with a 228 °C-day emergence model and historical borer infestation maps. Areas exceeding a risk threshold are designated as provisional 'red zones'. Unmanned Aerial Vehicles ("**UAVs**"), may then capture high-resolution imagery, canopy height data, and moth counts within these zones to refine risk scores. This satellite-UAV data fusion generates a risk atlas that guides the placement of ground sensors and scouts, thereby optimizing resource deployment and reducing detection time. This method can also be scaled to block and district level and act as an early alert system for potential YSB infestation for local administrative and municipal authorities.

This workflow addresses several operational constraints. The coarse resolution of satellite imagery (10 m) can obscure small plots, and infrequent revisit cycles (~5 days) are often delayed by cloud cover. Furthermore, paddy water dampens spectral signals before the jointing stage. As optical data cannot detect structural damage, digital surface models are required to monitor canopy height changes. To mitigate these issues, the proposed solution workflow incorporates a two-stage spatial filtering process, multimodal imaging (including radar or thermal channels), and adaptive sensor routing.

In-situ sensor array ("Arrays")- Following red-zone identification, custom sensor arrays are proposed to be installed in high-risk locations. These arrays can be housed in primary sensors we propose include (a)RGB Cameras to periodically scan the canopy to detect adult YSB moths, egg masses, and feeding damage; (b) a YOLO-based computer vision model to analyzes the imagery to flag positive detections; (c)Multispectral (IR/NIR) Sensors to monitor for thermal and spectral signatures associated with pest presence before visual symptoms appear (for example, localized thermal anomalies may indicate egg clusters, while changes in the NDVI can signify pest-induced stress); (d) sensitive piezoelectric acoustic sensors to monitor acoustic signals within rice tillers to detect the high-frequency vibrations produced by YSB larvae chewing inside the stem; and (e) onboard environmental sensors to measure ambient temperature, humidity, and soil nutrients to correlate pest activity with microclimatic conditions. These in-situ Arrays are proposed as self-contained, networked, solar-powered units. Hardware includes an Arduino Nano microcontroller, a LoRaWAN transmitter, and the aforementioned sensor modules. All data are geotagged and time-stamped. The architecture is modular, allowing for the integration of other Arrays to monitor other pests or agronomic parameters, transforming these Arrays into a multi-threat monitoring station.

Field Data Hubs ("Mother Nodes")- data from the Arrays are transmitted wirelessly to a local field hub using low-power, long-range wireless protocols (e.g., LoRaWAN) to communicate with the Arrays nodes over distances up to 1 km. It attests sensor data from the Arrays and transmits it to a storage solution via an internet connection. The different Mother Nodes would be connected to each other creating smart connected farms ("SCFs") and farmers who are networked with each other[28].

To manage intermittent rural connectivity, the Mother Nodes can buffer data and perform edge preprocessing, such as image compression or alert filtering, to reduce bandwidth requirements. Like the Arrays, each Mother Node is solar-powered for energy independence (and is proposed to be integrated with existing solar water pumps common on farms in Assam provided under the under the PM-Kusum scheme [29]). Physically a ruggedized server, a single Mother Node can service dozens of sensors within a given-kilometer radius, bringing edge computing capabilities to the farm level.

Agri-Data Management and Transaction Layer- Data from the Mother Nodes are integrated into a blockchain solution, forming an immutable agri-data ledger for archiving identified data. Each sensor reading is recorded as a transaction, with its cryptographic hash, timestamp, and geolocation immutably stored on-chain. The raw data file (e.g., an image) can be archived on a decentralized storage network like IPFS, or on centralized storge, in either case - with the on-chain hash serving as a tamper-proof fingerprint that guarantees data integrity and provenance. This creates a permanent, verifiable record of farm conditions for future use.

An access and transaction layer governs data interactions. This layer is designed for flexibility, supporting both token-gated access for specific stakeholders and open data models as required by regulation or policy. Leveraging privacy-enhancing technologies like zero-knowledge proofs the proposed architecture can ensure compliance by design with privacy laws, such as India's Digital Personal Data Protection Act, 2023.

Artificial Intellegence Layers- Upon access, a heterogeneous family of learning models transforms raw data into agronomic foresight leveraging Convolutional Neural Networks ("**CNNs**") [30], which excels in detecting plant diseases, weed identification, yield prediction, by extracting intricate patterns from complex, heterogeneous data sources such as sensors, drones, satellites or even light traps[31]. Further, emerging AI architectures like Generative Pre-trained Transformers ("**GPSs**") can analyse multimodal agricultural data[32. A single, monolithic model is insufficient because each data stream and analytical scale presents unique challenges. For instance, while object-detection models like YOLO are effective for identifying YSB moths in clear images, their accuracy degrades in cluttered field conditions. At the canopy level, hyperspectral sensors can detect crop stress, but underlying water in rice paddies can mask early spectral cues. Similarly, multi-source fusion networks require principled feature selection to be effective, and temporal forecasting models that link pest pressure to weather are often location-specific and fail to generalize across different agro-climatic zones. To preserve privacy, Vision-Language Model Based Lightweight Federated Learning Framework [33] can be considered to field conditions and triggers.

Application Layer- The final layer translates the sensory data from the Arrays, attested and managed through the Mother Nodes, and analysed by AI models into actionable decisions, functioning as a comprehensive Krishi Decision Support System ("**KDSS**"), which can be interfaced as a gamified app for the farmers, a dashboard for the FPOs and district authorities, and link with other stakeholders to create a unified agricultural platform.

The most basic functionality would be the processing of farmer queries using a multi-stage pipeline, leveredging a state of the art platform for language translation, a Retrieval-Augmented Generation model to formulate responses using real-time sensor data and domain literature, and a foundational Large Language Model to generate the final output in the user's native language. In addition to handling user queries, the KDSS would function as a proactive alert system. To ensure precision, the system integrates with India's GIS infrastructure, linking advisories to specific land parcels via the Unique Land Parcel Identification Number (Bhu-Aadhar) integration.

This human-centric architecture, built on open standards and APIs, is designed to support a permissionless ecosystem for third-party innovation. It completes the cyber-physical loop, effectively bridging the gap between artificial intelligence and daily agronomy.

6. Conclusion

The proposed solution for YSB management, upon full deployment, is designed to achieve predictive management of the rice YSB. The system's efficacy increases with each participating node, creating a network effect that overcomes the limitations of current pest control methodologies. The benefits of this data-driven approach are both immediate and cumulative, encompassing agronomic, economic, and ecological dimensions.

Ultimately, more effective YSB control is expected to increase rice yields and reduce year-to-year output volatility. While minor, early-stage tiller pruning from YSB may occasionally stimulate compensatory growth, significant infestations invariably reduce yield. By maintaining pest populations consistently below the ETL, yields can more closely approach their genetic potential.

The data collected offers further economic advantages. Verifiable records of field conditions and pest management practices, potentially secured on a distributed ledger, enhance traceability. A consumer could verify, for instance, that a batch of rice was produced using minimal-pesticide protocols, adding value and supporting claims for IPM or organic certifications. At a community level, more stable production strengthens local food security and farmer incomes, contributing to rural socioeconomic resilience.

In summary, the proposed solution offers a network of solution that addresses the primary problem of pest-induced yield loss, the secondary consequences of indiscriminate pesticide use, and third-order opportunities related to market integration and climate adaptation. It embodies a preventive, precision agriculture paradigm: detect the pest early, select an intelligent intervention, and learn from seasonal data to continuously improve outcomes.

Future scope of work

In this final section, we outline ten specific research tasks derived from the gaps, challenges, and insights identified earlier in our study. Each task is detailed clearly, ensuring results can directly translate into practical solutions for managing YSB infestations in Assam.

1. Creating an acoustic signature library and refining classifiers
2. Field validation of tri-modal sensor fusion.
3. Durability testing of solar-LoRa sensor units given Assam's challenging climate.
4. Economic assessment through rapid cost–benefit analysis.
5. Blockchain integration and Agri-stack compatibility testing.
6. Optimizing biocontrol application.
7. Early warning system using UAV-based hyperspectral imaging.
8. Maintaining accuracy in vision models through active learning.
9. Evaluating the role of silica and nitrogen in stem resistance through greenhouse experiments.
10. Quantifying Emissions Savings for Carbon Credit Opportunities.

Together, these targeted research initiatives will directly address the critical gaps and operational constraints highlighted throughout this paper, paving the way for practical, sustainable, and economically viable YSB management solutions.

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