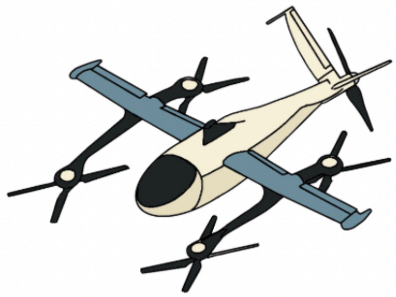
PH-LORA

Pheromonal Localized Overpopulation Regulation Aircraft



Columbia University Space Initiative

NASA's Gateway to Blue Skies Competition

2025: AgAir | Aviation Solutions for Agriculture

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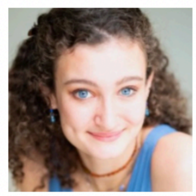

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Quad Chart

PH-LORA

Pheromonal Localized Overpopulation Regulation Aircraft

Project Summary:

Chemical pesticide use contributes greatly to a variety of environmental and health concerns. Though insecticide has severe detrimental impacts, its essentiality to farming practices urges innovation within the pest control sector. Phermonal pest control is non-toxic alternative, but has never gained widespread adoption due to the complexity and labor required in implementation and maintenance. PH-LORA is a hybrid winged UAV that is designed to carry out species specific operations in order to disperse pheromonal pest control autonomously. In communication with a ground surveillance system that identifies pest sexual maturation, PH-LORA then loads, navigates, and executes set dispersal methods 24 hours a day and in accordance with specific pest needs.

Project Image:

Team Composition/Roles:

A Columbia Space Initiative team that believes diversity in knowledge is the key to innovation. Our multidisciplinary background allows for us to approach agricultural problems from a holistic perspective.

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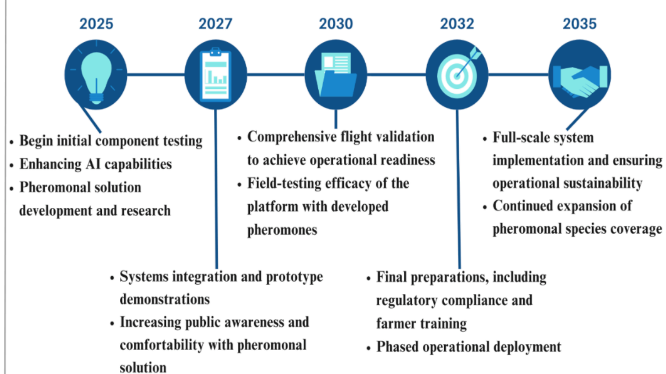
Proposed deployment timeline:



Abstract

The PH-LORA (Pheromonal Localized Overpopulation Regulation Aircraft) system, developed by Columbia University's Space Initiative, presents a novel, scalable solution to one of agriculture's most pressing challenges: reducing reliance on chemical pesticides (Brunelle et al., 2024). While chemical insecticides remain the backbone of modern agriculture and pest management, they carry severe environmental and public health costs. Pheromone-based pesticide control, a promising biological alternative, has demonstrated the ability to disrupt insect mating cycles without harming non-target organisms or ecosystems (Rizvi et al. 2021). Despite its proven efficacy, pheromonal pest management has been limited in scope due to the high labor demands, precision application requirements, and logistical challenges of maintaining species-specific treatments over large areas. PH-LORA addresses these barriers through an integrated system that combines ground-based artificial intelligence (Oracle) and autonomous aerial delivery. Oracle utilizes advanced optical sensors and machine learning algorithms to monitor insect populations, and predict optimal real-time intervention points (Güntsch et al. 2014). This data is relayed to PH-LORA, a drone-based delivery system that autonomously selects, loads, and applies pheromone formulations via a centralized docking and resupply platform (Nostos). This closed-loop design provides highly focused, adaptive, and cost-effective pheromone deployment, obviating the requirement for time-consuming manual deployment while minimizing operational expanse.

PH-LORA's modular design allows it to be customized to various agricultural environments, crop varieties, and pest species, with predictive flight patterns that factor in weather, terrain, and species behavior (Amarasingam et al. n.d.). The system's phased release strategy first addresses pesticide-resistant pests where chemical control is losing efficacy, then rolled out to larger agricultural settings. By addressing both biological and functional issues, PH-LORA can potentially transform the agricultural paradigm from chemical dependency towards ecologically benign, data-driven pest management. When projected full-scale deployment by 2035, PH-LORA offers a path towards more sustainable agricultural ecosystems, reduced environmental toxicity, enhanced farmworker protection, and stable food security. The system demonstrates technological feasibility of computer-regulated pheromonal release and lays the groundwork for world wide development of species-specific pheromones, providing a gateway for precision agriculture breakthroughs.

I. Agricultural Pest Management

A. Current Challenges in Crop Protection

A pesticide is a substance used to prevent, deter, destroy, or mitigate a pest that could harm crops ("What is Pesticide?" 2025). Exposure to pesticides can have a significant impact on a person's health. Acute exposure, typically affecting those administering the pesticide, can cause vomiting, skin and eye irritation, respiratory disorders and comas and can sometimes be fatal (Kalyabina et al. 2021). While long term exposure can occur through direct occupational exposure, it can also occur through the repeated consumption of food grown on contaminated soil (Kalyabina et al. 2012). Long term exposure can cause cancer, asthma, endocrine disorder, neurobehavioral disorders, and congenital defects (Kalyabina et al. 2021).

Pesticides also pose substantial environmental risks. During application, pesticide chemicals infiltrate and accumulate within the soil, leading to soil infertility, contamination of crops, and harm to non-target flora and fauna (Zhou et al. 2025). Air contamination occurs when pesticides are applied as aerosols, reducing air quality (Zhou et al. 2025). Additionally, agricultural runoff introduces pesticides into waterways, contaminating drinking water sources and enabling their entry into the food chain, where they biomagnify through trophic levels, increasing in concentration to potentially harmful levels at higher levels of the ecosystem (Zhou et al. 2025; Kalyabina et al. 2021). Moreover, pesticides can deplete dissolved oxygen levels in aquatic environments, jeopardizing aquatic life (Zhou et al. 2025).

Another critical challenge found in pesticide use is the development of resistance among insect populations. Over time, insect populations exposed to repeated applications of the same chemical compounds evolve mechanisms to detoxify or evade the pesticides, reducing their efficacy ("Insecticide Resistance"). This necessitates higher pesticide application rates or the development of new chemical treatments, perpetuating an unsustainable cycle of pesticide dependency and escalating environmental consequences.

One of the most extreme examples of pesticide resistance is the Colorado potato beetle (*Leptinotarsa decemlineata*), which has developed resistance to 52 compounds, spanning all major classes of insecticides (Alyokhin et al. 2008). As a result, the Colorado potato beetle represents a significant challenge for farmers, who must continuously seek alternative pest management strategies (Frank 2017). This has resulted in neonicotinoids being the most commonly used pesticide for this beetle (Frank 2017). These are particularly harmful pesticides as crops take up only 5% of them, while the rest disperse into the surrounding environment, harming non-target organisms such as bees (Wood and Goulson 2017). The widespread resistance of this species exemplifies the urgent need for sustainable and innovative pest control measures that do not rely solely on chemical pesticides.

B. Pheromone-Based Pest Control Solutions

Pheromonal treatments have emerged as a tool in modern agricultural pest management, providing an environmentally friendly alternative to conventional chemical insecticides. By leveraging insect communication systems, pheromone-based methods enable farmers to control pest populations, reduce pesticide use, and support sustainable agricultural practices ("Pheromones, Mulch and Wildflowers – How to Control Pests without Pesticides" 2021). A method known as integrated pest management, or IPM, utilizes synthetic sex pheromones to disrupt mating by overwhelming the area in pheromones, making males unable to isolate trails to the females and reducing pest populations while preserving beneficial insects (EPA 2018; "Pheromones, Mulch and Wildflowers – How to Control Pests without Pesticides" 2021). This approach has proven effective against pests like the codling moth in apple orchards (Witzgall et al. 2008). Pheromones interfere with communication rather than directly killing pests, significantly slowing resistance development (Cardé & Minks 1995). Additionally, mating disruption based pheromone systems have no effect on non-target flora or fauna, are environmentally benign, and are approved as organic (Tewari et al. 2014). As a result, pheromone-based strategies offer a more sustainable long-term solution for pest management in agricultural systems (Aktar et al. 2009).

Despite these advantages, pheromone treatments have not been widely implemented on a large scale due to several challenges. One key limitation is cost—synthesizing and deploying pheromones can be expensive, making them less accessible for large-scale farming operations (Wang et al. 2022). Additionally, the technology at the peak of IPM research was insufficient to meet the complex demand (Kogan 1998). Proposed solutions are widely limited to stationary traps and dispensers requiring constant maintenance (Witzgall et al. 2010). Furthermore, pheromone treatments are species-specific, meaning different formulations must be developed for each pest, adding to overall complexity (Witzgall et al. 2010). Finally, the awareness of pheromone-based pest control is limited, slowing adoption among farmers who are comfortable with conventional chemical solutions (Kabir et al. 2023). Addressing these barriers through research, cost reduction, and farmer education could enhance the feasibility of pheromone treatments for widespread agricultural use.

C. Pheromonal Synthesis

Pheromone treatments rely on synthetic replicas of naturally occurring chemical signals insects use to communicate, particularly for mating ("Insect Pheromones - an Overview" 2014). These compounds are typically long-chain hydrocarbons, alcohols, aldehydes, or acetates (Qu et al. 2024). The effectiveness of a pheromone depends not only on its molecular formula but also on the precise arrangement of atoms in three-dimensional space, as even small changes in structure can render it ineffective or attractive to the wrong species (Ginzel 1993). As insects often release blends of compounds in precise ratios, synthetic formulations must mimic both the chemical identity and proportion of each component (Wang et al. 2022).

Chemists use organic synthesis techniques to produce these pheromones at scale, often starting with petrochemical derivatives or bio-based precursors (Millar 2000) . Once synthesized, the pheromone is stabilized in a formulation, such as a polymer matrix or microcapsule, to control its release rate in the field. These formulations are then applied through dispensers or hollow-rope (*Behavior-Modifying Chemicals for Insect Management* n.d.). The production process emphasizes chemical accuracy and environmental stability, ensuring the pheromones remain active over weeks without degrading in sunlight or reacting with air and moisture (Hellmann et al. 2023).

While they are beneficial, the widespread use of pheromone treatments is constrained by economic and logistical factors. Stereochemically pure chemicals are expensive and difficult to synthesize, particularly for pheromones that require several isomers or those used in lower-valued crop applications (Takikawa & Kuwahara 2022). To combat this, breakthroughs in genetic modification have allowed researchers to biosynthesize insect pheromones in yeast cultures (Petkevicius et al. 2022). By inserting genes that encode enzymes responsible for synthesizing fatty acids, yeast can produce the pheromone of a specific species (Karolis Petkevicius et al. 2022). Engineered yeast can also produce pheromones in high titers and yields, making it suitable for large-scale production (Holkenbrink et al. 2020). The yeast fermentation method is far more cost effective than chemical synthesis (Holkenbrink et al. 2020).

II. Use Case And Proposed Solution

A. Identified Need for System

Implementing this system is vital for revolutionizing pest management in modern agriculture. Traditional pesticide-based solutions generate significant environmental and ecological risks while often leading to pesticide resistance among insect populations. This system provides a sustainable, scalable alternative by integrating autonomous drones, AI-driven monitoring, and precise pheromone distribution. Reducing chemical dependency, minimizing labor-intensive monitoring efforts, and enhancing targeted pest control with a real-time data analysis system can work for all agricultural endeavors. This approach optimizes agricultural yields and aligns with environmentally responsible farming practices, ensuring long-term agricultural sustainability and resilience against evolving pest threats.

B. System Overview

The proposed system integrates these technologies into a comprehensive pest management solution, combining autonomous drone delivery, precise pheromone distribution, and AI-driven pest monitoring. The technology in the system consists of three zero-carbon-emission hardware components and two software programs. This integration creates a seamless, automated pest management solution that addresses the complexities of modern agricultural needs.

C. Technological Components

1. Hardware

a. Drone and Droid (PH-LORA)

PH-LORA, an adaptation of Fly Zipline's medical/commercial P2 Zips delivery drone, is the foundation of this project’s pheromone distribution system. Featuring a hybrid-wing design with fixed wings for efficient transit and hover motors for precise maneuvering, the drone flies at around 300 feet under normal operation, minimizing wildlife disturbance. Its advanced flight control system includes airspace detection, collision avoidance, and centimeter-precise deployment accuracy, ensuring safe and effective operation through all phases of deployment (Zipline, n.d.).

Figure I. Image of PH-LORA

The novel retractable deployment mechanism represents a significant opportunity for advancement in precision agriculture technology. While the drone's size allows for a greater weight of pheromonal solution, the attached delivery droid fulfills the need for precise application to counter species-specific pest patterns, allowing full pheromone application from the crop base to the top if required for the optimum pheromone application. PH-LORA’s lowered droid would be altered to have a multi-nozzled bottom, allowing for precise positioning while its in-built active stabilization maintains accuracy across all flight conditions. PH-LORA's smart-release mechanisms, informed location, pest, and pre-emptive predictive data provided by Oracle enhance operational flexibility and pest control efficiency, optimizing coverage and safety (Zipline, n.d.). The PH-LORA system may be coordinated as a fleet if needed using Oracle’s suggested applications and the P2 Zip’s pre-existing collision avoidance and fleet coordination systems.

b. Docking Station (Nostos)

Along with the P2 Zips drone, the architecture of Fly Zipline's charging dock, Nostos, and loading station can work to increase efficiency within agricultural aviation. The smart docking infrastructure serves as a comprehensive hub for the entire system, acting as both the takeoff and landing zone and the charging station for the electric-powered drone (Zipline, n.d.). Landing will be handled using a vision-based approach in the absence of concrete alternative navigation data that has already been developed and proven to work by the Zipline company (Zipline, n.d.). Additionally, this station has autonomous capabilities for loading the pheromonal solution into PH-LORA, allowing for 24/7 deployment, further making IPM a viable solution by satisfying complex species-specific needs (US EPA, 2024).

c. Self-Sustaining Ground Insect Monitoring and Data Processing (Oracle)

To aid in the departure from sticky trap capture as a form of insect monitoring and classification, advancements in AI lend themselves to real-time, reduced labor insect monitoring. Oracle, a fully self-sufficient insect trap and its related backend data-processing systems, utilizes the architecture of the Trapview, a partially self-cleaning funnel and sensor with TRH Sensor Trap to identify insect maturity, locate potential problem areas, and automate the pest monitoring process. This automated camera trap operates mostly self-sufficiently without needing an external power source and has self-cleaning features that minimize maintenance efforts and the need for frequent trips, though it will still require a cleaning approximately once per quarter or season (Trapview, 2024).

2. Software Systems

a. Artificial Intelligence Identification and Pattern Recognition (Oracle)

Using Trapview's architecture as a foundation for Oracle's processing system, the number of insects that Oracle can identify will expand beyond the 60+ already within the Trapview database. Oracle would begin this expansion by targeting the largest insect threats to agriculture, including those that have developed pesticide resistance. Oracle additionally improves Trapview's system by categorizing each insect by its stage within its species growth cycle to measure breeding and population patterns. By collecting both region specific and crop specific data, we can isolate the most extreme pest cases first and feed a machine learning algorithm large datasets of sexual maturity indicators and mating behavior to train the AI to recognize the patterns, classify pests, and make species specific predictions.

For example, the pesticide resistant Colorado Potato Beetle, or CPB, has the sexual maturity marker of ten black lines running along its abdomen (Government of New Brunswick, n.d.). Species relative timelines can be produced as Oracle tracks the maturation, such as noting that CPB's reproductive organs take 7 to 9 days to develop after pupation (University of Massachusetts, n.d.). This specific pest is also known to mate on the underside of leaves. This recognition would trigger PH-LORA's CPB specific flying conditions, prompting the droid to fly low relative to the leaves of the crop while the nozzles point upwards, effectively spraying prime mating areas.

The AI is enhanced with the factors most relevant to the species' mating patterns. Physical indicators such as color, size, and appendage development, as well as location of mating and time of day are all factors weighed in the deployment of PH-LORA. Oracle will be based on existing, open-source neural network recognition software such as You Only Look Once V9000(YOLOv9000). YOLOv9000 uses neural networks to positively identify up to 9000 cases in real-time data analysis (Redmon). YOLOv9000 can be reconfigured to recognize a number of known insects and their various growth stages. Oracle will be based on this program in order to improve present identification mechanisms through extensive training on diverse pest lifecycle data, ensuring accurate species identification and maturation tracking. The system's real-time analysis capabilities enable near-immediate responses to emerging pest threats, while neurological network-based predictive modeling anticipates potential outbreaks based on a number of different factors, including historical pest data, weather conditions, geological conditions, and larger pest databases. When crop threats are detected, location data is sent by Oracle to load and deploy PH-LORA autonomously. This proactive approach allows for optimal timing of pheromone deployment, maximizing the effectiveness of pest control measures.

b. Remote Control and Insight Application (GaiaScope)

GaiaScope is a front-end intuitive mobile and web application developed by the PH-LORA team. GaiaScope operates as a hub for all operational needs, education, drone controls, and farm records, presenting all information collected by Oracle for easy access and analysis by any person.

GaiaScope Features

Features	Description
Real-Time Monitoring	Live data from Oracle & PH-LORA operations, including concentrations of pest activity.
Deployment Scheduling & Manual Control	Oracle's predictive modeling will plan deployment schedules relative to pest populations and insect specific needs. Manual control available to reschedule or recall for trouble shooting.
Data Analytics Dashboard	Visuals of pest trends, pest hot-spots, yield predictions, and cost savings.
Maintenance Alerts & Assistance	Automated reminders and repair walkthroughs with natural language support for system questions and operational help.
Historical Records	Archive of all past operations and pest activity for long term pattern recognition and pest migration tracking, exportable for reporting.
Education	Onboarding tutorials, video walkthroughs, FAQs, and access to an insect/pheromone knowledge hub; includes certifications, and multilingual support.

D. Improvements over existing solutions

Pest Management Comparisons

Features	Traditional Chemical Insecticdes	Organic Pest Control Methods	Stationary Pheromonal Pest Control	PH-LORA
Low Manual Labor Requirments	✓			✓
Cost- Low Initial	✓			
Cost- Low Long Term	✓			✓
Low Toxicity		✓	✓	✓
Minimal Environmental Damage		✓	✓	✓
Non-Target Fauna Protection			✓	✓
Slowed Resistance		✓	✓	✓

1. **Systems**
   a. **Connectivity**

Nostos will serve as a central hub for all processing and will communicate with PH-LORA using 2.4GHz radio to transmit high-level commands including location and pheromone amount and type, which PH-LORA will then process for autonomous navigation and pheromone distribution. Nostos will also contain a local Wi-Fi-based network to connect with GaiaScope and transmit information processed by the AI data processing component of Oracle and will additionally be able to connect to an uplink and cloud-based server for large-scale population trend analysis. Any Oracle trap will have the capability to locally process images and transmit numerical data over 2.4GHz frequencies back to Nostos for more intensive data processing and data uploads to a central cloud-based network to predict larger pest trends. Data transmission over long distances will be accomplished by daisy-chaining the network of Oracle traps to each other, ensuring reliability and reducing potential costs associated with implementation. This ensures that the entire system can function even in the absence of a reliable internet connection, especially important when considering the common unavailability of broadband in rural areas.

III. Implementation

A. Overview of Operations

Our proposed system is designed to be broadly applicable to a large variety of crops and climatic conditions, and we are expecting it to be useful in most agricultural contexts of all scales. For simplicity, this proposal will utilise a few selected examples as illustrative cases.

Precedents and Advantages

Drones for aerial dispersion of pesticides and related treatments are already in wide use in East Asia. In South Korea and Japan, for example, about 30% of the country's crops are sprayed using drones, mainly rice, but also including other crops like oats, soybeans, and wheat (Ozkan 2023a). These drones are primarily single-rotor helicopter drones. In China, multi-rotor drones are already being used on a massive scale for the dispersion of aerial pesticides. There are four main advantages that come with the recent deployment of drones in general. Firstly, drones perform well in topography that is unsuited to ground vehicles or conventional aircraft. Secondly, they are available and cheap when normal vehicles and aircraft are unavailable or prohibitively expensive. Thirdly, they perform especially well with smaller or irregularly shaped fields. Lastly, the dispersion system's unmanned nature minimizes direct farmer exposure, further reducing potential health and safety risks (Ozkan 2023b), (Suterra 2019).

Timeline:

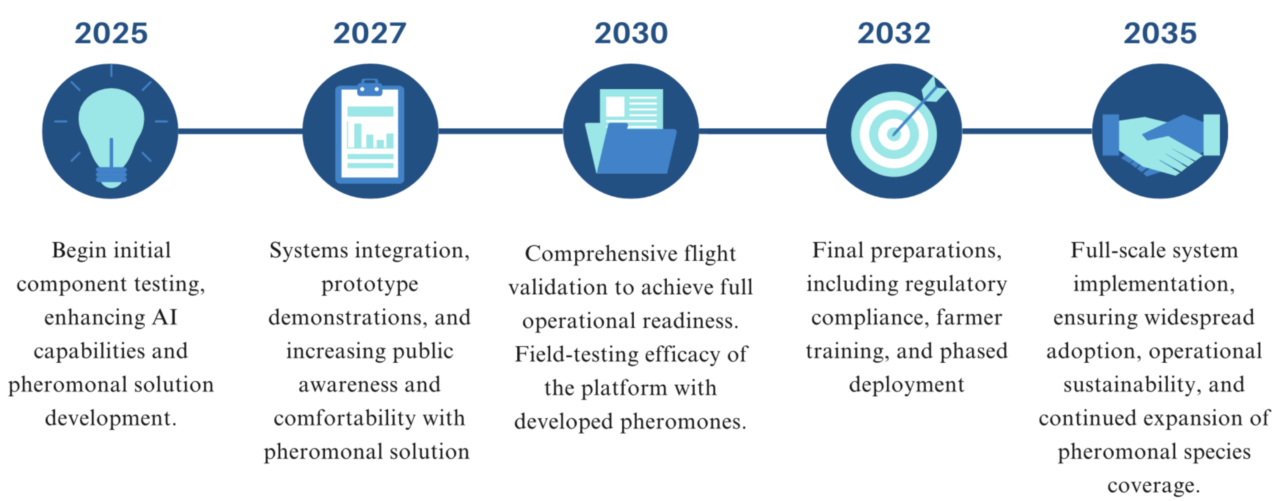


Figure II. Projected Timeline of PH-LORA

B. Integration into Existing Agricultural Practices

The integration of the PH-LORA system into existing agricultural practices is part of a holistic integrated pest management strategy (IPM). As part of an IPM strategy, our system is designed to complement and reduce the use of pesticides, but not totally replace them. In cases of extreme weather, unanticipated pest migration, or pheromone treatment failure, traditional insecticides may still be necessary. Research has shown that a combination of pheromonal treatments and traditional pesticide use tends to be most effective (Reddy and Guerrero 2010). Our system allows farmers to reduce overall pesticide use significantly by deploying pheromone treatments with precision and only when pest threats are detected. The system allows for real time monitoring of pests and crop conditions as part of a whole integrated system of holistic agricultural management.

Public understanding of pheromone-based pest control is critical. Currently, pheromonal treatments as the primary form of pest control is still relatively unknown, and farmers will have to be convinced that the use of pheromones and drones will be a safe and effective way of protecting their livelihoods. The general public will have to be educated about the safety of pheromonal treatments. Ideally, long-term scalability would be achieved through partnerships with various large agricultural cooperatives, including companies like CHS Inc. or Land O' Lakes Inc and university research programs. We will further look towards working with public agencies like the USDA, whose work already focuses on lessening pesticide runoff and encouraging climate-resilient agriculture.

The adoption of this system provides multiple advantages for stakeholders. Farmers would benefit from reducing reliance on chemical pesticides and minimizing environmental and health risks while maintaining crop yields. Consumers gain access to crops that align with environmentally friendly farming practices, enhancing marketability. This is a particular problem considering the farming industry's reliance on pesticide use (Lee 2023).

C. Cost Analysis and Return on Investment

The following are cost estimates for the components of the system:

GaiaScope Features

Component	Cost Breakdown
PH-LORA Unit: Drone Hardware	~$10,000 per unit ("Sprayer Drones" 2025) (Using commercially available agri-drones as an estimate as no pricing data available for Zipline)
Oracle AI Development & Integration	~$500,000 (one-time initial investment, based on large-scale industry model) (Ta 2024)
Oracle Hardware: Self-Cleaning Insect Sensors	~$25-50 per acre per year on a subscription basis (Courtney 2025) (Using Cropview as an estimate as no pricing data available for Trapview)
App Development & Dashboard Interface	~$50,000 ("Application Development for Agriculture: Process, Steps, & Cost - IDAP Blog" 2023)
Docking Station & Loading Infrastructure	~$10,000 per location ("DJI Dock 2" 2024) (Estimation from commercially available docking systems)
Pheromonal Production	~$70/kg (Stokstad 2022) if utilizing yeast biosynthesis, compared to ~$200/kg for chemically synthesized pheromones (Stokstad 2022)

The following table analyzes application cases of IPM across various geographical areas in the United States and across a variety of pests, proving the environmentally versatile nature of pheromonal solutions. When utilizing existing IPM strategies, it is most practical for higher-value crops in medium-sized farms, but can also be viable when crops are lower value. PH-LORA's pheromonal production method of genetically modified yeast in combination with its autonomous 24 hour operation would dramatically lower the overall cost long term.

Pest, Location, and Value Analysis

Pest & Crop	Location	Climate / Environmental Landscape	Crop Value	Cost Analysis
Navel Orangeworm in Almonds	Central Valley, California	Mediterranean climate (hot, dry summers; cool, wet winters)	High	Avg. profit ~$2,000/acre profit. Farms average 100 acres → ~$200,000/year profit. Pheromone cost ~$145–170/acre. PH-LORA system requires ~3% of annual profit if financed over 5 years. Helps prevent aflatoxin contamination & yield loss.
Pink Bollworm in Cotton	American South (e.g., TX, GA, MS)	Warm temperate to subtropical; prone to high humidity	Medium - Low	Avg. profit ~$200/acre. Avg. farm: 500 acres → ~$100,000/year profit. Capital cost is ~5% of profit if financed over 5 years. Pheromone + monitoring ~$102–127/acre. Effective when pesticides fail due to pest hiding in bolls.
Corn Rootworm in Corn	Midwest (e.g., IA, IL, NE)	Continental climate; fertile soils, moderate rainfall	Low	Avg. profit ~$164/acre. Avg. farm: 280 acres → ~$45,920/year profit. Capital cost ~1% of profit if financed over 10 years. System + monitoring: $25–50/acre. Still feasible with careful budgeting; pheromone market still maturing.

D. Target Users and Training

Successful implementation of the PH-LORA system will rely not only on its technical capabilities but also on comprehensive farmer training and public education. Firstly, Farmers must learn to interpret data visualizations from GaiaScope, safely maintain docking stations, and operate autonomous drones effectively to maximize the impact of pheromonal and pesticide dispersion. The initial target market comprises medium and large-scale farms (50+ acres) growing high-value crops, as these operations are best equipped with the necessary infrastructure to adopt advanced technologies and stand to gain the most in terms of reduced crop loss and improved sustainability. Pests that do not have effective management solutions available are also prime targets. To ensure effective onboarding, a tiered training program will be offered including maintenance guides and access to GaiaScope. Ultimately, widespread adoption will depend on users feeling empowered to integrate PH-LORA into their long-term pest management strategies for both human and environmental health.

IV. Path to Deployment by 2035

A. Technology Readiness

To assess the stage of development of the integrated system, this project utilizes the Technology Readiness Levels (TRL) standards devised by NASA to evaluate each component individually and the system as a whole (Manning 2023). Some individual components, such as the drone, the docking station, and the automated trap, are currently fully mature: these systems are "flight proven" at TRL 9. For example, the P2 Zip has all necessary FAA permissions to operate, and has performed over one million commercial deliveries in the last two years (Zipline, n.d.). Other components, such as the attached delivery droid and the software systems, are modifications of other products or entirely new concepts so require validation and demonstration, rating them as low as TRL 3. Overall, the PH-LORA system must undergo some component testing but mainly component integration and limited environment testing, reflecting its current TRL 5 rating. Moving toward higher readiness levels will require testing and validation of system performance in real-world agricultural settings. By anchoring development within these standards, the project ensures technical feasibility and a clear path towards a fully mature system ready for full-scale deployment.

B. Barrier Analysis

To ensure successful deployment, several key barriers must be addressed:

1. UAV Regulations in Agricultural Applications:

The FAA currently regulates drone operations, with the use of drones dispensing chemical and agricultural products substances governed under 14 CFR Part 137. There are three steps to gain a Part 137 UAS Certificate: petitioning for an exemption, submitting basic operational information, and applying for an Agricultural Aircraft Operator Certificate ("Dispensing Chemicals and Agricultural Products (Part 137) with UAS" 2025). The standardized training program implemented as part of the deployment process will provide guidance to facilitate compliance with FAA regulation and streamline the certification process, as well as educate farmers on the safe and legal operation of the system.

2. Environmental Safety and Pheromone Efficacy:

Pheromones offer a non-toxic and targeted alternative to conventional pesticides, minimizing their impact on non-target species and reducing ecological disruption (Battelle Insider 2023). Because pheromones successfully disrupt pest mating cycles, they provide an effective pest control solution (Smithsonian Institution n.d.). Unlike traditional pesticides, which can lead to environmental contamination and harm to non-target organisms, pheromone-based solutions present a promising approach to mitigating these issues (Aktar, Sengupta, and Chowdhury 2009). Comprehensive field testing and regulatory approval will be pursued to ensure the efficacy and environmental safety of the proposed pheromone dispersal system.

3. Industry Resistance and Market Disruption

Introducing a pheromone-based pest control system represents a direct challenge to the entrenched pesticide industry, which is unlikely to welcome such innovation without resistance. The global pesticide market was valued at approximately $79 billion in 2023 and is projected to exceed $119 billion by 2031, growing at a compound annual growth rate (CAGR) of over 5% (Jadhav 2024). This growth is fueled by increasing global food demand, intensive monoculture farming, and heavy reliance on chemical treatments. Major agrochemical companies have profound financial and lobbying interests in maintaining this status quo, investing heavily in product development and regulatory influence (Pretty & Bharucha, 2015).

Pheromone based alternatives threaten to cut into this market by offering a more sustainable, biologically targeted, and potentially safer approach to pest management. This could reduce farmers' long-term dependence on broad-spectrum pesticides, which currently account for significant annual expenditures - up to $93 per acre in almond production alone (University of California Agriculture and Natural Resources et al., 2024). While initially more expensive per acre, pheromone systems have demonstrated a serious potential to reduce crop loss and environmental damage. This would ultimately shift economic incentives away from chemical solutions. As such, market incumbents may engage in strategies to delay regulatory approval, challenge efficacy data and potentially promote hybrid approaches that would be able to maintain a role for chemical pesticides. Recognizing and preparing for this resistance - through strong data, strategic partnerships, and public awareness - will be essential for successfully adopting and scaling pheromone-based technologies.

4. Human Safety and Public Acceptance:

One of the main challenges in adopting pheromone-based pest management is gaining industry and stakeholder acceptance. Despite their proven safety for human exposure, pheromone solutions must be rigorously tested and strategically introduced to encourage widespread adoption (Exponent Staff 2023). The dominance of the pesticide industry presents an additional challenge, necessitating robust demonstrations of pheromone efficacy to gain market acceptance. To further enhance operational safety, each drone is equipped with an advanced aerial navigation system capable of detecting and avoiding human presence, ensuring safe operation in agricultural environments. Additionally, government subsidies or potential incentive programs aimed at reducing chemical pesticide use and supporting sustainable agriculture could play an important role in working to offset initial costs while working to accelerate farmer adoption.

5. Connectivity in Rural Areas

Connectivity and cloud-based solutions may be infeasible in rural areas where internet connectivity may be inconsistent. The proposed solution avoids these challenges by mostly using local processing and interconnection, allowing the system to be used even in the absence of a reliable internet connection. Simultaneously, Nostos' capability to be integrated with the internet will provide the significant benefit of predictive insect trends across a larger scale, allowing farmers to better predict pest patterns if they are able to opt in to such a service.

Conclusion

Traditional chemical insecticides continue to dominate agricultural pest control, despite their well-documented environmental and human health risks. Pheromone-based pest management systems offer a more sustainable and less harmful alternative, but their adoption has been limited by the labor-intensive nature of their deployment and the high level of precision required. PH-LORA resolves these issues through its two-pronged approach. Oracle, leveraging an AI-driven monitoring system, identifies the species, quantity, and life cycle stage of target insects to tailor the precise type and quantity of pheromones for dispersal. PH-LORA then autonomously distributes these pheromones with pinpoint accuracy, dramatically reducing the burden on human labor. Combined, these technologies transform pheromone dispersal into a viable, scalable alternative to chemical insecticide-centric solutions.

Since the original proposal, further analysis of currently used chemicals has been completed and the system has been significantly expanded. The harm that chemical pesticides pose to human health have been identified, highlighting the need for an alternative system. Real-time pest updates, mating-specific positioning (e.g., underside of leaves), AI tools like YOLOv9000, and an intuitive farmer app (GaiaScope) now enhance the system's capability and usability. A broader national deployment strategy was also developed, accounting for diverse crop types in different regions, farmer training, financing, systems support, and regulatory compliance. These advancements demonstrate that not only is the technology feasible—it is maturing rapidly. Based on this, PH-LORA could be fully implemented nationwide by 2035.

In conclusion, chemical insecticides are environmentally damaging and pose real threats to human well-being. Pheromone-based alternatives can resolve these issues.

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