A Survey of Physical and Biological Control in Sustainable Pest Management

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Abstract

This survey paper explores the integration of physical and biological control methods within sustainable pest management, emphasizing their critical role in reducing chemical pesticide use and promoting agricultural sustainability. The increasing global population and the resultant demand for food production underscore the necessity for effective pest management strategies to mitigate significant yield losses caused by plant diseases. Traditional reliance on chemical pesticides poses environmental and health risks, prompting the need for sustainable alternatives such as integrated pest management (IPM) and biological control. The paper systematically reviews various physical control techniques, including mechanical and environmental modifications, and explores innovative technologies like image-based detection systems and non-invasive monitoring methods. Biological control strategies leveraging natural predators and microbial interactions are also examined, highlighting their potential to enhance ecological balance and crop resilience. The integration of advanced technologies, such as machine learning, IoT, and UAVs, within IPM frameworks is discussed, showcasing their ability to improve pest monitoring and management precision. The paper concludes by identifying challenges, including regulatory barriers and data limitations, and suggests future research directions to enhance sustainable pest management practices. By synthesizing these insights, the survey underscores the importance of interdisciplinary approaches and technological innovations in achieving long-term agricultural sustainability and food security.

1 Introduction

1.1 The Need for Sustainable Pest Management

Sustainable pest management is crucial for addressing food security and environmental health amid a rapidly growing global population, projected to exceed 9 billion by 2050, necessitating a 70% increase in food production [1]. Infectious diseases contribute to up to 40% of potential yield losses, emphasizing the urgent need for effective pest management strategies [2]. The economic impact of plant diseases further complicates agricultural productivity and profitability [3].

Traditional pest management primarily relies on chemical pesticides, which pose significant environmental and health risks due to their non-specificity and potential ecological contamination [4]. The rise of antibiotic resistance exacerbates these issues, highlighting the necessity for sustainable approaches [5]. By integrating physical and biological control methods, sustainable pest management seeks to reduce chemical dependency and enhance agricultural sustainability [6].

Effective pest detection and management, illustrated by the boll weevil's impact on cotton yields, are vital for sustainable practices [7]. Advancements in technology, such as image-based detection systems, enhance the ability to differentiate between crops and weeds, leading to more precise interventions [8]. Non-destructive assessment methods, like measuring leaf size in tomatoes, are essential for monitoring plant health [9].

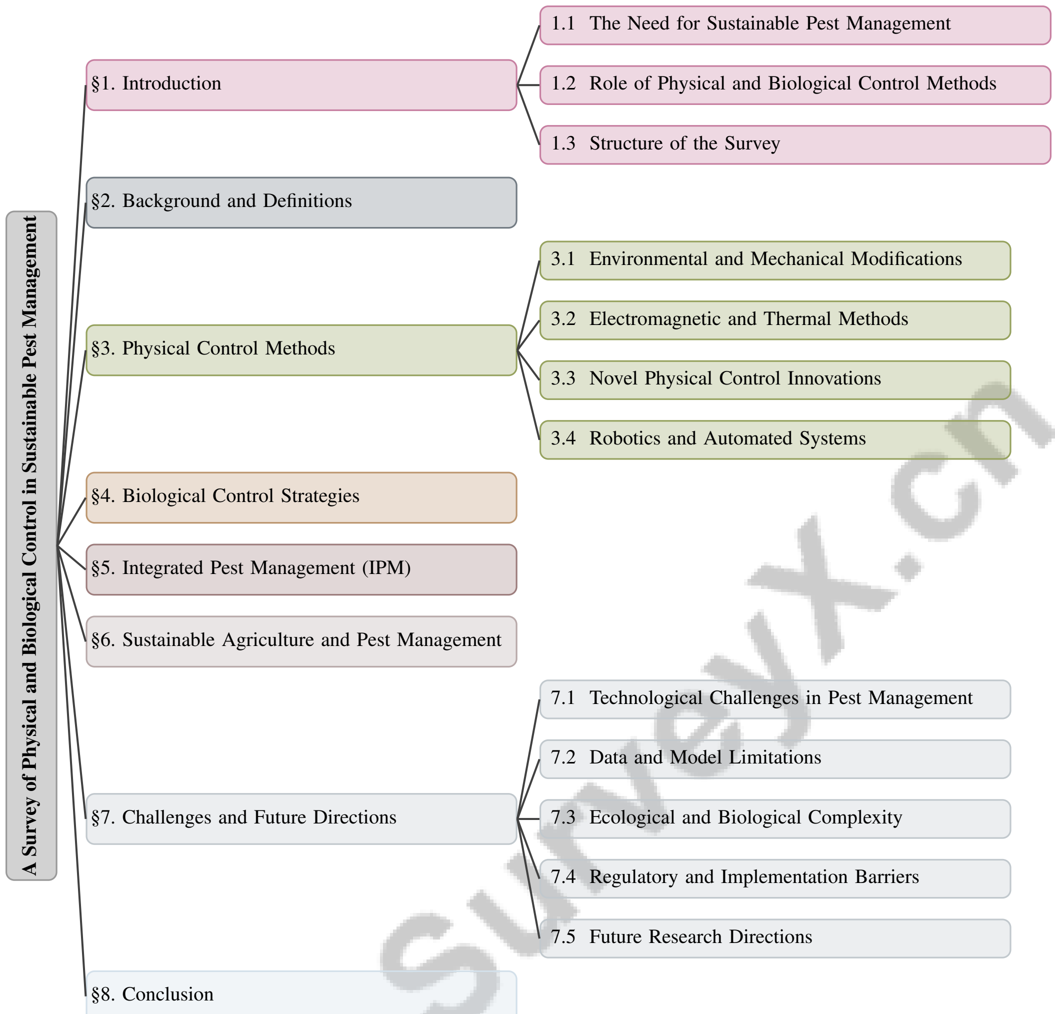

Figure 1: chapter structure

Understanding plant stress communication via Biological Volatile Organic Compounds (BVOCs) can mitigate agricultural losses [10]. Pests such as aphids, which transmit plant viruses, pose challenges in the context of climate change and food security [11]. The limitations of conventional chemical treatments for diseases like Citrus Variegated Chlorosis (CVC) further underscore the need for sustainable control methods [12].

Continuous monitoring of plant health and early disease detection are integral to sustainable pest management, preventing disease spread and minimizing crop losses [13]. Innovations in environmental monitoring, such as low ozone concentration detection, play a crucial role in maintaining plant health and productivity [14]. By addressing these multifaceted challenges, sustainable pest management supports not only immediate agricultural productivity but also long-term environmental conservation and economic viability. Reducing herbicide and pesticide usage is essential for enhancing crop quality and promoting biodiversity [15].

The unpredictable spread of diseases like coffee rust has significant economic implications, highlighting the need for sustainable pest management [16]. The declining populations of natural pollinators further emphasize the necessity for innovative pest management strategies [17]. Insights into plant structural biomechanics, such as glandular trichomes in tomatoes, reveal natural defense mechanisms that can be leveraged for sustainable pest management [18]. Developing comprehensive systems to measure physiological and environmental parameters in real-time will enhance sustainable pest management practices [19].

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The challenge lies in establishing a reliable system for monitoring environmental parameters and controlling irrigation in remote plantations, ensuring optimal crop growth conditions [20]. Accurate plant disease detection is vital for preventing crop losses and ensuring food security [21]. Understanding arbuscular mycorrhiza (AM) symbiosis is critical for sustainable pest management by minimizing complex chemical inputs [22]. Timely diagnosis of maize diseases can significantly improve agricultural product quality [23]. Accurately detecting and classifying multiple weed species in real-world settings is essential for effective pest management [24]. The inefficient distribution of internal resources in dynamic environments hampers self-organizing systems' ability to optimize resource extraction [25]. Low-cost, modular systems facilitate quantitative studies of growth processes and resource exchanges, underscoring the need for sustainable pest management [26]. The root microbiome of squash adapts to arid conditions, promoting plant health and drought resilience [27]. The mosaic disease affecting Jatropha curcas highlights the substantial economic and societal costs of plant diseases, particularly in agriculture-dependent developing countries [28].

1.2 Role of Physical and Biological Control Methods

Physical and biological control methods are essential for sustainable pest management, offering strategies that promote ecological balance and reduce chemical pesticide reliance. Physical control techniques, including mechanical barriers and traps, provide immediate pest reduction solutions while minimizing ecological disturbances [29]. The use of low-cost programmable growth chambers that incorporate modular components for environmental monitoring exemplifies the significance of physical control in optimizing agricultural conditions [26].

Biological control methods utilize natural predators, parasites, and pathogens to manage pest populations, enhancing biodiversity and ecosystem resilience. The integration of digital tools for pest control and crop monitoring, supported by curated image datasets, underscores the critical role of biological control in promoting biodiversity applications [30]. Minimal ecological models, such as those based on generalized Lotka-Volterra dynamics, provide insights into plant-soil microbe interactions, informing effective biological control strategies [31].

Technological advancements enhance the efficacy of these methods. For example, laser biospeckle activity can detect physiological changes in leaves associated with endophytic colonization, providing a non-invasive monitoring technique [32]. Insights into the mechanics of type VI glandular trichomes in tomatoes reveal natural pest defense mechanisms that can be harnessed for sustainable pest management [18]. Additionally, robotic precision pollination techniques address the increasing demands of the human population, highlighting the need for innovative pest management solutions [17].

The integration of physical and biological methods is vital for achieving sustainable pest management. These approaches not only reduce chemical inputs but also enhance agricultural system health and productivity, contributing to environmental and economic sustainability. Continuous technological and biological advancements are expected to significantly improve the effectiveness and adoption of sustainable pest management practices. Innovations, including transdisciplinary research collaborations, mathematical modeling for pest control, and robotic monitoring systems, are essential for tackling challenges posed by climate change and pest infestations. By integrating diverse scientific fields such as plant science, engineering, and social sciences, these efforts aim to enhance agricultural productivity while minimizing environmental impact, ensuring the long-term viability of agriculture and promoting ecological harmony [33, 31, 34, 11, 35].

1.3 Structure of the Survey

This survey provides a comprehensive overview of sustainable pest management, emphasizing the integration of physical and biological control methods. It begins with an introduction highlighting the necessity of sustainable pest management for reducing chemical pesticide use and promoting agricultural sustainability. The subsequent section analyzes how physical and biological control methods, including intercropping and aphid-resistant soybean varieties, contribute to sustainable pest management and enhance agricultural resilience against climate change and invasive species [11, 34, 31, 36].

The second section, "Background and Definitions," clarifies key concepts such as physical control, biological control, integrated pest management (IPM), and sustainable agriculture, discussing their significance in maintaining plant health and effective pest management.

The third section, "Physical Control Methods," examines various physical control techniques, including mechanical barriers, traps, and environmental modifications, assessing their effectiveness and limitations. This section is subdivided into discussions on environmental and mechanical modifications, electromagnetic and thermal methods, novel physical control innovations, and the role of robotics and automated systems.

The fourth section, "Biological Control Strategies," explores the use of natural predators, parasites, and pathogens in controlling plant pests and diseases. It discusses the benefits and challenges of implementing biological control in agricultural systems, including subsections on natural agents and biological mechanisms, technological advancements, and biological interactions in pest management.

The fifth section, "Integrated Pest Management (IPM)," delves into IPM principles and practices, emphasizing the integration of various control methods. It highlights case studies and examples of successful IPM implementations, with subsections on technological integration, interdisciplinary approaches, and successful case studies.

The sixth section, "Sustainable Agriculture and Pest Management," analyzes the role of sustainable agricultural practices in enhancing pest management. It discusses how these practices contribute to environmental and economic sustainability, with subsections on sustainable agriculture practices, enhancement of soil health and crop quality, and technological advancements supporting sustainable agriculture.

The seventh section, "Challenges and Future Directions," identifies challenges in implementing physical and biological control methods. It discusses future research directions and potential innovations that could enhance sustainable pest management, with subsections on technological challenges, data and model limitations, ecological and biological complexity, regulatory and implementation barriers, and future research directions.

The conclusion emphasizes the critical need for integrating physical and biological control methods in sustainable pest management. Approaches such as intercropping and using resistant crop varieties not only enhance pest control effectiveness but also offer significant benefits for environmental health and economic viability, especially in addressing climate change and the overuse of chemical inputs in agriculture. By adopting multifaceted strategies, we can foster more resilient agricultural systems that benefit ecosystems and agricultural productivity [11, 34, 31].The following sections are organized as shown in Figure 1.

2 Background and Definitions

2.1 Significance in Plant Health and Pest Management

The maintenance of plant health and effective pest management is crucial for enhancing agricultural productivity and ecological stability. Investigating the interactions between plant structures and pests is fundamental. Studies on glandular trichomes in tomatoes reveal their mechanical response to herbivores, offering insights into natural defense mechanisms that can be applied to pest management [18]. The impact of pathogens such as Hemileia vastatrix, responsible for coffee rust, further illustrates the importance of understanding plant-pathogen dynamics for effective pest control [16].

Symbiotic relationships, notably those involving arbuscular mycorrhizal fungi, are pivotal in reducing reliance on synthetic fertilizers and enhancing plant health [22]. Additionally, beneficial microbial communities, like those in the squash root microbiome, improve drought resilience, highlighting the role of microbial interactions in agricultural sustainability [27]. These interactions not only support plant health but also bolster the ecological resilience of agricultural systems.

Theoretical frameworks on plant-pathogen dynamics, which explore network architecture and emergent behaviors, provide essential insights into maintaining plant health [37]. Furthermore, adaptive resource redistribution models, which utilize real-time environmental feedback, enhance pest management by enabling timely interventions [25].

Emerging threats, such as mosaic disease caused by Begomovirus and spread by whiteflies, result in significant yield losses in crops like Jatropha curcas, underscoring the need for robust pest management strategies [28]. Early detection of plant diseases, especially fungal infections in forests, is vital for preventing ecosystem degradation and preserving biodiversity [38].

Advanced techniques, including Few-Shot Learning with context-aware embeddings, are critical for enhancing plant health monitoring and pest management [39]. These insights and technological advancements collectively contribute to developing integrated pest management strategies that promote sustainable agriculture and ecological resilience.

2.2 Historical and Theoretical Perspectives

Sustainable pest management has evolved through historical developments and theoretical advancements. The transition from manual phenotyping to advanced sensor technologies represents a significant milestone, enabling precise pest management strategies [40]. This shift has facilitated the integration of modern technologies, such as machine learning and mobile applications, to deliver accessible disease diagnostics to farmers, particularly in regions lacking expert assistance [1].

Theoretical frameworks often draw from complex systems and network theory to elucidate plant-environment interactions [37]. Mathematical models that describe interactions among healthy, infected, and latently infected plants and vector populations offer insights into the potential impacts of pest management interventions, highlighting the importance of timely responses [28].

Historical research on plant irritability, notably by Jagadish Chandra Bose, has laid the groundwork for understanding plant responses to environmental stimuli and stressors [41]. Bose's pioneering work on physiological responses informs contemporary pest management by emphasizing plant-environment interactions.

Furthermore, modeling plant stems as Duffing oscillators, accounting for nonlinearities in their resonant behavior, provides a theoretical foundation for understanding the structural dynamics of plants under stress [42]. These insights assist in developing pest management practices that consider the mechanical and structural properties of plants.

Despite advancements, sustainable pest management faces challenges such as regulatory barriers and the need for better integration between agricultural and medical biotechnology [35]. Addressing public concerns about GMOs and isolating active compounds from plants for antimicrobial applications remain significant hurdles [5]. These challenges highlight the need for ongoing research and innovation to improve the efficacy and acceptance of sustainable pest management practices.

In recent years, there has been a growing emphasis on integrating sustainable practices within pest management frameworks. This shift is largely driven by the need to reduce chemical pesticide reliance and to promote environmentally friendly alternatives. Figure 2 illustrates the hierarchical structure of physical control methods in pest management, highlighting key categories such as environmental and mechanical modifications, electromagnetic and thermal methods, novel physical control innovations, and robotics and automated systems. Each category is further divided into subcategories, showcasing specific techniques and technologies that contribute to sustainable agricultural practices and improved pest management strategies. By understanding this structure, researchers and practitioners can better identify and implement effective pest management solutions that align with ecological principles and agricultural sustainability goals.

3 Physical Control Methods

3.1 Environmental and Mechanical Modifications

Environmental and mechanical modifications are vital for sustainable pest management, offering non-chemical strategies that maintain ecological balance. These methods involve altering environmental conditions and employing mechanical interventions to control pest populations and disease spread. Modular growth chambers allow precise regulation of temperature, humidity, and light, optimizing plant health and enhancing resistance to pests and diseases [26]. Integrating population awareness into disease control strategies, through nutrient applications and insecticides, highlights the importance of informed interventions in reducing disease prevalence [28]. This synergy between environmental modifications and informed decision-making is crucial for effective pest management.

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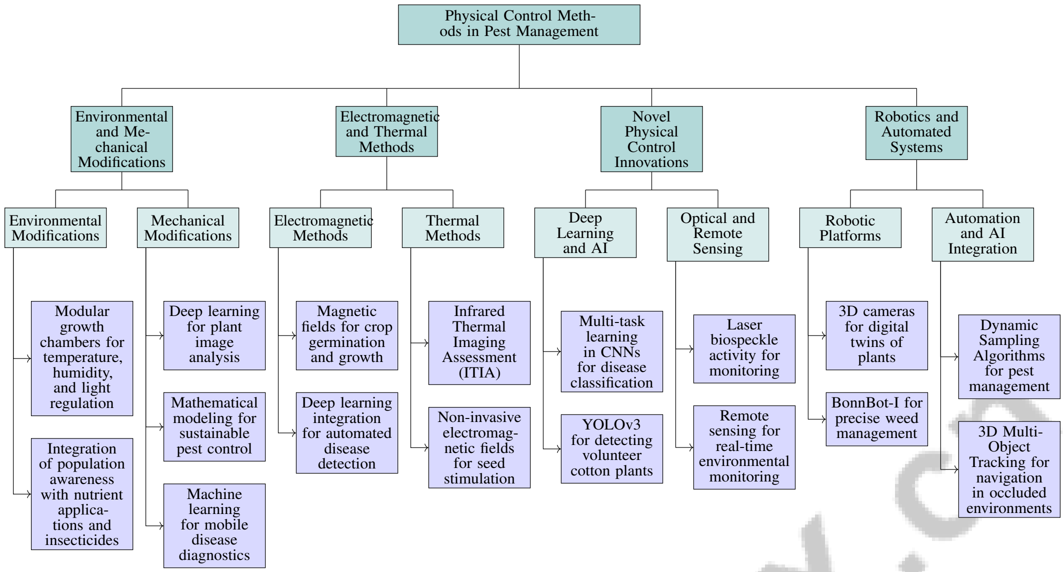

Figure 2: This figure illustrates the hierarchical structure of physical control methods in pest management, highlighting key categories such as environmental and mechanical modifications, electromagnetic and thermal methods, novel physical control innovations, and robotics and automated systems. Each category is further divided into subcategories, showcasing specific techniques and technologies that contribute to sustainable agricultural practices and improved pest management strategies.

Mechanical modifications have also advanced pest management precision. Deep learning techniques for image analysis, such as generating enriched embeddings for plant images, facilitate accurate classification of plant health status, enabling early detection and intervention [39]. The development of sophisticated models and technologies, including mathematical modeling for sustainable pest control and machine learning for mobile disease diagnostics, is essential for enhancing agricultural resilience against pests and diseases. These innovations, supported by transdisciplinary collaboration among plant science, engineering, and social sciences, aim to improve pest management strategies and crop health, addressing challenges posed by climate change and increasing global populations [1, 34, 11].

3.2 Electromagnetic and Thermal Methods

Electromagnetic and thermal methods offer innovative, non-invasive strategies in sustainable pest management, effectively monitoring and controlling plant health. Alternating and constant magnetic fields enhance germination and growth parameters in crops like soybeans, demonstrating the potential of electromagnetic methods to improve plant vigor and resilience [43]. These techniques exploit the interaction between electromagnetic fields and biological tissues to stimulate physiological processes, promoting healthier crop development and potentially reducing susceptibility to pests and diseases.

Infrared Thermal Imaging Assessment (ITIA) serves as a powerful tool for managing plant health by measuring leaf temperatures, providing a non-destructive means of assessing plant stress and detecting early signs of disease or pest infestation [44]. This method allows precise monitoring, enabling timely interventions that mitigate pest and disease spread without chemical treatments. The integration of deep learning techniques, such as Convolutional Neural Networks (CNNs), into electromagnetic methods enhances automated disease detection systems. The AMaizeD pipeline exemplifies this advancement, employing CNNs for rapid identification of diseases in maize crops, facilitating timely pest management decisions [45].

The combination of electromagnetic and thermal methods in pest control, including non-invasive electromagnetic fields for seed stimulation and autonomous robotic monitoring systems, marks significant progress in sustainable agriculture by improving pest management efficiency and reducing chemical pesticide reliance [11, 43, 33]. These methods provide effective, non-invasive solutions for monitoring and managing plant health, contributing to ecological balance in agricultural systems.

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3.3 Novel Physical Control Innovations

Recent advancements in physical control techniques for pest management have introduced innovative approaches that enhance monitoring and control precision and effectiveness. Non-invasive electromagnetic fields stimulate soy seeds, promoting healthier crop development and exemplifying a shift towards sustainable practices [43]. Deep learning approaches, particularly multi-task learning within Convolutional Neural Network (CNN) architectures, significantly improve the classification and severity estimation of plant diseases, enhancing pest management tasks' accuracy and efficiency [46]. Utilizing Neural Radiance Fields (NeRF) for accurate 3D reconstructions of plants enables detailed analysis of plant structures and their interactions with pests [40].

Innovative use of colored reference surfaces to correlate leaf temperature with plant health offers a more precise assessment compared to traditional methods, enhancing monitoring capabilities and early detection of pest infestations [44]. Furthermore, integrating image-based deep learning for disease classification with autonomous UAV navigation marks a significant advancement in real-time monitoring, enabling more responsive pest management interventions [47].

The application of YOLOv3 for detecting volunteer cotton plants in corn fields demonstrates the robustness of real-time detection models, achieving high accuracy across various image scales [48]. This capability is enhanced by combining advanced AI detection methods with RGB imagery, improving detection accuracy in uncontrolled environments and facilitating effective pest control strategies [49].

Optical studies of laser biospeckle activity offer a non-invasive technique for real-time monitoring of endophytic colonization, providing insights into plant health without causing damage [32]. Remote sensing and control systems enable real-time monitoring and management of environmental parameters, contributing to better resource management and increased agricultural productivity [20].

The introduction of early-warning indicators for impending regime shifts in plant health allows for proactive pest management strategies by predicting critical transitions between disease containment and outbreaks [38]. Collectively, these innovations represent a paradigm shift towards sustainable and precise pest management practices, reducing reliance on chemical interventions and enhancing agricultural resilience.

3.4 Robotics and Automated Systems

Robotics and automated systems are crucial in enhancing physical pest control methods, providing precision, efficiency, and sustainability in agricultural practices. These systems leverage advanced sensor technologies and artificial intelligence for non-destructive monitoring and management of crops, minimizing the need for chemical interventions. Robotic platforms equipped with 3D cameras create digital twins of plants, such as tomatoes, enabling accurate leaf size estimation and facilitating precise interventions without damaging the plants [9].

IoT-enabled smart plant monitoring systems exemplify automation's potential in agriculture. These systems automate essential gardening tasks using sensors to monitor soil moisture, temperature, humidity, and plant color, ensuring optimal growing conditions and reducing reliance on manual labor [50]. Robotic platforms like BonnBot-I, designed for precise weed management, employ sensor fusion and innovative weeding tools to effectively monitor crops and manage weeds, thereby reducing chemical inputs [51].

Dynamic Sampling Algorithms (DSA) represent a significant advancement in optimizing pest management by utilizing real-time data to prioritize sampling in areas with a higher likelihood of pest presence, enhancing monitoring efficiency [33]. Semi-autonomous systems integrating artificial intelligence for detecting saplings and controlling retractable cutting tools on tractors enable selective weed clearing, promoting sustainable agricultural practices [49].

Implementing 3D Multi-Object Tracking for World Modeling improves object tracking and localization in occluded environments, enhancing automated systems' capability to navigate complex agricultural settings [52]. Autonomous robotic systems like the Pheno-Robot, incorporating deep learning and motion planning for in-situ phenotyping, illustrate robotics' potential in advancing precision agriculture and pest management [53].

Simulations using plugins like GAZEBOPLANTS, which replicate plant dynamics and interactions with robotic systems, provide valuable insights into robotics' real-world application in agriculture, demonstrating the feasibility of automated harvesting and pest control methods [54]. Robotic systems like BrambleBee, designed for autonomous pollination, address challenges related to pollinator decline, ensuring crop productivity through precision pollination techniques [17].

Advancements in deep learning architectures, such as Mob-INC, which integrates MobileNetV2 and Inception modules, enhance maize disease recognition, showcasing advanced AI techniques' integration in robotic systems for improved pest management [23]. The method of 'cataloging' aims to automate the temporal and spatial identification of crops from UAV images, further emphasizing automation's role in agricultural monitoring [55].

Recent advancements in robotics and automation significantly enhance physical pest control methods by enabling precise monitoring and targeted interventions, improving crop yields, and promoting sustainable practices while decreasing dependence on chemical pesticides. Mobile robotic systems equipped with dynamic sampling algorithms can autonomously traverse fields to detect insect populations in real-time, while smart weeding technologies utilize deep learning for accurate weed identification, allowing for species-specific treatments that minimize herbicide usage. Transdisciplinary collaborations across scientific fields are essential for developing sustainable agricultural systems that address plant-environment interaction complexities and optimize resource use, contributing to a more resilient agricultural future [24, 34, 33].

4 Biological Control Strategies

4.1 Natural Agents and Biological Mechanisms

Natural agents and their biological mechanisms play a vital role in sustainable agriculture by offering eco-friendly alternatives to synthetic pesticides. The dynamics between local infestation rates and regional spread, as seen in coffee rust, highlight the effectiveness of natural agents in pest management [28]. These strategies maintain ecological balance while enhancing pest control efficacy.

Technological advancements, such as ensemble convolutional neural networks, have significantly improved pest classification, facilitating real-time monitoring and management over large agricultural areas [39]. This integration supports biological control measures through accurate pest identification.

Natural plant defenses, like the rapid rupture of glandular trichomes in tomato plants, are crucial mechanisms against herbivores [18]. These responses are essential for developing pest management strategies that leverage inherent plant defenses.

Symbiotic interactions, notably with arbuscular mycorrhizal fungi, enhance plant resilience and reduce dependence on chemical fertilizers. The CWC framework models these interactions, demonstrating their potential in effective pest control [22]. Moreover, certain microbial taxa from arid soils boost plant growth and drought resilience, showing promise for agriculture under climate change [27].

Innovative phytosensors that measure physiological parameters and enable real-time plant interactions represent a novel approach to integrating natural agents with technology [19]. These devices enhance plant health monitoring, prompting timely interventions and improving biological pest control effectiveness.

Furthermore, protein phosphorylation in plant mechanotransduction, as illustrated by TREPH1 and MKK2 in Arabidopsis, highlights biochemical pathways that can be targeted to enhance plant resilience against pests [56]. Understanding these mechanisms is crucial for developing biological control strategies aligned with sustainable agriculture principles.

As illustrated in Figure 3, natural agents and biological mechanisms are fundamental to ecosystem management. The first image shows a crop production economic model, emphasizing plant health's impact on economic outcomes and the need for disease management. The second image depicts cell division, a crucial biological mechanism for growth and reproduction. The third image captures a plant's physiological response to stimuli, demonstrating dynamic plant-environment interactions that can be utilized for biological control. Together, these examples underscore how natural agents and biological mechanisms enhance biological control strategies, promoting sustainable agricultural practices and ecosystem management [2, 35, 57].

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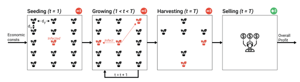
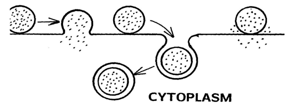
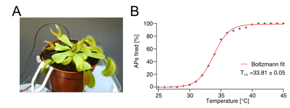


(a) The image depicts a simplified economic model of a crop production process.[2]



(b) The Image Represents a Cell Division Process[35]



(c) The image shows a plant with its leaves extended, possibly in response to a stimulus, and a graph representing the percentage of action potentials (APs) fired as a function of temperature.[57]

Figure 3: Examples of Natural Agents and Biological Mechanisms

4.2 Technological Advancements in Biological Control

Recent technological advancements have significantly enhanced biological control methods, providing innovative solutions for sustainable pest management. Advanced machine learning techniques, including Transformers and class-covariance-based metrics, have improved pest classification accuracy, facilitating precise monitoring in agricultural settings [39]. This accuracy is crucial for effective biological control strategies reliant on timely pest identification.

IoT-based smart plant monitoring systems, utilizing multiple sensors and mobile applications, have transformed real-time monitoring capabilities. These systems enable timely plant care interventions, thereby supporting biological control by optimizing conditions for plant growth and pest management [50]. Such innovations promote continuous plant health assessment, bolstering crop resilience against pests.

Robotic systems have also advanced biological control methods. Mobile robots equipped with sophisticated sampling algorithms enhance pest monitoring precision and responsiveness [33]. Integrating data from diverse viewpoints to create dynamic world models improves localization and object representation in complex agro-food environments, supporting more accurate biological control interventions [52].

Simulation tools, such as the Gazebo plugin utilizing Cosserat rods, enable realistic modeling of plant motion and robot interactions, facilitating advanced harvesting simulations that support biological control efforts [54]. Robotic pollination systems like BrambleBee demonstrate the potential of automation in addressing pollination challenges, further enhancing biological control methods [17].

The AMaizeD framework, which combines custom datasets with advanced CNN architectures and ensemble learning, exemplifies machine learning's role in improving disease detection and management [45]. The Mob-INC model showcases superior accuracy and efficiency in disease recognition, reinforcing effective biological control strategies [23].

Furthermore, high levels of automation and accuracy in plant identification and cataloging, as demonstrated by recent methods, facilitate large-scale agricultural data analysis, providing substantial support for biological control initiatives [55]. Collectively, these advancements represent a significant leap forward in biological control, offering sustainable, efficient, and precise pest management solutions.

4.3 Biological Interactions and Pest Management

The intricate interactions between biological agents and pests are crucial for developing effective pest management strategies. These interactions involve complex ecological and evolutionary dynamics that enhance pest control and promote sustainable agricultural practices. Studying these dynamics, such as the interplay between virulent and avirulent pathogen strains, offers insights into pest resistance mechanisms and informs targeted biological control strategies [31].

Beneficial microbial communities, particularly in the root microbiome of squash plants, underscore the significance of microbial interactions in enhancing plant resilience to environmental stressors, including pests [27]. These interactions contribute to overall agricultural health and productivity by fostering plant growth and reducing susceptibility to infestations.

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Mathematical models analyzing plant-pathogen dynamics provide critical insights into biological interactions, enhancing our understanding of pest management strategies like intercropping and resistant crop varieties, leading to more effective and sustainable agricultural practices [31, 58, 11, 38, 29]. These models consider factors such as network architecture and resource distribution, influencing emergent behaviors of plant populations under pest pressure. By simulating various scenarios, they help identify effective intervention strategies leveraging biological interactions for pest control.

Advanced technologies, including deep learning algorithms and IoT-based systems, significantly enhance real-time monitoring and analysis of biological interactions, such as pest infestations, enabling precise and timely interventions in pest management. For instance, deep learning models like CNNs can accurately assess Tuta absoluta infestation severity in tomato plants, achieving up to 87.2

Additionally, exploring plant defense mechanisms, such as the rapid rupture of glandular trichomes in response to herbivore attacks, highlights the potential of harnessing natural defenses in pest management [18]. Understanding these mechanisms lays the groundwork for developing innovative strategies that enhance crop resilience to pest pressures.

5 Integrated Pest Management (IPM)

5.1 Technological Integration in IPM

Technological advancements have significantly refined Integrated Pest Management (IPM), enhancing the precision and efficacy of pest control by integrating physical and biological methods. Convolutional Neural Networks (CNNs) and artificial intelligence (AI) have revolutionized plant disease identification and management, enabling swift and precise diagnostics essential for IPM [21]. CNNs, by extracting hierarchical features from plant imagery, support timely pest control decisions through accurate assessment of biotic stress severity, facilitated by mathematical pest dynamics modeling, robotic monitoring, and out-of-distribution detection algorithms [59, 11, 33].

Unmanned Aerial Vehicles (UAVs) exemplify technological integration, offering real-time crop monitoring and data collection that enable prompt pest management interventions. By reducing manual labor and enhancing disease detection accuracy, UAVs mitigate crop yield losses and optimize pesticide use. Equipped with image-based deep learning and multispectral imagery, UAVs facilitate timely disease identification in crops like wheat and maize, promoting sustainable practices through reduced chemical application and improved crop health [45, 47].

Advanced image processing, such as the YOLOv3 model, enhances real-time volunteer plant detection in aerial images, streamlining pest management. The YOLOv5 method further underscores technology's role in IPM, accurately identifying volunteer cotton plants in corn fields, aiding interventions against pests like the boll weevil and minimizing chemical treatments [51, 48, 33, 7].

The AMaizeD framework represents a significant advancement in integrating physical and biological control within IPM, reducing chemical reliance [45]. Additionally, integrating local and regional dynamics for managing diseases like coffee rust reflects IPM's holistic approach, emphasizing multi-scale management [16]. The Optimal Seeding Strategy Model (OSSM) combines epidemiological dynamics with economic analysis to optimize seeding during botanical pandemics, highlighting technology's role in IPM [2].

5.2 Interdisciplinary Approaches in IPM

Integrated Pest Management (IPM) thrives on interdisciplinary collaboration across agriculture, ecology, economics, and technology to address pest management challenges sustainably. By incorporating ecological principles, IPM strategies maintain ecological balance and enhance biodiversity through understanding pest-crop-environment interactions [16]. Economics guides resource allocation, cost minimization, and productivity maximization, as exemplified by the Optimal Seeding Strategy Model (OSSM), which integrates economic analysis with epidemiological dynamics to optimize seeding strategies during botanical pandemics [2].

Technological advancements, such as deep learning and UAVs, augment IPM by enabling precise pest population monitoring and management. CNNs enhance IPM through accurate disease detection and severity assessment, supporting timely interventions, while UAVs facilitate rapid crop monitoring

[60]. IPM's interdisciplinary nature is illustrated by collaborations among researchers, practitioners, and policymakers across diverse fields, developing strategies that control pests while promoting sustainable agriculture. Approaches like intercropping, supported by mathematical modeling, enhance pest control without chemical pesticides. Integrating stakeholder perspectives tailors strategies to community needs, contributing to agricultural resilience and sustainability amid challenges like climate change and rising food demand [1, 34, 11, 31]. This collaboration ensures IPM strategies are informed by the latest scientific research and technological innovations, addressing pest management challenges holistically to promote sustainable practices and enhance food security.

5.3 Case Studies and Successful Implementations

Integrated Pest Management (IPM) success is demonstrated by case studies showcasing advanced technology and interdisciplinary approaches in pest management. The Paddy Doctor visual image dataset enhances pest identification accuracy in rice cultivation, reducing chemical pesticide reliance [3]. Another success is a unified method for assessing citrus leaf damage from canker disease, offering faster and more accurate measurements for agricultural monitoring and management. This approach supports timely IPM strategy application, enhancing crop health and productivity [61].

These case studies highlight technological advancements enhancing IPM effectiveness. Innovations like advanced image analysis for disease detection, unmanned aerial system (UAS) imagery for spatial weed mapping, and real-time monitoring systems like BonnBot-I for precise weed management improve pest control accuracy and efficiency. These tools enable targeted herbicide and pesticide applications, reducing chemical use while maintaining crop health and yield. BonnBot-I improves crop monitoring tracking accuracy, while UAS technology allows site-specific weed control, saving land from herbicide application. Additionally, mathematical modeling of intercropping systems offers sustainable pest management solutions using natural control methods [11, 51, 4, 61]. These implementations demonstrate IPM's potential to promote sustainable agricultural practices, reduce chemical inputs, and enhance environmental and economic sustainability in agricultural systems.

6 Sustainable Agriculture and Pest Management

6.1 Sustainable Agriculture Practices

Sustainable agriculture practices are essential for effective pest management and environmental sustainability, focusing on reducing chemical inputs, enhancing biodiversity, and improving resource efficiency. Precision agriculture technologies, like the BonnBot-I system, illustrate this approach by minimizing chemical herbicide use through advanced tracking and weeding capabilities, thereby improving weed management and tracking accuracy [51]. Phytosensors offer another innovative practice, providing real-time monitoring of physiological and environmental parameters to optimize plant health and productivity, aligning with dynamic agricultural needs [19].

Indoor agriculture, particularly through Demand Response (DR) programs, enhances sustainability by optimizing energy use and reducing production costs by 15-23%, supporting sustainable practices and bolstering food production systems' resilience against climate change and resource scarcity [62]. Techniques such as intercropping, which utilizes mathematical modeling for optimal plant arrangements and trap crops, demonstrate effective pest control without chemicals. Compost application enhances soil quality and plant health, reducing synthetic fertilizer needs while promoting natural nitrogen cycling. Advanced technologies, including unmanned aerial systems for targeted weed management, enable precise herbicide application, further decreasing chemical use and promoting environmental sustainability [31, 34, 6, 11, 4]. These approaches collectively contribute to a sustainable agricultural framework that addresses pest challenges while maintaining productivity and ecological integrity.

6.2 Enhancement of Soil Health and Crop Quality

Sustainable agricultural practices are crucial for improving soil health and crop quality, which are vital for effective pest management. These practices enhance crop productivity and nutritional value, as demonstrated by the positive effects of compost application on root vegetables like carrots, fostering beneficial microbial communities and optimizing nutrient cycling [6, 34]. Bose's pioneering work

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in plant neurobiology, exploring plants' physiological responses to environmental stimuli, informs contemporary approaches to enhancing soil health and crop quality [41].

Beneficial microbial communities, such as arbuscular mycorrhizal (AM) fungi, improve soil structure and nutrient availability, enhancing plant growth and resilience while reducing synthetic fertilizer needs [6, 34, 27, 22]. Precision agriculture and advanced phytosensors enable real-time monitoring of soil and crop conditions, facilitating adaptive management strategies that optimize resource utilization while minimizing environmental impacts [33, 60, 34, 51, 19]. Crop rotation and cover cropping practices enhance soil organic matter and reduce soil erosion, improving soil health and crop resilience. Integrating innovative approaches such as compost application, intercropping, and nano-fertilizers improves soil health, optimizes nutrient use efficiency, and minimizes environmental impact, ultimately contributing to a resilient agricultural system amidst climate change and increasing food demands [33, 34, 6, 11, 63].

6.3 Technological Advancements in Sustainable Agriculture

Technological innovations are pivotal in advancing sustainable agriculture and pest management by enhancing efficiency, reducing environmental impact, and improving agricultural productivity. The Pheno-Robot system exemplifies such advancements, leveraging 5G technology for real-time data transmission and processing, facilitating in-situ digital modeling of plant phenotypes for precise crop health monitoring and management [53]. The Procedural Dataset Generation method, which creates diverse and realistic training data, enhances machine learning model training, improving their effectiveness in agricultural applications [64].

Recent digital technology advancements underscore their transformative role in sustainable agriculture, particularly through transdisciplinary collaborations integrating plant science, engineering, and social sciences to enhance resource efficiency, develop mobile disease diagnostics, and improve crop management practices [1, 34]. By integrating cutting-edge technologies such as 5G networks and advanced data generation methods, agricultural systems can achieve greater precision and sustainability in pest management. The continuous development and application of these innovations are crucial for optimizing agricultural practices and ensuring the long-term viability of food production systems.

7 Challenges and Future Directions

The complex landscape of pest management presents numerous challenges that impede progress in sustainable agriculture. This section explores technological obstacles affecting the efficacy of pest management strategies, highlighting existing limitations and potential innovations.

7.1 Technological Challenges in Pest Management

Technological advancements in pest management face several challenges impacting their effectiveness in sustainable agriculture. Current methods struggle with early pest detection, particularly pests like T. absoluta, delaying decision-making for farmers. The management of aphid populations and viral diseases in monocropped systems requires innovative strategies such as intercropping [7]. Automated systems often suffer from accuracy issues due to environmental factors like poor lighting, leading to misclassification [21]. The difficulty in detecting volunteer cotton plants among other crops can result in undetected infestations [7].

Additionally, current technologies face challenges in selectively targeting weeds without harming crops, increasing environmental impact [18]. Mobile robots are limited by financial and logistical constraints, hindering their coverage of entire fields [45]. Data quality issues, including poorly labeled images and geographical biases, complicate pest management [55]. Small training datasets exacerbate these issues by leading to overfitting, reducing system performance in real-world applications [25].

High costs and limited functionality of growth chambers also challenge pest management research [26]. Innovations like Integrated Laser Speckle Contrast (ILSC) provide promising solutions with non-invasive monitoring capabilities. Addressing these technological challenges is essential for improving pest management systems, requiring ongoing research and development to integrate advanced technologies into sustainable practices.

7.2 Data and Model Limitations

Data and model limitations pose significant challenges to advancing sustainable agricultural practices in pest management. A major concern is the lack of high-quality, annotated datasets that accurately capture real-world agricultural complexities. Existing datasets often exhibit geographical and cultural biases, as well as labeling inaccuracies, reducing the effectiveness of pest management systems [55]. Small training datasets lead to overfitting, diminishing model generalizability across diverse contexts [25].

Robust model development is hindered by a lack of comprehensive data capturing dynamic pest-crop-environment interactions. Simplified assumptions in current models overlook complex ecological dynamics, leading to inaccurate predictions and suboptimal strategies [37].

The integration of IoT and UAVs into pest management is limited by the availability of reliable, real-time data. Continuous high-resolution data collection is crucial but challenging in resource-constrained settings. Environmental factors affecting data quality, such as lighting and occlusion, further complicate detection and classification [21].

Innovative data collection and modeling techniques are needed to enhance research accuracy and applicability. Procedural dataset generation methods can improve model performance and reduce biases [64]. Interdisciplinary approaches combining ecological, technological, and economic perspectives can develop comprehensive models capturing pest management complexities.

Addressing data and model limitations through transdisciplinary collaboration among plant science, engineering, computer science, and social sciences is crucial for advancing research and promoting sustainable practices. This enhances understanding of complex systems and facilitates innovative solutions, such as mathematical modeling for sustainable pest control and robust insect classification using out-of-distribution detection algorithms [59, 34, 11]. Continued investment in data collection, model development, and interdisciplinary collaboration is vital for improving pest management strategies' precision and effectiveness.

7.3 Ecological and Biological Complexity

Ecological and biological complexities present significant challenges and opportunities in pest management. Understanding these complexities is crucial for developing effective strategies that align with ecological principles and enhance resilience. Interactions among plants, pests, and their environments are influenced by genetic diversity, species interactions, and environmental conditions [37].

Dynamic plant-pest interactions, shaped by biotic and abiotic factors, lead to emergent behaviors difficult to predict and manage with traditional methods. Network architecture of plant-pathogen interactions can influence disease spread and management effectiveness [37]. Understanding these dynamics is crucial for designing strategies that mitigate pest impacts while preserving ecological balance.

Beneficial microbial communities enhance plant resilience and reduce pest susceptibility. Microbial interactions within the root microbiome improve nutrient uptake, soil health, and plant tolerance to stresses, contributing to sustainable practices [27]. Pests' adaptive responses to environmental changes require continuous monitoring and strategy adaptation [25]. Advanced technologies like IoT and remote sensing enhance real-time monitoring, providing valuable data for informed decision-making [50].

Investigating ecological and biological complexity underscores the need for interdisciplinary strategies integrating ecological, technological, and socio-economic insights. Such approaches are essential for addressing sustainable agriculture's challenges, including reducing chemical pesticide reliance through innovative practices like intercropping. Transdisciplinary collaborations among plant science, engineering, and social sciences are vital for developing integrated solutions that improve crop resilience and productivity against climate change and pest pressures [34, 11, 31]. Embracing complexity allows tailoring pest management strategies to specific agricultural needs, promoting sustainability and resilience against environmental challenges.

7.4 Regulatory and Implementation Barriers

Sustainable pest management adoption is often obstructed by regulatory and practical barriers challenging implementation in agricultural systems. Regulatory frameworks vary significantly across regions, creating compliance inconsistencies. This landscape can hinder the implementation of innovative strategies, as stakeholders navigate complex regulations that may not align with scientific advancements in sustainable agriculture. Aligning regulatory frameworks with research findings is critical for fostering effective solutions that adapt to agricultural complexities and climate change challenges [34, 11].

A primary regulatory challenge is the slow approval process for new technologies and methodologies, stifling innovation and deterring research investment. Lengthy and costly approval processes for biological control agents and biopesticides limit their availability and use [5].

Practical barriers, such as inadequate infrastructure and resources, impede advanced technology adoption like IoT-based monitoring systems. These require reliable electricity, internet connectivity, and technical expertise, often lacking in resource-constrained settings [50].

Transitioning from conventional to sustainable practices necessitates changes in stakeholders' mindsets and behaviors. This shift is challenging, especially when traditional practices are deeply entrenched. Educational and training programs are essential for equipping stakeholders with the knowledge and skills to implement sustainable practices effectively [21].

Integrating sustainable methods requires coordinated efforts among researchers, practitioners, policymakers, and the agricultural community. This coordination is often lacking, leading to fragmented efforts and suboptimal outcomes. Collaborative initiatives uniting stakeholders can address barriers to sustainable practices by promoting knowledge exchange, aligning goals, and pooling resources for greater impact. Transdisciplinary efforts are crucial for tackling complex challenges, as evidenced by case studies demonstrating successful integration of technologies and perspectives to enhance resource use and food production amid climate change [1, 34].

To overcome regulatory and practical challenges, it is essential to streamline processes, invest in infrastructure, and foster interdisciplinary collaboration among experts in plant science, engineering, computer science, and social sciences. This approach facilitates integrating innovative technologies and perspectives, leading to improved resource efficiency and sustainability in food production systems [34, 62]. Creating an enabling environment for sustainable pest management enhances agricultural systems' resilience and sustainability, supporting global food security and environmental conservation.

7.5 Future Research Directions

Future research in sustainable pest management should focus on enhancing dataset diversity and model robustness to address agricultural environment complexities [24]. This includes expanding datasets and improving model adaptability for accurate pest identification across varying conditions. Exploring complex topological structures and their effects on self-adaptation in larger systems presents a promising avenue for advancing strategies [25].

Investigating long-term impacts of microbial inoculation on plant health is essential, focusing on identifying beneficial microbes and developing sustainable agriculture strategies [27]. This research could enhance crop resilience to pest pressures by leveraging plant-microbe symbiotic relationships.

Incorporating optimal nutrient and insecticide application strategies, along with pulse strategies, into models could improve intervention precision and efficacy. Modeling vector dynamics will provide insights into pest population control and disease spread [28].

Future research could refine embedding adaptation techniques and explore applications beyond agriculture, potentially enhancing model performance in various domains [39]. This approach could lead to more versatile and robust pest management systems.

These research directions offer significant opportunities for advancing sustainable pest management, promoting ecological balance, and ensuring agricultural resilience. Emphasizing transdisciplinary collaboration, innovative methods like intercropping, and advanced monitoring technologies, future innovations can improve pest management practices' effectiveness and sustainability. This comprehensive approach addresses agricultural systems' complex challenges while supporting long-term viability by minimizing environmental impact and enhancing productivity. Integrating insights from plant science, engineering, and social sciences can yield novel techniques and strategies, such as robotic monitoring systems and mathematical modeling for pest control, contributing to more resilient practices and better resource management [31, 33, 34, 11, 35].

8 Conclusion

The essential role of integrating physical and biological control methods in sustainable pest management is underscored by the diverse studies and innovations discussed in this survey. The integration demonstrated by the Paddy Doctor dataset exemplifies how combining these methods can lead to significant advancements in automated paddy disease detection and management. Plant-derived compounds emerge as promising alternatives to conventional antibiotics, offering safer pest management strategies. The exploration of nano-fertilizers highlights their potential to boost agricultural productivity sustainably, although further research is needed to evaluate their long-term safety and efficacy. The dynamics between virulent and avirulent aphids suggest that 'within-plant' refuges could enhance the sustainability of aphid-resistant soybean varieties. Technological progress, such as the use of advanced neural networks like Xception, InceptionResNet, and MobileNet, has demonstrated high accuracy in real-time disease monitoring, illustrating the benefits of integrating cutting-edge technologies in pest management. Understanding the interaction between local and regional dynamics is crucial for managing diseases like coffee rust, emphasizing the need for comprehensive, integrated approaches. Additionally, early-warning indicators provide critical insights for predicting transitions in forest disease outbreaks, improving management strategies for tree density and disease control. The AIWeeds benchmark has proven the effectiveness of under-canopy weed classification, significantly reducing herbicide use in precision agriculture. Lastly, the development of low-cost programmable growth chambers facilitates controlled biomass production studies, highlighting their contribution to advancing sustainable pest management practices.

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