Chapter

Improving Edible Oilseed (Oil Palm) Health and Productivity: Integration of Sustainable Pest Management, Precision Farming, and Stakeholder Collaboration

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Abstract

Among major edible oilseeds, oil palm (*Elaeis guineensis* Jacq.) stands out as a versatile tropical crop, globally recognized for its high productivity, versatility, and broad range of applications. However, *E. guineensis* plantations, particularly in tropical regions, face numerous pressures from a wide range of pests, including insects, pathogens, and vertebrate pests. Conventional pest control methods relying mainly on chemicals have raised serious concerns regarding environmental pollution, human health risks, and the development of pesticide resistance in target pests and pathogens. To address these issues, sustainable pest management, comprising integrated pest management strategies, can be augmented with precise agriculture technologies, including remote sensing and GPS-guided equipment for targeted pesticide application, and effective stakeholder engagement. This chapter aims to (1) outline major pest management challenges in *E. guineensis* plantations; (2) introduce the concepts and principles of precision farming and its application in pest management; (3) discuss the major applications of sensor technology, GPS, and remote sensing for pest monitoring; (4) emphasize the significance of stakeholder collaboration in integrated pest management; and (5) identify aspects that have been least explored in the current context.

Keywords: pest control strategies, agricultural sustainability, integrated pest management, technological innovations, community engagement

1. Introduction

Oil palm (*Elaeis guineensis* Jacq.) (an angiosperm monocot in the plant family Arecaceae) is a versatile tropical crop cultivated extensively for its valuable oil, known as palm oil, which holds significant importance in various industries worldwide.

E. guineensis is renowned for its high productivity, versatility, and wide range of applications, including food products, cosmetics, pharmaceuticals, and biofuels [1]. The oil extracted from the fruit of the *E. guineensis* serves as a major source of edible vegetable oil globally, contributing significantly to the world's vegetable oil supply [2, 3]. Its unique composition, characterized by a balanced ratio of saturated and unsaturated fatty acids, makes it suitable for a diverse array of food products, including cooking oils, margarine, and baked goods [1, 4]. Furthermore, *E. guineensis* oil finds extensive application in the cosmetic and personal care industry, where it is utilized in the formulation of skincare products, soaps, and detergents due to its emollient properties and ability to enhance product stability [1, 5, 6]. Additionally, *E. guineensis* oil is increasingly used as a feedstock for biofuel production, contributing to efforts aimed at reducing dependence on fossil fuels and mitigating environmental impacts associated with conventional fuel sources [7]. In terms of global production, Indonesia and Malaysia dominate the *E. guineensis* industry, collectively accounting for the majority of the world's palm oil output [2, 7–9]. These two countries are major producers and exporters of *E. guineensis* oil, with vast plantations spread across their respective territories. In recent years, other countries such as Thailand, Colombia, and Nigeria have also emerged as significant producers of *E. guineensis* oil, albeit on a smaller scale compared to Indonesia and Malaysia [3, 10].

E. guineensis plantations, predominantly found in tropical regions, face a myriad of pest pressures ranging from insects and pathogens to vertebrate pests [3, 11, 12]. Among the key pests, the African E. *guineensis* weevil (*Elaeidobius kamerunicus* Faust) stands prominent as a major threat to *E. guineensis* pollination, causing substantial yield losses [13, 14]. Additionally, the red palm weevil (*Rhynchophorus ferrugineus*) inflicts severe damage by feeding on palm tissues and transmitting various pathogens, exacerbating the economic impact on plantations [15]. In terms of diseases, the *Fusarium* wilt disease caused by *Fusarium oxysporum* f. sp. *elaeidis* (FOE) significantly affects *E. guineensis* cultivation, leading to substantial yield losses and economic setbacks [16]. Another significant threat is the *Ganoderma* basal stem rot (BSR) disease caused by *Ganoderma boninense*, which induces gradual decay of the palm's vascular system, resulting in reduced productivity and, ultimately, *E. guineensis* mortality [16, 17]. Furthermore, the incidence of bud rot disease, attributed to *Phytophthora palmivora*, poses a continuous challenge to *E. guineensis* plantations, particularly in humid tropical regions [18]. Bud rot causes the premature death of young palms, thereby impacting the overall productivity and sustainability of the plantation. Also, the escalating impacts of climate change, including altered pest distribution patterns and increased pest prevalence, further exacerbate the vulnerability of *E. guineensis* crops to pest damage [12, 15].

The sustainable management of pests in *E. guineensis* plantations stands as a critical imperative for the continued prosperity and resilience of the global edible oilseed industry. Unfortunately, most conventional pest control methods, often reliant on chemical pesticides, have been widely employed in *E. guineensis* plantations to manage infestations [11, 19–21]. Pesticides, including insecticides and herbicides, have been utilized to combat insect pests such as *Elaeidobius kamerunicus* Faust and *Asystasia gangetica* weed [22, 23], which are known to cause huge losses in *E. guineensis* oil production. Fungicides have also been applied to control diseases like *Fusarium* wilt and *Ganoderma BSR,* which threaten *E. guineensis* health and productivity [16, 24]. However, dependence solely on chemical pesticides has raised concerns regarding environmental pollution, human health risks, and the development of pesticide resistance in target pests and pathogens [25–27]. Moreover, indiscriminate use of pesticides may also disrupt ecological balance and eventually harm non-target organisms, including beneficial insects and soil microorganisms. A recent study revealed widespread use of conventional pesticides, including Roundtable on Sustainable Palm Oil (RSPO)-prohibited paraquat (**Figure 1**), in Indonesian E. *guineensis* plantations, which has underscored the persistence of unsustainable practices despite global sustainability initiatives [28].

Taking into the gravity of the situation, two major approaches, namely, integrated pest management (IPM) strategies and the collaboration of major stakeholders (including farmers, plantation companies, government agencies, and local communities), can be useful in sustainably managing major *E. guineensis* pests and also in the implementation of these sustainable pest management practices. There has been a growing emphasis on IPM approaches in *E. guineensis* cultivation, which aim to minimize reliance on chemical pesticides and promote sustainable pest control practices [29]. IPM strategies encompass a combination of cultural, biological, and mechanical control methods, alongside judicious use of chemical interventions when necessary. Biological control agents, such as predatory insects and microorganisms, are increasingly being employed to suppress pest populations naturally, reducing the need for synthetic pesticides [30–32]. Furthermore, advances in precision agriculture technologies, including remote sensing and Global Positioning System (GPS)-guided equipment, facilitate targeted application of pesticides and enable more precise pest monitoring and management [33, 34]. Precision farming, characterized by the strategic use of technology and data-driven decision-making, holds promise for optimizing pest control efforts while minimizing environmental impacts [35]. Leveraging advanced tools such as sensors, GPS, and remote sensing technologies, precision farming enables real-time monitoring of pest populations and precise application of control measures, thereby enhancing efficacy and reducing resource inputs. Notably, active involvement of various stakeholders throughout the oil palm supply chain, encompassing farmers, plantation companies, researchers or academies, governmental organizations, and local communities, is essential to effectively implement sustainable pest management strategies [36–38]. By fostering collaborative efforts, stakeholders can facilitate the exchange of knowledge, sharing of resources, and engagement with the community, thereby promoting collective resilience against pest challenges.

Given the above, (i) the major pest management challenges in *E. guineensis* plantation are overviewed; (ii) the concepts and principles precision farming are introduced, and its major role in pest management is highlighted; (iii) the major applications of sensor technology, global positioning systems, and remote sensing for pest monitoring are discussed; (iv) the significance of stakeholder collaboration in integrated pest management is enlightened; and (v) the major aspects so far least explored in the current context are enlisted. In summary, this chapter explores the diverse aspects of sustainable pest management in oil palm plantations, highlighting

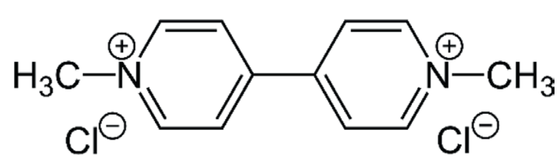

Figure 1.
Chemical structure of paraquat.

the interconnectedness between precision farming and stakeholder cooperation. Through a comprehensive and flexible approach, our goal is to outline a pathway toward improved productivity, environmental conservation, and socioeconomic durability within the edible oilseed industry.

2. Pest management challenges in oil palm plantation

Pest management is a critical component of *E. guineensis* cultivation due to the significant economic losses that pests and diseases can cause. In particular, insect pests, weeds, and diseases pose formidable challenges to oil palm plantations worldwide, affecting both yield and quality. Given the global significance of *E. guineensis* cultivation and its contribution to the agricultural sector, addressing pest management challenges is paramount. Sustainable pest management practices are essential for mitigating the adverse effects of pests and diseases on *E. guineensis* production while minimizing environmental impacts and ensuring the long-term sustainability of *E. guineensis* cultivation.

2.1 Pests in oil palm plantations

Insect pests represent a major challenge in *E. guineensis* cultivation, with several species causing significant damage to *E. guineensis* trees and affecting fruit yield. Among the most notable insect pests are the African E. *guineensis* weevil (*Elaeidobius kamerunicus* Faust) and the red palm weevil (*Rhynchophorus ferrugineus*). *Elaeidobius kamerunicus* is a notorious pest that inflicts significant damage to *E. guineensis* trees. These weevils primarily target the flowers of *E. guineensis* trees, where they feed and lay eggs. Their feeding activity disrupts the pollination process, leading to reduced fruit set and ultimately, diminished *E. guineensis* yields. Moreover, the larvae of these weevils tunnel through the trunk and crowns of *E. guineensis* trees, causing structural damage and weakening the palm's overall health [2, 39]. Similar to *Elaeidobius kamerunicus*, the red palm weevil (*Rhynchophorus ferrugineus*) poses a substantial threat to oil palm plantations. These weevils primarily attack the palm's growing tissues, including the crown and trunk, leading to wilting, stunting, and eventually, death of the *E. guineensis*. The larvae of *Rhynchophorus ferrugineus* tunnel through the vascular tissues in *E. guineensis*, disrupting nutrient and water flow and eventually compromising its structural integrity [40]. Infestations by *Rhynchophorus ferrugineus* can result in severe economic losses for *E. guineensis* growers [41, 42].

The population dynamics of *Elaeidobius kamerunicus* and its impact on *E. guineensis* pollination have been reviewed, which has revealed significant infestations of the weevil, leading to decreased pollination efficiency and subsequent declines in fruit production [43]. The authors have recommended to employ effective management strategies, including the use of pheromone traps and biological control agents, in order to minimize weevil populations and mitigate their impact on *E. guineensis* yields. The bagworm (*Metisa plana*) is another common insect pest that feeds on *E. guineensis* leaves, causing defoliation and reduced photosynthetic activity [44]. *M. plana* are another common pest in *E. guineensis* plantations, particularly in Southeast Asia [45]. Additionally, rhinoceros beetles are destructive pests that target oil palm plantations, particularly in their larval stage. The larvae of rhinoceros beetles feed on the roots of *E. guineensis* trees, leading to root damage and reduced nutrient uptake.

This can result in stunted growth, wilting, and ultimately, the death of *E. guineensis* trees. Adult beetles also cause damage by feeding on the leaves and causing wounds that serve as entry points for pathogens [46].

Weeds are one of the most significant sources of pests and diseases, compete with *E. guineensis* trees for essential resources such as water, nutrients, and sunlight, leading to reduced growth and productivity. Common weeds found in *E. guineensis* plantations include *Imperata cylindrica* (alang-alang) and *Mikania micrantha* (mile-a-minute weed). These aggressive weeds can quickly establish and spread, posing significant challenges for *E. guineensis* growers [47]. Research has also been done on the effects of weed infestation on *E. guineensis* growth and yield in Malaysia [48]. Their study demonstrated that weed competition resulted in a substantial reduction in *E. guineensis* productivity, highlighting the importance of effective weed management strategies. Integrated weed management approaches, incorporating cultural, mechanical, and chemical control methods, were recommended to minimize weed competition and optimize *E. guineensis* yield. Furthermore, weed management practices among smallholder oil palm growers were also the subject of investigation in Indonesia [49]. These authors revealed the widespread use of herbicides for weed control, alongside manual weeding and cultural practices. However, challenges such as herbicide resistance and environmental concerns necessitate the adoption of sustainable weed management strategies in oil palm plantations.

Diseases represent a significant threat to *E. guineensis* cultivation, with various fungal, bacterial, and viral pathogens causing substantial yield losses. *Fusarium* wilt and BSR disease are among the most prevalent diseases affecting *E. guineensis* plantations worldwide [16, 17]. Koussinou et al. investigated *Fusarium* wilt disease in *E. guineensis* and explored alternative control measures to mitigate its impact [50]. Their research highlighted the importance of disease-resistant *E. guineensis* varieties and integrated disease management strategies in controlling Fusarium wilt and maintaining *E. guineensis* productivity. *Fusarium* wilt leads to vascular tissue damage, wilting of fronds, and ultimately, *E. guineensis* death, resulting in substantial yield losses. Furthermore, Pilotti et al. investigated the interaction between *E. guineensis* and *G. boninense*, the causative agent of BSR disease [51]. Their findings emphasized the devastating impact of *Ganoderma* infection on *E. guineensis* plantations, causing progressive decay of the palm's vascular system and subsequent decline in productivity. *Ganoderma* spp. is a fungal pathogen that causes BSR disease in *E. guineensis* plantations. Rakib et al. identified three types of *Ganoderma* consistently found in *E. guineensis* plants in Sarawak, Malaysia, including *G. zonatum*, *G. boninense*, and *G. miniatocinctum*. Conversely, in Northern Columbia, the causative agent of basal stem rot (BSR) identified by Castillo et al. was *G. zonatum* [52]. However, Pilotti et al. asserted that *G. boninense* is the primary pathogen causing BSR in the Asia-Pacific region. This disease is one of the most serious threats to *E. guineensis* cultivation, particularly in Southeast Asia, where the majority of the world's palm oil is produced [51, 53]. *Ganoderma* infects the lower part of the *E. guineensis* trunk, leading to progressive decay of the vascular system and eventual palm death. Furthermore, studies have highlighted the challenges associated with managing pests and diseases in *E. guineensis* plantations. Traditional control methods, such as chemical pesticide and cultural practices, have shown limited efficacy in controlling the spread of the disease [11, 19–24]. Moreover, the long latency period of infection makes early detection and intervention challenging, often resulting in widespread damage by the time symptoms become apparent. Integrated pest management approaches have been proposed as a promising strategy for controlling pests and diseases in *E. guineensis* plantations. These approaches involve a combination of cultural practices, such as sanitation and planting of disease-resistant varieties, biological control methods, and judicious use of chemical fungicides [30–32]. However, effective management of pests remains a significant challenge due to the complex interactions between the pests, the *E. guineensis* host, and environmental factors. Continued research efforts are needed to develop innovative pest management strategies tailored to the unique agroecological conditions of *E. guineensis* cultivation regions.

2.2 Major impacts of pest damage on vegetable oil production

The impact of pests on vegetable oil production, particularly in the context of *E. guineensis* cultivation, is a critical consideration due to the significant economic losses and implications for food security and livelihoods. Pests such as insects, weeds, and diseases pose formidable challenges to *E. guineensis* plantations, affecting both the quantity and quality of vegetable oil produced.

2.2.1 Reduction in yield

One of the primary impacts of pest damage on vegetable oil production is the reduction in yield. Insect pests such as the African E. *guineensis* weevil and the red palm weevil target the reproductive structures of *E. guineensis* trees, including flowers and young fruits. Their feeding activities disrupt the pollination process and damage developing fruits, leading to a decline in fruit set and ultimately reducing *E. guineensis* yields [13–15]. Weeds also compete with *E. guineensis* trees for essential resources, inhibiting growth and development and further contributing to yield losses [23, 47–49]. Research by Satriawan and Fuadi highlighted the significant negative correlation between weed infestation levels and *E. guineensis* yield, with higher weed densities resulting in lower fruit production [47]. Similarly, fungal disease infestations have been shown to cause substantial reductions in *E. guineensis* yields, with severe infestations leading to yield losses of up to 50% [3]. Khoo and Chong reported that *G. boninense* infestation in *E. guineensis* plantations can lead to yield losses of up to 43% within 6 months, and the fungus's ability to persist in the soil presents a significant challenge for its control [24]. This loss in yield is attributed to symptoms such as wilted leaves accompanied by numerous unopened spear leaves until the plant eventually dies (**Figure 2**) [54].

2.2.2 Quality degradation

In addition to reducing yield, pest damage can also result in quality degradation of vegetable oil produced from affected crops. Insect pests such as the red palm weevil and the bagworm can directly damage *E. guineensis* fruits and leaves, causing physical injuries and contamination. These injuries provide entry points for microbial pathogens, leading to spoilage and deterioration of oil quality [55]. Furthermore, diseases caused by fungal pathogens such as *G. boninense* can have profound impacts on *E. guineensis* health and oil quality. Basal stem rot disease, caused by *G. boninense*, leads to the progressive decay of *E. guineensis* tissues, resulting in reduced oil extraction rates and poorer oil quality [54]. The presence of fungal pathogens and their metabolites in affected *E. guineensis* tissues can also lead to the production of off-flavors and odors in the extracted oil, rendering it unsuitable for consumption or industrial use [56].

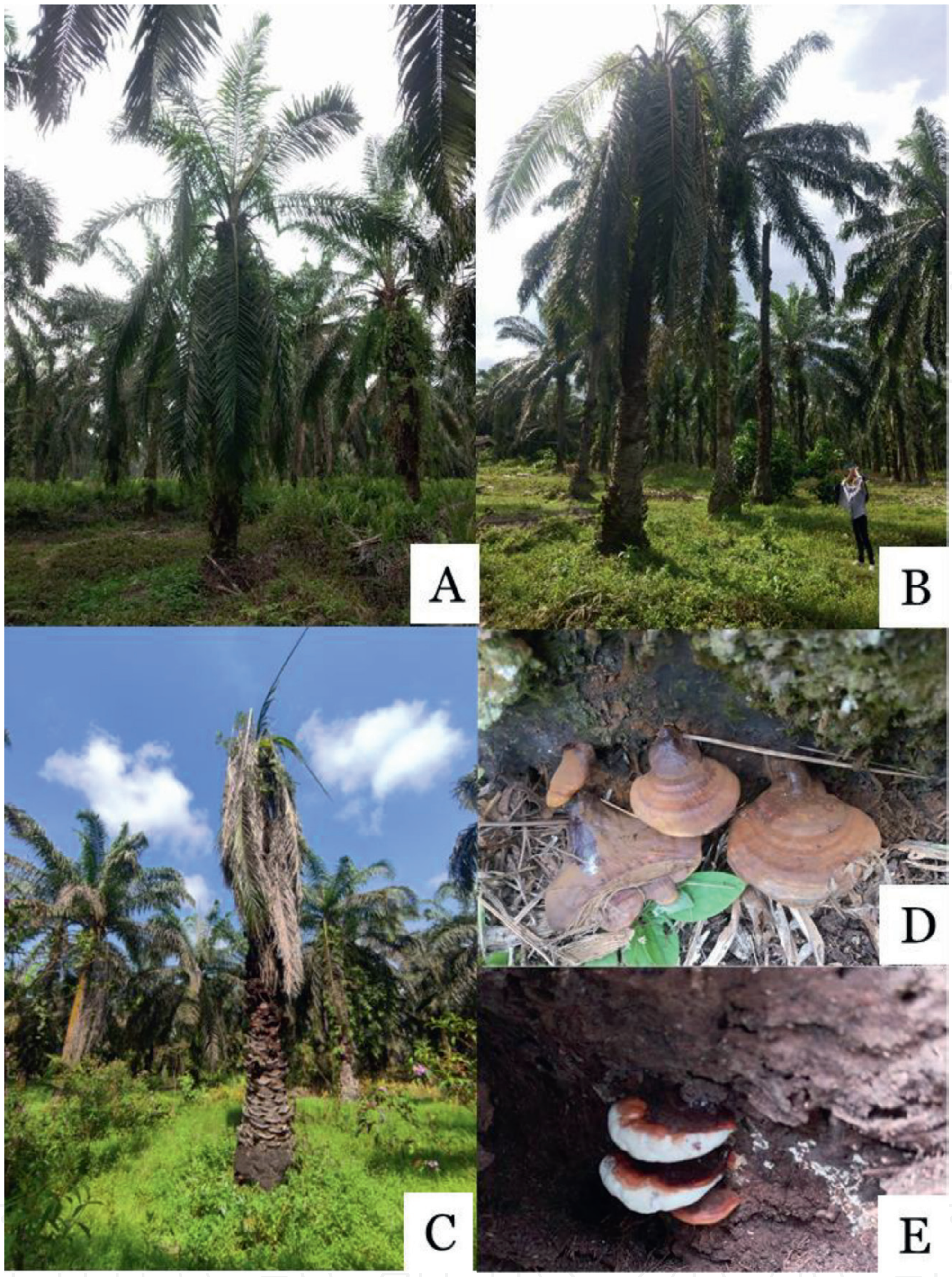

Figure 2.
Different levels of Ganoderma infection in oil palm plants (A–C) and the fruiting body of Ganoderma emerging at the base of the oil palm tree trunk (D–E).

2.2.3 Economic loss

The economic loss resulting from pest damage in *E. guineensis* plantations is substantial, encompassing both direct yield losses and indirect costs associated with pest management and mitigation efforts. Insect pest infestations can lead to significant reductions in *E. guineensis* yields, translating into substantial revenue losses for *E. guineensis* growers and producers. Weeds also incur costs for control measures, including labor, machinery, and herbicides, further adding to production costs [57, 58]. Moreover, the economic impact of pest damage extends beyond the immediate production cycle, affecting downstream industries and stakeholders in the vegetable oil supply chain. Reduced E. *guineensis* yields and quality can lead to fluctuations in vegetable oil prices, impacting consumer purchasing power and food security. Additionally, the reputational damage associated with poor-quality vegetable oil products can undermine market demand and investor confidence in the *E. guineensis* industry, further exacerbating economic losses [59]. The impact of pest damage on vegetable oil production, particularly in *E. guineensis* plantations, is multifaceted and far-reaching. Pests such as insects, weeds, and diseases pose significant challenges to *E. guineensis* growers, affecting both yield and quality of vegetable oil produced. Addressing these challenges requires concerted efforts from researchers, policymakers, and stakeholders to develop and implement effective pest management strategies that promote sustainable production and safeguard the economic viability of the vegetable oil industry.

2.3 Climate change and its impact on pest distribution

Climate change has emerged as a significant driver of environmental shifts, affecting various ecosystems and altering the distribution and abundance of pests worldwide [12, 15, 55]. The complex interplay between climate factors and pest dynamics presents novel challenges for agricultural systems, including *E. guineensis* plantations. Temperature fluctuations, driven by climate change, are disrupting traditional seasonal patterns and leading to an increased frequency of extreme weather events like heat waves and cold spells. These shifts directly impact the life cycles and distribution of pests, accelerating their development and reproduction in warmer conditions, while enabling the expansion of cold-sensitive pests into previously unsuitable areas [60, 61]. Similarly, alterations in precipitation patterns, including changes in rainfall intensity and distribution, profoundly affect pest dynamics by influencing habitat suitability, moisture availability, and resource accessibility. Increased rainfall may foster the proliferation of certain pests, such as fungal pathogens, by facilitating spore germination and disease propagation [24]. Conversely, drought conditions associated with reduced rainfall may exacerbate pest damage by stressing host plants and compromising their resistance to infestations [62]. Moreover, climate-induced shifts in pest phenology and behavior, such as changes in migration patterns and host-seeking behavior, further complicate pest management efforts. These alterations influence pest dispersal and colonization patterns, necessitating adaptive strategies to anticipate and mitigate emerging pest threats effectively [63, 64]. To this end, IPM strategies emerge as crucial tools in addressing the intricate interplay between climate change and pest dynamics [65]. By incorporating a holistic blend of cultural, biological, mechanical, and chemical control methods, IPM strategies aim to manage pests effectively while minimizing environmental impacts and fostering sustainable production practices [29]. Adaptive management techniques, such as crop rotation and conservation biological control, bolster the resilience of *E. guineensis* plantations to climate-induced pest pressures [30–32, 66]. Furthermore, the integration of climate-informed pest forecasting models and decision support tools enhances early detection and proactive management of emerging pest threats, facilitating timely intervention and mitigating the risk of yield losses [35]. Overall, the adoption of IPM strategies underscores the imperative of proactive and collaborative approaches in navigating the complex challenges posed by climate change on pest management in *E. guineensis* plantations.

2.4 Limitations of conventional approaches in pest control

Conventional pest control methods have long been employed in agricultural systems, including *E. guineensis* plantations, to manage pest populations and mitigate crop damage. However, these approaches are often associated with limitations and drawbacks, particularly in the context of evolving pest dynamics and environmental sustainability challenges.

2.4.1 Chemical dependency

Conventional pest control methods in *E. guineensis* plantations have traditionally relied heavily on chemical pesticides to suppress pest populations and reduce crop damage. While chemical pesticides can be effective in the short term, their indiscriminate use can lead to a range of adverse environmental and health impacts. Pesticide residues have the potential to accumulate within various ecological compartments including *E. guineensis* plants, soil, aquatic ecosystems, and non-target organisms, thereby presenting significant risks to both human health and ecosystem integrity, as well as biodiversity conservation efforts [67–69]. Moreover, the development of pesticide resistance among target pest populations can diminish the efficacy of chemical control measures over time, necessitating the use of increasingly potent and environmentally harmful pesticides [70].

2.4.2 Non-target effects

Another limitation of conventional pest control methods is their potential for non-target effects on beneficial organisms and ecosystem services. Chemical pesticides can harm beneficial insects such as pollinators, natural enemies of pests, and soil microorganisms, disrupting ecological balances and reducing the effectiveness of natural pest control mechanisms [25]. Furthermore, pesticide drift and runoff can contaminate nearby habitats and water sources, affecting non-target organisms and ecosystem functions beyond the boundaries of *E. guineensis* plantations [71].

2.4.3 Environmental degradation

The intensive use of chemical pesticides in *E. guineensis* plantations can contribute to environmental degradation and ecosystem disruption, with far-reaching consequences for biodiversity, soil health, and water quality. Pesticide runoff from agricultural fields can contaminate surface water and groundwater resources, leading to ecological imbalances and human health risks [72]. Moreover, the loss of natural habitats and biodiversity associated with pesticide-intensive farming practices can undermine ecosystem resilience and reduce the capacity of ecosystems to provide essential services such as pollination and pest regulation [73].

2.4.4 Limited long-term efficacy

Conventional pest control methods often exhibit limited long-term efficacy in managing pest populations and preventing crop damage, particularly in the face of evolving pest dynamics and environmental stressors. Pest species may develop resistance to chemical pesticides over time, rendering them less effective or ineffective in controlling pest outbreaks [74]. Additionally, the reliance on chemical pesticides can disrupt natural pest control mechanisms and exacerbate pest problems in the long run, leading to a cycle of dependence on increasingly intensive pest management practices [26, 75].

No.	Study title	Year	Key findings	Ref.
1	Integrated pest management (IPM) in oil palm, *Elaeis guineensis* Jacq	2022	Oil palm sustainability is vital for all stakeholders. Pest control is crucial to minimize losses. Integrated management and low-cost technologies are essential for sustainability.	[14]
2	Study on the commitment of oil palm companies to achieve sustainable agriculture in Riau Province from the perspective of pesticide use	2021	This study underscores oil palm companies' commitment to sustainable agriculture, particularly regarding pesticide use. Despite initial assumptions downplaying pesticide concerns, alarming findings reveal significant land contamination in three districts managed by selected companies.	[28]
3	Local and landscape management of biological pest control in oil palm plantations	2016	Ants and orthoptera are primary predators of oil palm pests. Border types influence predation pressure. Surrounding diverse vegetation aids pest control.	[29]
4	Do silvopastoral management practices affect biological pest control in oil palm plantations?	2023	Livestock integration aids weed control sustainably. Predation pressure consistent across weeding systems. Arthropods dominant in pest control. Site characteristics influence predation. Livestock-oil palm integration reduces herbicide use.	[30]
5	A review of entomopathogenic nematodes as a biological control agent for red palm weevil, *Rhynchophorus ferrugineus* (Coleoptera: Curculionidae)	2022	*R. ferrugineus*, a global palm tree pest, prompts IPM adoption. Biological controls, like entomopathogenic nematodes (EPNs), offer eco-friendly solutions.	[31]
6	Morphological characterization of *Trichoderma spp*. isolated from the oil palm rhizosphere in peat soils and its potential as a biological control for *Ganoderma sp*. in vitro	2022	*Trichoderma* spp. from oil palm rhizosphere, notably LPTUNRI-Trc003, exhibits potent antagonistic activity against *Ganoderma* sp., demonstrating promising potential for biological control.	[32]
7	How landscape characteristics in a heterogeneous oil palm plantation mitigate pest abundance: A case study from Mapiripan, Colombia	2023	The integration of local ecosystems within the oil palm plantation landscape enhances connectivity and reduces the abundance of key oil palm pests, supporting biodiversity and sustainable pest management. This suggests that heterogeneous agricultural landscapes can offer effective pest control ecosystem services to oil palm plantations.	[65]
8	Efficacy of oil palm intercropping by smallholders. Case study in South-West Cameroon	2015	Intercropping oil palm with food crops benefits smallholder farmers economically and reduces weeding costs, but requires careful management to avoid long-term yield reduction.	[66]

Table 1.
Representative studies on integrated pest management in oil palm (Elaeis guineensis Jacq.).

2.4.5 Need for sustainable alternatives

Given the limitations and drawbacks of conventional pest control approaches, there is a growing recognition of the need for sustainable alternatives that prioritize ecological integrity, human health, and economic viability. IPM strategies offer a holistic and multifaceted approach to pest control, combining cultural, biological, mechanical, and chemical control methods to minimize pest damage while minimizing environmental impacts [29]. By integrating pest monitoring, biological control, habitat manipulation, and agronomic practices, IPM aims to optimize pest control efficacy while reducing reliance on chemical pesticides and promoting ecosystem resilience [14, 65]. Conventional pest control approaches in *E. guineensis* cultivation are associated with various limitations and challenges, including chemical dependency, non-target effects, environmental degradation, and limited long-term efficacy. Addressing these challenges requires a transition toward more sustainable and integrated pest management strategies that prioritize ecological sustainability, human health, and economic resilience. By embracing innovative and holistic approaches to pest control, *E. guineensis* growers can effectively manage pest populations while safeguarding the long-term productivity and environmental integrity of *E. guineensis* plantations.

The representative of various studies on sustainable pest management in oil palm can be found in **Table 1**, providing an academic overview of integrated approaches and strategies employed in the field.

3. Precision farming in pest management

3.1 Precision farming: concepts and principles

Precision farming, also known as precision agriculture or smart farming, represents a paradigm shift in agricultural management practices, aiming to optimize resource use, enhance productivity, and minimize environmental impacts through the targeted application of inputs and management interventions.

3.1.1 Conceptual framework

At its core, precision farming embodies the integration of advanced technologies, data analytics, and decision support systems to tailor agricultural practices to the specific needs and conditions of individual fields or crop units. Unlike conventional farming approaches that rely on uniform application of inputs across large spatial scales, precision farming enables growers to adopt a site-specific and data-driven approach to crop management, optimizing resource allocation and minimizing waste [76]. The conceptual framework of precision farming revolves around four key principles: spatial variability, data-driven decision-making, targeted interventions, and continuous monitoring and adaptation. By harnessing information from various sources, including remote sensing, geospatial data, soil sensors, and crop monitoring technologies, precision farming enables growers to identify and respond to spatial variations in soil properties, crop health, and environmental conditions, thereby optimizing input use efficiency and crop performance [34].

3.1.2 Spatial variability analysis

A fundamental tenet of precision farming is the recognition and characterization of spatial variability in agronomic parameters within agricultural fields. Soil properties, topography, climate, and other environmental factors can exhibit considerable spatial heterogeneity, influencing crop growth and performance. Precision farming employs geospatial technologies such as geographic information systems (GIS), GPS, and remote sensing to map and quantify spatial variability in key agronomic parameters, enabling growers to delineate management zones and tailor management practices accordingly [77]. Spatial variability analysis allows growers to identify areas of the field with distinct soil types, nutrient levels, moisture regimes, and pest pressures, guiding targeted interventions to address specific agronomic constraints and optimize crop production. By matching input application rates and management practices to the spatial characteristics of individual field zones, precision farming maximizes resource use efficiency, minimizes input wastage, and enhances overall agricultural sustainability [78].

3.1.3 Data-driven decision-making

Central to the concept of precision farming is the utilization of data-driven decision-making processes to guide agronomic management practices. Precision farming relies on the collection, integration, and analysis of vast amounts of data from multiple sources, including field observations, remote sensing imagery, weather records, soil analyses, and crop performance metrics. Advanced analytics techniques, such as machine learning, artificial intelligence, and statistical modeling, are employed to derive actionable insights from complex datasets and inform management decisions [35]. Data-driven decision-making in precision farming encompasses a range of activities, including crop planning, seed selection, fertilizer application, irrigation scheduling, pest monitoring, and harvest forecasting. By leveraging real-time data streams and predictive analytics algorithms, growers can optimize input use efficiency, minimize production risks, and maximize crop yields while reducing environmental impacts [79].

3.1.4 Targeted interventions

Precision farming enables growers to implement targeted interventions tailored to the specific needs and conditions of individual crop units or management zones within a field. Instead of applying inputs uniformly across entire fields, growers can utilize variable rate technology (VRT) and site-specific management practices to adjust input application rates and timing based on spatial variability in soil properties, crop health, and pest pressures [80, 81]. Targeted interventions in precision farming encompass a range of agronomic practices, including variable rate fertilization, variable rate irrigation, variable rate seeding, and variable rate pesticide application [82]. By matching input application rates and management actions to the spatial characteristics and agronomic requirements of individual field zones, precision farming optimizes resource use efficiency, minimizes input costs, and maximizes crop yields while minimizing environmental impacts [83].

3.1.5 Continuous monitoring and adaptation

A key feature of precision farming is the emphasis on continuous monitoring and adaptation of agronomic management practices in response to evolving conditions and dynamic feedback mechanisms. Precision farming systems are equipped with sensors, monitoring devices, and automated control systems that enable real-time data collection, analysis, and decision-making, facilitating rapid response to changing environmental conditions, pest pressures, and crop performance metrics [84]. Continuous monitoring and adaptation in precision farming involve the iterative process of data collection, analysis, decision-making, and implementation, guided by the overarching goal of optimizing crop production while minimizing environmental impacts. By leveraging real-time data streams and adaptive management strategies, growers can proactively manage agronomic risks, mitigate production uncertainties, and enhance the resilience and sustainability of agricultural systems [85]. Precision farming represents a transformative approach to agricultural management, offering a suite of advanced technologies and data-driven decision support systems to optimize resource use, enhance productivity, and minimize environmental impacts in modern agriculture. By embracing the principles of spatial variability analysis, data-driven decision-making, targeted interventions, and continuous monitoring and adaptation, precision farming enables growers to achieve more efficient and sustainable crop production while mitigating the challenges posed by climate change, pest pressures, and resource limitations.

3.2 Application of sensor technology, GPS, and remote sensing for pest monitoring

Precision farming revolutionizes pest management by leveraging advanced technologies such as sensor technology, Global Positioning Systems (GPS), and remote sensing to monitor pest populations, assess pest damage, and implement targeted interventions.

3.2.1 Sensor technology in pest monitoring

Sensor technology plays a pivotal role in pest monitoring within precision farming systems, enabling real-time detection and quantification of pest populations, environmental parameters, and crop health indicators. Various types of sensors, including optical, electrochemical, thermal, acoustic, and electromagnetic sensors, are utilized to capture spatial and temporal variations in pest activity, facilitating timely and targeted management interventions [86, 87]. Optical sensors, such as multispectral and hyperspectral cameras, are commonly used to detect spectral signatures associated with pest infestations, nutrient deficiencies, and crop stressors. These sensors capture images of agricultural fields at different wavelengths, allowing growers to identify areas of pest damage, chlorophyll content, and vegetation indices indicative of pest presence [88]. Thermal sensors measure infrared radiation emitted by plants, which can vary in response to pest feeding, water stress, and disease infection. By detecting changes in plant canopy temperature, thermal sensors enable early detection of pest infestations and facilitate targeted management interventions to mitigate crop damage [89]. Acoustic sensors detect sound emissions produced by pests, such as insect-feeding activity and movement within crop canopies. By monitoring acoustic signals in agricultural fields, growers can identify areas of high pest activity and deploy pest control measures accordingly, minimizing crop losses and optimizing pest management strategies [90]. Electromagnetic sensors measure variations in soil moisture, conductivity, and texture, which can influence pest habitat suitability and population dynamics. By assessing soil properties and moisture levels, electromagnetic sensors help predict pest outbreaks and guide irrigation scheduling and soil management practices to reduce pest pressures [91].

3.2.2 GPS technology for spatial mapping and monitoring

Global Positioning Systems (GPS) technology plays a crucial role in precision farming by providing accurate geospatial data for spatial mapping, navigation, and monitoring of agricultural activities, including pest management. GPS receivers installed on agricultural machinery, drones, and handheld devices enable growers to precisely track their location within fields, facilitating targeted scouting, sampling, and treatment of pest-affected areas [92]. GPS technology enables growers to create detailed spatial maps of pest infestations, damage severity, and distribution patterns, allowing for the identification of hot spots and spatial correlations with environmental variables. By overlaying GPS-based pest maps with soil maps, weather data, and historical pest records, growers can better understand the drivers of pest dynamics and implement site-specific management strategies to mitigate crop damage [82, 86, 93]. Real-time kinematic (RTK) GPS systems provide centimeter-level accuracy in positional data, enabling precise navigation and georeferencing of pest monitoring activities. RTK GPS technology enhances the efficiency and effectiveness of pest scouting, sampling, and treatment operations, enabling growers to target pest-infested areas with greater precision and optimize resource use efficiency [94].

3.2.3 Remote sensing techniques for pest detection and monitoring

Remote sensing techniques, including satellite imagery, unmanned aerial vehicles (UAVs), and aerial photography, offer valuable tools for pest detection and monitoring in precision farming systems. These techniques provide high-resolution spatial data on crop health, vegetation indices, and pest infestation levels, enabling growers to assess pest pressures over large spatial scales and monitor changes in pest populations over time [77]. Satellite imagery offers wide-area coverage and temporal continuity, allowing for the monitoring of pest outbreaks and crop conditions across entire agricultural landscapes. By analyzing satellite-derived vegetation indices, such as normalized difference vegetation index (NDVI) and enhanced vegetation index (EVI), growers can detect changes in crop health and identify areas of pest damage for targeted intervention [94]. Unmanned aerial vehicles (UAVs), or drones, provide flexible and cost-effective platforms for high-resolution aerial imaging and monitoring of pest infestations at the field level. Equipped with multispectral and thermal cameras, drones can capture detailed imagery of crop canopies, enabling growers to detect early signs of pest damage, assess crop health, and prioritize management interventions [95]. Aerial photography, conducted using manned aircraft or helicopters, offers detailed visual inspection of agricultural fields and canopies, allowing for the identification of pest damage, weed infestations, and crop stressors. Aerial photographs provide valuable contextual information for ground-based pest scouting and sampling efforts, facilitating targeted pest management decisions and resource allocation [96].

Table 2 provides an overview of representative studies concerning the role of precision farming in managing significant pests in oil palm (*Elaeis guineensis* Jacq.). The table includes various studies conducted to explore precision farming techniques and their efficacy in pest management within oil palm plantations. Each study offers insights into different aspects of precision farming, highlighting its importance in

No	Study title	Year	Key findings	Ref.
1	Expert systems in oil palm precision agriculture: A decade systematic review	2022	Expert systems (ESs) play a vital role in oil palm precision agriculture (PA), particularly in crop, water, and soil management. Analysis of 108 articles from 2011 to 2020 reveals emerging trends and identifies future research directions for ES applications in oil palm PA.	[34]
2	Classification of oil palm female inflorescences anthesis stages using machine learning approaches	2021	Machine learning (ML) approaches, particularly random forest (RF) models, offer efficient solutions for predicting oil palm pollination stages. RF outperformed k nearest neighbor (kNN) and support vector machine (SVM), indicating its potential for developing autonomous pollination systems in oil palm plantations.	[35]
3	Mapping the strength of agro-ecological lightweight concrete containing oil palm by-product using artificial intelligence techniques	2023	Sentinel-1 dual-polarization C-band synthetic aperture radar (SAR) offers reliable detection of oil palm plantations in humid tropics. A novel method combining Landsat-8 and Sentinel-1 data enhances accuracy in distinguishing mature and young oil palm trees, achieving a detection accuracy of 96.08%.	[77]
4	Leveraging on advanced remote sensing-and artificial intelligence-based technologies to manage palm oil plantation for current global scenario: A review	2023	Advanced remote sensing technologies, coupled with AI algorithms and image processing, offer precise monitoring of palm oil plantations, aiding in early disease detection and sustainable management practices. Despite achieving high accuracy levels in detecting palm oil trees, AI models require diverse training data and fine-tuning for further improvement.	[79]
5	Design considerations of variable rate liquid fertilizer applicator for mature oil palm trees	2022	The designed variable rate liquid fertilizer applicator achieves precise nutrient application around oil palm trees, ensuring optimal distribution and structural safety during field operations.	[81]
6	Design of disease detection system on oil palm leaves using deep learning-based convolutional neural networks algorithm	2022	Implementing precision farming principles in oil palm plantations requires efficient disease detection and control. A machine learning and computer vision-based system achieved an 85.5% accuracy rate in real-time disease recognition, facilitating sustainable plantation practices.	[84]
7	Development of an electrochemical sensor for detection of secondary metabolite quinoline in *Ganoderma boninense* infected oil palms.	2018	Key findings: quinoline, a secondary metabolite excreted by oil palms when infected by *Ganoderma boninense*, offers potential for early detection of the pathogenic fungus, facilitated by a newly developed electrode based on functionalized multi-walled carbon nanotubes.	[86]
8	Identification of *Ganoderma boninense* infection levels on oil palm using vegetation index.	2018	Multispectral analysis of UAV images using various vegetation indices effectively identifies *Ganoderma boninense* infection levels in oil palms, providing a faster and less labor-intensive method compared to manual observation, essential for timely disease control in endemic areas.	[94]

Table 2.
Representative studies on the role of precision farming in the management of major pets in oil palm (Elaeis guineensis Jacq.).

addressing pest-related challenges and enhancing sustainable oil palm production practices. In addition to monitoring, precision farming can also be employed to control pests and diseases by integrating the use of environmentally friendly alternative pesticides. Research conducted by Munawaroh et al. has developed a trap based on attractant pheromones derived from pineapples to control the rhinoceros beetle (*Oryctes rhinoceros* L.). This innovative approach capitalizes on precision farming techniques to target-specific pests while minimizing environmental impact [97]. Despite the potential benefits of sensor, GPS, and remote sensing technologies for pest control and monitoring in precision farming, several challenges remain to be addressed. These include the cost of acquiring and maintaining equipment, the need for specialized technical expertise for data analysis and interpretation, and the integration of heterogeneous data streams from multiple sources [98]. Future research directions in this area include the development of cost-effective sensor technologies, the refinement of data analytics algorithms for pest detection and prediction, and the integration of emerging technologies such as artificial intelligence and Internet of things (IoT) for real-time monitoring and decision support [99].

3.3 Advantages of precision in pesticide application and fertilization

Precision farming techniques offer numerous advantages in the application of pesticides and fertilizers, enabling growers to optimize resource use efficiency, minimize environmental impact, and enhance crop yields.

3.3.1 Reduced chemical input

Precision farming enables growers to apply pesticides and fertilizers only where and when they are needed, minimizing overall chemical input and reducing environmental contamination. By accurately targeting pest-infested areas and nutrient-deficient zones within fields, growers can optimize the efficacy of chemical treatments while minimizing off-target effects and non-point source pollution [100]. For example, variable rate application (VRA) systems, integrated with GPS technology, allow growers to adjust pesticide and fertilizer rates in real time based on spatial variations in pest pressures and soil nutrient levels. This targeted approach to chemical application reduces overuse and wastage of agrochemicals, resulting in cost savings for growers and reduced environmental impact [83].

3.3.2 Improved pest control efficacy

Precision farming technologies enhance the efficacy of pest control measures by ensuring precise delivery of pesticides to target organisms while minimizing exposure to non-target organisms and beneficial insects [76]. By accurately mapping pest distribution patterns and monitoring pest dynamics over time, growers can implement timely and targeted pest management interventions to prevent outbreaks and minimize crop damage [101]. For instance, aerial drones equipped with multispectral cameras and GPS navigation systems enable growers to conduct aerial scouting missions to identify pest hot spots and assess pest damage levels across large agricultural areas. This aerial reconnaissance facilitates rapid response to emerging pest threats and allows for strategic deployment of pesticide applications to suppress pest populations effectively [102].

3.3.3 Optimized nutrient management

Precision farming techniques enable growers to apply fertilizers with greater precision, matching nutrient inputs to crop requirements and soil fertility levels [82]. By conducting soil nutrient testing and mapping soil variability within fields, growers can develop site-specific fertilizer application maps to guide variable rate fertilization practices [82, 103]. Variable rate fertilization (VRF) systems, integrated with GPS and sensor technologies, enable growers to adjust fertilizer rates based on spatial variations in soil nutrient levels and crop demand. This adaptive approach to nutrient management optimizes fertilizer use efficiency, minimizes nutrient runoff, and reduces the risk of groundwater contamination [83].

3.3.4 Enhanced crop yield and quality

Precision farming practices contribute to enhanced crop yield and quality by optimizing pest management strategies and nutrient inputs to meet crop requirements [104]. By maintaining optimal pest control and nutrient levels throughout the growing season, growers can minimize yield losses due to pest damage, nutrient deficiencies, and environmental stressors [105]. Precision irrigation systems, integrated with soil moisture sensors and weather data, enable growers to deliver water precisely to crops based on their water requirements and growth stage. This efficient use of irrigation water ensures adequate moisture supply for optimal crop growth and development, resulting in improved yield and quality [106]. Ensuring food safety standards are met is paramount in the production of good edible oils such as palm oil. Residues of pesticides on *E. guineensis* trees may potentially contaminate the harvested fruits and processed palm oil, posing risks to human health and compromising product quality, because some studies found pesticide in *E. guineensis* leaves [21, 67]. By adopting precision farming practices, farmers can minimize pesticide residues on *E. guineensis* trees, thus safeguarding the quality and safety of the final product.

3.3.5 Environmental sustainability

Precision farming contributes to environmental sustainability by reducing the environmental footprint of agricultural production systems and promoting ecosystem resilience. By minimizing chemical inputs, optimizing resource use efficiency, and reducing greenhouse gas emissions, precision farming practices help mitigate environmental degradation and climate change impacts [107]. Furthermore, precision farming techniques facilitate the adoption of IPM strategies, which emphasize the use of multiple pest control tactics, including biological control, cultural practices, and habitat manipulation, to minimize reliance on chemical pesticides [65, 108]. This holistic approach to pest management promotes ecological balance, reduces pesticide resistance development, and preserves beneficial insect populations [108, 109]. Precision farming offers significant advantages in the application of pesticides and fertilizers, enabling growers to optimize resource use efficiency, enhance pest management practices, and promote sustainable agricultural production. By leveraging advanced technologies such as GPS, sensor, and remote sensing systems, growers can implement precise and targeted pest control and nutrient management strategies, resulting in improved crop yield, quality, and environmental stewardship.

4. Stakeholder collaboration for integrated Pest management

4.1 Roles and engagement of stakeholders in integrated pest management

In the pursuit of sustainable pest management in *E. guineensis* plantations, stakeholder collaboration plays a pivotal role in fostering effective and holistic approaches. By examining the contributions and engagements of each stakeholder group, we can gain insights into how their collective actions can address complex pest management challenges while promoting environmental sustainability and socioeconomic development.

4.1.1 Farmers: custodians of cultivation knowledge

Farmers represent the frontline actors in pest management, responsible for implementing pest control strategies on the ground. Their intimate knowledge of local ecosystems, traditional farming practices, and pest dynamics are invaluable assets in devising effective pest management plans [110]. Farmers play a vital role in monitoring pest populations, identifying pest outbreaks, and implementing control measures in a timely manner [65, 111]. Additionally, their feedback and observations contribute to refining pest management strategies, enhancing their adaptability and efficacy [112, 113].

4.1.2 Oil palm companies: stewards of sustainable agriculture

E. guineensis companies hold a significant responsibility in promoting sustainable pest management practices within their plantations. As key stakeholders in the *E. guineensis* industry, these companies are tasked with implementing pest control measures that prioritize environmental conservation and human health. By investing in research and development, adopting integrated pest management approaches, and adhering to best management practices, *E. guineensis* companies can minimize the ecological footprint of their operations while safeguarding the productivity and profitability of their plantations [114].

4.1.3 Government: guardians of regulatory frameworks

Government agencies play a crucial role in providing regulatory oversight, policy guidance, and technical support to facilitate the implementation of sustainable pest management practices. Through the formulation of laws, regulations, and standards, governments set the framework for pest management activities, ensuring compliance with environmental and safety requirements [115]. Moreover, government agencies provide extension services, training programs, and financial incentives to encourage adoption of integrated pest management practices among farmers and plantation owners [116].

4.1.4 Researchers or academics: architects of innovation

Researchers and academics serve as architects of innovation in sustainable pest management, conducting fundamental and applied research to develop novel solutions to pest and disease challenges. Their contributions span various domains, including pest biology, ecology, genetics, and control methods [117]. Through interdisciplinary collaborations, researchers explore innovative approaches such as biological control, host plant resistance, and precision agriculture to enhance the resilience and sustainability of *E. guineensis* cultivation [118].

4.1.5 Local communities: guardians of environmental health

Local communities residing near *E. guineensis* plantations play a critical role in safeguarding environmental health and promoting sustainable land management practices. As stewards of natural resources, these communities possess valuable traditional knowledge and indigenous practices that complement modern pest management strategies [119]. Engaging local communities in pest management initiatives fosters a sense of ownership and stewardship, empowering them to contribute to the conservation of biodiversity and ecosystem services [120]. The successful implementation of integrated pest management in *E. guineensis* plantations hinges on the active engagement and collaboration of diverse stakeholders. By leveraging their unique expertise, resources, and perspectives, stakeholders can collectively address pest and disease challenges while promoting environmental sustainability, economic prosperity, and social well-being in *E. guineensis* cultivation.

4.2 Advantages of collaboration in sustainable pest management

Collaboration among stakeholders in sustainable pest management offers numerous advantages that contribute to the effectiveness and long-term viability of pest control strategies in *E. guineensis* plantations. Firstly, collaboration fosters the sharing of knowledge and expertise among diverse stakeholders, including farmers, researchers, government agencies, and industry representatives. This exchange of information allows for a more comprehensive understanding of pest dynamics, control methods, and best practices, leading to improved decision-making and problem-solving [121]. Furthermore, collaboration facilitates resource sharing and collective action, enabling stakeholders to pool their financial, technical, and human resources to tackle pest challenges more effectively [122]. By leveraging combined resources, stakeholders can implement larger-scale pest management initiatives, invest in research and development, and adopt innovative technologies that may be beyond the capacity of individual actors. Moreover, collaboration enhances coordination and communication among stakeholders, leading to more coherent and integrated pest management strategies [122, 123]. Through regular communication channels and collaborative platforms, stakeholders can coordinate pest monitoring efforts, share early warning alerts, and synchronize pest control interventions across different locations and stakeholders [124].

Additionally, collaboration promotes adaptive management and learning, allowing stakeholders to respond effectively to changing pest pressures and environmental conditions [125]. By continuously monitoring and evaluating pest management outcomes, stakeholders can identify successful practices, refine strategies, and adapt to emerging pest threats in a timely manner [126]. Collaboration strengthens pest monitoring and early detection systems, enabling timely responses to emerging pest and disease threats. Through collaborative surveillance networks and information-sharing platforms, stakeholders can detect pest outbreaks, monitor pest populations, and assess pest trends across different regions and landscapes [127]. Early warning systems, supported by data from remote sensing, weather monitoring, and pest modeling, provide valuable insights into pest dynamics and enable proactive pest management strategies [94]. By detecting and responding to pest incursions early, stakeholders can minimize crop damage, reduce yield losses, and prevent the spread of invasive pests and diseases [128]. Furthermore, collaboration enhances stakeholder engagement and buy-in, fostering a sense of ownership and shared responsibility for pest management outcomes [129]. Through participatory decision-making processes and inclusive stakeholder engagement, stakeholders are more likely to adhere to pest management protocols, comply with regulations, and contribute actively to pest surveillance and control efforts [126]. In general, collaboration among stakeholders in sustainable pest management offers numerous advantages, including knowledge sharing, resource pooling, coordination, adaptive management, and stakeholder engagement. By harnessing the collective expertise, resources, and efforts of diverse stakeholders, integrated pest management initiatives in *E. guineensis* plantations can achieve greater effectiveness, resilience, and sustainability in the face of evolving pest challenges.

4.3 Strategies to support and engage local communities in pest control

In the endeavor to achieve IPM in *E. guineensis* plantations, the involvement and support of local communities are paramount. Engaging local communities in participatory decision-making processes is fundamental to ensuring their ownership and commitment to pest and disease control initiatives. By involving community members in the planning, implementation, and evaluation of pest management programs, stakeholders can harness local knowledge, priorities, and resources to develop contextually relevant strategies [130]. Participatory approaches, such as community meetings, focus group discussions, and participatory rural appraisals, enable stakeholders to co-design interventions that address community needs and aspirations while promoting environmental sustainability and social equity [131]. Investing in capacity building and training programs empowers local communities with the knowledge, skills, and tools necessary to actively participate in pest and disease control activities. Training workshops, field demonstrations, and extension services provide community members with practical training on IPM principles, pest identification, monitoring techniques, and alternative pest control methods [132]. By building local capacities in pest management, stakeholders enhance community resilience, reduce dependency on external inputs, and promote self-reliance in addressing pest and disease challenges [133]. Moreover, capacity-building initiatives contribute to the long-term sustainability of pest management interventions by fostering a culture of learning, innovation, and continuous improvement within local communities.

Establishing community-based surveillance and early warning systems also enables local communities to actively monitor pest and disease dynamics and respond swiftly to emerging threats. Community members serve as frontline observers, reporting unusual pest sightings, crop damage, and disease symptoms to relevant authorities and stakeholders [134]. By leveraging indigenous knowledge and traditional monitoring practices, communities can complement scientific surveillance efforts and enhance the detection and control of pests and diseases [119]. Early warning systems, supported by participatory monitoring and communication networks, facilitate timely decision-making and coordinated responses to pest outbreaks, minimizing crop losses and safeguarding livelihoods [128]. Promoting sustainable livelihood diversification strategies provides alternative income sources and incentives for local communities to engage in pest and disease control activities. Agroforestry, for example, offers opportunities for crop diversification, integrated pest management, and ecosystem restoration, reducing reliance on monoculture *E. guineensis* plantations and enhancing landscape resilience [135]. Income-generating activities, such as beekeeping, mushroom cultivation, and handicraft production, empower communities to generate additional revenues while contributing to biodiversity conservation and environmental stewardship [136]. By integrating pest management with sustainable livelihood initiatives, stakeholders can address socioeconomic vulnerabilities, alleviate poverty, and build community resilience to pest and disease risks.

Engaging and empowering local communities are essential components of successful integrated pest management in *E. guineensis* plantations. By adopting participatory approaches, investing in capacity building, establishing community-based surveillance systems, and promoting sustainable livelihood diversification, stakeholders can harness the collective wisdom, resources, and resilience of local communities in addressing pest and disease challenges sustainably. Moving forward, fostering inclusive and collaborative partnerships with local communities will be crucial for achieving environmentally sound, economically viable, and socially equitable pest management outcomes in *E. guineensis* cultivation.

5. Conclusions and prospects

The integration of precision farming techniques and stakeholder collaboration offers a transformative opportunity for revolutionizing sustainable pest management strategies in *E. guineensis* plantations. By leveraging cutting-edge technology and collaborative efforts, growers can effectively combat pest pressures, mitigate environmental impacts, and fortify industry resilience against unforeseen challenges. The strategic use of precision farming tools such as sensor networks, GPS technology, and remote sensing enables growers to monitor pest dynamics accurately, facilitating targeted interventions and reducing reliance on chemical pesticides. Additionally, stakeholder collaboration facilitates knowledge exchange, resource sharing, and innovative solution co-creation tailored to *E. guineensis* cultivation contexts. Looking ahead, continued investment in research, innovation, and stakeholder engagement is essential to fully exploit the potential of sustainable pest management practices in *E. guineensis* cultivation. Advancements in precision farming technologies and interdisciplinary research initiatives offer opportunities to enhance pest management efficacy while minimizing environmental footprints. Furthermore, ongoing collaboration among growers, government agencies, research institutions, and local communities is vital for fostering a culture of innovation, resilience, and sustainability within the *E. guineensis* industry. By embracing precision farming principles and stakeholder collaboration, stakeholders can navigate toward a more resilient, environmentally responsible, and economically viable future for *E. guineensis* cultivation.

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