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A Framework for Enhancing Adoption of Mobile-based Surveillance for Crop Pest and Disease Management by Farmers in Kenya

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ABSTRACT

Traditional methods of managing crop pests and diseases in Kenya face challenges in meeting the demands of rising global food needs. While autonomous biosecurity technologies present advancements, obstacles such as affordability, infrastructure limitations, and insufficient farmer skills hinder their widespread adoption. This study introduces a groundbreaking Participatory Farmer-Centric e-Surveillance Framework to empower Kenyan farmers through accessible mobile-based solutions. Conducted in Homa Bay County, Kenya, the research utilized a mixed-methods approach involving surveys of 367 farmers and interviews with 31 extension officers. The findings underscore the substantial impact of pests and diseases on farmer livelihoods and agricultural productivity. Existing surveillance strategies struggle with accurate identification, diagnosis, and timely decision-making. Mobile-based solutions emerge as a promising alternative due to their cost-effectiveness and widespread accessibility. The proposed framework emphasizes farmer centricity, actively involving them in reporting pest and disease occurrences through mobile phones. A central e-Surveillance Data Center aggregates and analyzes data to generate real-time pest and disease maps and forecasts. The digital ecosystem ensures farmers receive timely alerts, tailored advice, and access to relevant agricultural resources. An incentivization mechanism, including rewards and recognition programs, encourages active farmer participation and data sharing. This farmer-centric approach aims to empower individuals with real-time information and decision-making tools, with overarching goals of enhancing agricultural productivity, ensuring food security, improving farm-level resilience, and promoting the long-term sustainability of Kenya's agricultural sector. Leveraging mobile technology and fostering farmer-centric support systems, the framework represents a promising avenue for transforming Kenya's agricultural landscape, contributing significantly to a more sustainable agricultural future for the nation.
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1. Introduction

The escalating global demand for food places immense pressure on agricultural sectors, particularly in regions such as Sub-Saharan Africa. Here, the persistent menace of crop pests and diseases leads to devastating pre-harvest losses (FAO, 2017a; A. M. Otieno, J. K. Kiboi, & M. C. Mugo, 2023). Kenya, with smallholder farmers contributing over 90% of its agricultural production (Mbugua, Kiboi, & Karanja, 2023; Wanyonyi, Kihiko, & Kinyanjui, 2022), grapples with significant challenges in managing these threats. Limited access to reliable extension services and inadequate pest management skills further compound the issue (Pratt, Constantine, & Murphy, 2017). Recent outbreaks of Fall Armyworm, Maize Lethal Necrosis Disease, Cassava Brown Streak Disease, and locusts underscore the gravity of the problem, causing substantial crop losses and economic hardship

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(FAO, 2019; Otieno, Otieno, & Githinji, 2023). Strengthening crop monitoring, especially in vulnerable agro-ecological zones, becomes crucial for safeguarding Kenya's food security and economic growth (Breisinger, Karugia, Keenan, & Mbuthia, 2022; Muthoni, Otieno, Kuria, Ochieng, & Wanyeki, 2018). However, traditional monitoring methods often prove inefficient and reactive.

Addressing the challenges posed by crop pests and diseases requires innovative approaches. Autonomous biosecurity surveillance technologies, such as satellite systems, Wireless Sensor Networks (WSN), Unmanned Aerial Vehicles (UAV), or Drones, emerge as potential game-changers. However, implementing these technologies in Africa's diverse and often resource-limited context presents a spectrum of challenges, both technological and social-political (FAO, 2023; W. Otieno, W. Kiboi, & W. Mugo, 2023). Technological hurdles, starting with the lack of reliable infrastructure, hinder the operation and data transmission of these technologies in vast rural areas lacking internet connectivity, electricity, and data storage facilities (World Bank, 2022). Moreover, their high cost can be prohibitive for many farmers and governments (Mwaya, 2020). The technological skills gap adds to the complexity, as expertise for installation, operation, and data analysis is often scarce (Akpoti, Obeng-Opare, & Danso, 2022). Concerns about data security and potential misuse, particularly in the absence of robust legal frameworks, can discourage adoption (Agyemang, Owusu-Nsowah, & Agyarko, 2021). Social and political considerations also play a crucial role, with lack of awareness among farmers about the benefits and accuracy of these tools hampering trust and willingness to integrate them into their practices (Adetunji, Ajayi, & Adebayo, 2023). Additionally, the diverse ecosystems across Africa raise concerns about the suitability of existing autonomous biosecurity technologies and their potential unintended consequences on specific environments (Akindeinde, Yusuf, & Adebayo, 2020).

However, the integration of Artificial Intelligence (AI) in sensor-based mobile devices provides a potential solution to some of the adoption challenges associated with common biosecurity surveillance technologies (Cui, Ling, Zhu, & Keener, 2018; Ullo & Sinha, 2020). Mobile-based solutions offer a promising avenue for overcoming challenges in the adoption of autonomous biosecurity tools for crop pest and disease management in Kenya. While autonomous biosecurity surveillance technologies face obstacles like high costs, infrastructure limitations, a missing legal framework, and complex operation that may require a prolonged period to address locally, mobile-based surveillance solutions are generally affordable, provide a user-friendly interface, and are easily accessible, putting these solutions within the reach of even the most resource-constrained farmers (Mwaya, 2020). Mobile solutions leverage existing mobile networks, simplifying data transmission. In terms of technology dissemination, mobile apps can be a gentle introduction to biosecurity concepts, building trust through pilot programs and demonstrations. Through mobile-based solutions, farmers can share experiences and learn from each other via peer-to-peer mobile platforms, empowering communities with awareness and understanding (R. She, 2020; Yuanhao Sun et al., 2019; Yuanhao et al., 2021). Mobile platforms can facilitate enhanced data collection and sharing, consolidate pest and disease information, and empower farmers with real-time access to critical knowledge and resources (Kabbiri, Dora, Kumar, Elepu, & Gellynck, 2018). Addressing issues of data security, technical skills, and trust, these apps integrate blockchain technology, training modules, and intuitive interfaces.

Despite the promising potential of mobile technology in managing crop pests and diseases, its efficacy in Kenya is hindered by the widespread reluctance among farmers to adopt it. This reluctance is attributed to various challenges, including the digital divide, lack of adequate support, skill gaps, and the presence of irrelevant solutions, as highlighted by Jayashankar, Nilakanta, Johnston, Gill, and Burres (2018). These challenges pose significant barriers to progress in the realm of mobile pest surveillance. In light of these obstacles, our study proposes a comprehensive framework designed to address these issues and promote the widespread adoption of mobile-based surveillance solutions among Kenyan farmers. In essence, this framework is not merely a technological solution but a holistic approach towards creating a more resilient and secure future for Kenya's agricultural landscape.

1.1 Problem Definition and Research Objective

1.1.1 Problem Definition

Kenya's agricultural sector grapples with persistent pest and disease management challenges, leading to substantial pre-harvest losses and jeopardizing food security. Conventional surveillance methods struggle with accurate identification, timely diagnosis, and effective decision-making, ultimately hindering effective responses to outbreaks. Key issues include limited access to extension services and expertise, as well as inefficient traditional monitoring methods that contribute to significant losses. While autonomous biosecurity technologies like wireless sensor networks, satellites, UAVs, and ground robots offer promising solutions, their adoption is hindered by affordability, infrastructure limitations, and insufficient farmer skills. Mobile-based surveillance solutions emerge as a compelling alternative due to their mobility, ubiquity, and affordability, overcoming limitations of autonomous systems. To address the shortcomings of traditional methods and barriers to adopting autonomous technologies, we need to leverage mobile-based solutions to empower farmers in effectively reporting and managing pest and disease occurrences. However, low adoption rates among Kenyan farmers highlight the need for a collaborative framework involving farmers, researchers, extension services, innovators, digital solution providers, and policymakers to unlock the full potential of smartphones for pest surveillance and achieve widespread adoption of these valuable tools.

1.1.2 Research Objective

This research aims to increase the adoption of mobile-based pest and disease surveillance apps among Kenyan farmers by overcoming current adoption barriers, including lack of awareness, technical limitations, and insufficient training. Specifically, this research focus on developing a farmer-centric e-surveillance framework in Homa Bay County, Kenya.

Therefore, the main objective of this research is to:

i. Assess the impact of pests and diseases on farmers' livelihoods, the effectiveness of surveillance strategies, and digital surveillance ecosystems in Homa Bay County, Kenya.
ii. Develop a farmer-centric e-surveillance framework to increase adoption of mobile-based pest and disease surveillance among farmers in Homa Bay County, Kenya.

2. Related Study

Globally, the agricultural sector faces substantial threats from crop pests and diseases, leading to billions in annual losses, particularly in Africa where estimates reach $1 billion (FAO, 2017b; Gounou. et al., 2022). This vulnerability is particularly pronounced among Kenyan farmers, who grapple with the ineffectiveness and unsustainability of traditional calendar-based control methods (Goverment of Kenya, 2020; Venter, 2019). The consequential underperformance in agriculture, driven by crop pests and diseases, triggers a cascade of negative consequences, notably affecting rural areas with economic instability and heightened poverty (World Bank, 2019b). Studies suggest that pest and disease infestations can result in crop yield losses of up to 40% in the country, exacerbating existing vulnerabilities and impeding economic development (Adesina & Ndungu, 2023; Bett et al., 2021; UN, 2020). For instance, the Fall Armyworm and Maize Lethal Necrosis Disease (MLND) induced panic among farmers in North Rift and Western Kenya, causing up to a 50% crop loss in 2018 (FAO, 2019). The witnessed impact of crop pests and diseases remains severe among most smallholders, who have limited pest and disease management skills and face challenges accessing reliable extension services that enable effective monitoring and control (Early et al., 2016; Pratt et al., 2017). Given changing climatic conditions, globalization, and trade, which accelerate the spread of these pathogens, critical research should prioritize enhancing crop pest and disease surveillance and improving access to data and control information (Gounou, Day, Adomou, Toko, & Wydra, 2021; C. Zhang, Li, Liu, Zhang, & Guo, 2023). Therefore, this study explores innovative and sustainable approaches to pest and disease surveillance and control to safeguard the livelihoods of smallholder farmers and promote broader economic resilience.

In the relentless battle against crop pests and diseases threatening global agriculture, autonomous pest monitoring technologies have emerged as powerful tools (Preti, Verheggen, & Angeli, 2021). Despite their value in early detection and intervention, these advancements face limitations and issues of unequal access, painting a complex picture (Adesina & Ndungu, 2023; Bett et al., 2021; UN, 2020). Satellite technology, while promising for monitoring crop health and detecting outbreaks (Thenkabail, Gumma, & Teluguntla, 2016), encounters challenges hindering widespread adoption. Issues include limited resolution affecting accurate pest identification, complex data analysis demanding advanced expertise (Czajkowski & Gowda, 2018), weather dependence causing data gaps (Lobell & Azzari, 2017), and high costs limiting accessibility (Waldman et al., 2016). Ethical concerns regarding data privacy and ownership further complicate its application (Ait-Chamhouch & Filali, 2020)

Wireless Sensor Networks (WSNs) function as vigilant sentinels, monitoring environmental conditions that may indicate pest presence (López et al., 2012). However, challenges such as limited memory, battery life, coverage range, and high costs hinder their widespread adoption, especially among resource-constrained smallholder farmers (Azfar, Nadeem, Alkhodre, & Ahsan, 2018; Patil & Chen, 2017). Ground robots offer mobility for data collection (Jurdak et al., 2015), but their sophisticated navigation, high costs, and technical complexity limit their suitability for resource-constrained settings(Santos, Santos, & Valente, 2020). Unmanned Aerial Vehicles (UAVs) capture high-resolution images but face challenges in cost, flight time, and restrictive regulations, particularly in developing countries (Hayden, 2021) (CTA, 2019). The existing gaps in comprehensive and accessible crop pest and disease surveillance persist due to cost and technical limitations, widening the access divide and leaving many farmers behind (FAO & ITU, 2018; Pant, Joshi, Kumar, & Patil, 2019).

Despite these challenges, this paper envisions a promising future by addressing these gaps. Hybrid systems, combining different technologies, are proposed as a comprehensive and cost-effective solution (Trad, Jurdak, & Rana, 2015). Smartphones, emerging as a promising alternative, are highlighted as more than mere communication devices. Their sensor-rich capabilities, including high-resolution cameras and motion sensors, make them ideal for large-scale pest and disease surveillance where traditional technologies fall short (Chessa, Corradi, Foschini, & Girolami, 2016). The potential of smartphones extends beyond data collection, with AI and machine learning algorithms providing on-the-go diagnostics (Chepkwony, Bommel, & Langevelde, 2020; CIP, 2020). Leveraging AI-powered data analysis can significantly improve pest detection accuracy and resource allocation (Maslekar, Kulkarni, & Chakravarthy, 2020). This study emphasizes tailoring these affordable and easily deployable technologies to specific needs and contexts, empowering smallholder farmers and placing surveillance capabilities directly in their hands (Panda, 2020). It envisions scenarios where farmers capture an image of a suspicious leaf and, within seconds, receive real-time insights and actionable recommendations for pest control, bridging the gap between knowledge and action for smallholder farmers and extension agents.

Smartphones, due to their mobility, ubiquity, and affordability, overcome limitations of other autonomous systems. They can conduct surveillance across vast fields, addressing the limited coverage of WSNs. Their computing power enables the operation of complex applications, mitigating technical barriers associated with certain autonomous systems (Jingcheng et al., 2019). This study underscores the transformative role of mobile technology, highlighting "Ag-Apps" that provide functionalities from pest identification to nutrient analysis, bridging the digital divide and offering vital information to farmers in remote or underserved areas(Ciampitti & Albers, 2016; Panda, 2018). However, unlocking the full potential of smartphones for pest surveillance requires a collaborative effort. Researchers, innovators, infrastructure providers, policymakers, and farmers must work together to develop robust AI and ML models tailored to diverse pests and diseases, address data privacy and security concerns, and design user-friendly and culturally appropriate mobile applications for widespread adoption.

The high and rising smartphone ownership in Kenya, estimated at 21.69 million by Statista (2021) and projected to reach 33.45 million by 2025, presents a significant opportunity for leveraging smartphone technology in crop pest and disease surveillance. This trend, coupled with increasing internet accessibility (World Economic Forum, 2016) and the popularity of social media platforms like WhatsApp and Facebook (Vries, 2016), creates fertile ground for the adoption of Mobile Crowd-Sensing (MCS) paradigms. As Perez, Popadiuk, Roux, and Cesar (2017) highlight, MCS paradigm offer valuable tools for improved information exchange, collaboration, and knowledge diffusion, fostering a more connected and informed agricultural ecosystem. MCS, powered by AI and advanced sensor technology, has the potential to revolutionize pest surveillance by enabling farmers to contribute data through their smartphones, essentially creating a vast network of citizen scientists (Mrisho et al., 2020). However, achieving large-scale participation in MCS initiatives requires addressing the challenge of user motivation. Farmers need incentives to offset the costs associated with data collection, such as battery consumption, data usage, and time commitment (Luo, Kanhere, Huang, Das, & Wu, 2017). This study explores how farmers can be incentivized to actively participate in pest surveillance through MCS offering real-time insights to improve pest forecasting, and guide targeted control measures.

3. Methodology

This study adopted a pragmatic philosophical approach, emphasizing the practical application of research findings and allowing for diverse research methods. To gather data, a mixed-methods approach was employed, utilizing surveys with both closed-ended and open-ended questions, semi-structured interviews with extension officers, and secondary sources like online materials, research papers, and case studies. This diverse approach aimed to paint a comprehensive picture of the research topic, grounded in both quantitative and qualitative perspectives.

The study was conducted in Homa Bay County, Kenya. The county's economy heavily relies on smallholder agriculture, yet grapples with persistent food insecurity due to challenges such as frequent pest outbreaks, limited extension services, and high poverty rates (KNBS, 2019; PAI, 2016). Situated along Lake Victoria, the county comprises 8 sub-counties (Rachuonyo South, Rachuonyo East, Rachuonyo North, Rangwe, Homa Bay Town, Ndhiwa, Suba North, and Suba South), with densely populated areas known for cultivating crops like maize, sorghum, and beans. Among the 193,000 households engaged in crop farming (HBC, 2018), the study honed in on the 4,389 farmers who had formally registered with the county's agricultural department through organized farm groups. These farmers, operating within groups of 20-30 individuals led by appointed representatives, formed the core participants of the study. Additionally, 31 ward extension officers, who provide crucial support and guidance to these farmers, were included in the research.

To ensure a representative and informative sample, the study employed distinct sampling strategies for farmers and extension officers. The sample size for the farmers was determined using Israel (2009)'s formula (3.1) and a census applied for the ward extension officers who were 31 in total.

$$n = \frac{\mathrm{N}}{1+\mathrm{N}(e)^2} \tag{3.1}$$

Where: n is the sample size, N is the population size, and e is the level of precision. Recognizing the need for increased precision in its findings, this study employed a ±5% precision and a 95% confidence level for sample size calculation, exceeding the recommendations suggested by Israel (2009) for populations exceeding 200. With a population of 4389 and a precision level of 0.05, the formula generated a sample size of 367, which was used in the study. This sample was then proportionally allocated across the 40 wards within the eight sub-counties based on farmer registration numbers of each subcounty. This study utilized survey questionnaires and interview schedules. To ensure the validity and reliability of these instruments, the we employed an expert review to eliminate misleading questions and conducted a pilot test in Kisii County, Kenya, to refine clarity and appropriateness. The questionnaire's reliability was assessed using Cronbach's alpha coefficient (α), and adjustments were made based on the pilot results.

Ethical considerations were prioritized throughout data collection, with research permits, informed consent, and confidentiality assurances in place. Researchers and research assistants directly administered the questionnaires, enabling immediate clarifications when needed. Quantitative data from closed-ended questionnaire responses was analyzed using descriptive statistics in SPSS software (IBM SPSS version 25). Specific statistics employed included, means, standard deviations and frequencies. Qualitative data, including text responses, interview notes, and audio recordings, underwent content, thematic, and narrative analysis. The qualitative data was coded and integrated with the quantitative data for presentation in tables, charts, and descriptive statistics.

4. Results and Discussion

4.1 Demographic Landscape Analysis for Digital Pest and Disease Surveillance Adoption among Farmers

In an attempt to motivate the adoption of mobile-based digital solutions by farmers in the surveillance of crop pests and diseases, this paper assesses the demographic landscape of farmers that influences the adoption of agricultural technologies. Studies have recognized that demographic characteristics, including age, gender, and education, play a vital role in influencing the adoption of agricultural technologies (Gebre, Isoda, Rahut, Amekawa, & Nomura, 2019; Irungua, Mbuguaa, & Muia, 2015; Tata & McNamara, 2017). As envisioned in the proposed e-surveillance framework, analysing farmers demography is crucial for tailoring effective interventions. Our study findings in Table 1 indicate that the demographics of Kenyan farmers present both fertile ground and intricate challenges for the adoption of digital pest and disease surveillance (DPDS) tools.

Table 1: Gender and Age Distribution of Farmers

		Age					
		18-30 Years	31-40 Years	41-50 Years	51-60 Years	Over 60 Years	Total
Gender	Male	16	65	50	19	11	161
	Female	28	42	45	25	25	165
Total (Percentage) Mean Age: 42		44 (13.5%)	107 (32.8%)	95 (29.1%)	44 (13.5%)	36 (11.0%)	326 (100.0%)

Source: Researcher, 2021

The average age of farmers is 42, with the largest group falling within the 31-40 age bracket. The involvement of youthful farmers offers a promising opportunity for collaboration and knowledge-sharing between younger generations adept in digital technologies and older generations with rich agricultural experience. These younger farmers can act as mentors, guiding their peers in navigating the intricacies of DPDS platforms, while older farmers can share their wisdom on traditional pest control practices and local environmental nuances. However, the existing demographic landscape is not without its obstacles. Although the ratio of female to male farmers is almost the same, 1:1, gender disparities still persist, with women facing greater difficulty in accessing resources and training compared to their male counterparts as observed by Tufa et al. (2022). In addition, cultural norms and traditional divisions of labor often contribute to these inequalities, hindering women's ability to fully embrace technological advancements like DPDS (Gebre et al., 2019). To bridge this gap and achieve truly inclusive agricultural technology adoption, comprehensive support programs are crucial, not only to address technological barriers but also social and cultural factors that impede technological adoption by women.

To facilitate farmers in adopting and proficiently using DPDS, education assumes a pivotal role, as emphasized by Saidu, Clarkson, Adamu, Mohammed, and Jibo (2017). Education equips farmers to seamlessly engage with digital content and follow English-based instructions. Encouragingly, our findings from Table 2 indicate that about 75% of the surveyed farmers have achieved at least a secondary education level, creating a notable opportunity for them to interact with the majority of emerging English-based crop pest and disease digital applications.

Table 2: Education Level and Age of Farmers

		Age					Total		
		18-30 Years	31-40 Years	41-50 Years	51-60 Years	Over 60 Years	No	%	Cumulative %
Education Level	Bachelor's Degree	0	12	2	2	0	16	4.9%	4.9%
	Diploma	6	10	7	5	2	30	9.2%	14.1%
	Certificate	13	20	19	10	4	66	20.2%	34.3%
	Secondary Level	19	46	43	16	9	133	40.8%	75.1%
	Primary Level	6	19	22	10	17	74	22.7%	97.8%
	None	0	0	2	1	4	7	2.2%	100%
Total		44	107	95	44	36	326	100%	

Source: Researcher, 2021

This educational attainment, coupled with the diverse age distribution, presents a favorable landscape for leveraging technology to enhance agricultural practices. Despite this promising scenario, persistent skills gaps among most rural farmers, as highlighted by Nampeera et al. (2019), necessitate targeted training programs. These programs are essential for addressing existing gaps and providing farmers with the requisite knowledge and confidence to effectively employ DPDS tools. While the demographics of Kenyan farmers pose both opportunities and challenges for DPDS adoption, the potential for positive change is undeniable. By nurturing collaboration between generations, addressing gender disparities through targeted support, and delivering additional training to bridge skills gaps, we can empower Kenyan farmers to embrace DPDS technology. This, in turn, unlocks farmers potential for fostering a more sustainable and inclusive agricultural future

4.2 The Impact of Crop Pests and Diseases on Small-Scale Farming

Kenya's agricultural landscape is marred by a grim reality: devastating pre-harvest losses due to rampant crop pests and diseases. Studies by CABI (2018) and Pratt et al. (2017) paint a chilling picture, with maize yields in the Western region dropping by over 50% in just one year (FAO, 2019). The survey of 326 farmers in Homabay County, Kenya, revealed a strong consensus among farmers about the continuous negative impact of pests and diseases on crop yield and production costs, highlighting the urgency for targeted interventions. The findings, presented in Table 3, provide a quantitative snapshot of farmers' perceptions.

Table 3: Descriptive Statistics on the Impact of Pests and Disease on Farming

Item	Number of Farmers (N)	Minimum Score	Maximum Score	Mean Score	Standard Deviation
Crop pests and diseases are currently the major contributors of the reduction in crop yield	326	1.00	5.00	4.1227	.8135
Cost of pests and diseases control has significantly increased cost of crop production	326	2.00	5.00	4.3436	.6692
The effect of crop pests and diseases is felt almost every planting season	326	2.00	5.00	4.3221	.7829
Average Mean				4.2628	0.7552

(1 = Strongly Disagree, 2 = Disagree, 3 = Neutral, 4 = Agree and 5 = Strongly Agree)

Source: Researcher, 2021

The study reveals that farmers agree (Mean Score: 4.1227) that crop pests and diseases significantly contribute to reduced crop yield, highlighting a consensus on the substantial impact of these challenges. Additionally, farmers readily acknowledge (Mean Score: 4.3436) that controlling pests and diseases substantially increases the overall cost of crop production, indicating a financial burden. The perception that these issues are felt almost every planting season is widely shared (Mean Score: 4.3221), emphasizing the recurrent nature of the problem. With an average mean score of 4.2628, there's a significant negative impact of pest and diseases on small-scale farming in the County. Despite response variability as indicated by the standard deviations, overall findings highlight a clear consensus among farmers about pests and diseases' harmful effects, emphasizing the urgency for tailored interventions for sustainable management strategies.

To address these challenges, the adoption of mobile-based digital surveillance offers a promising solution. This approach enables real-time crop monitoring, facilitating early pest and disease detection and allowing for swift response measures to minimize crop losses (Y. She, Zhang, Liu, & Biao, 2020). Mobile tools empower farmers, enabling them to make well-informed and cost-effective decisions, optimizing the allocation of resources. Mobile technology can also support data collection for seasonal planning, aiding farmers in anticipating and mitigating challenges. The integration of educational components within the mobile platform enhances farmers' skills, fostering effective pest and disease control. Furthermore, mobile platforms can easily facilitate community collaboration, enabling knowledge sharing and collective problem-solving. The mobile-based surveillance establishes a feedback loop, enabling farmers to provide real-time information for adaptive management (Sun, Liu, Zhang, Li, & Jia, 2019). In summary, this proactive, data-driven approach empowers farmers, fostering increased agricultural resilience and productivity.

4.3 Crop Pest and Disease Surveillance strategies among farmers

Crop pest and disease surveillance entails essential strategies, encompassing regular surveys, reporting, mapping, forecasting, and the implementation of control measures (Chen, Epanchin-Niell, & Haight, 2018; PHA, 2020). Frequent scouting of farms and accurate identification of pests and diseases by farmers have been recommended by De Groote et al. (2020) as key strategies for managing Fall Armyworm (FAW). In an effort to empower and involve farmers in e-surveillance for pests and diseases through the adoption of mobile digital solutions, this study explores farmers' status and perspectives on these strategies. It specifically examines scouting, monitoring, reporting, and the potential for technological empowerment.

4.3.1 Scouting and monitoring through regular surveys

The study finding in Table 4 presents the cross-tabulation of farmers' scouting frequency and crop health assessment visits. A notable finding is that the majority of farmers (93.56%) engage in scouting activities within a two-week period, emphasizing their proactive approach to monitoring crop health. Additionally, a high percentage (97.55%) of farmers scout within a four-week period, further indicating their commitment to regular crop health assessments. Farmers play a crucial role in pest and disease surveillance due to their firsthand knowledge of local conditions. Their frequent scouting visits enable them to detect early signs of pests and diseases, contributing to effective and timely management. However, a small percentage (2.45%) lacks this crucial practice, potentially hindering timely identification of pests and diseases.

Table 4: Farmers' Scouting Frequency and Crop Health Assessment Visits

Cross-tabulation of the frequency of farmers' visits to assess the health condition of crops in their farms and their scouting status						
		The frequency of farmers' visits to assess the status of crops in their farms.				Total
		Daily	between 1-2 weeks	3-4 weeks	Never	
Scout (walk in) farms to check the status of health condition of crops	No	0	0	0	8	8
	Yes	115	190	13	0	318
Total		115 (35.38%)	190 (58.28%)	13 (3.99%)	8 (2.45%)	326
Scout within a two-week period		305 (93.56%) *				
Scout within a four-week period		318 (97.55%) **			2.45%	

a. * Farmers who engage in scouting activities at least once every two weeks
b. ** Farmers who engage in scouting activities at least once every four weeks

Source: Researcher, 2021

The data suggests that farmers are instrumental in actively monitoring the health of their crops. The adoption of mobile-based surveillance solutions can significantly enhance farmers' ability to monitor pests and diseases. Mobile tools provide a convenient platform for recording and sharing real-time information on crop conditions. With mobile applications, farmers can receive alerts, access relevant information, and collaborate with experts and peers. This technology facilitates quick decision-making and targeted interventions based on the data collected during scouting visits. By integrating mobile-based solutions into their existing scouting practices, farmers can strengthen their role in pest and disease surveillance, ultimately contributing to more resilient and sustainable agricultural practices.

4.3.2 Crop Pest and Disease identification, diagnosis and Control by Farmers

In Sub-Saharan Africa, the effectiveness of crop pest and disease surveillance and control faces challenges associated with the technical and logistical aspects of pest identification and disease diagnosis (Piñero & Keay, 2018). This study assesses farmers' ability to independently diagnose and identify crop pests and diseases on their farms, utilizing a five-point Likert scale to gauge difficulty levels. Findings in Table 5 highlights significant challenges encountered by farmers in accurately identifying pests and diseases, emphasizing the need for support. The results show that farmers encountered challenges in correctly identifying pests and diseases (Mean = 3.8712, SD = 0.7817), describing infections (Mean = 4.2178, SD = 0.6646), and diagnosing diseases based on symptoms (Mean = 4.3528, SD = 0.6620). These findings emphasize the need for assistance in these critical aspects.

Table 5: Statistics on Pest and diseases diagnosis and identification difficulties farmers face

Item	Number of Farmers (N)	Minimum Score	Maximum Score	Mean Score	Standard Deviation
It is difficult to correctly identify the pests and diseases in my farm.	326	1.00	5.00	3.8712	.7817
Describing the pests and disease infections is always difficult.	326	1.00	5.00	4.2178	.6646
Diagnosis of diseases from presented symptoms is a challenge	326	1.00	5.00	4.3528	.6620
Average Mean				**4.1473**	**.7028**

(1 = Strongly Disagree, 2 = Disagree, 3 = Neutral, 4 = Agree and 5 = Strongly Agree)

Source: Researcher, 2021

Additionally, the study highlights challenges in making informed decisions about crop pest and disease control. The findings in Table 6 reveal that Information overload is a significant hurdle, with farmers feeling confused about making the right choice due to numerous available control options (Mean = 3.8129, SD = 0.6117). Challenges also include the need for guidance on choosing appropriate control methods (Mean = 4.2423, SD = 0.6223), difficulty recalling effective methods from the past (Mean = 4.2607, SD = 0.6489), unreliable advice (Mean = 4.3742, SD = 0.5983), and a weak linkage between farmers and agricultural experts (Mean = 4.4325, SD = 0.5975). The overall average mean score of 4.22 underscores the significant challenges farmers face in making informed decisions about pest and disease control. Additionally, the study findings in Table 6 reveal that recalling effective methods from the past proves challenging (mean score of 4.2607), emphasizing the need for knowledge management tools. Farmers also face unreliable advice (mean score of 4.3742), underlining the importance of consistent communication and collaboration between farmers and experts through workshops and training programs. The weak linkage between farmers and experts, as indicated by the mean score of 4.4325, further emphasizes the necessity of strengthening connections to facilitate knowledge exchange. The overall average mean score of 4.2245 highlights the significant challenges farmers face in making informed decisions about pest and disease control.

Table 6: Descriptive Statistics on Control decision challenges

Item	Number of Farmers (N)	Minimum Score	Maximum Score	Mean Score	Standard Deviation
There are always several alternative controls and making right choice is always confusing.	326	2.00	5.00	3.8129	.6117
There is need for guidance on choosing the most appropriate control.	326	2.00	5.00	4.2423	.6223
Remembering the best control which worked in the previous situation is difficult.	326	2.00	5.00	4.2607	.6489
Sometimes the advice given works and at times it does not work	326	2.00	5.00	4.3742	.5983
The linkage between the farmers and agricultural experts is weak and should be strengthened	326	3.00	5.00	4.4325	.5975
Average Mean				**4.2245**	**.6157**

(Scale: 1 = Strongly Disagree, 2 = Disagree, 3 = Neutral, 4 = Agree and 5 = Strongly Agree)

Source: Researcher, 2021

The study proposes comprehensive strategies to address challenges in crop pest and disease identification, diagnosis, and control. These include simplifying information, establishing robust mobile platform connections, implementing knowledge management tools, and strengthening farmer-expert communication. The aim is to empower farmers with informed decision-making, best practices adoption, and enhanced pest and disease management capabilities. Aligned with broader goals of sustainable agriculture, increased productivity, and improved food security, this study emphasizes the crucial role of mobile solutions in providing comprehensive information and real-time support.

4.3.3 Crop Pest and diseases reporting Structure

Crop pest and disease reporting structure underpins effective pest and disease management, yielding numerous benefits (Cock & Ooi, 2019). This structure is a systematic framework that identifies, records, and communicates information about pest and disease occurrences in agriculture. It defines channels, protocols, and responsibilities for reporting, ensuring timely and accurate information flow to stakeholders. A robust reporting system is essential for successful pest and disease control, especially when farmers are unable to handle invasions independently. Furthermore, it facilitates the collection and mapping of pest and disease data, issuing warnings or alerts to other farmers for preventive interventions. To achieve this, proper reporting channels such as mobile apps or hotlines are necessary to enable swift information flow, ensuring rapid responses and targeted interventions that minimize damage and optimize resource allocation(Brown, Pérez-Sierra, Crow, & Parnell, 2020; Nyagumbo, Owino, & Nguyo, 2020)..

i. Pest and diseases incident reporting points

The findings in Table 7 presents the diverse strategies employed by farmers in handling unfamiliar pests and diseases, shedding light on their preferences and tendencies. The primary reporting points include reporting to local agrovet retailers (19.4%), extension officers (11.1%), sharing information with other farmers (28.0%), reporting to farm group leaders (15.6%), posting on social media (3.5%), waiting to see if the situation improves (4.0%), and calling someone to apply agrochemicals (pesticides) (18.4%). The percentages indicate the distribution of farmers' actions, with sharing among farmers in the neighborhood being a popular approach (66.4%). The findings reveal the varied approaches farmers take in response to crop pests and diseases, providing valuable insights for understanding their coping mechanisms and informing targeted interventions.

Table 7: Reporting of crop pests and diseases incidences by farmers

		Responses[b]		Percent of Cases
		N	Percent	
How farmers handle strange pests and diseases[a]	Report the condition to local agrovet retailer	149	19.4%	46.0%
	Report to extension officer	85	11.1%	26.2%
	Share with other farmers in the neighbourhood	215	28.0%	66.4%
	Report to farm group leader	120	15.6%	37.0%
	Post to social media	27	3.5%	8.3%
	Do nothing but just wait to see if the situation improves.	31	4.0%	9.6%
	Call someone to apply the agrochemicals (pesticides)	141	18.4%	43.5%
Total		768	100.0%	237.0%

a. Dichotomy group tabulated at value 1.
b. N – the total number of cases for handling strange pests and diseases

This study reveals that farmers often prefer informal networks over seeking support from extension officers for pest and disease management. They rely on fellow farmers, agrovet retailers, agrochemical applicators, and farm group leaders for advice. While this approach offers community support, dependence on agrochemical dealers and applicators may lead to overuse and limited, biased solutions (Sparks & Lorsbach, 2017). Effective information sharing within the farming community relies on collective knowledge and farmers' skills (Flor et al., 2020). When farmers possess the necessary pest and disease management skills, reporting to fellow farmers and farm group leaders fosters a strong support system. But because most farmers lack these skills, mobile phones emerge as a promising solution. They can accelerate information sharing, collaboration, and continuous learning by connecting farmers to expert advice for timely control measures and improved surveillance efforts. Therefore, we strongly encourage promoting mobile phone adoption among farmers to enhance information sharing between farmers and experts as well as between farmers themselves, fostering a supportive farming community.

ii. Channels for reporting pest and diseases incidences

Effective reporting channels play a crucial role in a surveillance system, enabling the collection and distribution of vital data for early detection, monitoring, and response to pest and disease threats (K. Sharma & Mathur, 2018; Zimmerman et al., 2022). Table 8 presents the channels utilized by farmers for reporting pest and disease incidences. The findings reveal that the primary means of communication include making phone calls (38.6%), sending text messages via platforms like WhatsApp (14.3%), emails (3.7%), and personal visits (43.4%). Making phone calls and personal visits are the most prevalent methods, accounting for 58.9% and 66.1% of cases, respectively.

Table 8: Channels for reporting incidences by farmers

		Responses[b]		Percent of Cases
		N	Percent	
Means of communication	Making phone calls	186	38.6%	58.9%
	Text Messaging i.e Send text messages, WhatsApp e.t.c	69	14.3%	21.8%
	Emails	18	3.7%	5.7%
	Personal visits (walk - in)	209	43.4%	66.1%
Total		482	100.0%	152.5%

a. Dichotomy group tabulated at value 1.
b. N – the total number of cases for each communication method

While farmers largely rely on phone calls and personal visits to report pest and disease outbreaks (Table 8), these methods may be time-consuming or lack real-time data capture. Mobile technology emerges as a game-changer, offering convenient and accessible channels like phone calls, text messages, and mobile apps. These solutions enable real-time reporting, improving data accuracy and facilitating faster responses. By bridging the gap between farmers and expert advice, mobile platforms also empower farmers with knowledge and foster collaboration, leading to more efficient and sustainable pest management practices. However, interviews with extension officers identified three key challenges in crop pest and disease reporting, as detailed in Table 9: late reporting (41.8%), poor scouting (16.4%), and inadequate pest/disease identification skills (41.8%).

Table 9: Challenges facing pest reporting

		Responses[b]		Percent of Cases
		N	Percent	
Pest reporting challenges[a]	Late reporting	23	41.8%	92.0%
	Poor scouting	9	16.4%	36.0%
	Poor identification skills	23	41.8%	92.0%
Total		55	100.0%	220.0%

a. Dichotomy group tabulated at value 1.
b. N- the number of cases for each reporting challenge

Source: Researcher, 2021

These challenges impede effective pest management, but the adoption of mobile technology emerges as a potent solution, significantly improving crop pest and disease reporting and empowering farmers. Late reporting, reported in 41.8% of cases, can be mitigated through real-time reporting capabilities of mobile tools; poor scouting practices, affecting 16.4% of cases, can be improved by mobile apps with geospatial features that guide systematic field coverage. Furthermore, mobile apps can integrate identification resources and tools like image recognition to address poor identification skills, a challenge faced in 41.8% of cases. Adopting mobile technology, with considerations for affordability, training, and digital literacy gaps, can revolutionize pest and disease reporting leading to faster pest and disease detection, more effective management, and potentially higher agricultural yields.

4.4 Digital Ecosystem for Adoption of E-Surveillance for Crop Pests and Diseases by Farmers in Kenya

Promoting the adoption of digital solutions for crop pests and diseases requires collaborative efforts from various stakeholders, including farmers, agricultural experts, technology providers, and government and non-governmental agencies (FAO & ITU, 2022). However, past initiatives to introduce these solutions to Kenyan farmers have encountered limited success due to unfavourable digital ecosystem (Akuku, Haaksma, & Derksen, 2019). Hence, the needs to gain a deep understanding of the local digital ecosystem and how the ecosystem variables can be optimized to improve the adoption of mobile digital solutions for pest and disease management among farmers in Kenya. These variables include ICT infrastructure, extension services, farmer-supporting technologies, agricultural research and development centres, farmer training and capacity building, and technical support, motivations and rewards as incentivization among others. Assessing factors like existing infrastructure, mobile device availability, internet access, digital literacy, social preferences, and trust in technology helps tailor solutions, avoid duplication of efforts, and ensure relevance and cultural appropriateness (Adugna & Asmare, 2022; Klerkx & Weatherspoon, 2020). By understanding the specific challenges farmers face and the data landscape within the ecosystem, we can design and develop cost-effective, scalable and sustainable digital solutions that empower farmers in the management of pests and diseases (Agyekum, Owusu-Ansah, Owusu-Darko, & Ansong, 2022), ultimately bring long-term benefits to Homa Bay County's agriculture.

4.4.1 ICT Infrastructure

The successful adoption of digital e-surveillance solutions in agriculture hinges on accessibility to a robust ICT infrastructure (A. K. Sharma, Kumar, & Chandel, 2021). This encompasses reliable internet connectivity, extensive mobile network coverage, and access to affordable devices such as smartphones and tablets (ITU, 2023). This study delves into assessing the accessibility of mobile phone devices and internet among farmers and further explores potential areas for improvement to foster the adoption of e-surveillance solutions. The findings in Table 10 reveal a robust 96.6% (315) of the sampled farmers were found to own mobile phones, indicating a slight uptick from the 90.4% reported in 2019 as the national penetration rate (CA, 2019). Notably, while 61.0% (199) owned smartphones, 35.6% (116) owned basic feature phones. Furthermore, a noteworthy 12.6% (41) of farmers with basic feature phones and 1.5% (5) with no phone at all were found to have access to a smartphone within their households, resulting in a cumulative 75.15% of the sample with access to a smartphone. This widespread access to smartphones among farmers not only facilitates the potential for the broad adoption of mobile-based surveillance solutions but also indicates promising opportunities to leverage the sensing capabilities of smartphones in future agricultural interventions.

Table 10: Mobile phone ownership and access to smartphones among farmers

			Access to a smartphone within household or own one			
		Total Farmers	Can not access		Can access	
Type of phone owned	None	11 (3.4%)	6	(1.8%)	5	(1.5%)
	Basic feature phone	116 (35.6%)	75	(23.0%)	41	(12.6%)
	Smartphone	199 (61.0%)			199	(61.0%)
		326	81	(24.8%)	245*	(75.2%)

* A total of 245 farmers in the sample have access to smartphones either within their households or individually.

Source: Researcher, 2021

Unobstructed internet access facilitates seamless data transmission, remote device management, access to cloud-based platforms, efficient data storage and analysis, and timely software updates, all of which are crucial for the effectiveness of these surveillance systems (A. K. Sharma et al., 2021). Mobile technology and mobile Internet services have rapidly advanced in Kenya, with 3G coverage reaching 95.8% of the population, 4G coverage reaching 64.3%, and the implementation of 5G underway (FAO & ITU, 2022). Consistent with the finding in Table 11, our study reveals that a majority of sampled farmers agree (Mean=4.2086, SD=0.9764) that mobile network coverage is indeed adequate, allowing them to access cellular networks. However, despite the widespread network coverage and mobile phone ownership across many African countries, the cost of internet access remains a significant barrier (World Bank, 2019a). Our findings in Table 11 indicate that most farmers agree (Mean=4.1442, SD=0.9450) that the cost of airtime and data bundles remain too high.

Table 11: Internet connectivity

Item	Number of farmers	Minimum score	Maximum score	Mean score	Standard Deviation
Network coverage in my area is adequate	326	1.00	5.00	4.2086	.9764
The cost of airtime and bundles are too high need to be subsidised.	326	1.00	5.00	4.1442	.9450

(Likert Scale: 1 = Strongly Disagree, 2 = Disagree, 3 = Neutral, 4 = Agree and 5 = Strongly Agree)
Source: Researcher, 2021

The adoption of mobile-based surveillance solutions for crop pests and diseases in Kenya faces challenges due to high costs of airtime and data bundles, hindering internet-dependent solutions. Overcoming some of the above barriers requires addressing internet access costs, device affordability, and data usage charges. Solutions include expanding rural internet infrastructure, providing subsidies for access and devices, developing data-efficient solutions, and exploring alternative data transmission methods. Reducing costs can empower farmers, ensuring effective pest management and crop protection.

4.4.2 Farmers' Access to Support

The role of farmer support services in the digital ecosystem is instrumental for the successful adoption of e-surveillance tools in Kenya, particularly for managing crop pests and diseases (Mugendi, 2020). These services act as facilitators, bridging the gap between technology developers and end-users (Marescotti, Demartini, Filippini, & Gaviglio, 2021). They provide crucial assistance, guidance, and training to farmers, ensuring a thorough understanding and effective use of e-surveillance tools. Technical support and extension services play a key role in addressing challenges farmers may encounter during the adoption process, promoting seamless integration of digital solutions into agricultural practices. This study assessed the level and adequacy of support for farmers, revealing challenges such as insufficient support, limited expert access, and unclear support channels, as highlighted in Table 12. Farmers expressed concerns about the inadequacy of current support and advice, with an average score of 3.9877, indicating a substantial disparity between farmers' needs and existing support systems. Additionally, access to agricultural experts was inconsistently assured, with a mean score of 4.2546, suggesting difficulties in reaching experts for vital guidance. The perceived lack of clarity in channels for seeking technical support, with a mean score of 4.3006, indicated uncertainty among farmers, posing a significant obstacle to accessing available resources.

Table 12: Technical Support Availability and Adequacy

Item	Number of farmers	Minimum score	Maximum score	Mean score	Standard Deviation
The current level of support and advice given to farmers in controlling crop pest and diseases is inadequate	326	1.00	5.00	3.9877	.7605
Getting access to agricultural experts for advice on pest and disease management is not always guaranteed.	326	2.00	5.00	4.2546	.6560
Channels for seeking technical support is not clear to many farmers.	326	2.00	5.00	4.3006	.6623
Average Mean				**4.1810**	**0.6929**

(Scale: 1 = Strongly Disagree, 2 = Disagree, 3 = Neutral, 4 = Agree and 5 = Strongly Agree)
Source: Researcher, 2021

The average score of 4.1810 and a standard deviation of 0.6929 across three items in Table 12 indicate a moderate consensus among farmers on the inadequacy of support in managing crop pest and disease. The standard deviation of 0.6929 suggests moderate variation in opinions, emphasizing nuanced perspectives and underscoring the need for tailored support to address individual farmer needs. The study further revealed that Homa Bay County has only 31 ward extension officers serving around 193,812 households, resulting in a ratio of 1:6,288, highlighting the necessity for scalable and targeted support strategies (HBC, 2019; KNBS, 2019). The impact of the shortage is evident in the frequency of visits by extension officers to farmers. Figure 1 indicates that 75 farmers (21.1%) have never received a visit, 126 farmers (38.6%) rarely receive visits, while only 17 farmers (5.2%) always receive visits. The lack of regular visits hinders extension officers' ability to assess crop conditions, provide timely advice, and address farmers' concerns. On a scale of 1 to 5, with 1 representing 'never' and 5 representing 'often,' the findings in Figure 1 (with a mean score of 2.21) establish that farmers are rarely visited by extension officers. These findings highlight the urgent need to address the issue of inadequate support for farmers within Homa Bay County.

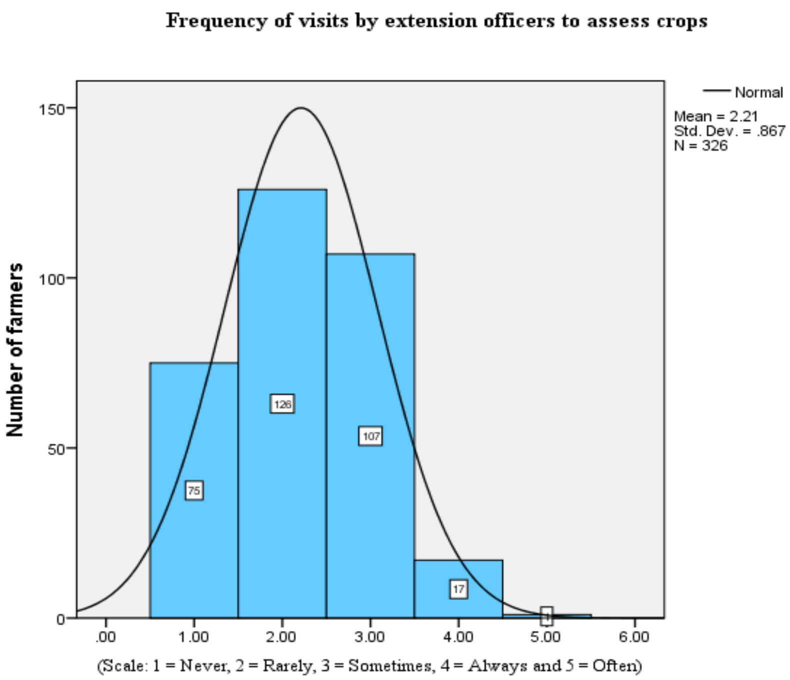

Figure 1: Farm visits by extension officers

Similar to the challenges facing extension services, technical support given to these extension officers on emerging digital solutions remains inadequate. A significant 92% (23) of interviewed extension officers expressed dissatisfaction with the level of technical support provided by digital solution vendors. The insufficient support for extension officers, combined with their limited number, hampers the adoption and use of digital solutions by both farmers and extension officers. Mobile-based surveillance solutions offer a practical remedy to these challenges by providing real-time information, connecting farmers with experts through digital platforms, and simplifying channels for accessing technical support. Moreover, mobile platforms can foster knowledge sharing and collaboration among farmers, experts, and extension agents. Therefore, adopting mobile surveillance solutions can empower farmers to overcome support challenges, ensuring agricultural productivity, food security, and sustainability.

4.4.3 Motivations and Strategies for Farmer Participation in Pest and Disease Surveillance

Participation in an event is driven by self-interest or common good, rooted in rewards, recognition, role responsibility, accountability, lifelong learning opportunities, interpersonal engagement, corporate vision, and social purpose (Waseem, Biggemann, & Garry, 2021). Engaging farmers in the fight against crop pests and diseases requires understanding what drives their participation. This study delves into the motivations behind farmer engagement in pest and disease surveillance, revealing a compelling combination of self-interest and a strong sense of community responsibility. Key observations from Table 13 reveal distinct motivations influencing farmers' participation in pest and disease surveillance. Foremost is the prominence of financial incentives, as evidenced by the highest average score of 4.0706, indicating a strong preference for direct monetary compensation. Following closely is the farmers' commitment to community well-being, reflected in a score of 4.2301, showcasing their collective concern for a pest-free environment. Additionally, the sense of social responsibility is evident with a score of 4.1871, highlighting farmers' commitment to reporting pests as a duty to their community. Furthermore, the high score of 4.4908 underscores the importance farmers place on guaranteed access to reliable information about reported cases, emphasizing the value of knowledge sharing. Notably, the desire to create awareness for preventive measures among fellow farmers receives an even higher score of 4.4049, indicating a strong inclination towards collaborative efforts to mitigate outbreaks.

Table 13: Descriptive Statistics motivation for participation in pest and disease surveillance

Items	Number of farmers	Minimum Score	Maximum Score	Mean Score	Standard Deviation
Compensation in monetary value – i.e Cash payment, or credits /discounts on agricultural products	326	1.00	5.00	4.0706	.7047
Willingness to support the effort for crop pest and disease-free community.	326	2.00	5.00	4.2301	.6557
Reporting of all pests and diseases infection in my farm is my social responsibility in the society.	326	2.00	5.00	4.1871	.7095
Creation of awareness to other farmers to take preventive measures in case of outbreaks.	326	2.00	5.00	4.4049	.6090
Guaranteed access to reliable pest and disease control information for the reported cases	326	2.00	5.00	4.4908	.5751
AVERAGE MEAN				**4.2767**	**.6508**

(Likert Scale: 1 = Strongly Disagree, 2 = Disagree, 3 = Neutral, 4 = Agree and 5 = Strongly Agree)
Source: Researcher, 2021

In response to these findings, several strategies can be employed to encourage farmers to embrace mobile-based surveillance solutions. These include integrating micro-payment schemes or reward systems linked to data reporting and proactive pest management for financial incentives. Framing mobile solutions as tools for collective benefit can enhance community focus, emphasizing their contribution to a healthier agricultural ecosystem. Implementing gamification elements or public recognition programs can foster social recognition for active participants. Ensuring that apps provide timely, localized pest and disease information, along with best practices and management strategies, contributes to knowledge empowerment. Facilitating communication channels within the app for farmers to share experiences, tips, and success stories supports peer-to-peer learning. Additionally, addressing affordability and accessibility concerns through user-friendly interfaces, offline functionality, and exploring low-cost data options helps overcome digital barriers. Understanding farmers' diverse motivations and tailoring strategies to address their specific needs can lead to wider adoption of mobile-based surveillance solutions, empowering Kenyan farmers to actively participate in safeguarding their crops and communities from pest and disease threats.

4.5 Framework for Large-Scale Adoption of E-Surveillance for Pest and Disease Management among Farmers

This study revealed that crop pests and diseases have a significant and continuous impact on farming, affecting agricultural productivity and profitability (see Table 3). While farmers attempt to scout their farms for crop pests and diseases, they face challenges with pest identification and disease diagnosis (see Table 4 and Table 5). It was established that farmers are ill-prepared in making control decisions (see Table 6), with the majority of them lacking clear reporting structures, reporting incidences to various points (see Table 7). Delays in getting feedback on reported cases are a noticeable hindrance to effective pest and disease management. While some farmers attempt to report pest incidences using phones (see Table 8) and seek support from extension officers, many are not prompt in their reporting (see Table 9). Furthermore, getting alerts and warnings on impending infestations remains a challenge as farmers heavily rely on their neighbors or personal observations. To address the pest and disease challenges faced by farmers, the study recommends the adoption of electronic surveillance (e-surveillance), specifically mobile-based surveillance and control solutions. However, the successful adoption of e-surveillance requires the presence of proper ICT infrastructure, access to technical support, training and capacity building, improved digital literacy, and assurances of data privacy and security as key motivators (Eitzinger et al., 2019; ISPM, 2018; Jin, Su, Xiao, & Nahrstedt, 2016; Mugendi, 2020; Pivoto et al., 2019).

The study identified several opportunities for farmers to embrace e-surveillance solutions. These include the demographic landscape, increasing ownership of mobile devices, and the expansion of network coverage in the region. There is a shift in farming demographics towards a more balanced representation of young and educated farmers of both genders (see Table 1 and Table 2), which could positively influence the adoption of e-surveillance. Younger, tech-savvy farmers can support older farmers in effectively embracing digital tools, fostering collaboration and peer-to-peer learning among them. Additionally, most farmers have attained higher levels of education, making them more likely to adopt e-surveillance due to improved digital literacy. While the adoption of mobile-based e-surveillance solutions may bring numerous benefits to farmers, including improved crop management, early pest detection, and enhanced resource utilization, farmers may be hesitant to adopt such technology due to factors such as cost, lack of awareness, or perceived complexity (Dhraief et al., 2018; Ibrišević, 2020; Nkhata et al., 2020).

However, the findings from Table 13 indicate that farmers are motivated to participate in pest and disease surveillance for different purposes. Key motivating factors identified include receiving compensation in the form of cash, credits, or discounts on agricultural products and the willingness to support efforts for a pest and disease-free community. Additionally, farmers feel socially responsible for reporting all pests and diseases on their farms and are motivated to raise awareness among other farmers about preventive measures during outbreaks. Moreover, the assurance of reliable pest and disease control information for reported cases is a strong motivator. Authors have recommended various incentive mechanisms to enhance the adoption of Mobile Crowdsensing applications (Bopp, Engler, Poortvliet, & Jara-Rojas, 2019; Restuccia, Ghosh, Bhattacharjee, Das, & Melodia, 2017). In the context of technology-driven agriculture, particularly e-surveillance, both intrinsic and extrinsic motivations can accelerate farmers' adoption (Zhou, Zhang, & Zhong, 2017). For long-term sensing tasks and crowd-sensing initiatives, hybrid incentives have been suggested as ideal extrinsic motivations (Anawar & Yahya, 2013; Ogie, 2016; Wei, Wu, & Long, 2020; Zhan, Xia, & Zhang, 2017; X. Zhang et al., 2016). To encourage farmers' active involvement in e-surveillance activities, offering various forms of extrinsic incentives, such as subsidies, grants, training programs, crop insurance benefits, among others, is crucial. Collaboration among stakeholders, including farmers, digital solution providers, infrastructure providers, agricultural experts, Agricultural research and development, financial service providers, and government agencies, can help realize these incentives as well as the overall goal of e-surveillance.

The study proposes a Participatory Farmer-Centric e-Surveillance Framework for Pest and Disease (Figure 2) as a roadmap to implement and improve the adoption of e-surveillance solutions by farmers.

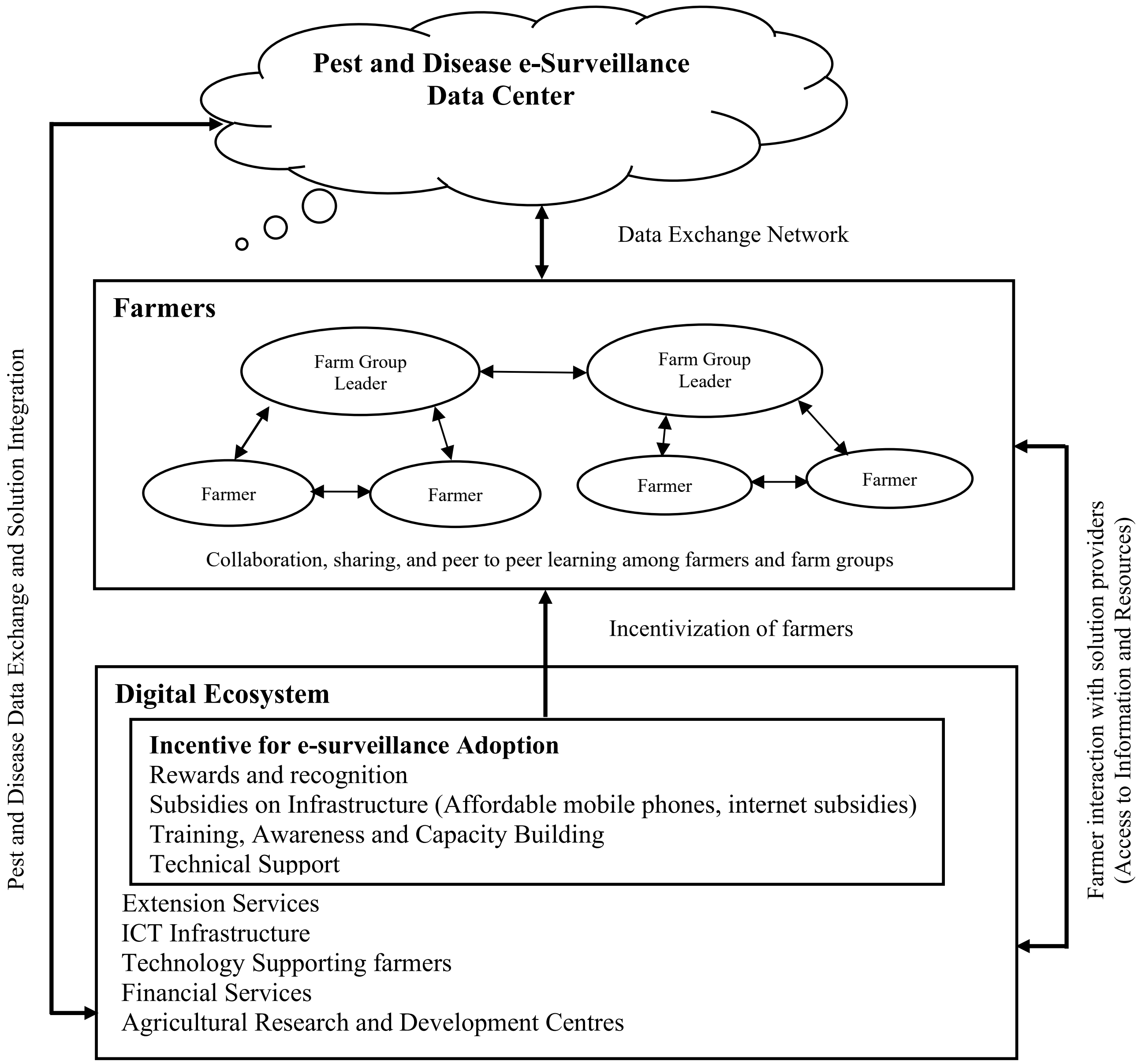

Figure 2: A participatory Farmer Centric e-Surveillance Framework for Pest and Disease

The major components of the framework include Pest and Disease e-Surveillance Data Center Farmers, Farmers, Digital Ecosystem and Incentivization Mechanism. Pest and Disease e-Surveillance Data Center is a centralized platform or facility where farmers can send pest and disease information/data and retrieve solutions. It serves as a hub for collecting, analyzing, and disseminating information about pest and disease outbreaks, providing real-time alerts and recommendations to farmers. It could integrate various sources of data, such as farmer reports, satellite imagery, weather data, and pest population data, to provide comprehensive insights and solutions. Stakeholders, like farmers and researchers, can submit data, access it for analysis, and integrate it with other digital tools and platforms. This real-time monitoring allows for timely alerts and decision support, helping stakeholders combat pests and diseases effectively. The Data Center's role in data management and integration enhances the ecosystem's ability to provide valuable insights and recommendations for better pest and disease management strategies. It allows stakeholders to access important data, make informed decisions, and work together effectively to combat pests and diseases in agriculture.

On the other hand, farmers are central to the e-surveillance framework as they contribute firsthand information on data related to pest and disease outbreaks, ensuring comprehensive data collection. The information collected by farmers is uploaded to the cloud-based E-surveillance Data Center via Data Exchange Network (DEN). Similarly, through DEN, farmers can access cloud-based solutions and insights derived from the aggregated data, enabling them to make informed decisions and benefit from the collective information shared on the platform. In the proposed framework, farmers and farm groups collaborate, share knowledge, and engage in peer-to-peer learning to combat crop pests and diseases through e-surveillance initiatives. Collaboration between farmers and farm groups enables the exchange of valuable information and experiences, allowing farmers to benefit from each other's expertise and practical knowledge. This supportive environment fosters continuous improvement and widespread adoption of e-surveillance technologies in agriculture.

The success in E-surveillance adoption is driven by the digital ecosystem. The digital technologies encompass ICT Infrastructure and Technology Supporting farmers, including data collection sensors, mobile apps, secure digital storage, data analysis algorithms, communication systems, and automated pest and disease monitoring systems. Major stakeholders involved are farmer support systems like extension services, infrastructure providers, financial service providers, and Agricultural Research and Development. The Farmer Support System offers capacity-building initiatives, such as training programs, workshops, awareness campaigns, and technical assistance, to equip farmers with the necessary knowledge and skills for effective e-surveillance adoption. The digital ecosystem enables real-time monitoring and decision-making, promotes collaboration and knowledge exchange, and ensures scalability and accessibility of surveillance solutions. Decision support systems within the digital ecosystem provide real-time information and recommendations, fostering collaboration among farmers, researchers, and government agencies. Agricultural Research and Development Centers, also known as Agricultural R&D Centers, are specialized institutions focused on agricultural research, development, and innovation. These centers conduct research, experiments, and technology development in various agricultural areas, facilitate knowledge and innovation transfer to farmers and stakeholders, collaborate with other institutions, provide policy advice, and contribute to capacity building.

Incentivization is identified as a key component of the proposed farmer-centric surveillance E-surveillance framework, and this study proposes various incentives to overcome barriers to the adoption of e-surveillance in agriculture. The identified barriers include technological infrastructure challenges, digital literacy, time and effort constraints, training and capacity building needs, technical support requirements, and information access limitations. To address infrastructural barriers, we suggest providing subsidies or grants for acquiring essential technology infrastructure, such as smartphones or internet connectivity. For improving digital literacy, the recommendation is to prioritize training and capacity-building programs, accompanied by tailored and inclusive technology design to empower farmers in effectively embracing e-surveillance. Recognizing and rewarding active farmer participation in e-surveillance activities is proposed to overcome time and effort constraints. Training and capacity-building initiatives, including workshops and webinars, are proposed to enhance farmers' confidence and skills in utilizing e-surveillance tools. Ensuring easy access to technical support through helplines or digital platforms is suggested to alleviate issues related to technological infrastructure and technical difficulties. Lastly, providing early access to information about potential pest outbreaks, weather patterns, and marketing information is recommended to keep farmers informed and enable proactive decision-making. These incentives collectively aim to facilitate the widespread adoption of e-surveillance in agriculture.

The proposed farmer-centric surveillance framework serves as a comprehensive pest and disease monitoring and data collection system that prioritizes the needs of farmers. It utilizes tailored technologies, including mobile digital tools and sensors, to empower farmers in effectively managing their crops within the surveillance framework. This comprehensive system ensures delivery of real-time information on crop conditions, weather, and pest and disease outbreaks, via user-friendly interfaces accessible to farmers with varying technological literacy. By providing actionable data, it empowers decision-making in crop health management, resulting in increased efficiency, improved yields, and reduced resource inputs. Emphasizing community collaboration, the framework fosters information sharing, creating a network effect within the farming community. Customized support addresses individual needs, overcoming technology adoption barriers and ensuring inclusivity across diverse farming backgrounds. Ultimately, the farmer-centric surveillance framework seeks to enhance the overall well-being and productivity of farmers by equipping them with valuable information and tools for informed decision-making in agricultural practices. This approach aligns technology with the practical needs of farmers, fostering a sustainable, efficient, and resilient farming ecosystem that contributes to the overall development of the agricultural sector.

5 Conclusion and Recommendation

The escalating threat of crop losses in Kenya due to pests and diseases demands a transformative approach to agricultural management. This study proposes the Participatory Farmer-Centric e-Surveillance Framework, envisioning a future where farmers actively safeguard their crops with mobile-powered surveillance. The framework recognizes the crucial role of farmers as data contributors, placing them at the heart of the information gathering process. This farmer-centric approach is enabled by the establishment of a central Pest and Disease e-Surveillance Data Center, acting as a hub for real-time data exchange and analysis. Through this hub, farmers receive timely alerts, personalized recommendations, and actionable insights, empowering them to make informed decisions regarding pest and disease control.

However, the success of this framework hinges not only on technology but also on a robust digital ecosystem. This ecosystem necessitates investments in ICT infrastructure, fostering seamless connectivity across rural areas. Collaboration among diverse stakeholders, including extension services, agricultural researchers, and digital solution providers, is also crucial. By working together, these actors can provide essential support and knowledge transfer to farmers, addressing concerns about technological complexity and fostering widespread adoption. Effective incentivization strategies are another key pillar of the framework. Recognizing the diverse motivations of farmers, such as subsidies, training programs, and rewards, must be considered to encourage active participation. Furthermore, the framework promotes collaboration and knowledge exchange among farmers, creating a supportive environment for peer-to-peer learning and fostering a sense of community ownership.

As the framework evolves and adapts to farmers' needs and technological advancements, it holds the potential to transform the agricultural landscape in Kenya. By empowering farmers with real-time information and decision-making tools, we can pave the way for increased productivity, improved food security, and a more resilient and sustainable agricultural future. However, future research is necessary to explore the effectiveness of different incentive models and their influence on farmer participation and data quality.

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