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SPECIAL ISSUE: CELEBRATING 20 YEARS OF GEOGRAPHY IN KADUNA STATE UNIVERSITY - ADVANCES AND FRONTIERS IN GEOGRAPHY

Role of Technology and Digital Tools in Crop Protection under Climate Stress

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ABSTRACT

Climate change intensifies threats to global food security by increasing plant pest and disease prevalence, exacerbating yield losses annually. Traditional crop protection methods, which rely on reactive measures and broad-spectrum pesticides, struggle to address these evolving challenges amid rising temperatures, erratic rainfall, and extreme weather events, but with low results. This paper examines the transformative role of digital technologies in enhancing climate-resilient agriculture. Remote sensing, artificial intelligence (AI), and the Internet of Things (IoT) enable early pest detection, predictive analytics, and real-time monitoring, facilitating targeted interventions that reduce chemical use and optimize resource efficiency. Precision agriculture tools, such as variable rate technology, improve input application and strengthen crop resilience. However, adoption barriers persist, including unequal access to technology, high costs, and data privacy concerns. Overcoming these challenges requires collaborative efforts among governments, institutions, and farmers. This approach prioritizes digital infrastructure, capacity building, and equitable policy frameworks. Integrating technological innovation with ecological principles offers a pathway to sustainable agricultural systems capable of safeguarding food security in a climate-stressed scenario.

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1 Introduction

Managing crop pests and diseases under climate change with respect to food security in an unstable economy remains a critical global concern, especially under the dual pressures of economic instability and climate change. Agriculture, as a sector that is directly reliant on predictable environmental conditions, is at the forefront of this challenge. Climate change significantly alters ecosystems and exacerbates the incidence and spread of plant pests and diseases, posing a substantial threat to global food security (Lu et al., 2020). Escalating food demands, desiccating water resources, rising average temperatures, increasingly erratic precipitation patterns characterized by both intensified droughts and floods, a heightened frequency of extreme weather events such as heatwaves and storms and the consequential shifts in the distribution and virulence of agricultural pests and diseases are collectively diminishing crop yields and jeopardizing the livelihoods of farming communities worldwide (FAO, 2021; IPPC, 2021).

With global warming, yield losses in major staple crops, such as wheat, rice, and maize, are projected to further increase. In this era, defined by heightened environmental uncertainty and volatility, traditional crop protection strategies, which often rely on reactive measures and broad-spectrum interventions, are increasingly inadequate for addressing the scale and complexity of these emerging threats. These changes necessitate innovative approaches to crop protection that can mitigate the adverse effects of climate stress. Fortunately, a powerful and rapidly developing array of technological advancements and sophisticated digital tools is emerging in support of the response of agriculture to climate stress. These innovations offer the potential to revolutionize crop protection, providing farmers and agricultural stakeholders with novel and effective solutions to mitigate the adverse effects of a changing climate on agricultural productivity and sustainability (FAO, 2021). This paper examines the vital and increasingly indispensable role of technology and digital tools in safeguarding plant health and ensuring crop protection under challenging conditions. This will ultimately lead to a sustainable agricultural system capable of ensuring food security in a climate-challenged world.

1.1 Impact of Climate Stress on Crop Health

The intensification of climate stress manifests through interconnected environmental changes, each exerting distinct and often synergistic negative effects on crop health and overall productivity. Changes in key climatic factors like temperature and rainfall can significantly disrupt the delicate phenological cycles of plants, increasing the vulnerability of crops to synchronized attacks by pests and diseases during critical and sensitive growth stages (Richards et al., 2024).

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For example, earlier springs triggered by rising temperatures might lead to a mismatch between the emergence of insect pests and the developmental stage of their host crops, potentially exacerbating infestation levels. Similarly, altered rainfall patterns, characterized by prolonged dry spells punctuated by intense downpours, can induce physiological stress in plants, weakening their natural defence mechanisms and increasing their susceptibility to opportunistic pathogens.

The increasing frequency and intensity of extreme weather events, such as prolonged droughts, devastating floods, and heatwaves, pose direct and often catastrophic threats to crop health and survival. Drought conditions induce severe water stress, leading to wilting, stunted growth, reduced photosynthetic capacity, and ultimately significant yield losses. Moreover, water-stressed plants often exhibit increased susceptibility to pest infestations and disease outbreaks. Conversely, prolonged periods of excessive rainfall and flooding can lead to waterlogged soils, root hypoxia, and the proliferation of waterborne pathogens. Physical damage to crops caused by strong winds and other extreme weather events can create entry points for opportunistic fungal and bacterial pathogens, further compounding direct yield losses (FAO, 2021). The cumulative effect of these direct and indirect impacts of extreme weather is significant erosion of crop resilience and increased vulnerability to biotic stresses (Mohammed et al., 2023).

Figure 1 shows declining precipitation across a time span of 30 years in the Numan wetland in Adamawa State. The declining standardized precipitation index (SPI) indicates increasing drought conditions in the region. Figure 2 shows the temperature condition index of the region for the 30 years, indicating areas with stronger drought conditions due to an increase in temperature. The TCI examines plant stress due to temperature. Floods can destroy certain crops that cannot withstand direct moisture for a long time. Fig. 3 shows flood occurrences and spatial impacts over the region. Nearly half of the wetland was denuded in 2020 and 2022 (Mohammed et al., 2023).

Compounding these challenges is the significant alteration in the geographical distribution and life cycles of agricultural pests and diseases in response to changing climatic conditions. Warmer temperatures can expand the habitable range of many insect pests and disease vectors towards higher latitudes and altitudes, introducing new threats to previously unaffected regions (FAO, 2021). Furthermore, warmer winters can lead to increased overwintering survival rates for many pests, resulting in larger initial populations in the spring and potentially earlier and more severe infestations. Changes in temperature and humidity can also accelerate the life cycles of many pests and pathogens, leading to more generations per growing season and a more rapid development of resistance to conventional control measures. The emergence of novel pest and disease strains, which are potentially better adapted to altered climatic conditions, further exacerbates the complexity of crop protection under climate stress.

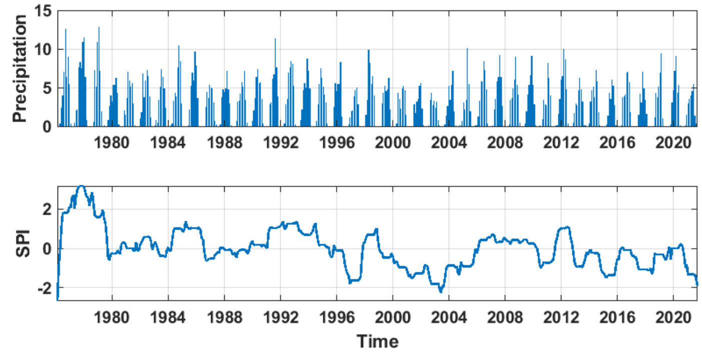

Figure 1: Area-averaged precipitation and standardized precipitation index (SPI) of the Numan wetland
Source: Mohammed et al., 2023

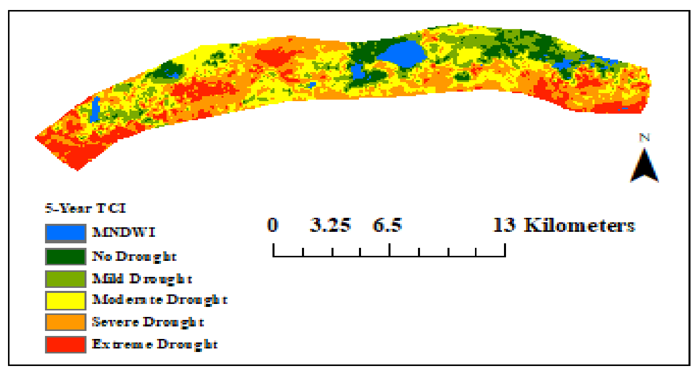

Figure 2: Temperature condition index (VCI) for the study period (2014--2022) with a one-year interval)
Source: Mohammed et al., 2023

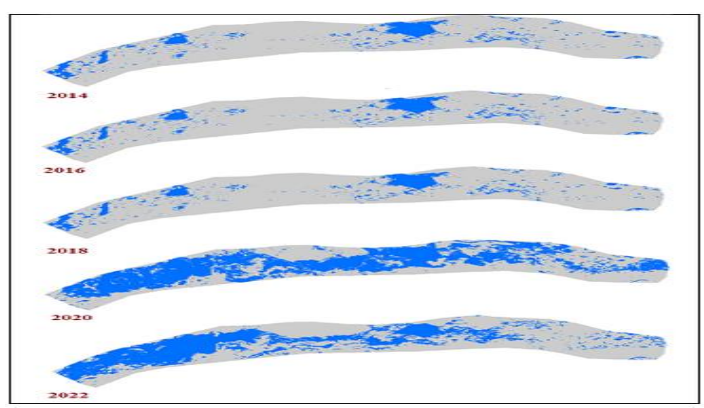

Figure 3: Flood occurrences in the Numan wetland between 2014 and 2022
Source: Mohammed et al., 2023

1.2 Limitations of Conventional Crop Protection

In the face of these rapidly evolving and intensifying threats, the inherent limitations of conventional crop protection methods have become increasingly apparent. The traditional reliance on broad-spectrum synthetic pesticides, while often providing rapid control of pest outbreaks, has significant environmental consequences.

These chemicals can disrupt delicate ecological balances by negatively impacting beneficial insect populations, including pollinators and natural enemies of pests, leading to secondary pest outbreaks and a decline in biodiversity (Kalogiannidis, 2022). Furthermore, the widespread use of synthetic pesticides can contaminate water sources and pose risks to human health through dietary exposure and occupational hazards. A particularly concerning consequence of the sustained application of broad-spectrum pesticides is the selection pressure they exert on pest populations, leading to the development of pesticide resistance, rendering these once-effective control measures increasingly futile.

Traditional pest and disease monitoring techniques, often based on manual scouting of fields and the analysis of historical data, may be too slow, labor-intensive, and localized to address the rapidly evolving and geographically shifting threats posed by climate change effectively. Manual scouting can be time-consuming and may not provide a comprehensive overview of pest or disease pressure across large agricultural landscapes. Moreover, reliance on historical data may fail to capture the novel patterns and distributions of pests and diseases emerging under altered climatic conditions (Kalogiannidis, 2022). The lag time between detection and the implementation of control measures via traditional methods can often result in significant yield losses before effective action can be taken.

Similarly, reactive approaches to managing weather-related stresses, such as providing post-disaster relief efforts after droughts, floods, or other extreme events, are often insufficient to prevent significant and long-lasting yield losses and economic hardship for farmers. While important for immediate humanitarian aid, these reactive measures do not address the underlying vulnerabilities of agricultural systems to climate extremes (Shamshiri, 2023). A proactive and predictive approach is needed to increase resilience and mitigate the impacts of these events before they occur.

Therefore, a fundamental paradigm shift in crop protection strategies is urgently needed. A transition towards proactive, data-driven, and technologically enabled approaches is essential to ensure the long-term sustainability of agricultural production and guarantee food security in an increasingly climate-challenged world. This necessitates embracing the transformative potential of digital tools and technologies to increase our ability to anticipate, monitor, and respond to the complex and interconnected threats facing crop production.

1.3 Transformative potential of digital technologies

Digital tools and technologies offer a comprehensive suite of capabilities that can significantly enhance crop protection efforts under the increasing pressures of climate stress. These innovative tools leverage recent and rapid advancements in diverse fields, including remote sensing, sophisticated data analytics, the power of artificial intelligence (AI), the interconnectedness of the Internet of Things (IoT), and the precision and efficiency of precision agriculture techniques (Lottes et al., 2017). By harnessing the power of these technologies, farmers, agricultural researchers, and policymakers can gain access to timely and actionable information, derive valuable predictive insights into potential threats, and implement highly targeted and effective interventions.

The fundamental advantage offered by these technologies lies in their ability to enable more precise and efficient management practices across all stages of crop production. This enhanced precision not only optimizes the allocation and utilization of critical resources such as water, fertilizers, and pesticides, thereby minimizing waste and reducing the environmental footprint of agriculture, but also directly contributes to enhancing the overall health, vigour, and resilience of cropping systems to a wide range of climate-related challenges (Lu et al., 2020). By empowering more informed and timely decision-making, these technologies are instrumental in building more sustainable and climate-resilient agricultural systems capable of ensuring food security for a growing global population.

1.4 Remote Sensing and Geospatial Technologies

One of the most transformative applications of technology in the realm of crop protection lies in the sophisticated capabilities offered by remote sensing and geospatial technologies. Platforms such as Earth-orbiting satellites, unmanned aerial vehicles (UAVs) or drones, and even fixed-wing aircraft equipped with advanced multispectral and hyperspectral sensors can capture highly detailed information about important aspects of crop health, patterns of growth and development, and prevailing environmental conditions over vast spatial scales (Lottes et al., 2017). The data captured by these sensors extends beyond what is visible to the human eye, encompassing information across different wavelengths of the electromagnetic spectrum that can reveal subtle indicators of plant stress (Thomas et al., 2014). For example, Abubakar et al. (2025) effectively utilized remote sensing and GIS tools to analyse the environmental and spatial factors influencing disease distribution to reveal patterns and enable risk assessment models that are difficult to achieve.

The rich datasets generated through remote sensing can be meticulously analysed to identify early and often subtle signs of various forms of stress, including nutrient deficiencies, the onset of water stress due to drought or inadequate irrigation, and the initial stages of pest and disease infestations, often long before these symptoms become visually apparent during traditional field scouting. By providing a synoptic and spatially comprehensive view of field conditions, remote sensing technologies enable timely and highly targeted interventions, significantly reducing the need for indiscriminate and environmentally damaging blanket applications of pesticides or fertilizers across entire fields.

Furthermore, geospatial technologies, particularly geographic information systems (GISs), are important for integrating and analysing data from a multitude of diverse sources. This includes data derived from remote sensing platforms, ground-based weather stations providing localized climate information, detailed soil maps outlining soil properties and nutrient availability, and historical yield data providing insights into past performance and potential vulnerabilities. By overlaying and analysing these disparate datasets, a GIS can generate comprehensive risk maps and sophisticated decision support systems specifically tailored for crop protection. For example, areas within a larger agricultural landscape that exhibit a greater likelihood of pest outbreaks on the basis of a confluence of favourable environmental conditions and historical infestation patterns can be precisely identified and mapped (Lu et al., 2020). This allows for the implementation of proactive monitoring efforts and the deployment of preventative measures, such as the targeted application of biopesticides or the implementation of specific cultural practices, in these high-risk zones, thereby minimizing the overall risk of widespread damage and reducing the reliance on reactive interventions.

Satellite technology can be used to map soil moisture at different depths. The annual surface and profile (10 m) soil variability results (Fig. 4) were mapped to complement the spatial data examined via Landsat. The data show annual variability across the years (Fig. 4d, e). The surface soil moisture is lower in magnitude than the profile soil moisture. Mean annual maximum and minimum anomalies showing the influence of rainfall on surface and subsurface soils moisture conditions. Analysis of soil moisture at a depth of 10 m indicates moisture availability for vegetation and crop growth within the lake environment (Mubi et al., 2022). The available information revealed a link between surface and subsurface soil moisture. Years with high antecedent surface moisture availability also have high amounts at the subsurface. The soil moisture content, both on and in the subsurface, is influenced by many factors, such as soil materials, vegetation cover, and the basin morphology of the land, rather than solely by the amount of rainfall falling over an area. This likely explains the high moisture availability within the lake environment.

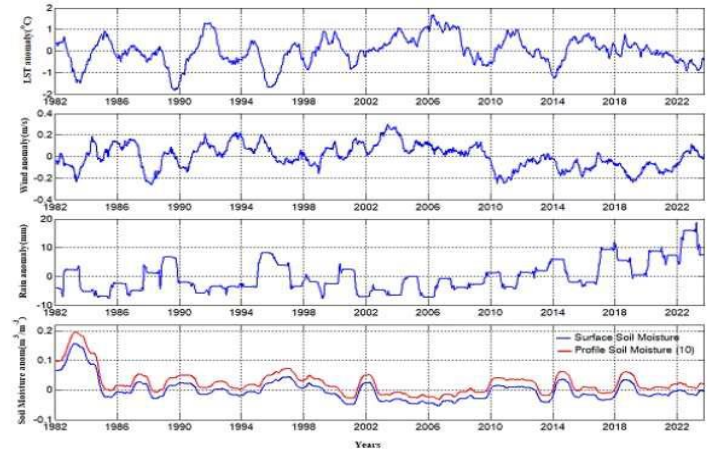

Figure 4: Anomalies of the annual moving average of Lake Chad physical feature anomalies: a) LST, b) Wind, c) Rainfall, d) Surface soil moisture, and e) Profile soil moisture (10 m) Mubi, et al. (2022).

1.5 Crop Residue Mapping

Crop residue is important for maintaining healthy soils and supporting crop production. It contributes to soil moisture retention, reduces soil erosion, facilitates soil nutrient cycling, and enhances soil carbon sequestration. Therefore, monitoring crop residue cover (CRC) is essential for understanding the distribution and quantity of crop residues in a field and for developing appropriate management strategies (Thomas *et al*., 2014). Remote sensing is a valuable geospatial technique that allows for the repeated collection of images over large areas, which greatly aids in CRC mapping (Hively *et al*., 2019). The normalized difference tillage index (NDTI) and shortwave infrared normalized difference residue index (SINDRI) are the major indices employed by remote sensing to map crop residues at spatial scales.

1.6 Data analytics and artificial intelligence

The vast quantities of data generated by remote sensing platforms, networks of weather stations, an array of in-field sensors, and various other digital sources represent a wealth of potential knowledge. However, extracting meaningful and actionable insights from these complex datasets requires the application of sophisticated data analytics techniques and artificial intelligence (AI). AI algorithms, encompassing a range of methodologies, including machine learning and deep learning, are particularly well-suited for identifying intricate patterns, discerning subtle correlations, and developing robust predictive models for complex agricultural phenomena (Richards, 2024).

In the context of crop protection, AI algorithms can be trained using historical data on pest and disease outbreaks, coupled with corresponding environmental variables (temperature, humidity, rainfall), detailed crop characteristics (variety, growth stage, health status), and even historical management practices. Once trained, these predictive models can provide farmers and agricultural advisors with early and accurate warnings regarding the potential occurrence and likely severity of future pest and disease outbreaks. This lead time allows for the proactive implementation of timely and targeted control measures, significantly reducing the potential for substantial yield losses that might occur if interventions are delayed until symptoms become visually apparent.

Robotic technology offers a novel approach to pest control. Robots can be designed and programmed to identify and eliminate pests in a highly targeted manner, which reduces reliance on broad-spectrum pesticides. This targeted approach increases the efficiency of pest control and significantly minimizes environmental and health risks (Sutton *et al*., 2020). Robotic pest control systems often employ advanced technologies such as machine learning, artificial intelligence (AI), and computer vision to detect and identify pests. Equipped with high-resolution cameras and sensors, these robots can traverse agricultural fields, identify pests in real time, and take appropriate action (Lottes *et al*., 2017).

Furthermore, AI can be effectively employed to optimize a wide range of pest management strategies. For example, AI algorithms can analyse data on pest population dynamics, weather forecasts, and crop growth models to determine the optimal timing and precise dosage of pesticide applications, ensuring maximum efficacy while simultaneously minimizing environmental impact and reducing input costs for farmers. The integration of AI with image recognition algorithms deployed on drones or ground-based robotic platforms enables the automated detection and precise identification of specific pests and diseases directly in the field. This capability facilitates highly targeted interventions, such as the localized spraying of only the affected plants, further reducing the overall use of pesticides and promoting more sustainable pest management practices.

1.7 Internet of Things (IoT)

The Internet of Things (IoT) represents another pivotal technological enabling for significantly enhancing crop protection strategies. An IoT ecosystem in agriculture comprises a network of interconnected sensors, actuators, and various other intelligent devices strategically deployed throughout agricultural fields and within controlled environment agriculture systems. These devices are capable of autonomously collecting real-time data on a diverse range of critical environmental and plant health parameters, including the soil moisture content at various depths, ambient and canopy temperatures, relative humidity levels, essential soil nutrient concentrations, and even the activity and population densities of specific pest species (Lottes et al., 2017).

This granular and highly localized information provides farmers with an unprecedentedly detailed and dynamic understanding of the microclimate and specific conditions prevailing within their fields. This level of insight empowers farmers to make more precise and timely management decisions tailored to the specific needs of different areas within their farms. For example, soil moisture sensors integrated with automated irrigation systems can trigger irrigation events only when and where they are needed, optimizing water resource utilization and significantly reducing the risk of water stress, which can weaken plants and increase their vulnerability to pest and disease attacks. Similarly, insect traps equipped with sophisticated sensors can provide real-time data on pest populations, enabling farmers to implement targeted control measures, such as the localized application of biopesticides or the release of beneficial insects, before pest infestations reach economically damaging levels (Lehmann *et al*., 2020).

1.8 Precision agriculture

Precision agriculture technologies leverage the power of data and digital tools to optimize the application of essential resource inputs and refine management practices at a highly granular, subfield level. A key component of precision agriculture is variable rate technology (VRT), which is guided by precise GPS positioning systems and real-time data collected from in-field sensors and remote sensing platforms. VRT enables the site-specific application of critical inputs such as fertilizers, pesticides, and irrigation water, precisely matching the unique needs of different zones within a single field (Balasundram et al., 2023).

This targeted approach to resource management not only significantly improves overall resource use efficiency, minimizes waste, and reduces the environmental impact of agricultural operations but also directly enhances the health, vigour, and inherent resilience of crops (Lehmann et al., 2020). For example, applying the optimal amount of nitrogen fertilizer on the basis of site-specific soil nutrient levels can promote balanced and healthy plant growth, making crops less susceptible to certain diseases and pest infestations that often target stressed or nutrient-deficient plants. Similarly, variable-rate irrigation systems can precisely deliver water to areas of a field experiencing drought stress, maintaining optimal plant hydration and reducing vulnerability to pest infestations that can thrive in water-stressed conditions. By tailoring inputs and management practices to the specific needs of different areas within a field, precision agriculture contributes to a more uniform and resilient crop stand that is better equipped to withstand the challenges posed by climate stress.

1.9 Mobile applications and cloud tools

In addition to these core technologies, a range of other digital tools are playing an increasingly significant role in supporting and enhancing crop protection efforts under the increasing pressures of climate stress. User-friendly mobile applications and sophisticated cloud-based platforms provide farmers with convenient and readily accessible access to a wealth of critical information, including up-to-date weather forecasts, timely pest and disease alerts based on regional monitoring networks, comprehensive databases of best management practices tailored to specific crops and regions, and even valuable market information to inform their decision-making processes (Lost-Filho *et al*., 2022). These digital tools empower farmers to make more informed and proactive decisions regarding crop protection and implement timely interventions on the basis of the most current and relevant information.

Furthermore, the emergence of digital extension services, leveraging the ubiquity of online platforms and various communication technologies, is transforming the way agricultural knowledge and expertise are disseminated to farmers, particularly in remote or underserved regions where access to traditional in-person extension services may be limited. Through online portals, video conferencing, and mobile messaging applications, farmers can gain remote access to expert advice and tailored support for a wide range of crop protection strategies, which are specifically adapted to their unique local conditions and circumstances. This virtual access to expert knowledge can be particularly important in addressing novel pest and disease threats emerging under changing climatic conditions, for which local experience may be lacking.

1.10 Blockchain Technology

While not directly involved in real-time crop monitoring or intervention, blockchain technology holds significant promise for indirectly contributing to enhanced crop protection under climate stress by fostering greater transparency and traceability throughout the agricultural supply chain. Blockchain, a distributed and immutable ledger system, can provide a secure and verifiable record of all inputs used in crop production, including seeds, fertilizers, and pesticides, as well as the specific management practices employed and the origin of the final product (Lu *et al*., 2020). This level of transparency can help ensure the quality and authenticity of agricultural inputs, reducing the risk of farmers using substandard or counterfeit products that could compromise crop health and increase vulnerability to pests and diseases.

Furthermore, blockchain technology can facilitate the rapid and accurate tracking of pest and disease outbreaks across geographical regions. By providing a secure and auditable record of plant health information at various points in the supply chain, blockchain can enable faster and more effective responses to emerging threats, allowing for quicker identification of the source of an outbreak and the implementation of targeted containment measures to prevent widespread dissemination (Lu *et al*., 2020). This enhanced traceability can contribute to more efficient and coordinated efforts to manage and mitigate the impacts of pest and disease outbreaks, particularly those exacerbated by changing climatic conditions.

1.11 Case Studies of Digital Technologies in Crop Protection

For clarity and simplified illustrations, detailed case studies and examples of successful implementations of digital technologies in crop protection are summarized in Table 1.

Table 1: Case studies of digital technologies in crop protection

Technology/ Project	Digital Technology Type	Crop Protection Use Case	Outcomes/ Impacts	Challenges/ Success Factors	Sources
Plant Village Nuru	AI-based smartphone application	On-field diagnosis of cassava viral diseases and pest symptoms using image recognition	Accuracy ranging from 65% to 88% when multiple leaves are used in field conditions; accuracy improved after two weeks of use	Requires smartphone; correct image capture; farmer's adoption	Arinaitwe *et al.*, (2024); King *et al.*, (2021); Ramcharan *et al.*, (2020); Andrade-Piedra *et al.*, (2021)
FAO FAMEWS (Fall Armyworm Monitoring and Early Warning System)	Mobile App plus global data platform	Real-time FAW scouting, reporting, and mapping for early warning	Improved data harmonization across countries; supports timely responses; works offline in low-connectivity areas	Requires national data validation; user training essential; consistent scouting	FAO (2018); FAO (2019)
Remote Sensing plus FAMEWS Integration (NDVI anomaly method)	Satellite-based monitoring (Sentinel-2 NDVI analysis)	Regional detection of FAW stress using NDVI anomaly validated with FAMEWS ground data	NDVI anomaly approach achieved R^2 = 0.81; demonstrates scalability for regional FAW surveillance	Susceptible to stresses (e.g., drought, nutrient); requires integration with field data	*Nji et al.*, (2022); Mwangi *et al.*, (2020)
Aerobotics (Viljoen Farms)	Drone imagery plus machine learning	Early detection of insect pests (e.g., mealybug) in high-value fruit crops	7% reduction in infested acreage; approximately 62 acres recovered; revenue protection estimated at $325,490	Requires drone service access; data processing, strong IT infrastructure; agronomist interpretation	Aerobotics (2023); Odindi *et al.*, (2021)
mKRISHI (India)	Mobile advisory platform (IVR/SMS/app)	Delivery of localized pest/disease advisory information	Highly effective - 47% of surveyed farmers; improved access to extension services	Sustainability depends on: updated advisory content; cropping season	Singh *et al.*, (2023); TCS Innovation Labs (2016)

1.12 Challenges in the adoption of digital technologies

Despite the immense potential of these technologies and digital tools to revolutionize crop protection under climate stress, their widespread adoption and effective utilization are not without significant challenges. The persistent digital divide, characterized by unequal access to essential technology, reliable internet infrastructure, and adequate levels of digital literacy, poses a substantial barrier to widespread adoption, particularly among smallholder farmers in developing countries, who are often the most vulnerable to the adverse impacts of climate change. Without equitable access and the necessary skills to utilize these tools effectively, the benefits of technological advancements may not reach those who need them most.

Concerns regarding data privacy and security, particularly those associated with the collection, storage, and sharing of sensitive agricultural data, also need to be carefully addressed to build trust and encourage the adoption of these technologies. Farmers need assurances that their data will be protected and used responsibly, and clear guidelines and regulations are necessary to govern the collection and use of agricultural data. Moreover, the seamless integration of different technologies and data platforms can be technically complex and often requires the development of interoperability standards and user-friendly interfaces that allow seamless exchange of information between different systems. The lack of standardization and the complexity of some existing platforms can hinder their widespread adoption and effective use by farmers. Finally, the initial cost of investment in some of these advanced technologies, such as sophisticated sensors, drones, and data analytics software, can be a significant limiting factor, particularly for resource-constrained smallholder farmers, who may lack the financial capacity to adopt these innovations without financial assistance or supportive policies.

1.13 Data Privacy, Security, and Accessibility of Digital Technologies

The ever-increasing use of digital technology, including remote sensing, IoT sensors, mobile platforms, cloud systems, and AI, inevitably results in the generation of large volumes of sensitive farm data. These include information such as land use, production estimates, pest occurrence patterns, financial records, and market activities. Therefore, adequate safeguards are needed to abate the risks of unauthorized data access, profiling by input suppliers, inequitable data monetization, and exposure to cyberattacks targeting agricultural systems. Moreover, ambiguous ownership and unclear regulations on agricultural data management can erode trust and hinder adoption (Lehmann et al., 2020).

To mitigate these risks, policy and technical best practices need to be provided. As such, measures need to be implemented by countries to promote farmer confidence, enabling broader adoption of digital agriculture tools for crop protection with a focus on clear data governance frameworks. Here, governments establishing data governance policies specifying data ownership, permissible uses, consent protocols, and sharing mechanisms are essential. In this way, farmers retain ownership and full rights to their data, and any third-party usage should require informed consent. In another form, implementing advanced encryption, secure cloud architectures, and anonymization techniques can protect sensitive geospatial and production data from unauthorized access. For example, transport layer security (TLS)-encrypted communication protocols should be standard for IoT-based farm sensors.

While standardization for agricultural data security ensures that digital systems secure and consistent communication, certification frameworks for agricultural digital platforms can reassure farmers of system reliability and safety. This, therefore, increases transparency and trust among farmers, hence farmer-centered data agreements that specify data gathering, collection, access, and storage. Furthermore, digital literacy training, pertaining to basic cybersecurity practices, is needed: password protection, recognition of phishing attempts, proper use of digital devices, and understanding of privacy settings in mobile applications. Finally, policymakers should establish national committees on agricultural digitalization to review data security incidents, monitor compliance, and ensure that technology providers uphold ethical data practices.

1.14 Strategies for Overcoming Challenges

To effectively overcome these challenges and fully realize the transformative potential of technology and digital tools in enhancing crop protection under climate stress, a concerted and collaborative effort involving governments, agricultural research institutions, the private sector, nongovernmental organizations, and, most importantly, the farmers themselves is essential. Strong policy support from governments is absolutely critical for creating an enabling environment that fosters the widespread adoption of these technologies. This includes strategic investments in the development of robust digital infrastructure, including reliable internet connectivity in rural areas, as well as sustained funding for agricultural research and development focused on developing and adapting these technologies for diverse farming systems. Furthermore, investing in comprehensive capacity-building programs and digital literacy training for farmers is important to ensure that they possess the necessary skills and knowledge to effectively utilize these tools and interpret the information they provide.

Public–private partnerships can play a vital role in facilitating the development and dissemination of affordable and accessible technological solutions that are specifically tailored to the unique needs and constraints of different farming systems, ranging from smallholder operations to large-scale commercial agriculture. These partnerships can leverage the innovation and agility of the private sector with the public sector's capacity for outreach and policy implementation. Farmer education and training programs are paramount to ensure that farmers not only have access to these technologies but also possess the necessary skills and knowledge to effectively utilize them in their daily farming practices. These programs should focus on practical applications, provide hands-on training, and utilize extension methods that are culturally appropriate and easily understandable. Peer-to-peer learning networks and farmer-led demonstration sites can also be highly effective in promoting the adoption and diffusion of these technologies.

Furthermore, the promotion of open data initiatives and the development of accessible data sharing platforms can significantly accelerate the development of more robust and accurate predictive models and user-friendly decision support systems. Making relevant agricultural data publicly available, while respecting data privacy concerns, can foster innovation and collaboration among researchers, developers, and agricultural service providers.

1.15 Economic Analysis and Funding Models

High costs remain among the most persistent barriers to the adoption of drones, AI tools, IoT sensors, and precision agriculture systems. Smallholder farmers often lack the capital required for upfront purchases or subscriptions to digital services (Lost-Filho *et al.*, 2022). Therefore, expanding adoption requires innovative economic models and inclusive financing options such as the following:

- Pay-As-You-Use (PAYU) Digital Services: Farmers pay small fees for on-demand services such as drone scouting, satellite-derived crop health maps, pest detection alerts, and precision spraying services. This model drastically reduces capital burdens and has already been successful in Kenya and India, where "drone-as-a-service" simplifies access for smallholders.
- Cooperative and Community-Based Ownership Models: Farmer cooperatives can jointly purchase digital tools and hire trained operators. Shared ownership reduces per-farmer cost, promotes local expertise, and ensures the continuous use of shared equipment. This model works particularly well for weather stations, soil testing tools, and remote sensing services.
- Public–private partnerships (PPPs): Governments can subsidize early adoption by offering grants for sensors and digital kits, co-funded technology hubs, and integrating digital tools into national extension services. Here, the private sector contributes to technical support, software maintenance, and innovation. PPPs are effective in scaling digital extension platforms (e.g., India's e-Choupal, Ethiopia's ATA digital programs).
- Microfinance and low-interest credit lines: Agricultural microfinance institutions can create tailored loan products for purchasing digital tools. Such products may include flexible repayment aligned with crop cycles, low collateral requirements, and interest subsidies for climate-smart technologies. Bundling loans with extension support increases successful adoption and repayment rates.
- Government and Donor Subsidies for Climate-Smart Technologies: National governments or development partners (FAO, IFAD, World Bank) can offer voucher systems for digital Agric services, subsidies for precision irrigation, renewable energy packages to power IoT sensors, and startup funding for Agric-tech innovators. Such incentives reduce market entry barriers for both farmers and technology service providers.
- Market-Based Incentives through Climate Insurance: Insurance programs using remote sensing or IoT data to assess risk can reduce premiums for farmers using digital crop protection tools and create financial incentives for adopting early warning systems and precision agriculture. By lowering risk exposure, digital tools become economically justified, even for low-income farmers.
- Integration into Value Chain Contracts: Agribusiness companies and processors can supply digital tools to contract farmers to ensure quality control, pest and disease monitoring, and stable supply chains. Costs are recovered through crop sales, reducing upfront expenses for producers.

2 Conclusion

In conclusion, this paper highlights the critical nexus between climate change and plant health. Altered climatic conditions have the potential to exacerbate pest and disease incidence, disrupt plant physiology, and threaten global food security. Technology and digital tools are now indispensable for effective crop protection under intensifying climate stress. From advanced monitoring and prediction to precise interventions and sustainable practices, these innovations offer crucial solutions for safeguarding food security. However, equitable access, data responsibility, and the integration of ecological principles are vital for realizing their full potential in building climate-resilient agricultural system scenarios.

It is hereby recommended with emphasis on a coordinated, multi-stakeholder approach to managing climate-driven crop pests and diseases: Researchers should address key knowledge gaps by developing robust climate-informed predictive models, assessing pest–disease–crop interactions under different climate scenarios, exploring adaptation strategies, as well as fostering interdisciplinary collaboration. This, in essence, will create accessible, farmer-friendly digital tools. Climatologists and meteorologists should provide localized climate data and work closely with agricultural scientists to strengthen early warning systems. Furthermore, Scientists and technologists should prioritize affordable, secure, interoperable, and AI-enabled digital innovations tailored to smallholder farmers. On the other hand, governments and policymakers should invest in rural digital infrastructure, sustain research funding, promote capacity building and public – private partnerships, as well as establish clear data governance frameworks. In the whole, farmers should enhance their digital literacy, adopt and evaluate digital tools, and participate in responsible data sharing. This will help in integrating digital technologies with sustainable farming practices to build resilient and environmentally sound agricultural systems.

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