International Journal for Multidisciplinary Research (IJFMR)

E-ISSN: 2582-2160 ● Website: www.ijfmr.com ● Email: editor@ijfmr.com

Data Driven Biosecurity: Strengthening Global Agricultural Resilience Against Emerging Threats

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Abstract

Pests, plant pathogens, and zoonotic diseases are becoming increasingly common and severe, posing serious concerns to global agricultural systems and food security. Climate change, international trade, and ecological disruptions compound these dangers by allowing new hazards to spread and arise more rapidly. This research review explores how predictive analytics and bio-surveillance technologies are used to improve agricultural resilience in three different regions: the United States, Africa, and Latin America. According to the findings, the United States leads in advanced infrastructure for integrated bio-surveillance, with AI-driven monitoring systems used in both crop and livestock sectors. Africa and Latin America, despite limited infrastructure, display innovation through certain community-based reporting systems and mobile diagnostic platforms. In conclusion, data-driven biosecurity is an important approach for strengthening global agricultural resilience to future threats.

Keywords: Digital agriculture, Food security, Data-driven approaches, Surveillance systems, Pest and Disease management

1. INTRODUCTION

Agricultural biosecurity has evolved as an important pillar of global food system resilience in the twenty-first century, owing to the increased severity of biological threats to crop and livestock production, food safety, and human health (Pal et al., 2019). Biosecurity is an integrated approach that includes policies and measures intended to protect the agricultural sector against biological threats (Kantor et al., 2024). The Food and Agriculture Organization (FAO) of the United Nations defines biosecurity as a strategic and integrated concept that analyses and manages risk in food safety, public health, animal and plant health, and environmental risk (FAO, 2007).

Particularly, pests, plant and animal illnesses, invasive species, and zoonotic viruses all pose serious challenges to food production systems, the economy, and public health. However, the growing interconnectedness of global agriculture, combined with climate change, habitat disruption, and increased transboundary trade, has broadened the scope of biosecurity to include proactive, systemic, and intelligence-driven approaches (Skendžić et al., 2021; Bett et al., 2025). Therefore, the increasing frequency and complexity of threats in both plant and animal systems highlight the critical need for a

paradigm shift in how biosecurity is conceptualized and implemented.
The resilience of global agriculture in the context of growing threats is challengd by a convergence of complex and interconnected concerns. These include the increasing incidence of invasive pests, transboundary animal and plant illnesses, the rise of zoonotic infections, and accelerating climate variability occurring in the context of expanding global trade, ecological degradation, and food system interconnection (Malhi et al., 2021). The ability of the agricultural system to absorb, adapt to, and recover from perturbations while sustaining basic functions such as food production, income generation, and environmental balance is referred to as agricultural resilience, however, building resilience remains a defensive measure and a strategic need for guaranteeing long-term food security, sustainable livelihoods, and the stability of national and international food systems (Shilomboleni et al., 2024). As emerging threats continue to outstrip existing response systems, incorporating digital information into global and regional biosecurity plans can potentially enable innovation and is also necessary for the sustainability and resilience of agriculture worldwide (Finger, 2023).
The expansion of digital technology, big data, and computational tools has created new opportunities for predictive modelling, remote sensing, and real-time surveillance (Abiri et al., 2023). Specifically, data-driven initiatives are altering the scope of agricultural biosecurity such that predictive analytics, for example, enables stakeholders to shift from reactive crisis response to proactive risk anticipation by projecting the appearance and spread of pests, diseases, and zoonotic hazards using environmental, meteorological, and socioeconomic data (Raji & Njoku, 2024). Machine learning algorithms can potentially assess various variables, including weather patterns and soil conditions, trade trends, and farmer-reported field observations, to detect possible outbreak regions and inform strategic responses (Mishra & Mishra, 2023).
Furthermore, data-driven frameworks enable cross-sector collaboration by combining epidemiological data with environmental, economic, and sociopolitical aspects to generate comprehensive risk assessments. These technologies can also democratize access to information, particularly when used with mobile platforms and open-access databases, empowering farmers, extension workers, and policymakers alike (Bitetto et al., 2021). In areas where formal monitoring systems are poor or underfunded, such as Sub-Saharan Africa or rural Latin America, digital surveillance and community-based reporting systems offer alternate avenues to improve situational awareness and reaction capacity. Data-centric techniques include technological add-ons essential to a modern biosecurity paradigm that values agility, foresight, and resilience (Omuse et al., 2025). Therefore, this review aims to explore how data-driven technologies are transforming agricultural biosecurity efforts across three diverse geopolitical contexts: the United States, Africa, and Latin America.

2. Biosecurity in Agriculture

The dangers of agricultural biosecurity include invasive species, plant and animal pests and diseases, and zoonotic pathogens that can spread from animals to people (Hulme, 2020). Previously, agricultural biosecurity was concerned largely with border protection, quarantine processes, and epidemic control methods (Msimang et al., 2022). However, in a globalized world characterized by rapid trade, climate change, and increasing land-use demands, biosecurity has grown into a multifaceted discipline including environmental stewardship, public health, economic stability, and food security (Pawlak & Kołodziejczak, 2020).
Current biosecurity frameworks emphasize prevention as the most cost-effective approach, requiring a

system capable of recognizing biological dangers before they escalate into public catastrophes (Soleimani, 2024; Zhou et al., 2019). In this regard, agricultural biosecurity necessitates cross-sectoral collaboration among plant protection agencies, veterinary services, public health authorities, research institutes, and community stakeholders (Hulme et al., 2023). It demands unified legal frameworks, real-time communication networks, and scientific techniques that enable rapid intervention (Sharan et al., 2023). Biosecurity is also widely recognized as a dynamic and iterative process, necessitating ongoing surveillance, fast adaptation to new threats, and investment in technical and institutional advances.

2.1 Role of Data Science and Predictive Analytics

Data science and predictive analytics have enhanced the biosecurity systems by bringing tools for proactively identifying, assessing, and mitigating hazards based on evidence . These methods use computational algorithms, statistical models, machine learning, and artificial intelligence to analyze large and heterogeneous datasets (Kalogiannidis et al., 2024). Satellite imagery, meteorological data, trade and transportation records, genetic sequences, field reports, social media trends, and citizen-science observations are some of the resources available.

Researchers and policymakers can use predictive analytics to forecast the spread of pests and illnesses, estimate their potential influence on agricultural productivity, and simulate intervention scenarios under various climatic or trade situations (Abiri et al., 2023). In essence, pest risk models can predict future invasion risks by combining climate forecasts and previous breakout trends. Similarly, animal disease transmission models can forecast zoonotic emerging hotspots based on movement data and environmental characteristics (Adelusola, 2024). Data science also contributes significantly to situational awareness and decision support. Visualization dashboards, interactive maps, and early warning alerts transform complex data streams into usable insights for farmers, extension workers, and regulators. In the United States, systems such as the United States Department of Agriculture (USDA)- supported real-time tools have proved the value of combining weather, pest monitoring, and producer data to inform pest management decisions (Abiri et al., 2023). Furthermore, developments in machine learning are increasing anomaly detection, for example, recognizing agricultural stress from drone or satellite imagery and facilitating the quick classification of diseases via bioinformatics (Araújo et al., 2023). Therefore, these capabilities improve early detection and broaden the geographic scope and temporal resolution of surveillance systems, resulting in a more agile and anticipatory biosecurity environment.

2.2 Bio-surveillance Systems

Bio-surveillance systems are key infrastructures that help identify, monitor, analyze, and disseminate information on biological risks in agriculture and public health. These systems combine data from a variety of sources, field observations, laboratory diagnostics, environmental monitoring, and administrative records, to create a continuous, real-time picture of biosecurity threats (Kman & Bachmann, 2012). An effective bio-surveillance system serves as the central nervous system of a data-driven biosecurity framework, allowing for rapid decisions and coordinated responses.

The expansion in global trade and biosecurity risks has taken place alongside rapid breakthroughs and cost-efficiency in monitoring technology and data volume.

Given its numerous goals, from early warning systems, through evaluation and from containing an invasion to confirming pest-free areas for trading purposes, the goal is to ensure independence (Devitt et al., 2019). Biosecurity surveillance utilizes several technologies, including bug traps and lures, geographical information systems, and diagnostic biochemical tests. Bio-surveillance methods are constantly evolving due to technology advancements. Establishing regional networks of wirelesscommunicating "smart traps" can provide significant benefits, particularly in rural places (Aziz et al., 2025). Recent technologies like satellite imagery and remote sensing are now used to scan the landscape for pests (Rhodes et al., 2021). These technologies can improve monitoring by detecting breaches and responding quickly. However, they also increase the amount of data collected on private land. Data can reveal personal or sensitive information, such as individual movements or crop husbandry practices, affecting a farmer's freedom to operate with minimal outside interference and maintaining societal trust in farmers. Sharing farm information might carry risks, so farmers should use caution. While enhanced bio-surveillance has the potential to improve global food security, ethical concerns for individuals, such as privacy violations, unauthorized access, and loss of control over personal information, must be addressed alongside technological advancements (Kaur et al., 2022).

Generally, the structure of the system of bio-surveillance varies by area and sector, such that in the United States, federal and state agencies operate a distributed network of monitoring nodes, including the National Animal Health Laboratory Network (Cardwell & Bailey, 2022). These networks are linked by digital platforms that collect and analyze data for national-scale risk assessment. Regional bio-surveillance activities in Africa include the FAO's Desert Locust Information Service and the African Union's Pan-African Veterinary Vaccine Centre (FAO Sector Annual Report Fiscal Year 2021). Furthermore, Latin America has established its regional systems through institutions like the Instituto Interamericano de Cooperación para la Agricultura (IICA) and the Comité Regional de Sanidad Vegetal del Cono Sur (COSAVE), which promote standardized surveillance protocols, data sharing, and capacity building among member countries (FAO, 2018). Several countries, notably Brazil, Colombia, and Mexico, have implemented national digital platforms to track animal and plant health incidents (FAO, 2021). Despite their differences, beneficial bio-surveillance systems share four characteristics: interoperability, timeliness, scalability, and stakeholder inclusion. They not only supply data but also translate it into understanding and action. With the integration of predictive models, mobile apps, and artificial intelligence, modern bio-surveillance is becoming increasingly dynamic, capable of adapting in response to new diseases, changing surroundings, and emerging socio-political forces. As climate change disrupts ecological balances and trade networks become more complicated, these systems will be critical to maintaining agricultural and public health in an uncertain future (Zhang et al., 2023).

3. Emerging Threats to Global Agriculture

In recent times, agriculture is experiencing a period of vulnerability, characterized by an increase in developing challenges to the stability, productivity, and sustainability of global food systems (Toromade et al., 2024). These threats, which range from invasive pests and highly adapted plant pathogens to rapidly spreading zoonotic diseases, are becoming more common, severe, and difficult to control (Singh et al., 2023). Climate change, ecological degradation, globalized trade, and intensive farming techniques have all contributed to extraordinary rates of biological agent emergence, evolution, and dispersal across borders. Simultaneously, inadequate surveillance infrastructure in many countries and inadequate predictive capacity impede prompt responses, allowing localized outbreaks to develop into regional or global crises (Muluneh, 2021). These dangers are becoming more complex and interwoven, posing significant hazards not only to agriculture and the economy but also to public health, food security, and international cooperation.

3.1 Agricultural Pests, Pathogens and Zoonotic Diseases

Agriculture has consistently encountered biological dangers; however, in recent decades, the incidence, magnitude, and complexity of such threats have increased considerably (Food and Agriculture Organization of the United Nations, 2021b). Invasive pests, novel plant pathogens, and zoonotic diseases are currently among the most serious threats to agricultural production and global food security. Pests like the autumn armyworm (Spodoptera frugiperda), which originated in the Americas, have rapidly spread throughout Africa and Asia, decimating major crops like maize and sorghum (Feldmann et al., 2019). Similarly, locust swarms, particularly Schistocerca gregaria in the Horn of Africa, have destroyed enormous areas of agriculture, jeopardizing national food supplies and farmer livelihoods (Mongare et al., 2023).

Plant pathogens, including fungal infections such as wheat rust (Puccinia graminis) and banana wilt (Fusarium oxysporum TR4), are evolving resistance to conventional treatments and expanding into new territories as commerce and climate change (Hossain et al., 2024). Animal agriculture is also vulnerable; diseases like African swine fever, foot-and-mouth disease, and avian influenza have resulted in massive losses, wiping out entire herds and causing trade prohibitions, economic dislocation, and protein shortages (Penrith et al., 2023).

Furthermore, zoonotic infections, which spread from animals to people, have grown increasingly visible and deadly as a result of their dual impact on public health and food supply. The COVID-19 pandemic highlighted how closely linked world health and agriculture have become. Other zoonotic risks, such as brucellosis, Nipah virus, and Rift Valley fever, continue to spread, particularly in areas where wildlife, livestock, and human populations coexist (Varela et al., 2022). Therefore, weakened veterinary infrastructure, insufficient surveillance, and considerable biodiversity make these areas ideal for transmission. As a result, the biological risks to agriculture are numerous and more complex, necessitating methods that integrate plant, animal, and human health disciplines.

3.2 Climate Change and Globalization

Climate change is a major amplifier of biosecurity risks in agriculture. Rising temperatures, changed precipitation patterns, increased frequency of extreme weather events, and altered agroecological zones contribute to the emergence, resurgence, and redistribution of pests and illnesses (Prajapati et al., 2024). Increasing temperatures can increase insect pests' breeding cycles and geographical ranges, allowing them to infiltrate previously untouched areas. According to Zekeya et al. (2017), Tuta absoluta, a tomato leafminer endemic to South America, has spread throughout Africa and portions of Asia, partly due to favourable climatic circumstances and trade routes. Climate change, in addition to facilitating the spread of harmful organisms, weakens plant and animal immunity by causing environmental stress, reducing crop vigour, and limiting access to water and nutrients (Alotaibi, 2023). These stressors create conditions that allow pathogens to establish themselves more easily. Climate models project that such stress-induced vulnerabilities will disproportionately affect smallholder farmers in tropical and subtropical regions, thereby widening global inequality in food production capacity and resilience (Talukder et al., 2021).

Globalization exacerbates these risks by increasing the volume and velocity of trade, travel, and agricultural commodity exchanges. While trade increases food availability and economic development, it also speeds up the inadvertent spread of pests and diseases across borders (Spence et al., 2019). Agricultural inputs such as seeds, livestock, and food products can act as vectors, while tourists and migratory workers may unknowingly spread pathogens. Modern supply chains, while efficient, are frequently fragile and poorly screened for biosecurity breaches. Furthermore, the rise of megacities and peri-urban agriculture generates new interfaces where animals, crops, and people cohabit in high numbers, enhancing the possibility of novel disease emergence (Manuja et al., 2014). Owing to this, climate change and globalization increase the possibility of outbreaks, and also challenge the efficacy of established containment strategies, necessitating a biosecurity paradigm that is dynamic, proactive, and data-driven.

3.3 Cross-Border Implications for Food Security

The transboundary nature of agricultural risks emphasizes the relevance of regional and international collaboration in biosecurity governance. Pests and diseases that exceed borders can have far-reaching consequences, interrupting trade, lowering yields, raising food prices, and causing widespread food insecurity (FAO, 2021b). The 2019-2021 locust crisis in East Africa affected over 21 million people in different countries (Bennett, 2024), while autumn armyworm infestations have resulted in billions of dollars in crop losses in Latin America and Africa, limiting the supply of vital commodities such as maize, sorghum and rice (Mlambo S. et al., 2024).

Biosecurity breaches in exporting countries can cause supply delays, price instability, and a reduction in access to safe, inexpensive food, making food-importing countries susceptible. In an increasingly integrated food system, a localized outbreak can have global consequences, such as the outbreak of African swine flu in China, which reduced the country's pork production by more than 27%, caused global swings in meat pricing and trade flows that impacted markets as far afield as Brazil and the European Union (Frezal et al., 2021). These cross-border implications are both economic and political. Governments under food security duress may impose export bans, border closures, or coercive control measures, straining diplomatic relations and undermining collective actions. Effective multinational cooperation, initiatives and regional bodies are required as critical platforms for standardizing protocols, sharing data, and launching joint responses to new threats.

4. Predictive Analytics for Biosecurity

Predictive analytics uses data science approaches such as Machine learning (ML), artificial intelligence (AI), statistical modelling, and big data analysis to improve risk identification and management across agricultural systems (Subeesh & Mehta, 2021). Therefore, by combining various data sources such as climate factors, trade routes, field sensor outputs, and real-time surveillance reports, these systems enable proactive, scalable, and cost-effective biosecurity strategies.

4.1 Machine Learning and AI for Threat Detection

Machine learning (ML) and artificial intelligence (AI) have emerged as critical tools for enhancing biosecurity, notably for the early detection of agricultural threats. These technologies can filter through enormous and complicated datasets to detect tiny patterns and correlations that may indicate the onset of biological risks long before they are visible to the human eye or standard monitoring systems (Mishra & Mishra, 2023). Therefore, by training algorithms on historical outbreak data, climate records, pest behaviour, genetic sequences, and geographical patterns, AI systems may learn to forecast the emergence, spread, and potential impact of pests, pathogens, and zoonotic illnesses with amazing precision.

Supervised learning algorithms, for example, can classify incoming data to distinguish between healthy and sick crops using imaging or sensor input. Unsupervised learning approaches, such as clustering, can detect abnormalities in pest or disease occurrence without prior labelling, making them suitable for identifying new or unexpected threats (Chithambarathanu & Jeyakumar, 2023). Natural language processing (NLP), a subset of AI, can be used to mine open-source text from news media, social networks, and academic journals for early warning signs of impending outbreaks, supplementing more formal monitoring systems (Domínguez et al., 2024). AI-enabled models have been used in livestock systems to monitor animal movements and behaviour for signs of disease onset, lowering response times and preventing the spread of dangerous diseases such as foot-and-mouth disease or avian influenza (Ghavi Hossein-Zadeh, 2025). This can be achieved through AI detection and adaptive learning, such that as new data becomes available, these models can recalibrate their predictions, improving in accuracy and relevance over time.

The United States is at the forefront of integrating predictive analytics and AI into agricultural biosecurity. The approach leverages technological infrastructure, extensive information, and interagency coordination to monitor, forecast, and respond to biological threats. Federal agencies such as the United States Department of Agriculture (USDA) collaborate with other agricultural departments, universities, and private-sector partners to develop AI-powered pest and zoonotic disease early detection systems (Werner, 2025). However, for zoonotic infections, the CDC's One Health strategy uses AI to analyze trends in animal, human, and environmental health sectors. AI systems monitor veterinarian records, farm-level animal movement, and environmental data to predict the advent of diseases such as avian influenza and swine flu (Zhang et al., 2023). Predictive techniques detect irregularities in animal behaviour or unexpected health changes before clinical signs appear, allowing for fast containment methods. Furthermore, real-time genomic monitoring and ML techniques are increasingly used to track pathogen alterations, allowing for more precise vaccination and quarantine protocols.

In Africa, on the other hand, where infrastructural constraints offer substantial hurdles to conventional surveillance systems, predictive analytics has emerged as a disruptive alternative, notably using mobile technologies, crowdsourced data, and machine learning platforms. Many countries throughout the continent are using AI and machine learning systems tailored to local contexts to effectively combat agricultural pests and zoonotic illnesses (Ayim et al., 2022). Specifically, the FAO's eLocust3 system, widely used in East Africa, is a mobile-based surveillance tool allowing field officers and farmers to input locust sightings, which are then geo-tagged and uploaded in real time (Halubanza et al., 2023).

Latin America is increasingly using predictive analytics and bio-surveillance methods to improve agricultural resilience, particularly against pests and zoonotic diseases that endanger economically important crops and livestock. In Brazil, platforms use AI-powered predictive models to estimate and predict soybean yield, with models being effective at forecasting soybean rust outbreaks (Monteiro et al., 2022). Farmers receive localized alerts via smartphone devices, which allow them to apply fungicides more efficiently and decrease crop losses. Brazil is also advancing the use of in livestock disease forecasting, combining farm-level data with climatic and transportation metrics to model disease outbreaks such as foot-and-mouth and bluetongue viruses (Mendes et al., 2020).

4.2 Real-Time Data Collection and Analysis

According to Shar et al., (2024), the incorporation of real-time data gathering technologies, which enable continuous monitoring of agricultural and ecological conditions, significantly improves the effectiveness of predictive analytics in biosecurity. In this regard, remote sensing uses satellite and drone pictures to enable wide-area surveillance of croplands, woods, and rangelands, allowing for the long-term detection of vegetation stress, atypical growth patterns, and insect infestations. These observations are frequently combined with meteorological data, such as temperature, rainfall, and wind direction, to simulate outbreak-prone conditions.

Internet of Things (IoT), including soil moisture sensors, climate stations, wearable animal health monitors, and mobile diagnostic tools, enables hyper-localized, real-time data streaming from farms and agricultural enterprises (Salisu et al., 2023). These data points are entered into centralized systems, where AI algorithms process them to identify deviations from normal parameters, predict dangers, and send out early notifications. Smart traps, for example, may count and identify pest species in the field while providing data to a cloud server, which updates threat maps and advises farmers or authorities on proper remedies (Aslam et al., 2024). The combination of remote sensing and IoT has resulted in the creation of comprehensive digital twins, virtual representations of agricultural landscapes that can be replicated and analyzed under various circumstances (Purcell & Neubauer, 2023). These computational models can forecast the results of interventions like pesticide spraying, quarantine imposition, and vaccination programs, optimizing both time and resource allocation.

The United States uses an advanced ecosystem of real-time data collection for agricultural biosecurity, utilizing remote sensing platforms, IoT-enabled infrastructure, and digital decision-support systems. This system monitors environmental conditions, crop health, livestock behavior, and pest movement, identifying biological threats before they manifest (Aziz et al., 2025). In animal farming, the National Animal Health Monitoring System uses IoT devices to detect signs of illness, stress, or biosecurity breaches. Private companies and research institutions are developing cloud-based platforms for farmers to upload drone footage, thermal images, and sensor data for immediate analysis. Therefore, this integration of technology allows the United States. to deploy data-driven interventions against plant and animal health threats (Neethirajan 2025).

Africa is transforming agricultural biosecurity through real-time data collection and analysis, particularly in regions with limited surveillance infrastructure. Decentralized, mobile-enabled systems are being adopted, allowing farmers and local officers to feed real-time observations into national and regional surveillance platforms (Ayim et al., 2022). These approaches are enhanced by remote sensing, low-cost IoT solutions, and open-access data initiatives. Mobile-based applications like PlantVillage allow farmers to report plant disease symptoms and receive instant diagnostics and advice. IoT devices are also being used in the livestock sector, with wearable animal health monitors detecting early signs of illness and enabling faster diagnosis and containment of zoonotic diseases (Kariyanna & Sowjanya, 2024).

In the United States, Africa, and Latin America, real-time data collection and analysis have become the foundation of current bio-surveillance systems (Jones et al., 2017). Whether through high-resolution satellites, cloud-connected sensors, or mobile diagnostics, these technologies deliver a constant supply of actionable data that fuels predictive analytics and speeds up danger identification (Tan et al., 2023). Therefore, as global agricultural risks become more frequent and complex, investment in scalable and interoperable real-time data systems will be critical to defending food systems and public health on a global scale.

5. Conclusion

As global agriculture faces an increasing number of biological threats ranging from invasive pests to zoonotic diseases, there is a critical need to change from reactive to proactive biosecurity policies. This review has shown that data-driven biosecurity, which is powered by predictive analytics and real-time bio-surveillance, provides a transformational framework for increasing agricultural resilience across varied geographies. Based on findings from the United States, Africa, and Latin America, it is obvious that incorporating data science into agricultural health systems can drastically cut reaction times, optimize resource allocation, and mitigate the socioeconomic effects of emerging hazards. In the United States, robust infrastructure, inter-agency collaboration, and high-resolution data streams enable exact modeling and early actions against plant and animal health threats. Africa demonstrates how mobile-enabled surveillance, community-driven data gathering, and AI-powered diagnostics can provide low-cost, scalable solutions even in resource-limited areas. The regional networks and investments of Latin America in remote sensing, IoT, and collaborative platforms demonstrate the importance of coordinated real-time monitoring in addressing cross-border hazards and climate vulnerabilities.

Across these contexts, ML, AI and real-time analytics have proven critical in forecasting biological threats and initiating timely, localized interventions. However, achieving the full potential of data-driven biosecurity necessitates addressing persisting challenges such as fragmented data systems, limited interoperability, infrastructural limitations, and the requirement for inclusive capacity building. Addressing these problems through policy innovation, technical investment, and international collaboration is critical to ensuring that predictive systems are egalitarian, responsive, and consistent.

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