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Technological Innovation in Disease Detection and Management in Sugarcane Planting

Ameng Li
CRO Service Station, Sanya Tihitar SciTech Breeding Service Inc., Sanya, 572025, Hainan, China
Corresponding author email: 1073985433@qq.com

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Abstract The objective of this study is to systematically examine recent technological innovations in disease detection and management within sugarcane cultivation. It seeks to identify key advancements in digital imaging, molecular diagnostics, and genetic engineering that have significantly improved the detection, monitoring, and control of sugarcane diseases, aiming to enhance overall crop health and productivity. This study identifies several crucial technologies that have reshaped disease management strategies in sugarcane cultivation. It highlights the effectiveness of machine learning algorithms and remote sensing technology in detecting and diagnosing plant diseases at early stages. Developments in molecular diagnostics have allowed for rapid and precise pathogen identification. Additionally, genetic engineering has contributed to the creation of disease-resistant sugarcane varieties, thereby reducing dependency on chemical treatments. Integration of these technologies has led to improved disease surveillance and management, resulting in healthier crops and increased yields. The convergence of machine learning, remote sensing, molecular diagnostics, and genetic engineering represents a transformative shift in managing sugarcane diseases. These technologies not only enhance the ability to detect and manage diseases more efficiently but also contribute to sustainable agriculture practices by reducing chemical use and improving crop resilience. Continued innovation and integration of these technologies hold the promise of further gains in productivity and sustainability in sugarcane agriculture.

Keywords Sugarcane cultivation; Disease detection; Machine learning; Remote sensing; Molecular diagnostics; Genetic engineering; Sustainable agriculture

Sugarcane is a critical agricultural commodity with a significant role in the global economy, providing raw material for sugar production and biofuels, among other products. The cultivation of sugarcane is not without challenges, particularly in the form of diseases that can severely impact yield and quality. Common diseases affecting sugarcane include those caused by fungi, bacteria, viruses, and phytoplasmas, which can lead to substantial economic losses. The traditional methods for disease detection, which often rely on visual inspection, are labor-intensive and can be inaccurate. Moreover, the asymptomatic nature of some diseases makes early detection difficult, necessitating more advanced and reliable methods. Technological innovations in disease detection and management are therefore essential to sustain and improve sugarcane production.

Recent advancements in machine learning and image processing techniques have shown promise in addressing these challenges. Support vector machines (SVM) and machine vision technology have been utilized to detect sugarcane borer diseases with high accuracy, demonstrating the potential of these methods to replace laborious manual selection processes. Similarly, machine learning classifiers applied to multispectral images from unmanned aerial vehicles (UAVs) have been effective in detecting white leaf disease in sugarcane, even at early stages (Narmilan et al., 2022).

Deep learning frameworks have also been explored for their ability to identify diseased sugarcane plants by analyzing leaf and stem characteristics, with some models achieving high levels of accuracy (Srivastava et al., 2020). The Internet of Things (IoT) has been integrated into agricultural practices, enabling targeted disease management and reducing the environmental impact of excessive pesticide use (Thangadurai et al., 2020). Transfer learning approaches using deep learning models like VGG-16 and ResNet have been applied to sugarcane disease classification, further illustrating the potential of these technologies to revolutionize disease detection in agriculture (Daphal and Koli, 2021).

Moreover, the development of mobile applications using deep learning architectures like Faster Region-based Convolutional Neural Network (Faster RCNN) has made it possible for farmers to detect diseases in sugarcane crops quickly and efficiently (Murugeswari et al., 2022). These technological innovations represent a significant step towards more sustainable and effective disease management in sugarcane cultivation, which is crucial for maintaining the crop's global economic importance.

In summary, the need for technological innovation in the detection and management of sugarcane diseases is clear. The integration of advanced machine learning techniques, remote sensing, and IoT into agricultural practices offers promising solutions to improve disease management and ensure the sustainability of sugarcane production worldwide.

1 Innovations in Disease Detection

1.1 Machine vision and image processing

Recent advancements in machine vision and image processing have significantly improved the detection of diseases in sugarcane crops. Support vector machines (SVM) have been utilized to detect sugarcane borer diseases with a high accuracy rate, demonstrating the effectiveness of machine vision technology when combined with threshold segmentation and image processing techniques. Similarly, image processing based disease detection for sugarcane leaves has been implemented, focusing on major diseases such as red rot, mosaic, and leaf scald. The use of computer vision techniques has shown promise in changing the agricultural landscape by enabling automatic disease detection. Furthermore, deep learning frameworks have been proposed to detect diseased sugarcane plants by analyzing leaves, stems, and color, with models like Inception v3, VGG-16, and VGG-19 showing high accuracy in disease identification (Srivastava et al., 2020). The application of transfer learning approaches, such as VGG-16 net and ResNet, has also been explored for sugarcane foliar disease classification, yielding promising results even with limited datasets (Daphal and Koli, 2021). Additionally, the use of Convolutional Neural Networks (CNNs) has been proposed for the automated recognition of sugarcane diseases, further illustrating the potential of machine vision and deep learning in disease detection (Kotekan et al., 2023).

1.2 Molecular diagnostics

Molecular diagnostics have emerged as a powerful tool for the management of major diseases in sugarcane. The development of specific and sensitive diagnostic tools using PCR-based detection methods has facilitated the timely detection of pathogens, which is crucial for disease management. These molecular techniques have been applied to a range of sugarcane diseases, including red rot, smut, yellow leaf syndrome, and others, highlighting the need for highly sensitive, specific, and cost-effective detection tools for large-scale applications.

1.3 Remote sensing and UAV technologies

Remote sensing and UAV (Unmanned Aerial Vehicle) technologies have been recognized as innovative approaches for plant disease detection. These techniques, coupled with spectroscopy-based methods, allow for the rapid preliminary identification of primary infections and high spatialization of diagnostic results. Novel sensors based on the analysis of host responses, such as differential mobility spectrometers and lateral flow devices, can deliver instantaneous results and effectively detect early infections directly in the field. Biosensors based on phage display and biophotonics have also been developed to provide instantaneous infection detection, which can be integrated with other systems for enhanced disease management. Additionally, the integration of IoT (Internet of Things) in agriculture has led to the development of automated systems that can identify diseases in sugarcane leaves with high accuracy, demonstrating the potential of technology-driven solutions to improve agricultural production and minimize risks (Thangadurai et al., 2020).

2 Innovations in Disease Management

2.1 Genetic engineering and breeding

Recent advancements in sugarcane genomics have played a pivotal role in enhancing agronomic traits and crop yield, addressing the increasing global demand for sugar and biofuel amidst climate change challenges. Conventional breeding methods face difficulties due to the complex, polygenic nature of agronomic traits and the highly heterozygous autopolyploid nature of the sugarcane genome. However, the identification of superior agronomic traits/genes for higher cane yield, sugar production, and disease/pest resistance has been facilitated through quantitative trait loci mapping, genome-wide association studies, and transcriptome approaches (Meena et al., 2022). Genetic engineering approaches have also been employed to enhance insect pest resistance in sugarcane by overexpressing cry proteins, vegetative insecticidal proteins (vip), lectins, and proteinase inhibitors (PI). Additionally, cutting-edge biotechnological tools such as host-induced gene silencing (HIGS) and CRISPR/Cas9 offer sustainable control of insect pests (Iqbal et al., 2021).

2.2 Agronomic practices

In Tucumán, Argentina, an integrated management approach incorporating biotechnological tools has significantly improved sugarcane productivity. The use of molecular markers to identify the Bru1 gene for brown rust resistance and SNP alleles linked to novel sources of resistance has been instrumental in developing resistant varieties. Furthermore, seed cane sanitation projects employing hydrothermal therapy, in vitro culture techniques, molecular diagnosis, and bionanoparticles have reduced the incidence of systemic diseases (Racedo et al., 2023). In India, agronomic approaches and physical methods like heat therapy, along with the propagation of disease-resistant varieties, have been effective in managing sugarcane diseases. The multiplication of sugarcane through tissue culture is advocated to produce disease-free planting materials.

2.3 Advanced biological and chemical treatments

The application of biotechnology in sugarcane agriculture and industry has evolved significantly, with advances in genomics, proteomics, and metabolomics enhancing our understanding of genetic material and its expression. These advancements have facilitated the development of transgenic or GMO crops, the identification and utilization of molecular markers for traits, and the improvement of value-added products such as biofuel. Transgene-free genome editing techniques, such as the delivery of ribonucleoprotein (RNP) complexes, virus-induced genome editing (VIGE), and transient expression of CRISPR/Cas reagents, have emerged as promising methods for creating new cultivars with improved resistance to biotic and abiotic stresses (Krishna et al., 2023). Biotechnological developments have also focused on in vitro culture systems, radiation/chemical-induced mutagenesis for mutant isolation, and the application of genomics tools for a detailed understanding of stress responses, which are crucial for sugarcane improvement.

3 Case Studies and Success Stories

3.1 Detailed analysis of technological adoption in Brazil, the world’s largest sugarcane producer

Brazil's sugarcane industry has significantly benefited from the adoption of precision agriculture (PA) technologies, particularly in São Paulo state, which accounts for 60% of the country's sugarcane production. The use of PA technologies has led to managerial improvements, higher yields, lower costs, and minimized environmental impacts. Moreover, the quality of sugarcane has improved due to these technological advancements. A study investigating the extent of PA technology adoption in the sugar-ethanol industry revealed that companies utilizing these technologies have experienced substantial benefits. The research also highlighted the importance of primary data obtained from questionnaires sent to companies in the region, which provided insights into the adoption and impact of PA technologies (Meena et al., 2022).

The Brazilian sugarcane innovation system has played a crucial role in the success of the industry, which is not solely due to natural comparative advantages but also as a result of technological learning and incremental innovations. The innovation system around the sugarcane industry is based on the interaction of various institutional actors, including sugar and ethanol mills, industrial goods suppliers, public and private research institutions, and governmental agencies. This system has been instrumental in developing a trajectory of technological advancements that have led to the production of low-cost bioethanol with low greenhouse gas emissions, positioning Brazil as a global leader in sugarcane bioethanol production (Iqbal et al., 2021).

3.2 Impact of technology on sugarcane yield and disease management in India

In India, integrated disease management (IDM) practices have shown a positive impact on sugarcane yield and quality. Field experiments conducted at the Sugarcane Research Station in Nayagarh, Orissa, demonstrated that IDM practices resulted in significant improvements in yield, germination, millable cane per hectare, average cane weight, and sucrose content. Additionally, there was a notable reduction in Grassy Shoot Disease incidence. These findings underscore the economic viability and practical feasibility of IDM practices in enhancing sugarcane production in India (Racedo et al., 2023).

Another study conducted at the IISR institute farm in Lucknow focused on IDM strategies for red rot disease in sugarcane. The study revealed that IDM practices not only reduced red rot incidence but also enhanced growth parameters and quality attributes of sugarcane compared to non-integrated disease management practices. The use of IDM practices led to improvements in various yield and quality parameters in both plant and ratoon crops, highlighting the benefits of IDM in controlling red rot and improving the overall health and productivity of sugarcane.

3.3 Case study of integrated disease management approaches in Australia

The Australian sugarcane industry has faced challenges with diseases such as smut and orange rust. However, the industry has responded with the development of disease-resistant varieties and the incorporation of new technologies in disease control strategies. The adoption of green technologies, such as in vitro propagation, has provided opportunities for the development of novel varieties with disease resistance and improved potential for cane yield and sugar recovery. These advancements have been crucial in managing existing diseases and combating emerging threats to the industry (Hoarau et al., 2021).

In addition to breeding and variety selection programs, the Australian sugarcane industry has also benefited from the use of image processing techniques for disease detection. Research on the effectiveness of image processing and computer vision techniques for detecting diseases in sugarcane plants has shown promise in improving disease management practices (Figure 1). These technologies enable rapid and early detection of diseases, which is essential for implementing timely and effective control measures.

Overall, the case studies from Brazil, India, and Australia demonstrate the significant impact of technological innovation on disease detection and management in sugarcane planting. The adoption of precision agriculture, integrated disease management practices, and advanced imaging techniques has led to improvements in yield, quality, and sustainability of sugarcane production in these countries.

4 Integration of Technology and Farmer Practices

4.1 Education and training for farmers

The integration of technology in disease detection and management in sugarcane planting necessitates the education and training of farmers. As advanced methods of plant disease detection evolve, including DNA-based and serological methods, farmers must be trained to understand and utilize these tools effectively. The use of machine learning techniques over UAV multispectral images for the detection of white leaf disease in sugarcane is a prime example of technological advancement that requires a certain level of technical knowledge for operation and interpretation (Narmilan et al., 2022). Furthermore, the application of image processing techniques for disease detection in sugarcane leaves indicates a shift towards more sophisticated agricultural practices that farmers need to be acquainted with.

4.2 Technological accessibility and affordability

While the development of novel sensors and remote sensing techniques offers instantaneous and effective disease detection, the accessibility and affordability of such technologies are critical for widespread adoption by farmers.

The use of support vector machines (SVM) for detecting sugarcane borer diseases demonstrates the potential for technology to reduce labor and misjudgment in disease detection. However, the cost and complexity of these technologies must be considered to ensure they are accessible and affordable for farmers, particularly in less developed agricultural settings.

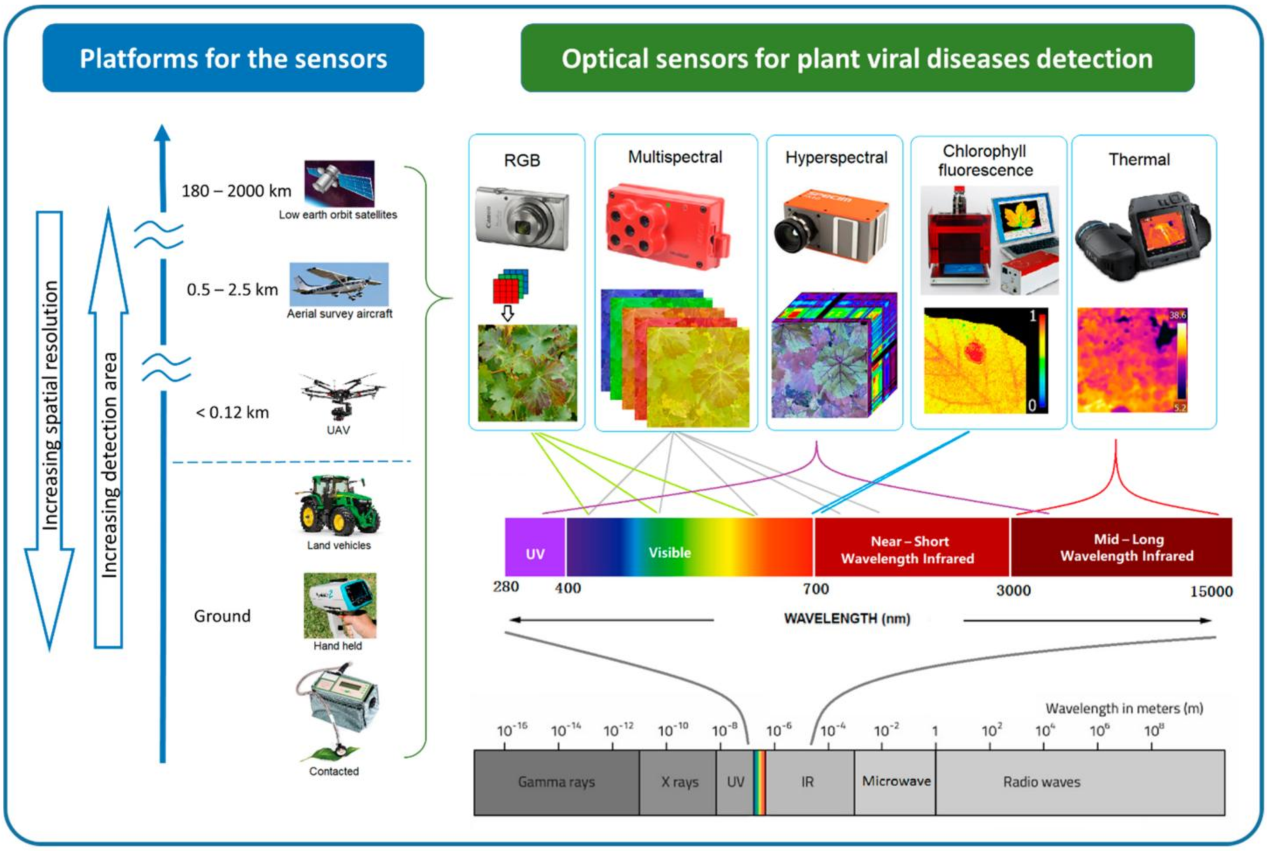

Figure 1 Optical sensing technologies for plant viral disease detection can be classified by their platform and associated spatial resolution and extent (Photo credit: Wang et al., 2022)

Image caption: Sensors also vary by band position, the spectral range within the whole electromagnetic spectrum (Adopted from Wang et al., 2022)

4.3 Data management and decision support systems

The implementation of machine learning algorithms and deep learning frameworks for sugarcane disease detection generates a significant amount of data that must be managed efficiently (Srivastava et al., 2020). The use of IoT for disease detection in sugarcane leaf further emphasizes the need for robust data management systems that can handle the information collected from sensor nodes. Decision support systems that can process this data and provide actionable insights are essential for farmers to make informed decisions regarding disease management. Transfer learning approaches to sugarcane foliar disease classification and the development of mobile applications for disease detection are examples of how technology can aid in data management and decision-making processes (Daphal and Koli, 2021).

In conclusion, the integration of technology in sugarcane disease detection and management involves a multifaceted approach that includes educating farmers, ensuring the accessibility and affordability of technologies, and implementing effective data management and decision support systems. These components are crucial for the successful adoption of technological innovations in the agricultural sector (Murugeswari et al., 2022).

5 Challenges and Future Directions

The integration of technological innovation into sugarcane disease detection and management heralds a new era of efficiency and sustainability. However, the adoption and implementation of such technologies are not without challenges. Addressing these challenges is critical to further refine these innovations and broaden their application in the agricultural sector.

5.1 Technical limitations and the high cost of advanced technologies

One of the primary barriers to the widespread adoption of advanced technological solutions in sugarcane cultivation is the high cost associated with these technologies. Advanced imaging systems, remote sensing technologies, and automated diagnostic tools often require significant capital investment, which can be prohibitive for small to medium-sized enterprises and farmers in developing countries. Furthermore, the technical complexity of these systems demands skilled personnel for operation and maintenance, adding to the overall cost.

Moreover, there are inherent technical limitations in the current technologies that may affect their effectiveness. For example, remote sensing technologies, while capable of monitoring large areas, may lack the resolution needed to detect early-stage disease symptoms or differentiate between diseases with similar phenotypic expressions. Overcoming these limitations requires continuous research and development, which necessitates additional funding and resources.

5.2 The need for improved diagnostic tools that are both specific and sensitive

Current disease detection methods in sugarcane still face challenges in terms of specificity and sensitivity, particularly under field conditions. Many diagnostic tools are effective in controlled environments but fail to perform with the same accuracy in the field due to variable environmental factors and the presence of multiple pathogens. This can lead to false positives or negatives, complicating disease management efforts.

The development of diagnostic tools that are both highly specific and sensitive is crucial. These tools must be capable of accurately identifying a disease pathogen among a multitude of environmental samples and biological contaminants. Advances in molecular diagnostics, such as PCR-based techniques, offer promising improvements, but these too require enhancements to adapt to the rapid and diverse nature of pathogen evolution.

5.3 Prospects for AI and machine learning in further enhancing disease detection and management

Artificial intelligence (AI) and machine learning (ML) present significant opportunities to transform disease detection and management in sugarcane cultivation. These technologies can process vast amounts of data from various sources, such as satellite images, drone footage, and sensor data, to quickly identify patterns that may indicate disease presence. The ability of AI and ML to learn and improve over time could lead to increasingly accurate predictive models for disease outbreak and progression.

Moreover, AI can integrate data from genetic, environmental, and management practice variables to develop holistic disease management strategies that are both proactive and reactive. For instance, machine learning algorithms can predict disease spread based on weather conditions and crop density, allowing farmers to implement targeted interventions before diseases become widespread.

As the field of agricultural technology continues to evolve, future research should focus on reducing the costs and improving the accessibility of advanced technologies so that they can be deployed more widely. Additionally, efforts should be directed towards enhancing the interoperability of different technological systems to provide a more integrated approach to disease management. Collaboration between researchers, technology developers, farmers, and policy-makers will be essential to address these challenges and harness the full potential of technological innovations in the sugarcane industry.

6 Conclusion

The systematic review of the literature on technological innovation in disease detection and management in sugarcane planting reveals a significant impact on the industry. Biotechnological advancements have been pivotal in addressing the challenges faced by sugarcane agriculture, such as the crop's narrow gene pool, complex genome, and long breeding cycles. The creation of transgenic plants with improved agronomic traits, advances in genomics, and molecular markers have been notable achievements in this field. Furthermore, the integration of information technology has revolutionized biotechnological research, enabling scientists to collect comprehensive data and utilize molecular tools to enhance sugarcane breeding programs.

Disease management strategies have also evolved, with a focus on developing high-yielding, disease-resistant varieties as the most cost-effective and environmentally friendly approach. The sequencing of the sugarcane genome and the use of marker-assisted selection are expected to become routine components of successful variety development programs. Additionally, the resilience of sugarcane to abiotic stresses, such as climate change, is being enhanced through biotechnological interventions and the development of climate-resilient varieties.

The future outlook for the development of more resilient sugarcane crops is promising. With the world population increasing and the demand for sugarcane-derived products rising, there is a pressing need for continued innovation. Genetic modification and biotechnological approaches are expected to play a crucial role in improving biotic and abiotic stress tolerance, thereby improving the value and sustainability of the crop. The integration of production technologies and the development of new sugarcane varieties tailored to specific environmental conditions will be essential in increasing farmers' income and ensuring the profitability and sustainability of the sugar industry.

In conclusion, technological innovations have had a profound impact on the sugarcane industry, improving disease detection and management, and enhancing crop resilience. The continued advancement of biotechnological tools and the integration of these technologies into breeding programs are expected to drive the development of more robust and productive sugarcane varieties, securing the future of the industry in the face of global challenges.

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