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A wireless sensor network-based smart agriculture for the detection of plant pathogens with agricultural biotechnology

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Abstract

Objective

Smart agriculture (SA) is a revolutionary method of farming that maximizes crop productivity and reduces environmental damage by using cutting-edge technology like sensors, robots, and data analytics. By using less pesticides, fertilizers, and other materials that damage ecosystems, it seeks to increase production efficiency and make agricultural methods more environmentally friendly. The combination of Wireless Sensor Networks (WSN) with microfluidic lab-on-a-chip technologies for real-time plant health monitoring and management is one of the most novel developments in SA.

Results

Agricultural biotechnology (ABT) in conjunction with networked microfluidic detectors may improve the identification and control of plant diseases. These biosensors can identify even minute levels of pathogens in plant tissues or environmental samples since they are designed to be very sensitive, inexpensive, and portable. Precision agricultural methods and a thorough image of disease propagation are made possible by the integration of these biosensors into a Wireless Sensor Network (WSN), which allows data to be wirelessly sent to a central server for real-time analysis.

Conclusions

In order to identify plant diseases, traditional agricultural systems often depend on time-consuming techniques including visual inspections, manual sampling, and diagnostic laboratory testing. Micro-fluidic biosensors provide a quicker and more accurate way to detect plant diseases locally and in real time. These technologies, when integrated with Wireless Sensor Networks (WSN), provide an effective framework for ongoing plant health monitoring, allowing farmers to identify diseases early and take prompt action.

Keywords: Agricultural Biotechnology, Plant Pathogens, Smart Agriculture, Wireless Sensor Networks

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Introduction

By 2050, the world's population is expected to exceed 10 billion, putting unprecedented strain on the farming industry to produce enough affordable and nutritious food. Crop illnesses resulting from bacteria, fungi, and pathogenic viruses pose significant obstacles to agricultural output, potentially impeding attempts to fulfill future dietary requirements (Paymode & Malode 2022). These illnesses of plants cause substantial financial and food security implications by destroying approximately 25-45% of worldwide crop yield every year (Arya 2021).

Global warming is exacerbating the spread of crop infections and intensifying the severity of illnesses in affected areas (Arya 2021). The microbiome structure and activity in soils used for farming and plant communities are influenced by increasing temperatures, changing precipitation trends, and severe storms. Greenhouse investigations have discovered that even a minor increase in temperature of 1-4°C leads to accelerated reproduction, increased spread, and increased aggressiveness among certain crop diseases that cause economic damage (Maharjan et al. 2022). Extreme weather conditions such as flooding, drought, and heat waves can weaken plant immunity, making crops susceptible to opportunistic disease attacks. An instance of this is the oomycete *Phytophthora infestans*, which is accountable for causing severe late blight in potato and tomato crops. Due to increasing temperatures, this organism has extended its geographical distribution in recent decades (Zoran et al. 2022). Drought circumstances worsen the proliferation of aflatoxin-producing by Fusarium fungi in significant crops such as corn, grains, and rice throughout their growth and storage phases (Surendar et al. 2024). The inventory of overwintering infection for rice blast fungi is expected to increase twofold in temperate regions due to warming temperatures, which allows for survival during milder winters (Jones 2021).

Small-scale farmers in Asia and Latin America will face significant challenges due to the escalating impact of plant illnesses caused by warming temperatures (Kozicka et al. 2020). These farmers frequently cultivate unproductive fields with exhausted soils, utilizing stored seeds with poor genetic resilience. Farms and ranches may be resilient if they can adapt to changing circumstances and emerge stronger than before. A resilient agricultural system can withstand and even thrive in dealing with of the numerous modern-day challenges to the environment, economy, society, and institutions.

Subsistence-oriented agricultural production is a limited safeguard against possible insect or weather disturbances that could significantly reduce crop yields (Radhika & Masood 2022). Because pathogenic plants are becoming more damaging as a result of rising temperatures, the advantages of increasing the production of disease-free crops are being exceeded (Singh et al. 2023). It is crucial to urgently create comprehensive advancements encompassing predictive modelling, gadgets, diagnostics, and crop genomics to enhance plants' ability to resist diseases, particularly in small-scale farming operations in poor countries with Smart Agriculture (SA). Moreover, data generation in agriculture and biotechnology has greatly increased in recent years due to the very rapid development of high-performance technologies (Mohammadabadi et al. 2024). These data are obtained from studying products, foods, diseases, and biological molecules, such as metabolites, proteins, RNA, and DNA, to understand the role of these products and molecules in determining the structure, function, and dynamics of living systems (Pour Hamidi et al. 2017). Functional genomics is a field of research that aims to characterize the function and interaction of all the major components (DNA, RNA, proteins, and metabolites, along with their modifications) that contribute to the set of observable characteristics of a cell or individual (i.e., phenotype). Artificial neural networks have been proposed to alleviate this limitation of traditional regression methods and can be used to handle nonlinear and complex data, even when the data is imprecise and noisy (Pour Hamidi et al. 2017). Agricultural data can be too large and complex to handle through visual analysis or statistical correlations. This has encouraged the use of machine intelligence or artificial intelligence (Ghotbaldini et al. 2019). Thus, this review aimed to find out the recent studies on smart agriculture.

History

In recent years, there has been a rapid advancement in the creation of sensors and wireless sensor networks (WSN) designed explicitly for agriculture (Adday et al. 2022). Sensors are used to track signs of crop well-being and the conditions of the surroundings. These sensors are connected wirelessly in networks, allowing for broader coverage across different locations. They automatically gather data and send it to cloud libraries. It is dependent upon the field's plant diversity. To arrange varied monitoring rates and monitor plant diseases, we typically need 20 sensors per acre of land. The number of sensors may be cut in half if the plant is homogeneous. Because micro-fluidic biosensors are less expensive to install, small farmers would also benefit from them. In the field, these biosensors are inexpensive, require minimal knowledge, and quickly identify the pathogens of concern. Additionally, the biosensors are very sensitive and focused.

Real-time analysis of this data is done from both the detectors and the cloud. Analytical capabilities in the cloud provide many of the same benefits as those in on-premises data analytics. In contrast to hosting everything in-house, cloud analytics allows users to construct, implement, scale, and manage data analytics in the cloud using another party's infrastructure.

These methods offer unparalleled accuracy in space and time to simulate, monitor, and address the occurrence of new plant disease outbreaks (Jones 2021). Microfluidics' adaptable architecture has made it possible to detect plant diseases quickly, accurately, and affordably. Early identification of traces of pathogens is made possible by integrating modules for separation, preconcentration, amplification, and detection, which improves crop protection.

Standard sensor types used in agriculture include optical detectors, thermal detectors, electrochemical detectors, location detectors, aerial detectors, and soil monitors. In agriculture, keep an eye on and manage environmental variables and plant conditions. WSNs are useful for:

Field monitoring: WSNs may assist farmers in keeping an eye on their fields to boost agricultural yields and guard against damage.

Irrigation control: WSNs have the ability to regulate irrigation.

Identify plant disease: By identifying plant diseases early on, WSNs may reduce the need for pesticides.

Evaluate plant condition: WSNs may be used to evaluate greenhouse climate and plant condition. These devices can monitor several plant health metrics such as crop canopy temperatures, moisture anxiety (Deficiency of wetness in plant cells causes abiotic stress), evapotranspiration paces, nutrient stages (growing plants' nutritional demands), leaf area measures, soil mineral stages (Plant nutrition depends on soil minerals at different stages), and pest species or signs of damage (Angin et al. 2020). Independent WSNs may collect data from many places for further analysis (Nabi et al. 2022).

Several WSN-based early detection methods for crop disease have lately emerged. Barreto et al. integrated spectral detectors and Machine Learning (ML) techniques to achieve early identification of sugar beet illnesses (Barreto et al. 2020). The WSN data was used to produce indicators of vegetation, which were then used as training inputs (sensor data) for Support Vector Machine (SVM) and Neural Network (NN) classifications. Both SVM and CNN are machine learning techniques used for classification. In agriculture, computer vision-enabled systems can identify and classify plant diseases using various extracted features or symptoms. It follows a well-defined set of procedures, starting with image capture and moving on to different image-processing tasks including scaling, filtering, segmentation, feature extraction, and selection. Lastly, various algorithms are used for detection and classification.

These classifications were used to distinguish between typical plants and plants infected with fungus or virus diseases (Camgözlü & Kutlu 2023).

Wagg et al. created a method using ML to identify potato bloom early (Wagg et al. 2021). Zigbee creates personal area networks using low-power, low-cost, and lightweight digital radios. Specialized for short-range use. A Zigbee WSN of 15 nodes was utilized to monitor crucial environmental factors in potato fields, including humidity, precipitation, wind velocity, and leaf dryness. The information is inputted into a NN framework to forecast the degrees of illness severity and the likelihood of an epidemic. Location-related information enhanced the ability to target controlling illnesses at particular spots.

Multiple studies have investigated using Uncrewed Aerial Vehicles (UAVs) for aerial satellite imagery to map the evolution of agricultural diseases (Del Cerro et al. 2021). Neupane et al. employed a UAV equipped with RGB (Red, Green, Blue), hyperspectral, and thermal imaging technology and ML to identify several crop diseases in small-scale farms throughout Bangladesh (Neupane & Baysal-Gurel 2021). The crops targeted for disease detection included carrots, tomatoes, potatoes, and grain. Random forest networks trained with disease-specific parameters classified over 90% of data.

WSNs detect plants' health and measure the atmosphere factors that impact the growth and transmission of pathogens, such as temperatures, humidity, rainfall, and leaf wetness. The

Internet of Things (loT) software can incorporate this data into field-specific epidemiological simulations to provide information for warning systems and predictions of epidemic risks (Dhanaraju et al. 2022). This application collected sensor information from approximately 40 industrial vineyards in the local meso-network (A local meso-network might be a brain network or networked governance system). Weather surveillance and disease prediction algorithms accurately estimated the likelihood of bacterial and fungal infections such as powdery mildew, downy mildew, and black rot (plant diseases) (Nabeesab Mamdapur et al. 2019). These models guided where and when to apply fungicides, resulting in a significant reduction of approximately 20 percent in spraying required. This spraying decrease did not reduce disease incidence or severity.

These sensor systems offer detailed and precise crop health data regarding space and time to enhance the understanding, modelling, prediction, and management of plant disease development. When combined with Micro-Fluidic (MF) detection equipment with Agricultural Bio-Technology (ABT), as explained in the following section, they provide quick on-site identification of pathogens to validate the results of predictive models.

WSN-based plant pathogens detection

Another development used an MF instrument integrated with implanted optical fibers to identify virus-infected *Phalaenopsis amabilis* plants and blossoms. The MF stirring device was fabricated using Polydimethylsiloxane, and fiber optics were incorporated into it to enhance the light emitted for identification. The gadget could do RNA separation and processing in SA. The process of amplifying nucleic acid was utilized for reverse transcription loop-mediated isothermal amplification. An experiment was conducted to investigate the transmission of Capsicum chlorosis tospovirus on pepper plants, serving as an illustrative example. The early version of a portable MF method utilizes a thin-film amorphous silicon photoreceptor to measure transmission by visual transmission by altering the resistors in the wiring. This technique enables the sensor to provide readings in both medium and low light circumstances. In a portable configuration, the device could measure currents as small as 10 to 13 A. The system can control a peristaltic pump for MF movement within the channel and a Light-Emitting Diode (LED) light generator. It was employed in a bioassay to demonstrate the prototype's functionality in the portable identification of fungal infections in plants. Figure 1 displays a fundamental diagram of an MF technology that identifies phytopathogens with ABT.

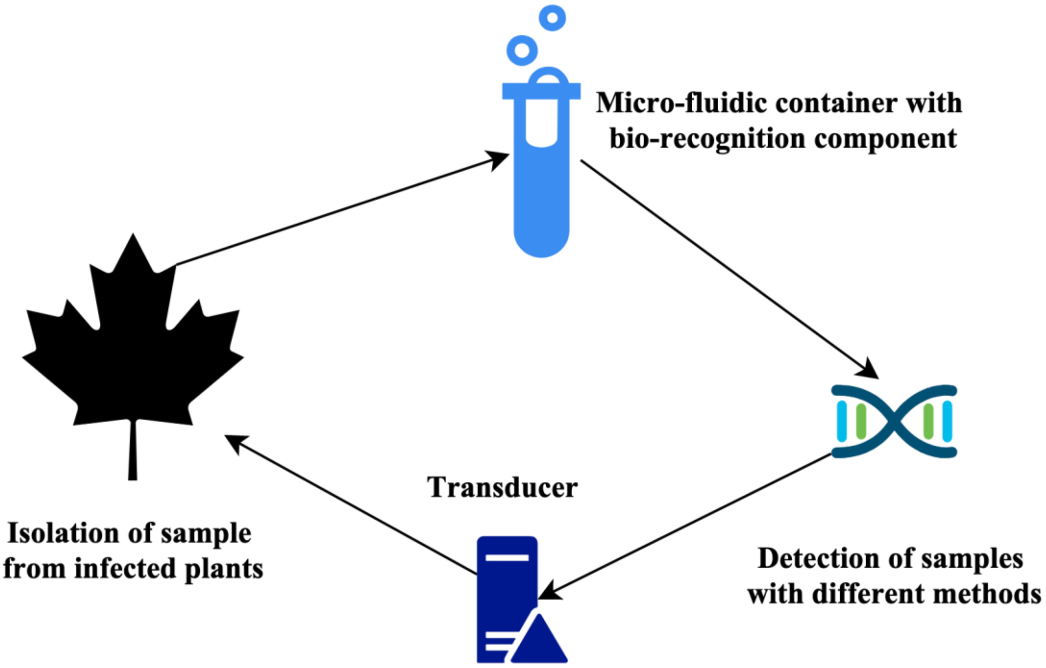

Figure 1. Pathogen detection process

The advantages of MF plant biosensors and WSNs are highly compatible with SA. The integration of these innovations can streamline operations and identify crop diseases in real time throughout farming operations. This article showcases notable instances of interconnected MF devices tracking plant pathogens.

MF DNA Detectors with WSN

A WSN incorporating modular MF DNA biosensors was implemented to identify *Ralstonia solanacearum*, the pathogen responsible for bacterial wilt in crops such as tomatoes and tubers (Pour Hamidi et al. 2017). The MF device utilizes loop-mediated isothermal amplifiers with ABT to identify pathogen DNA in soil specimens (Dhanaraju et al. 2022).

The sensor nodes transmit detection findings and positions to a base station using wireless communication. The WSN can continuously monitor the presence of bacteria and wilt infections at many locations in the field, providing real-time data. This enables the WSN to function as a system for early warning. Automated functioning decreases the need for manual labor and allows for rapid installation of quarantine or therapeutic measures to restrict the spread of illnesses. A kind of control to stop the spread of diseases and pests is quarantine. It includes any legal measures used to keep plant or animal diseases or pests out of a location, region, nation, or collection of nations. This method of using a networked MF system for monitoring could be expanded to include different types of pathogens found in the soil or within the vascular systems of plants.

Utilizing Drone-based MF Tests

UAVs or drones fitted with microfluidic analyzers provide swift inspection and evaluation of crops. A recent study employed a UAV, a drone, to conduct Enzyme-Linked Immunosorbent Assay (ELISA) tests to detect plant viruses. Leaf samples afflicted with illness were obtained via drone from a wheat field and placed into single-use MF chips containing pre-determined substances. The drone conducted the immunoassay while flying and sent the image-based findings to the landowner for each sampling area using SA. Compared to time-consuming manual inspections, this satellite imaging approach enables rapid assessment over extensive areas. Utilizing drones for MF tests could aid in detecting initial infection with virus sites, allowing for prompt containment measures. The utilization of drones for both collecting and on-site analysis instead of sample transfer leads to a decrease in cost. MF tests could be integrated with advanced UAV sensing capacities, such as hyper-spectral photography.

WSN for Parallel MF Biosensor

A sophisticated, adaptable WSN system was created to identify many plant diseases simultaneously. The system comprises a central node that is linked to a farm server, as well as several WSN nodes that are scattered throughout. Every node contains MF slots that can accommodate interchangeable test sections, which have been initially tested using ELISA and genetic assays. Automated pumping transports extracts from plants or chemicals to many interconnected MF instruments.

Nodes and servers can regulate and share information in real-time. It is possible to perform automated, simultaneous testing of a single sample against several diseases. The adaptable "lab-on-a-node" framework enables the efficient implementation of various MF biosensors across extensive and diverse farms. The flexible capacity could facilitate coordinated pest and illness management through multifactor surveillance.

Key Considerations

- The WSN nodes for SA are typically 100-300 meters, using protocols such as ZigBee, Bluetooth connectivity, or WiFi. To provide coverage over expansive areas, it is necessary to utilize range extension nodes or implement mesh networking.
- Minimizing replacing batteries in remote nodes is crucial for optimizing network power. Energy harvesting methods such as solar and vibrational power and low-power gadgets contribute to sustaining continuous operation.

- The seamless connection between the hydrodynamic assays and the WSN node is crucial for the MF interface. Interchangeable fluidic test components and nodes can be connected using standard interactions, enabling flexible and adaptable installation of WSNs.
- Handling fluids can be automated using MF valves, controls, and mixing. This allows for automatic sampling, loading of reagents, and analysis once microchips are put into the wireless terminals.
- Using standards and calibrating techniques in qualitative sensing improves the processing of signals from MF biosensors, allowing for accurate measurement of pathogens in field specimens.
- Protective enclosures ensure that WSN nodes and tiny pumps can function effectively under challenging environmental circumstances such as dust, winds, drizzle, and severe temperatures.

Challenges and Future Scope

Integrating MF and WSNs in SA presents numerous prospects and technical and adoption hurdles in ABT. Continued MF advancements are necessary, encompassing advanced, dependable methods for detecting infections in their early stages. Existing MF biosensors face difficulty detecting exceedingly low pathogen levels, especially during subclinical phases. Enhanced sensitivity can be achieved by utilizing amplifier nanoparticles or preconcentration techniques, which can assist in the early detection of pre-symptomatic individuals.

Multiplexed assays enable the simultaneous detection of many threats in a panel. Most MF plant disease sensors are limited to detecting only one specific type of pathogen. By utilizing multiplexed evaluation, it becomes possible to analyze a single sample for a wide range of organisms, such as fungi, viruses, and bacteria, simultaneously. It is possible to achieve this using multitarget antibodies, distributed DNA detectors, and several indicator dyes.

- Rapid and flexible modular designs suitable for emerging diseases: The rapid development of detection techniques is necessary for outbreaks of novel diseases. Modular MF elements, such as plug-and-play biosensors, can expedite adapting existing chips to address emerging risks.
- Effortless and automated connection with WSNs: MF plant sensing should be immediately included with WSN nodes using standard physical and data interchange connectors. This enables the versatile deployment of fields and data analysis in real-time.
- Long-lasting chips with extended lifetime that eliminate the need for a cold chain: MF chips require refrigerators. Utilizing desiccated and preserved reagents and heat-resistant

biological sensors would streamline distributing, storing, and using them in distant SA areas.

To ensure efficient execution in the field, it is essential to take into account the following factors:

Optimizing the coverage, strength, and cost of WSNs: Optimal WSN placement yields valuable information with excellent resolution, albeit at an elevated price. Efficiently balancing the distribution of resources to ensure connectivity, meet power requests, and maximize the value of sensing sites is necessary.

Integration and information interchange with SA equipment and structures: WSNs for plant illnesses should connect with machinery used for fertilization, watering, spraying, and gathering to coordinate disease management measures. Application Programming Interfaces (API) and information protocols facilitate connectivity with farm administration software.

Methods for ensuring and maintaining the quality of products, processes, and equipment, including techniques for calibration and diagnosis. Effective operation of connected MF instruments necessitates implementing evaluating, setting up, and upkeep procedures. Efficiency is monitored using onboard quality control and validation specimens.

Diagnostic techniques that identify damaged nodes help reduce the occurrence of incorrect information.

Organizational structures about the provision and maintenance of technology: To successfully commercialize their products, companies that offer MF chips, substances, WSN nodes, and software to farmers need to establish viable business models. Possible choices encompass selling consumable goods, leasing hardware, offering sensing services as a subscription, and providing suggestions based on data.

Providing training to producers on surveillance and making choices is essential for adopting plant pathogen surveillance and implementing appropriate actions. WSN analysis and farm managers are necessary for delivering agronomic recommendations.

Ensuring SA sensor data's security, confidentiality, and ownership is paramount. Blockchain or distributed databases have the potential to enhance the transparency of information, confidentiality, and legal ownership.

To achieve widespread use, the expenses of connected MF surveillance must be competitive with manual scouting. The pricing of MF and WSN elements will decrease due to the implementation of large-scale production and competitive distribution networks.

Additional field testing is necessary to evaluate performance in real-world conditions, mainly when dealing with extensive scales, including several nodes and MF detectors spread across vast

ABT areas. Solutions formulated in controlled contexts need more reliability when confronted with unanticipated circumstances such as severe weather. Sensors necessitate durable packaging and ample redundancies.

Notwithstanding these obstacles, the expansion of interconnected SA is gaining momentum on a global scale. WSNs facilitate data transmission with various agricultural machinery, watering systems, drones, livestock tags, and other devices, propelling the development of the IoT.

With the decreasing prices and increasing interoperability of systems, adopting data-driven precision farming will become widespread. By addressing the critical technological and operational obstacles discussed, integrating MF with connected devices can contribute to achieving the goal of intelligent, programmed, and highly efficient agricultural production to ensure future food supplies.

Conclusions: Data-driven solutions in SA can enhance agricultural output and reduce environmental impact significantly. Harnessing this potential necessitates inventive remedies for enduring the constraints of farm methodologies. The conventional plant pathogen identification and treatment field needs modernization through ABT implementation. This research highlights the convergence of developing MF biosensors and WSNs, facilitating a novel approach to automated, instantaneously in-field crop disease surveillance. Plant infections have a substantial negative impact on agricultural production globally. The delayed and labor-intensive nature of conventional diagnostic procedures hinders the ability to control these diseases effectively. Scouting conducted by skilled personnel needs to exhibit more precision, promptness, and extent of coverage.

WSNs provide significant advantages for SA by enabling data collection from WSN in real-time across a large region. Nodes equipped with sensors, Central Processing Units (CPUs), and radios can be dispersed over fields to provide comprehensive and precise spatiotemporal surveillance that would be impractical to accomplish physically. This allows for identifying favorable circumstances for illness and early detection of diseases before any visible symptoms appear. The benefits of WSNs include decreased labor requirements, increased flexibility, enhanced decision-making assistance, automated processes, and early detection of issues through continuous evaluation.

Combined MF biosensors and wireless sensor networks are becoming increasingly recognized as a highly intriguing platform for SA. They can offer comprehensive and automated crop surveillance to identify diseases early and promptly respond to them. Networked MF detectors have the potential to change significantly data-driven, site-specific control of diseases in agriculture as part of the digital shift. The advancements mentioned are the initial stages of a technological field that holds immense potential advantages for farming, dietary safety, and the responsible management of the planet's valuable water and land assets.

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چکیده

هدف: کشاورزی هوشمند (SA) یک روش انقلابی برای کشاورزی است که با استفاده از فناوری‌های پیشرفته مانند حسگرها، ربات‌ها و تجزیه و تحلیل داده‌ها، بهره‌وری محصول را به حداکثر می‌رساند و آسیب‌های زیست‌محیطی را کاهش می‌دهد. با استفاده کمتر از آفت کش‌ها، کودها و سایر موادی که به اکوسیستم ها آسیب می رسانند، کشاورزی هوشمند به دنبال افزایش راندمان تولید و سازگاری بیشتر روش های کشاورزی با محیط زیست است. ترکیب شبکه‌های حسگر بی‌سیم (WSN) با فناوری‌های میکروسیال آزمایشگاهی روی یک تراشه برای نظارت و مدیریت بلادرنگ سلامت گیاه یکی از جدیدترین پیشرفت‌ها در SA است.

نتایج: بیوتکنولوژی کشاورزی (ABT) در ارتباط با آشکارسازهای میکروسیال شبکه‌ای ممکن است شناسایی و کنترل بیماری‌های گیاهی را بهبود بخشد. این حسگرهای زیستی می‌توانند حتی سطوح کمی از پاتوژن‌ها را در بافت‌های گیاهی یا نمونه‌های محیطی شناسایی کنند زیرا بسیار حساس، ارزان و قابل حمل هستند. روش‌های کشاورزی دقیق و تصویری کامل از انتشار بیماری با ادغام این حسگرهای زیستی در یک شبکه حسگر بی‌سیم (WSN) امکان‌پذیر می‌شود، که اجازه می‌دهد داده‌ها به صورت بی‌سیم به یک سرور مرکزی برای تجزیه و تحلیل بلادرنگ ارسال شوند.

نتیجه‌گیری: به منظور شناسایی بیماری‌های گیاهی، سیستم‌های کشاورزی سنتی اغلب به تکنیک‌های زمان‌بر از جمله بازرسی‌های بصری، نمونه‌برداری دستی و آزمایش‌های آزمایشگاهی تشخیصی وابسته هستند. بیوسنسورهای میکروسیال روشی سریعتر و دقیقتر برای تشخیص بیماری‌های گیاهی به صورت محلی و در زمان واقعی ارائه می‌دهند. این فناوری‌ها، هنگامی که با شبکه‌های حسگر بی‌سیم (WSN) ادغام می‌شوند، چارچوبی مؤثر برای پایش مداوم سلامت گیاه فراهم می‌کنند و به کشاورزان اجازه می‌دهند بیماری‌ها را زود تشخیص دهند و اقدامات فوری را انجام دهند.

واژه‌های کلیدی: بیوتکنولوژی کشاورزی، پاتوژن های گیاهی، شبکه های حسگر بی سیم، کشاورزی هوشمند

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