Biological Forum – An International Journal 15(9): 649-659(2023)

ISSN No. (Print): 0975-1130
ISSN No. (Online): 2249-3239

Innovative Plant Disease Monitoring Technologies

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(Received: 03 July 2023; Revised: 02 August 2023; Accepted: 30 August 2023; Published: 15 September 2023)
(Published by Research Trend)

ABSTRACT: The prevalence of plant diseases has significantly expanded as a result of human activities. Currently, the presence of pathogens in food results in a decrease in crop productivity, compromised product quality, diminished economic worth, and reduced financial gains. Therefore, the focus in plant pathology has shifted towards the importance of early detection and the development of diagnostic methods that are fast, accurate, and cost-effective. This emphasis is particularly relevant for emerging diseases or challenging infections that are transmitted by asymptomatic individuals exhibiting minor first signs, making them difficult to effectively manage. The utilization of cutting-edge tools designed for field usage is emerging as a crucial area of focus for diagnostic laboratories operating in a globalized market that is highly responsive to epidemics. This emphasis on developing instruments and methods that are suitable for operational conditions aims to ensure their effectiveness and practicality. The inclusion of portable systems and Internet of Things (IoT) connectivity plays a vital role in the overall design of this architecture. In this paper, we examine diagnostic approaches in agriculture that are based on nanotechnology, as well as explore emerging perspectives on the utilization of information and communication technology (ICT) in the agricultural sector. These advancements have the potential to enhance agricultural and rural development, while also revolutionizing the approach to combating phytopathogens through proactive measures.

Keywords: Diseases, early detection, pathogens and nanotechnology.

INTRODUCTION

The necessity for strong plant pathogen diagnosis technology has been emphasized by recent epidemics, particularly in the context of climate change and increased worldwide trade (Buja *et al.*, 2021). Numerous hazardous "alien" species, encompassing viruses, phytoplasmas, bacteria, fungi, insects, nematodes, and weeds, have a global distribution facilitated by human activities and the movement of goods, including plant materials. This widespread dispersal of such species poses significant challenges to agricultural systems. Consequently, the timely detection of plant pathogens has become progressively crucial in the surveillance of plant health, enabling the effective management of disease infections at various stages of growth and the mitigation of disease transmission (Anderson *et al*., 2014; Brasier *et al*., 2008; Miller *et al*., 2009; Strange *et al*., 2005). According to the Food and Agriculture Organization (FAO), it has been estimated that pests are responsible for causing damage to around 20% to 40% of agricultural production worldwide. This includes significant losses in crops such as rice, wheat, corn, potatoes, soy, and cotton, occurring at both national and regional scales across many continents (Oerke *et al*., 1994, 2006). According to Savary *et al*. (2019), regions experiencing food insecurity, characterized by the presence of emerging and re-emerging pests and diseases, tend to suffer from higher crop losses. Conversely, regions with food surpluses generally have lower levels of crop loss. An examination of the ten most significant pathogens. The references provided include the works of Mansfield *et al*. (2012), Dean *et al*. (2012), Rybicki *et al*. (2015); Scholthof *et al*. (2011). The European Commission has recently published a catalogue of 20 quarantine species that have been identified as having significant impacts on crop productivity, trade and regulatory expenses, employment rates, food safety and availability, landscapes, and biodiversity. These organisms have been identified as key areas of concern for the European Union Member States. In the previous decade, the European Union has seen numerous significant instances of infectious epidemics caused by novel plant pests, resulting in substantial consequences. *Xylella fastidiosa*, classified as a disease of quarantine significance on both the European Union (EU) and the European and Mediterranean Plant Protection Organization (EPPO) lists under category A2, represents a very perilous infection with global implications, owing to its profound morbidity and epidemiological characteristics. *Xylella fastidiosa* subsp. *pauca* strain De Donno has been identified as the causative agent of the quick decline syndrome observed in olive trees located in the Salento peninsula of Italy

(Saponari *et al*., 2013). This strain has exhibited a rapid dissemination throughout southern Italy (Region, 2020), resulting in extensive landscape devastation. The primary means of transmission for this pathogen is the meadow bug *Philaenus spumarius*. *Xylella fastidiosa* affects multiple species (Janse *et al*., 2010), and the initial symptoms manifest several months following infection (Martelli *et al*., 2016), hence facilitating the covert dissemination of the disease. Extensive research on the disease has been conducted in the United States for over a century. However, despite these efforts, no effective therapeutic interventions have been developed. Furthermore, the presence of several genotypes of the bacteria in Italy, France, and Spain has emerged as a significant concern, posing a substantial risk to the Mediterranean basin and other European areas (Sicard *et al*., 2018). An additional illustration may be found in the mushroom species *Hymenoscyphus fraxineus*, which has resulted in extensive harm and a significant fatality rate among ash (*Fraxinus excelsior*) communities in Europe for a duration exceeding two decades. Moreover, this species is progressively expanding its range to include Norway, the United Kingdom, Ireland, France, and Italy (Coker *et al*., 2019).

International initiatives aimed at managing the dissemination of pests encompass the regulations established by the Commission on Phytosanitary Measures (IPCC, 2020) as well as the comprehensive phytosanitary surveillance conducted by the European Food Safety Authority (EFSA) and the European and Mediterranean Plant Protection Organization (EPPO). From a diagnostic standpoint, there is a pressing need for more action to effectively mitigate the global spread of dangerous organisms. Nezhad *et al*. (2021) propose the development of portable devices capable of simultaneously detecting many phytopathogens. These devices should possess characteristics such as rapid reaction time, ability to handle heterogeneous and complex analyses, and user-friendly convenience. The lowering of analysis costs is an additional crucial criterion in monitoring programs due to the substantial number of plants involved. The implementation of on-field molecular techniques could effectively decrease decision-making durations, hence mitigating the transfer of pathogens to neighboring plants or previously unaffected areas. This overview will encompass the prevalent plant diagnostic approaches, followed by an examination of developing sensors that have the potential to significantly transform the field of phytopathology.

PLANT PATHOLOGY TECHNOLOGIES

A. Sensor Platforms on-field

The development of sensor platforms has been driven by the demand for technologies that are rapid, cost-effective, and user-friendly. These platforms have been designed to detect target pathogens without the need for labeling, offering high levels of sensitivity and specificity. As a result, they have the potential to circumvent conventional diagnostic methods and the expertise of trained scientists (Buja *et al*., 2021). The utilization of a quartz crystal microbalance (QCM) and the measurement of mass change resonance frequency to detect Maize chlorotic mottle virus (MCMV) represents an instance of label-free detection (Huang *et al*., 2014; Sauerbrey *et al*., 1959). The researchers employed a self-assembled monolayer (SAM) functionalized with MCMV-specific antibodies for the purpose of detecting a concentration of 250 ng mL-1. The sensitivity of this test is comparable to that of the ELISA test, and it offers additional advantages such as ease of use, affordability, rapidity, heightened sensitivity, and real-time applicability (Montagut *et al*., 2011). The study conducted by Lin *et al*. (2014) employed surface plasmon resonance (SPR) as a technique to observe alterations in the refractive index of the sensor surface resulting from the presence of the analyte in solution and a ligand that was immobilized. The researchers employed gold nanorods (AuNRs) that were modified with antibodies targeting two distinct orchid viruses, namely Cymbidium mosaic virus (CymMV) and Odontoglossum ringspot virus (ORSV). The detection limits achieved for both viruses were 48 and 42 pg mL^{-1}, respectively, which is significantly lower than the ELISA value of 1200 pg mL^{-1} for both viruses. Surface-enhanced Raman spectroscopy (SERS) has the potential to detect and identify unique chemical signatures. The detection of Alternaria mycotoxins in pear fruit at a concentration of 1.30 g/L was achieved using silver nanoparticles (AgNPs) according to a study conducted by Pan *et al*. in 2018. Surface-enhanced Raman spectroscopy (SERS) exhibited superior performance compared to high-performance liquid chromatography (HPLC) in terms of accuracy, sensitivity, speed, and limit of detection (LOD).

The utilization of electrochemical impedance spectroscopy (EIS) sensors has been demonstrated by Katz *et al*. (2003) for the purpose of detecting plant viruses and illnesses within the field of plant and agriculture sciences, as highlighted by Jocsak *et al*. (2019). The technique of Electrochemical Impedance Spectroscopy (EIS) is highly advantageous for on-field examination due to its simplicity and sensitivity. It enables rapid response without causing sample destruction. Additionally, the availability of portable readers allows for monitoring of device impedance alterations when target analytes are detected. In a recent study by Khater *et al*. (2019), a DNA hybridization sensor utilizing screen-printed carbon electrodes that were modified with gold nanoparticles (AuNPs) was developed. This sensor demonstrated the ability to selectively detect Citrus tristeza virus (CTV), even in the presence of other non-specific DNAs. This capability is particularly valuable in the context of mixed infections, which are frequently observed in cultivated plants. In the study conducted by Jarocka *et al*. (2011), a discerning electrochemical immunosensor was developed for the purpose of detecting Plum pox virus (PPV). This immunosensor utilized colloidal gold nanoparticles as a means of immobilizing antibodies within extracts derived from plum (*Prunus domestica*) and tobacco (*Nicotiana benthamiana*) leaves. The sensor exhibits a highly favorable detection limit of 10 picograms per milliliter (pg/mL) and a dynamic range spanning from 10 to 200 pg/mL for viral detection. This enables the differentiation between healthy plant samples and those contaminated by 0.01% extract derived from infected plant material. In a study conducted by Jarocka *et al*. (2013), a research team successfully designed a platform for the detection of *Prunus* necrotic ringspot virus (PNRSV) using glassy carbon electrodes as both platforms and transducers. In addition to viruses, bacteria can be identified. Therefore, a biochip utilizing electrochemical impedance for the detection of *Xylella fastidiosa*. According to a recent study conducted by Chiriaco *et al*. (2018), there have been reports of the presence of the pauca strain De Donno in olive trees. These reports indicate that the strain has been found in both naturally infected trees and in plants that show no symptoms of infection. This approach could potentially be employed for the monitoring and testing of olive trees in field conditions due to its moderate sensitivity, which falls between that of the Enzyme-Linked Immunosorbent Assay (ELISA) and quantitative Polymerase Chain Reaction (qPCR) methods.

B. Volatile Organic Compounds

The quantification of volatile organic compounds (VOCs) serves as an indirect approach for the identification of plant pathogens, as these compounds are generated and emitted by plants as a means of defense (Scala *et al*., 2013). Plant volatile organic compounds (VOCs) encompass biomolecules and metabolites that possess notable characteristics such as high vapor pressure, low boiling point, and low molecular weight. According to Baldwin *et al*. (2006), plants release a variety of volatile organic compounds (VOCs) that play crucial roles in their growth, defensive mechanisms, survival, and inter-plant communication. Pathogenic diseases have the capability to emit distinct volatile organic compounds (VOCs) that serve as indicators of the physiological well being of plants. These VOCs can be harnessed for the purpose of non-invasive disease surveillance. Volatile organic compound (VOC) profiling is increasingly recognized as a valuable technique for plant disease diagnosis due to its non-destructive nature, rapidity, high sensitivity, and absence of chemical interventions. Conventional approaches for detecting volatile organic compounds (VOCs) often employ gas chromatography–mass spectrometry (GC–MS) (Cellini *et al*., 2016; De Lacy Costello *et al*., 2001; Ewen *et al*., 2004; Spadafora *et al*., 2016). However, this approach is characterized by its complexity, time-consuming nature, high cost, large size, and the need for considerable training (Sharma *et al*., 2019). The literature discusses current advancements in the monitoring of volatile organic compounds (VOCs) as described by Fang *et al*. (2015), Martinelli *et al*. (2015); Sanati Nezhad *et al*. (2014); Sankaran *et al*. (2010). Electronic noses (ENs) are efficient, straightforward, and well-suited for the detection of volatile organic compounds (VOCs). According to Wilson *et al*. (2018), EN is a cost-effective and expeditious alternative to GC-MS in several applications due to its non-invasive nature. The system described incorporates a multimodal array, an artificial neural network information-processing unit, software equipped with digital pattern-recognition algorithms, and reference-library databases in order to replicate the olfactory capabilities of humans (Persaud *et al*., 1982). The technology under consideration exhibits a wide range of applications, encompassing sectors such as agriculture and forestry (Wilson *et al*., 2018), plant pest monitoring (Laothawornkitkul *et al*., 2008), food quality assessment (Ampuero *et al*., 2003; Peris *et al*., 2009), and the automotive industry (Kalman *et al*., 2000). However, it is important to acknowledge that certain limitations persist, such as the challenge of detecting signals in open fields due to atmospheric interference, necessitating the need for further enhancements (Cui *et al*., 2018). According to Sharma *et al*. (2019), the implementation of a completely automated portable gas chromatography (GC) equipment for on-site analysis effectively removed a significant number of limitations. The equipment, weighing 4.5 kilograms, operates independently to gather and analyze samples. It utilizes a machine learning system to interpret data obtained from gas chromatography. The research encompassed a sample size of ten milkweed plants, specifically *Asclepias syriaca*. Half of the plants were infested with aphids. A total of thirty-five volatile organic compound (VOC) peaks were successfully separated and detected within a span of eight minutes. This achievement showcases a remarkable accuracy range of 90-100% in effectively discriminating between healthy and diseased plants. Moreover, this discrimination may be achieved within a relatively short time frame of 48-72 hours following the onset of the attack, which is notably 3-4 days sooner than the findings of previous studies.

In a study conducted by Chanupowicz *et al*. (2020), bacteria's luminescent responses to volatile organic compounds (VOCs) were utilized to develop a biosensor based on entire cells. The objective of this biosensor was to detect the presence of *Penicillium digitatum* in oranges. In this study, *E. coli* strains were cultured in alginate beads and subjected to a two-hour incubation period with fruit within a hermetically sealed container. Subsequently, the beads were transferred to a 96-well plate for the purpose of measuring bioluminescence using a plate reader. Buja *et al*. (2021) reported that on the third day of infection, four bioluminescent strains of *Escherichia coli* were able to detect fungal activity prior to the manifestation of visible symptoms in oranges. This phenomenon is plausible due to the ability of the bioluminescent strain to perceive alterations in volatile organic compound (VOC) profiles. Consequently, it can be utilized to enhance postharvest orange management by the integration of bioreporters in field-operable real-time equipment.

A recent study by Wang *et al*. (2019) introduced a novel electrical biosensor array that utilizes single-walled carbon nanotubes (SWNTs) modified with single-stranded DNA (ssDNA) for the purpose of detecting four volatile organic compounds (VOCs) - ethylhexanol, linalool, tetradecene, and phenylacetaldehyde. These VOCs are emitted by citrus trees infected with Huanglongbing during the asymptomatic stage of the disease. Various mathematical models have been developed to differentiate volatile organic compound (VOC) species and their concentrations. The introduction of single-stranded DNA (ssDNA) functionalization addresses the issue of limited selectivity in sensors based on single-walled carbon nanotubes (SWNTs), as discussed by Spaii *et al*., (2005). This functionalization enables the discrimination of various odors by these sensors, while also exhibiting fast reaction and recovery durations. The devices incorporating single-stranded DNA (ssDNA) and single-walled carbon nanotubes (SWNTs) exhibit enhanced sensitivity and repeatability compared to SWNTs alone within the range of analyte concentrations that have been validated. The deployment of this approach in practical settings remains hard due to its lack of specificity. Consequently, scientists have proposed a shift in focus towards the detection of real-time volatile organic compound (VOC) combinations emitted by diseased citrus trees.

In a recent study conducted by Li *et al*. (2019), it was demonstrated that non-invasive diagnosis of late blight, caused by *Phytophthora infestans*, may be achieved by smartphone-based leaf volatile fingerprinting. The study focused on the development of high-sensitivity plasmonic nanoparticles that specifically targeted green leafy aldehyde, also known as (E)-2-hexenal, which is a main marker for late blight. The nanomaterials were able to detect this marker at levels below one part per million, indicating a very low limit of detection. A disease detection algorithm, exhibiting a 95% accuracy rate, successfully identified 10 distinct plant volatiles present in both laboratory-inoculated and field-collected tomato leaves. This algorithmic approach enables the diagnosis of diseases at an earlier stage, prior to the manifestation of visible symptoms. Volatile organic compounds (VOCs) have the potential to serve as indicators of the presence of sickness, although they do not possess the capability to identify specific pathogens. The subsequent sections provide an introduction to wearable sensors and Internet of Things (IoT) technologies in the context of online plant disease monitoring.

C. Microfluidic Devices

According to McDonald *et al*. (2000), microfluidics offers the advantage of providing rapid and uncomplicated sample-in-response-out techniques, utilizing minimal sample volumes, and facilitating the integration of sample preparation, reaction, separation, and detection inside a single tiny system. The development of lab-on-a-chip (LOC) devices has experienced significant advancements during the 1980s and early 1990s, employing many design tactics and approaches (Ducree *et al*., 2012; Foudeh *et al*., 2012). According to Khandurina *et al*. (2002), microfluidic devices have the capability to efficiently and expeditiously detect chemical and biological targets, hence making them valuable tools in several domains such as therapeutics, environmental monitoring, and food safety. According to Zhang *et al*. (2019), microfluidics has the capability to identify intricate samples, address challenges related to sample purification, and extract substances from a wide range of matrices by employing physical, chemical, and biological methodologies.

Miniaturized polymerase chain reaction (PCR) systems are utilized in several phytopathology applications. The study conducted by Julich *et al*. (2011) demonstrates the efficacy of a Lab-on-a-Chip (LOC) device that combines both polymerase chain reaction (PCR) and hybridization phases within chambers ranging from 12 to 15 liters. This particular LOC has been proven to accurately identify five distinct *Phytophthora* species with a notable level of specificity. Furthermore, the device exhibits a remarkable detection limit of 14.4 femtograms for the target molecule present in the PCR mixture. The chip components are encapsulated within the polymeric microfluidic module, which features leak-proof tubes that direct fluids over the microarray zone. Septa facilitate the aseptic injection of fluid samples and chemicals, while an electrical readout is employed to gather data. The detection of specific *Phytophthora* species was achieved through the utilization of a comparable approach as described by Schwenkbier *et al*. (2015). This involved the implementation of helicase-dependent isothermal amplification (HDA) and on-chip hybridization, wherein silver nanoparticles were employed as a label for both visual and electrical detection. The investigation effectively amplified template DNA derived from *Phytophthora* cells and plants that were subjected to infection. In a separate investigation conducted by Chang *et al*. (2013), an integrated microfluidic system was employed to detect *Phalaenopsis* orchid viruses in fresh leaves through the utilization of LAMP. The device employed magnetic beads, the loop-mediated isothermal amplification (LAMP) reaction, and optical detection based on turbidity to isolate and refine RNA. The fluidic system is equipped with a reaction chamber designed for the purpose of sample, bead hybridization, and RT-LAMP reaction. Additionally, there are three separate chambers dedicated to the storage of LAMP reagents, one chamber for the storage of washing buffer, and finally, one chamber each for positive and negative control, which serve the purpose of quality control. Automatic fluidic transfer is facilitated by the utilization of micropumps, microvalves, and a vacuum pump. The microfluidic loop-mediated isothermal amplification (LAMP) method successfully identified four distinct orchid viruses, namely Cymbidium mosaic virus (CymMV), Odontoglossum ringspot virus (ORSV), Calanthe mosaic virus (CaCV), and Tomato spotted wilt virus (TSWV), exhibiting a detection threshold of 35 picograms. Lin *et al*. (2015) developed a comparable integrated LOC. The proposed methodology does not necessitate the utilization of a substantial gel electrophoresis or fluorescence detecting apparatus, rendering it well-suited for field applications. The detection of RT-LAMP products was accomplished by directly utilizing optical signals that were caused by changes in turbidity and positive amplification on the device. The limit of detection was determined to be 25 femtograms (fg). The feasibility of this achievement was facilitated by the incorporation of an integrated micro-stirring mechanism within the device, as well as the integration of a detection module that utilizes an optical fiber that is concealed within the device. The researchers propose the utilization of an integrated microfluidic system to achieve a rapid, precise, and automated identification of viral pathogens with high sensitivity, completing the process within a time frame of 65 minutes. In the study conducted by Qu *et al*. (2017), the authors employed laser-induced fluorescence detection (LIFD) and thermal denaturation techniques to restore oligonucleotide arrays for the purpose of identifying fungal pathogen DNA. During the process of hybridization and denaturation, the fluorophores of hybridized spots inside the microchannel were stimulated by a green solid-state laser. Subsequently, a cooled CCD camera, along with a low bandpass interference filter, was employed to capture and measure the fluorescence intensity in real-time. The potential regeneration of the arrays presents a cost reduction opportunity and enhances the system's feasibility for detecting multiple samples. However, the utilization of a cooled CCD camera restricts its applicability in field settings.

D. Wearable sensors

Field-exposed plants undergoing pathogen infection are subjected to abiotic stresses such as drought, cold, salinity, or a combination thereof. The biotic stresses are effectively characterized by scientific literature (Korner *et al*., 2003; Morten *et al*., 2000; Sanchez *et al*., 2004; Sunkar *et al*., 2010; Zhu *et al*., 2001). Nevertheless, the manner in which plants react to a combination of stressors is distinct and cannot be precisely deduced from their reactions to each stressor applied alone. This limitation undermines the dependability of non-diagnostic methodologies. The application of cutting-edge smart sensor technology has facilitated the monitoring and management of several aspects of plant physiology, including abiotic and biotic stress, as well as environmental and botanical parameters. This has been made possible through the utilization of wearable sensors. According to Suzuki *et al*. (2014), smart agriculture technologies facilitate farm management practices, while botanists utilize these technologies to discover the specific growth requirements of plants.

In order to safeguard plants' physiological processes and maintain optimal flexibility, stretchability and biocompatibility, it is imperative that sensors possess compactness, compliance, and lightness. In their study, Lee *et al*. (2014) investigated the utilization of flexible wearable sensors comprising single-walled carbon nanotubes (SWCNT) and graphitic electrodes. These sensors were designed to be placed on both planar and nonplanar substrates, with the aim of establishing interaction with living plants for the purpose of wireless and real-time monitoring of dangerous gases. In contrast, researchers developed stomatal electro-mechanical pore size sensors (SEMPSS) as a means to quantify electrical resistances. Additionally, they employed microscale printing techniques to fabricate biocompatible microcircuits directly onto the leaf surface. This innovative approach enabled the monitoring of individual stoma-aperture dynamics (Koman *et al*., 2017).

Wearable technologies have the capability to monitor the growth of plants. This can be achieved by the utilization of graphite/CNT inks on electrodes, which offer mechanical stability and stretchability. These properties enable nanometer-scale resolution, allowing for the observation of rhythmic growth rates at a temporal resolution of seconds. The use of this detection method circumvents the need for pre-treatment plant destruction, as opposed to the utilization of scanning electron microscopies, as demonstrated by Tang *et al*. (2019). In order to consistently assess the most favorable conditions for growth, a study conducted by Nassar *et al*. (2018) employed wearable sensors to gather data on temperature, humidity, and strain. These sensors were utilized to monitor the elongation and growth of plants, with a high level of sensitivity to length variations at the micrometer scale, as well as sufficient stretchability. Coppede *et al*. (2017) proposed the utilization of a biomimetic textile-based biosensor for the purpose of detecting sap solute levels within plant tissues. Water use statistics can be recorded by researchers and farmers using these devices. An other captivating application involved the development of a minuscule graphene sensor that may be affixed to plants (Oren *et al*., 2017). The process involves the deposition of a graphene sheet onto polydimethylsiloxane (PDMS) using drop-casting. Excess graphene in nonpatterned regions is then eliminated by employing scotch tape. Subsequently, the patterned graphene is transferred from the interior of negative features, such as channels or cut-out sections on the PDMS surface, onto a designated tape.

The utilization of miniature wearable sensors on plants enables the detection of transpiration rates without causing any detrimental effects on plant growth or crop yield. The potential of this technology to revolutionize environmental monitoring is significant, yet its current application is mostly focused on comprehending plant physiological reactions, such as those related to water, nutrients, light, and biomonitoring. Nevertheless, the precise physiological response of the plant is sometimes inadequately defined, leading to a more complex stress scenario that poses challenges for investigation when the stressors originate from several sources and encompass both abiotic and biotic factors. Nevertheless, this technology has the potential to facilitate novel scientific breakthroughs, such as advancements in agricultural disease research and pesticide testing.

E. Internet of Things and Remote Sensing

The contemporary agricultural sector and food industry encounter challenges such as population growth, climate change, and phytopathological adversities. According to Maksimovic *et al*. (2017), the utilization of nanotechnologies and the Internet of Things (IoT) has the potential to contribute to the attainment of sustainability. Contemporary advancements in agriculture encompass the utilization of "real-time communication" and "wireless sensing." Additionally, the concept of "smart farming" leverages information and communication technology (ICT) tools such as remote sensing (Bastiaalssen *et al*., 2000), cloud computing (Hashem *et al*., 2015), and the Internet of Things (IoT) (Weber *et al*., 2010) to enable farmers to remotely monitor field conditions or receive on-site technological assistance. According to Ampatzidis *et al*. (2017), robotics play a significant role in various aspects of agricultural practices, including seedling and plant management, fruit harvesting, plant protection, and weed control.

The process of remote sensing include the collection of both qualitative and quantitative data through the utilization of various platforms such as satellites, airplanes, unmanned aerial vehicles (UAVs) or unmanned ground vehicles (UGVs), and probes. The examination of how agricultural systems evolve over time and vary across different locations, as well as the potential of non-destructive sensing techniques to mitigate environmental repercussions by preventing resource depletion, holds great importance for our society. Molecular interactions and the biophysical or biochemical characteristics of crop stress can be examined through analysis, as demonstrated by Mulla *et al*. (2013). Additionally, variations induced by plant stress, such as changes in leaf area index, chlorophyll content, or surface temperature, can be detected even at early stages. This detection leads to the development of a distinct fingerprint that differs from the characteristics of a healthy condition, as observed by Meroni *et al*. (2010). The application of remote sensing in precision farming was initially introduced during the 1980s, mostly utilizing a limited number of visible or near infrared bands. However, it subsequently evolved into hyperspectral remote sensing technology. According to a previous study conducted by West *et al*. (2003), various aspects of plant-related phenomena can be observed and analyzed using different spectral regions. These include the detection of pathogen propagules, which can be identified in the visible (VIS) region depending on the specific pathogen. Additionally, the degradation of chlorophyll, characterized by necrotic or chlorotic lesions, can be observed in both the VIS and red-edge regions (550 nm, 650-720 nm). Disturbances in photosynthesis, manifested as fluorescence, can be measured in the wavelength ranges of 450-550 nm and 690-740 nm, as well as in the thermal infrared (TIR) region spanning from 8000 to 14,000 nm. Lastly, the process of senescence can also be monitored. Agricultural crops can be detected for the presence of diseases. The researchers employed a hyperspectral radiometer to assess the inherent efficiency of photosystem II photochemistry by analyzing leaf reflectance. Specifically, they focused on the ratio of two leaf ChlF-derived parameters, namely Fv/Fm, which represents the variable and maximum fluorescence (Pemg *et al*., 2017). The reduction in Fv/Fm is large when leaves are under stress, although the chlorophyll content of the leaves remains same. The reflectance slope within the spectral range of 700-900 nm exhibited a rise concurrent with the observed decrease. Moreover, a strong association was seen between the first derivative of reflectance in the near-infrared (NIR) regions and the variable Fv/Fm.

Agricultural unmanned aerial vehicles (UAVs), also referred to as drones, have the potential to contribute to several agricultural tasks, including surveillance, crop seeding, pest control, and crop monitoring. The agricultural drone eBee SQ, developed by Sensefly *et al*. (2020), establishes communication with the eMotion Ag program in order to conduct analysis on multispectral photos. The program facilitates the direct transfer of drone multispectral photographs to cloud-based services, enabling the comprehensive coverage of vast agricultural areas spanning hundreds of acres. This process ensures precise crop monitoring and analysis. On the other hand, the characterization of airplane and satellite technologies has been comprehensively documented in previous studies (Omasa *et al*., 2006; Rudd *et al*., 2017). The former encompasses the utilization of satellite and aircraft remote sensors in various agricultural applications. These applications include the utilization of Landsat and Geographic Information System (GIS) data for assessing land use and nitrogen flow, the use of aerial hyperspatial data for estimating wheat growth or analyzing farms, and the application of aerial Lidar data for three-dimensional remote sensing of topography and forests. The final section highlights the advantages and disadvantages of satellites, unmanned aerial systems (UAS), and ground sensors, with a particular focus on the adaptability of UAS or the appropriateness of these two technologies for certain purposes (such as real-time processing capabilities of some ground sensors, enabling immediate herbicide applications without any delays in data processing). The utilization of low-cost mini-unmanned aerial vehicles (UAVs) for thermal and multispectral imaging is a further development of this technological field, as discussed by Bendig *et al*. (2012). The present study employed a mini-unmanned aerial vehicle (UAV) system, specifically HiSystems' MK-Okto, which had a payload capacity of approximately 1 Kg. This system was utilized to transport a handheld NEC F30IS thermal imaging system, known for its lightweight design, as well as a Tetracam Mini MCA four-band multispectral imaging system. The system obtained thermal and multispectral images that were georeferenced to ensure comparability. The brief duration of the 15-minute trip enables the implementation of small-scale applications.

Weiss *et al*. (2020) indicate that remote sensing is employed in the monitoring of agricultural land usage, forecasting crop yields, optimizing yields, and assessing ecosystem services. The study conducted by Huete *et al*. (2004) focuses on the application of remote sensing techniques for the purpose of environmental monitoring. This includes the monitoring and characterization of Earth's surface, the assessment of ecosystem sustainability, the mitigation of drought, the evaluation of human health, and several other environmental research. The implementation of Internet of Things (IoT) technology has the potential to significantly contribute to the enhancement of sanitary certification processes and the provision of industrial data for the purpose of traceability. The identification, storage, and tracking of *Prunus* spp. were facilitated through the utilization of RFID microchips, as discussed in the study conducted by Luvisi *et al.* (2011). Similarly, Pagano *et al.* (2010) explored the application of this technology in the context of grapevine clonal selection. The utilization of RFID technology has been employed for the purpose of identifying various plants by ampelographic, genetic, and sanitary tests. RFID technology has been employed for several purposes, including the retrieval of propagated material (Luvisi *et al*., 2012), the tagging of mother plant vineyards, and the certification of products. According to Rupanagudi *et al*. (2015), the utilization of video processing, cloud computing, and robots has demonstrated the capability to identify tomato borer insects when combined with suitable phytosanitary treatment management. The cloud program receives real-time video footage of tomato crops for processing. The utilization of image processing techniques enables a robotic system to autonomously administer pesticide spraying operations, hence facilitating comprehensive monitoring of agricultural fields. Perez-exposito *et al*. (2017) have forth a proposal for a wireless sensor network that spans an entire vineyard and consists of nodes that are self-powered. The hardware and software platform provided by VineSens incorporates epidemiological models to effectively mitigate diseases such as downy mildew. This proactive approach enables farmers to efficiently manage their crops and achieve cost savings by minimizing the need for phytosanitary treatments. The software facilitates the acquisition of meteorological data from diverse vineyard sites through a web-based interface accessible on both desktop and mobile platforms. The utilization of unmanned aerial vehicles (UAVs) equipped with advanced hyperspectral, multispectral, and digital RGB sensors, along with terrain-based data, is employed for crop management and insect pest identification (Vanegas *et al*., 2018). Arable and Semios are examples of agricultural monitoring systems that are utilized for crop surveillance. Arable *et al*. (2020) have developed a system that transmits weather and plant readings to a cloud-based platform, enabling immediate access to signs of stress, pest infestation, and disease. In their study, Semios *et al*. (2020) constructed a proprietary mesh network to deploy several technological devices in each orchard block. These devices included remote-controlled pheromone distributors, insect camera traps, soil moisture sensors, and leaf-wetness devices.

The monitoring of infections such as *Xylella fastidiosa* (Xf) can be achieved through the utilization of airborne platforms equipped with multispectral and thermal cameras. In this context, the selection of spectral bands that exhibit sensitivity towards Xf symptoms involves the pairing of blue bands with the thermal area (Poblete *et al*., 2020). Hornero *et al*. (2020) employed aerial hyperspectral imaging and Sentinel-2 satellite data in their investigation, whereby they developed a 3D radiative transfer modelling approach (3D-RTM) to evaluate the dynamics of *Xylella fastidiosa* (Xf) infection in olive orchards. The utilization of Sentinel-2 time-series imaging has revealed spatio-temporal indicators that can be employed for the purpose of monitoring the harm caused by Xf virus over extensive geographical regions. The authors Cheng *et al*. (2017), Polo *et al*. (2015), and Vazquez-arellano *et al*. (2016) have examined more agricultural applications. Furthermore, Kamilaris *et al*. (2017) have conducted a comprehensive evaluation of the present state of research on big data analysis in agriculture. A separate study conducted by Balasubramaniam *et al*. (2013) demonstrated the potential of utilizing nano-networked small sensors to gather detailed data from items and remote areas that are difficult to access. The provided citation by Cruz *et al*. (2019) is a complete overview that encompasses several aspects such as architectures, areas, trends, possibilities, and obstacles.

CONCLUSIONS

The examination of current plant disease detection technologies and the exploration of novel ways for symptom identification and pathogen prevention have been undertaken. In addition, we conducted an examination of advancements in sensor technology, microfluidics, wearable sensing devices, and Internet of Things (IoT) advances. The integration of bio-sensing platforms with electronic readers embedded into smartphones is creating new opportunities (Zarei *et al*., 2017). The integration of flexible sensors that resemble human skin with wireless communication technologies to enable real-time monitoring of plants is a concept that elicits interest. In contrast, the utilization of sensing and robotics technologies has the potential to develop novel analysis platforms known as "lab-on-a-drone." These platforms provide swift in-flight assays while being connected to smartphones, hence eliminating the need for sample collection and analysis time. Furthermore, they have the capability to support emergency response efforts, agricultural bio-surveillance, and veterinary field care. The utilization of a quadcopter drone designed for consumer use, equipped with smartphone connectivity, for the purpose of conducting nucleic acid tests in field settings. In a study conducted by Priye *et al*. (2016), *Staphylococcus aureus* and phage DNA targets were rapidly transported by flight within a time frame of less than 20 minutes. Smartphone technology has the potential to enhance the precision, intelligence, and portability of diagnostic systems (Mendes *et al*., 2020; Pongnumkul *et al*., 2015), hence facilitating global collaboration between farmers and institutions in combating plant diseases through the utilization of high-resolution imagery and advanced computational capabilities. These many technologies have the capability to interact with one another, thereby offering novel avenues for effectively and intuitively combating plant diseases and preventing their dissemination.

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How to cite this article: Prashanth Kumar A. (2023). Innovative Plant Disease Monitoring Technologies. *Biological Forum – An International Journal, 15*(9): 649-659.