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Communication

Diagnostic and Portable Point-of-Use Technologies as Plant Monitoring Tools for Plant Awareness

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Abstract: An increasing need for better agricultural practices that are sustainable to provide increased yields of crops for the ever increasing food demand to be met for the growing world population is a current necessity. It is estimated by the UN that in 2050 the world's populace may be as much as 9.8 billion global, yet, farmers still face several obstacles, which includes soil degradation, extreme temperatures, and drought which as increasingly becoming more severe with climate changes. Plant health monitoring is a method that will help to increase awareness about plant enhancing by studying how to increase crop yields while decreasing the environmental impacts. The use of low-cost, controlled environments, soil quality, water levels, and pathogenic and pests attacks can be regularly monitored. Currently, several diagnostic technologies and portable point-of-use methods and technologies are employed for detection of diseases, although, the current available lab-based methods used for plant's diagnostics test are inadequate for plant point-of-use monitoring. The promotion of use of these point of use methods will enable pathogen detection, poor plant growth, unsuitable environmental conditions and nutrient use efficiency allowing for immediate and timely corrective actions to ensure minimal damage to the plants with maximal yield. Increase in the use of sustainable agri practices are required for ensuring higher yields with minimal inputs and that are non-destructive to the land and the use of improved methodologies and technologies will be useful tools for achieving sustainable agriculture.

Keywords: Point-of-use technologies; plant health diagnosis; plant promotion; non-destructive analysis

1. Introduction

Several agricultural methods, practices or technologies are currently being used by farmers for maximal yields and plant growth, these include crop rotation, use of fertilizer (both organic and inorganic) for improved soil health, using genetic modified seeds, and the monitoring plants to detect pathogens, pests and stress (Mahlein 2016; Roper *et al.*, 2021). Plant's growths and developments requires the study of the controls processes the coordination processes that occurs within the organs, cells and in the entire plant. This studies usually involves changes in gene expression which occur as responses to the changes occurring within the environment especially climatic changes such as drought, heat, rainfall, e.t.c. Several imaging methodologies are currently available for use in collecting data for quantitative studies of plants their growths and developments. Multi-level data, from macroscopic (Jones, 1992; Freschet *et al.*, 2021; Roper *et al.*, 2021).

In future decades, increased productivity in agriculture is a necessity. To meet the food demands of the rising global populations which is grossly being hampered by drought, poor soil quality,

flooding, new emerging plant diseases and high temperatures with resulting negative impacts on plant yields. To assist in overcoming these challenges, in situ studies of rhizosphere interactions, using specialized plant growth houses/chambers or systems are developed which are able to mimic the natural growth environments for disease detection, stress detection, etc to determine how best to tackle these problems (Mahlein *et al.*, 2016; Farber *et al.*, 2019; Mohammed *et al.*, 2019)

There are also many diagnostic technologies, methods and tools that are being employed to study plants and their development and growth creating more awareness about plants and how to promote their health. Also, several hand-held and at-the-point-of-use technologies are available, including devices with a lateral flows or portable-devices for easy use on the field (Roper *et al.*, 2021). However, the recent lab-based methods and techniques available for plant's diagnostics for at-the-point-of-use plant monitorings are not sufficient or are limited in certain capacities as these devices usually requiring harvested and or processed plant tissue, thus un-conducive for continued monitorings. This review provides information on several methodologies being used in monitoring plants and how they improve awareness about plants.

2. Methods for Studying and Monitoring Plants

2.1. Phynotypic and Physiological Studies

These includes the study of traits and physical characteristics (phenological and morpho-physiological traits) such as growth rate, green-canopy-cover, total plant's biomass, the plant's height, the total number of seeds in a plant, total pod number, flowering, vigour, pod formation, maturity of seedling, leaf loss, wilting, growth rates, time to reach initiation of flowering, the time duration for pod to set, time to reach full maturity, the length of the vegetative stage, duration of reproduction stages, duration of time for complete seed fillings, seed lengths. They also include plant morphologies such as leaf size, the growth of stem, the plant's height, and plant root's development (Tang *et al.*, 2022; Yang *et al.*, 2018; Mohammed *et al.*, 2024).

2.2. Genotypic and Molecular Studies

This includes the study of the genetic characteristics and proteins and gene expression in plants.

2.2.1. Genomics

Genomics is an inter-disciplinary aspect of biology that is focused on the structures, evolutions, functions, mappings, and editings of genome. The genome is the organism's total DNA set, which includes all its genes their hierarchies, three-dimensional structures and configurations (Figure 1). These genes are highly important as they direct protein productions which is assisted by enzymes and the messenger molecules. Genomics differs from genetics, an involves the studies of the individual gene(s) and what role(s) they play in genetic inheritances. Rather, genomics is aimed at collective characterizations and quantifications of gene(s).

Functional genomics is the approach that makes use of a vast wealth of data which are produced through genomic projects (these include genome sequencing(s)) describing how they function and interaction especially genes and proteins.

Structural genomics works on describing the three-dimensional structures of all proteins which are encoded by specific given genomes.

Epigenomics studies the complete/total set of epigenetics which studies how and the way genes are expressed and change while remaining constant.

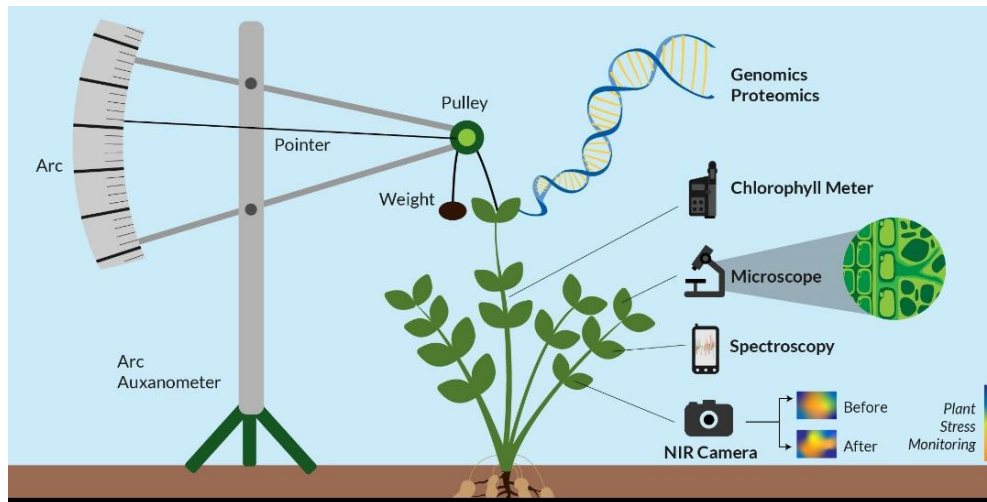


Figure 1. Non destructive monitoring of plant health and growth using mini machines and hand held-devices.

2.2.2. Transcriptomics

Transcriptomic analysis of bacteria associated with plant is done using two approaches either RNA sequencings (RNA-seq) or the gene(s) expression micro-arrays, this is able to reveal the gene(s) which are expressed differently under certain environmental conditions e.g for detection of genes that give responses when certain plant extract are present (Coutinho *et al.*, 2015; Levy *et al.*, 2018). In most cases, the bacteria are usually cultured first from host plants before RNA-seq is used. Metatranscriptomic on the other hand, sequences transcripts from the from the sample of the entire community present, providing more informations about simultaneous transcriptional states for an arrays of micro-organisms which maybe present in the samples (Coutinho *et al.*, 2015; Levy *et al.*, 2018).

2.2.3. Proteomics

The use of Proteomics or metaproteomics methods are majorly based on the use of the liquid-chromatography, the mass spectrometry techniques and with one obtaining semi quantitative informations about the majority of bacteria protein types which are produced in specific environmental samples (Figure 1). They also use proteins to enable the understanding of how microbes are able to contribute to changes in the soil ecosystem, providing more information about the secreted enzymes present in the soil, the microbial types and their ability to produce these metabolites. After protein extraction, isolation and fractionation is done after which mass spectroscopy is carried out, and the final results are compared with the data base proteome (Levy *et al.*, 2018).

2.3. Metabolomics

Metabolomics as a tool for analysis is becoming more recognized in the industrial and scientific sectors it intergrates both statistics and analytical chemistry to provide an understanding of the level of metabolites and how they change within a chemical or biological system (Levy *et al.*, 2018; Shen *et al.*, 2023). Plant metabolomics is a useful study area in plant sciences where quantitative analysis for metabolites is done for plant systems. It is also used as a tool for phenotypic and diagonistic research in plants (Hong *et al.*, 2016) these include Plant products characterization and evaluation (Favilla *et al.*, 2013), Plant pharmacology and nutrition (Schmidt *et al.*, 2008), Plant diseases and resistance (Hantao *et al.*, 2013), Plant genetic mutant and phenotyping (Hong *et al.*, 2016). Chromatographic metabolomics on the other hand has widely for performing plant's genetic mutants or phenotyping study. It is a powerful tool, that uses tensor method(s) and plays a highly important role to aid in understanding how important metabolite(s) traits and the associated targeted genetic factor(s) help

in plant development (Khakimov *et al.*, 2016; 2017). The fast developments of metabolomics as a technology is profoundly useful in the field of plant sciences. Another method is the use of Mass spectrometry based metabolomic or lipidomic measurement(s) which requires specified extraction procedures for different molecule to be MS-compatible (Stearns *et al.*, 2012, enabling the study of smaller volumes of metabolites and lipids contents (Nakayasu *et al.*, 2016). Another method is the use of nuclear magnetic resonance (NMR) metabolomics, to study metabolites that are present in soil study the types of responses given by certain organism to the different surrounding habitat stimuli thus revealing pre-symptomatic signs and signals of inherent plant stress(es) and plant disease(s) (Rochfort *et al.*, 2005).

Tools, Devices and Machines Used for Monitoring Plant

Crescograph: is the device used for measurement plant growth, and it was first designed by an Indian scientist known as Sir Jagdish Chandra Bose in the 20th century. It used batches of clocks gears alongside a dark glass-plate for recording the tiny movement(s) of the top most tip of the plant. It provides real-time informations about the plant's growth, for studying it's water status in the soil-plant atmosphere and also measures and records the plant growth under certain environmental and climatic factors such as temperature, chemical reactions, electric supply, the effect of gases a modern electronic device was designed by Randall Fontes which has a range of 1:1000 to 1:10,000 of an inch (Bose, 1920) (Figure 1).

3.2 Auxanometer: is a instrument used for determining the rate of growth and development in plants and it usually consists of a flexible wire which runs over a pulley that is connected to an indicator that shows the value of plant growth on a curved shaped scale (Bovie and Bovie, 1915; Gallagher *et al.*, 1976).

3.3 Potometer: is a H-shaped device with a capillary tube instrument used for measuring the rate of transpiration in green leafy plant shoot. It tells the rate of uptake and evaporation of water. It also measures the loss of water from the leaves (Figure 1). It is known as the Ganong's potometer or a transpirometer. Water uptake in plant is usually caused by photosynthesis and transpiration (Bohdan 1974).

3.4 Non-Contact Device- These devices are able to measure the growths of plant by the use of a single sensor or set of sensors. They study the movements in plants without making physical contact with them and be use at a minimal distance or close to them the sensor is able to sense the movements in the plant and also keeps records for other further measurements an example is the sensor metre.

3.5 MRI (magnetic resonance imaging): uses analytical techniques to for studies of water, its properties and is done without ionizing or breaking down the water sample. The use of portable magnetic resonance imaging (MRI) a a tool for field experiments is expanding rapidly and provides substantial advantage(s) in plant science(s) (Figure 1). The MRI allows for a non-invasive studying of the content of plant water, its structure, it's fow, it's stress responses, and any other physiological process(es), as such a large array of informations maybe obtained together while the method is being used, and can be measured in-situ within the natural enviroment of the plant (such as greenhouses, climate chambers, and in natural environments), as they are handy portable devices. (Blystone *et al.*, 2024).

3.6 High quality 3D informations for microscopic morphology of plant tissue: this method studies the cell spatial organization and tissue intercellular spaces providing a better understanding of the physiological processes occuring within the plant or tissue cell. An example of such tool is the X-ray micro-CT which provides 3D micro-structural informations about the inter-cellular pore spaces, sizes and tissue shapes. It's limitation is its inability to properly segment the cells because of the density difference(s) at cell-to-cell interface(s). Also, deep learning models have been trained and also tested allowing for segmentation of cells individually using an X-ray micro-CT scan images for the parenchyma tissues or samples with different cell and porosity characteristics (Blystone *et al.*, 2024; Leen *et al.*, 2024).

3.7 X-ray micro-computed tomography (micro-CT): this device acquires complex 3D images of plants structure and the great advancement in developing high-resolution X-ray micro-CT lab

instrument(s) making it much easier for plant scientist and researchers to carry out meaningful studies with out the use of synchrotron facilities (Piovesan *et al.*, 2021; Duncan *et al.*, 2022; Leen *et al.*, 2024).

3.8 Contrast-enhanced micro-CT: this device scans and provides images by highlighting the plant cell wall structure (Wang *et al.*, 2017; Xiao *et al.*, 2021; Leen *et al.*, 2024).

3.9 Disease detection: Precise, accurate and quick early disease detection has great significance in ensure precise spraying to avoid extensive spread of disease(s) and improved crop yields and quality (Zhang *et al.*, 2023). Never the less, the signs and symptoms between the healthy leaves, and early leaf disease infection are quite similar, which makes detecting the early characteristics of the diseases still a challenge. The BPNN (also known as the back propagation neural network), SVM (also known as the support vector machine) and RF (also known as the radio frequency) are model machine learning which have been developed and tested for the detection of gray-mold and anthracnose in strawberry early, respectively, with the use of spectral fingerprints, VIs used alone or together provide rapid, precise, and also non-destructive identification of the strawberry's types of gray-mold and anthracnose disease in early stage (Wang *et al.*, 2015; 2018) which showed much success with accuracies of 97.78%, 94.44% and 93.33% in the three different machine learning model types (BPNN, SVM and RF), respectively (Cortis *et al.*, 2017; Wu *et al.*, 2019). This machine learning models may also be considered for detection of several other diseases in other plants.

3.10 Drought monitoring: The thermography device is a useful tool for monitoring changes that occur in plant water-use behaviour and responses to water. The quantity of the emission of thermal infrared (TIR) radiations coming from a plant is closely or approximately related to the plant's body temperature, which indirectly depends on received radiation and plant transpiration rate as the rate at which latent heat vaporizes at the leaf's surface (Jones, 1992). Combinations of the thermal infrared (TIR) and the hyper-spectral imaging used in monitoring how drought affects a plant's transpiration rate (E) was quantified, with the TIR indices being used in monitoring plant's drought stress and in developing prediction models, providing more accurate values of plant temperatures, ambient air temperature and relative humidity (Mertens *et al.*, 2023).

3.11. Imaging Techniques and Approaches

Imaging techniques include thermography, fluorescent imaging, RGB imaging, and hyper-spectral imaging (Farber *et al.*, 2019). The RGB imaging works by utilizing digital cameras which are able to measure the change(s) in transmittance. Also simple short digital videos and images maybe used to monitor a different sets of plants in the field. These devices may be used on plants in conjunction with smart-phone sensors, and drones for monitoring larger fields. Also, several machine learning algorithms are presently being designed for detection of patterns to show disease infections. In the study by Mahlein, the several use for RGB imaging are described (Roper *et al.*, 2021; Mahlein *et al.*, 2019).

3.11.1 Fluorescent imaging: it is a non-invasive imaging technique which helps with visualizing biological processes that occurs within a living organism. This method is highly similar to the RGB imaging; it however differs with the use of a laser along side the camera, and allows for the occurrence of fluorescent excitations. One the most regular uses of the fluorescent imaging technique is the chlorophyll SPAD meter, it reads/ detects the fluorescence in the plant and compares it with standard baseline values (Figure 1). when chlorophyll is excited by specific light type it fluorescences naturally allowing the amount of chlorophyll to be read (Roper *et al.*, 2021; Bolhar-Nordenkamp *et al.*, 1989). They are also used for photographing fluorescent-dyes and fluorescent-proteins helping in marking molecular mechanisms and structures. This technique has low cost, is highly sensitive and relatively safe.

3.11.2 Chlorophyll fluorescence: this portable hand held device helps to provide information about photosynthetic activities of a plant. The technique is based on the Since chlorophyll is fluorescent nature of chlorophyll under intensive sunlight, it works as a simple fluorimeter that takes measurements in the field. It is non-destructive, non-invasive and very handy for field use, although it is unable to carry out the diagnose of specified types of abiotic or biotic stress factors its response

may fluctuate depending on the type of factors (either biotic or abiotic) (Roper *et al.*, 2021; Mohammed *et al.*, 2019).

3.11.3 Hyperspectral imaging: this technique uses an electromagnetic spectrum to analyse light and evaluates the changes which aren't visible in the RGB images formed. It is able to detect the more significant changes more effectively than the visual and the fluorescence images counterparts, but is limited in that only general changes can be detected on plant surfaces. In future with more significant studies, the use of hyper-spectral patterns may be more precise and specific in detecting changes. The work of Zhang *et al.* 2012 for example, where analysis of the hyper-spectral features for yellow rust disease was done and followed by statistical analysis, it was possible to differentiate the yellow rust disease from nutritional leaf/ plant deficiencies (Roper *et al.*, 2021; Zhang *et al.*, 2012).

3.11.4 Polydiacetylene polymer (PDA) and functional DNA single-walled carbon nanotubes: this methodology was carried out in a laboratory setting where (SWCNTs) were incorporated inside the plant leaves before imaging to study the leave molecular contents it may also have promising potentials to be used in the field.

3.11.5 Root imaging: Instead of using the traditional method where there is a destructive sampling of soil, root washing, and advancement is the imaging technology, which allows for the significant advance(s) in phenotyping of roots making root studies much easier (Farber *et al.*, 2019). it allows for observation of roots in the soil, and measurements can be taken repeatedly, using the X-ray tomography (Mooney *et al.*, 2012) to the use of the electrical resistant tomography method (Amato *et al.*, 2008; Baykalov *et al.*, 2023). 2D images of the growing roots can taken using the non-destructive techniques such as rhizo-boxes, or (mini-) rhizotrons (MR). The Rhizotron systems uses a fat, transparent (plexi-)glass window to take larger but images with similar structures better than tube installed MR cameras, although the infrastructure costs are more, with greater or more significant disturbance within the soil and may have reduced flexibility for experimental uses. A better method is the use of MR camera systems that are able to observe the timings (phenology) of the plant's root emergence, it's growth and it's decay rate in the field providing the window for an un-disturbed rhizosphere which may not be possible with other methods (Freschet *et al.*, 2021; Baykalov *et al.*, 2023).

3.12. Spectroscopy techniques and approaches

One major method used for rapid diagnosis is the use of spectroscopy, it is used in molecular methods which includes PCR (real-time) method, and the ELISA (which are commonly used in plant disease(s) diagnosis and can be very invasive sometimes). Some common methods of spectroscopy include X-ray spectroscopy, Raman spectroscopy, and mass spectrometry. The Raman spectroscopy works by detecting vibrational frequencies of molecules present in the sample; and can also determine the type(s) of chemical footprints of the structure(s) for identification of molecules by using the illumination from a monochromatic laser. The interaction between the and the sample results in a shift in energy helping to tell the type of molecules present. Altangerel *et al.* 2017 worked on developing a hand-held Raman spectroscopy instrument which uses the coleus lime as it's model organisms and carotenoids and anthocyanins (photosynthetic pigments) as target molecules (Roper *et al.*, 2021; Altangerel *et al.*, 2017).

3.13. Electrical-Based Approaches

Many several studies have used electrical components to monitor plants in-vivo. They require external materials and equipments and also use nanotechnology for integration into plants examples of such are:

3.13.1 Microneedle Electrodes: In the study carried out by Jeon *et al.* Salinity was measured by using real-time monitoring systems which were developed to detect the salinity (a very important factor for plant growth and health) in tomato plants in a no-destructive manner, which is a highly important factor in the plant health and crop yield (Roper *et al.*, 2021; Jeon *et al.*, 2017).

3.13.2 Organic Electrochemical Transistor-Based Sensors (OECT): these devices have been explored for it's use as biosensing tools. It based on the use of conductive polymers (poly (3,4-ethylene-dioxythiophene) which are doped with diverse attached side groups) and films or channels

were put in close contacts with electrodes and electrolytes with the electrode being connected with a channel along gate electrodes for electrical connections. Coppede *et al.* were able to develop an OECT sensor which can be used for continuously monitoring plant health based by studying the changing sap solutes (Roper *et al.*, 2021; Coppede *et al.*, 2017).

4. Fostering of More Methodologies and Techniques

The current available lab methods and techniques for plant analysis and devices are not sufficient for plant monitoring at point-use. These techniques and devices can allow for precision in agriculture, minimizing usage of expensive resources and maximizing crop yield. In addition, the availability of the affordable technologies with ready accessible for large and small farming is highly vital necessity for increased agricultural productions. Some of the pressing challenges of some these technologies includes their implementation under field conditions. Some of the major factors to put into considerations for the successful use of in-vivo sensors may include, yet not limited to, it's accuracy, sensitivity, specificity, ease of use, cost, durability, and ultimately the environmental after impacts. More researches should be done for developing deep learning frame-works for replacing traditional machine learning methods for detection of early plant disease infection, detection of stress, and plant monitoring to foster better understanding of plants under different environmental conditions.

5. Conclusions

Several different sets of needs are required for better studies of plant diagnostics technologies and the most suitable technologies for farmers will mostly be dependent on land size they cultivate, the crop types and their specific needs, natural, economical, and social environments. The current technologies available for measurement of plant's health and/or diagnosis of disease have high costs, are invasive, and need to be sent as samples to laboratory facilities for processing, therefore, there is urgent need for developing more simple, cheaper, accurate and precise point of use technologies methodologies and devices for better understanding of plant growth and health monitoring. Development arrays of sensors and new innovative techniques and technologies are a necessity to meet agricultural food demands for the increasing large world populations.

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Conflicts of Interest: The authors declare that there are no conflict of interest.

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