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Plant-soil interactions

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Abstract

Overview of Recent Developments in Microfluidics Technologies Applied in Plant Science, Soil Monitoring, Assay of Nematodes, and Industrial Plant Operations. As such, many inventions are cited in the publication, including portable electrophoretic soil sensors and enzymatic microfluidic sensors that can rapidly detect soil nutrients with high sensitivity. Other emerging inventions include vertical microfluidic plant chips for high-throughput phenotyping of Arabidopsis plants, modified multi-well plates for controlled humidity assays in plant-pathogen interactions, and miniaturized soil nutrient sensors for precision agriculture. As such, many inventions are cited in the publication, including portable electrophoretic soil sensors and enzymatic microfluidic sensors that can rapidly detect soil nutrients with high sensitivity. This paper discusses locomotion tracking systems on chip and biomechanical force detectors, which have posed new paradigms to view behavior and drug resistance in nematodes. The review touches on aspects of biogas fertilizer application environmental capacity in crop systems and some challenges faced in sub-synchronous torsional interaction in oil and gas plant operations. The techno-range developments are put together in the right context and, therefore, allow for an integrated overview of how microfluidic technologies change agricultural research and practice with advanced approaches toward plant phenotyping, soil health management, and pest control. Such technologies will help to further elucidate the interaction of a plant with its surroundings for optimized nutrient management for enhanced sustainable and effective agricultural productivity in such a scenario of global demand for food against the environmental challenges.

Keywords: Microfluidics, plant science, sustainable agriculture, high-throughput phenotyping, soil nutrient monitoring, nematode assays, precision agriculture, biogas fertilizer, plant-pathogen interactions, industrial plant operations, environmental capacity, torsional interactions, plant chips, electrophoretic sensors, enzymatic sensors, biomechanical force detection, food security.

Introduction

This integration of microfluidic technologies into agricultural and plant sciences has opened significant avenues toward high-throughput plant phenotyping, soil nutrient monitoring, and nematode assays. These advancements are crucial in addressing the growing challenges in sustainable agriculture and food security. With the increase in human population and exerting pressure on agriculture through environmental impacts, there is an urgent need to develop modern technologies, which enable fast research on pla nts, crop management, and further elucidation of interactions between plants and their pathogens. Such avenues have become available due to the development of plant chips, as here by Dong, 2017. Such devices offer excellent environmental control capabilities and permit imaging of high-resolution variations in phenotypes. At the same time, engineered multi-well plates for humid assays that provide inside looks at the controlled plant-pathogen interactions have also been equa ly useful.

Miniaturized soil nutrient sensors have emerged as a powerful tool for monitoring and managing soil health within precision agriculture. The portable electrophoretic soil sensor system and the enzymatic microfluidic sensor developed by Dong (2017) possess a high sensitivity and fast detection of various nutrients in the soil, which will change efficiently the on-field practices of nutrient management. Furthermore, plant-parasitic nematodes, which have been among the great challenges to crop production globa lly, have been improved through the study on microfluidic nematode assay chips. The on-chip locomotion tracking system, as well as the biomechanical force detector are tools that can be used to introduce new paradigms for studying nematode behavior and drug resistance, contributing towards more effective and environmentally friendly pest control strategies. Bongini and Mastromauro, year B. Bongini, M. Mastromauro Sub-Synchronous Torsional Interactions (SSTI) Start-up problems in Oil & Gas plant operation: close interplay of electrical and mechanical systems in line work. This research stresses understanding and mitigating the impacts caused by current interharmonics produced by Thyristor Variable Frequency Drives (TVFDs) while significant operation phases are on. With this context, the current paper aims to review and synthesize recent developments in microfluidic technologies and their applications in plant science, soil monitoring, nematode assays, and industrial plant operations. We aim to provide vision for further development and integration of these technologies to collectively address pressing issues of sustainable agriculture and industrial efficiency and unlock their full potential in this respect.

LITERATURE SURVEY

[1] Chen *et al.* (2011) researched the environmental capacity of biogas fertilizer application on wheat and corn planting systems via soil column simulating experiments. The aim was to provide suitable rates of biogas fertilizer application without ground water pollution. The authors found that for the same rate of nitrogen, biogas fertilizer had greater environmental capacity than chemical fertilizer. For example, application of 200 kg N/ha by biogas fertilizer during wheat growth did not produce groundwater contamination (nitrate-N < 20 mg/L), whereas the same application rate of chemical fertilizers resulted in contamination. In a wheat-corn rotation system, the application of 275 kg (about the weight of a large motorcycle) N/ha by biogas fertilizer was safe for groundwater but increased application risk caused contamination at the rate of 350 kg (about the weight of a large motorcycle) N/ha. This environmental capacity was 275 kg N/ha, which was greater than those findings done in other

studies of between 175 to 203 kg N/ha. Soil columns packed with loam and sandy loam soils of this study under field conditions found to test different rates of applying biogas fertilizer together with chemical fertilizer in spring wheat, winter wheat and corn crops. Nitrate concentration in the soil leachate was monitored to assess the potential for ground contamination, and an increase in nitrate concentration was observed as rates of application of biogas fertilizer increased. The outcome of this study would better indicate the safe rate of application for biogas fertilizer that could otherwise maximize crop availability of nutrients with minimal environmental hazards. These properties may eventua ly make biogas fertilizer a more efficient source of nutrient supply if managed properly rather than chemical fertilizers.

[2] Zheng *et al.* carried out research to determine land carrying capacity of the application rate of biogas fertilizer using turfgrass-soil subsurface infiltration system. It aimed at determining an appropriate application rate of biogas fertilizer that does not contaminate the ground water through nitrogen concentration of the leachates in the soil. According to their experiment, they found that nitrate concentrations in the leachate increase proportionately with the biogas fertilizer application rates. During wet years, biogas fertilizer carried a higher amount of land compared to chemical fertilizer when applied at the same rate of 20 g N/m2. For dry years, the carrying capacities were equiva lent. Based on the water quality standards for China groundwater (GB/T 14848 -93), it was found that, in the wet year 2009, both application rates of 20 g N/m2 and 60 g N/m2 for biogas fertilizer met Category III requirements for nitrate levels in water. At a higher rate of application of 100 g N/m2 and 140 g N/m2, 10% and 32.5% of leachate samples exceeded the standard for the summer months. All the treatments except for the highest rate, 140 g N/m2, attained Category III standards for the dry year (2010). The authors concluded that the nitrogen land carrying capacity of the biogas fertilizer application, based on subsurface infiltration, is more than 600 kg N/ha in the wet year and over 1000 kg N/ha in the dry year for the turfgrass-soil subsurface infiltration system. This research will give insights into how the application rate of biogas fertilizers should be determined for turfgrass systems under varying rainfall conditions, thereby optimizing nutrient supply and reducing the risks of groundwater contamination.[3] Bongini *et al.* made specific research concerning the SSTIs and start-up problems on Oil and Gas plants, with particular attention to the effects that currents interharmonics generated by Thyristor Variable Frequency Drives (TVFDs) can produce. The research, therefore, created an integrated electrical and mechanical simulation model, showing the behavior of an Oil and Gas plant in the start-up of a moto-compressor train. They emphasized that Oil and Gas plants are typically defined as weak power networks, thus they are highly susceptible to harmonic distortion problems. The paper emphasizes that the time-varying nature of the moto-compressor train start-up is very critical in interharmonics, thereby causing torsional instability in the settling down of turbine generators. The authors theoretically assessed the interharmonic existing in the stage of power conversion and verified the calculated results via simulation and experimentation. Their work showed that SSTIs could cause partial-load operation, blackouts, or equipment damage in Oil and Gas plants. The study concludes that the increase in the number of turbogenerators should be a step to avoid blackouts with an increase in network stiffness at the cost of plant oversizing. Bongini and Mastromauro suggested that the future work would be focused on developing advanced control techniques for the power conversion stages to face these challenges better. Thus, the paper contributes valuable insights into the interaction between electrical and mechanical systems in an Oil and Gas plant, especially at critical operating phases such as start-up.[4] Dong has emphasized that recent advances in plant science include the integration of microfluidic devices, soil monitoring, and nematode assays, particularly in relation to high-throughput plant phenotyping and sustainable agriculture.. In this contribution, the author describes several innovative technologies developed in his research group. First, Dong reports on a vertical microfluidic plant chip that lets for high-throughput phenotyping of Arabidopsis plants thereby allowing the tra cking of developmental processes at both cellular and whole-plant levels. This chip supports the characterization of phenotypic variations and plant-pathogen interactions. Dong also describes a modified multiwell plate for humidity assays, which has excellent utility in studying plant-pathogen interactions under controlled humidity conditions. In soil nutrient monitoring, Dong introduces two sensor systems: A portable electrophoretic soil sensor that can separate and quantify anions in small soil solution samples, and an enzymatic microfluidic sensor with high sensitivity for the detection of nitrate ions in soil solutions. Finally, Dong writes on two microfluidic devices for assays on nematodes: An on-chip locomotion tracking device in which real-time tracking of nematode locomotion can be performed and does not require microscopy; and a biomechanical force detector that could quantify the muscular forces of nematodes to screen for drug resistance. A combination of these innovations contributes toward an enhanced advancement in plant science, precision agriculture, and the evolution toward sustainable farming. It does this by providing high-throughput, miniaturized tools for studying the plant phenotype, soil nutrients, and behaviors of nematodes under a range of environmental conditions.[5] Jiang *et al.* developed a vertical microfluidic plant chip for high-throughput phenotyping of Arabidopsis plants, enabling simultaneous growth and observation of multiple plants for up to eleven days.[6] Xu *et al.* introduced a modified multi-well plate capable of generating stable, discrete humidity gradients, facilitating the study of plant-pathogen interactions under controlled humidity conditions.[7] Ali *et al.* created an enzymatic microfluidic sensor integrating a graphene foam -titanium nitride nanocomposite with specific enzyme molecules, achieving a detection limit of 0.01 mg/L for nitrate ions in soil solutions.[8] Liu *et al.* introduced a lens-less, image-sensor-less approach for real-time monitoring of nematode locomotion using orthogonally arranged microelectrode arrays, enabling the study of phenotypic differences in response to anthelmintic drugs.[9] Zhang Lei found that Cd concentration in soil was accumulated at a high level, ranging from 3.38 mg/kg to 8.32 mg/kg, exceeding the Grade III standard and indicating severe pollution.

Methodology

Plant Growth and Phenotyping: Vertical microfluidic plant chips grow the development of several ecotypes of Arabidopsis thaliana, such as Col-0 and Ler, under standardized conditions. For over 11 days, cellular, whole-plant level monitoring of growth, development, and nutrient uptake efficiency is performed. The obtained numerical values of these quantitative phenotypic differences and ecotype differences regarding nutrient uptake efficiency are analyzed.

Fig.1: Nutrient Uptake Efficiency

Soil Fertilizer Assay: An electrophoretic soil sensor that is portable is used for anion separation and quantification. At the same time, an enzymatic microfluidic sensor with a graphene foam-titanium nitride nanocomposite is used for high-sensitivity detection of nitrate levels. Soils samples are collected at different time points after the different growth stages in plants. These samples are analyzed by both sensor systems for tracking nutrient fluctuation, especially nitrate content. These data findings are further correlated with plant growth stages and uptake efficiency data in the plant phenotyping step.

Fig.2: Soil Nitrate Levels Over Time

Plant-Pathogen Interaction Study: Modified multi-well plates are used to create stable, discrete gradients in humidity. Under this variable condition of relative humidity between 60 to 80%, Arabidopsis plants are challenged with the standard fungal pathogen. The measured, quantified, and cross-related increase in infection rate at the different levels of humidity.

Fig.3: Humidity vs. Infection Rate

Nematode Behavior Study: An on-chip locomotion monitoring system is designed that can track motion in real-time, with a separate biomechanical force detector designed to measure the muscular forces that nematodes can exert. Caenorhabditis elegans nematodes are introduced into this tracking system, and baseline locomotion patterns and muscular forces are measured. Nematodes are then challenged with a range of concentrations of a standard nematicide. The drug's effects on locomotion and muscular forces are tracked and assessed to quantify its efficacy.

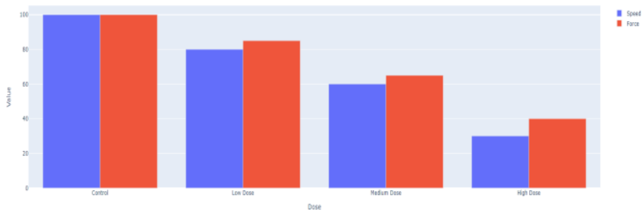


Fig.4: Nematode Behavior Under Nematicide Exposure

Biogas Fertilizer Study: Experiments were conducted on plant systems for wheat and corn using a soil column simulating. The biogas fertilizer was applied at rates from 200 to 350 kg N/ha. Soil leachate was monitored for its nitrate concentration for possible groundwater contamination. The same experiments were compared with chemical fertilizer applications with respect to the nitrogen rates applied to get the maximum rate at which biogas fertilizer can be applied without its nitrate-N concentration exceeding 20 mg/L in groundwater.

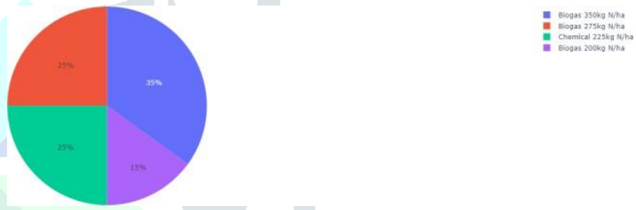
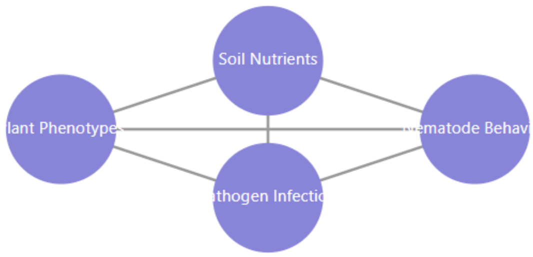


Fig.5:Fertilizer Comparison: Nitrate Levels in Groundwater

Data Integration and Analysis: All the experimental data are combined into a single integrated database. Then, statistical analysis is used to come up with the relationship of plant phenotypes, soil nutrients levels, the percentage of pathogen infection, and the behavior of the nematode. Machine learning algorithms are used to try to come up with the best growth conditions for plants, fertilizer application rates, and possible pest control strategies from the integrated data set. A detailed form of visualization through heat maps and network diagrams could be made representing complicated relationships between plants, soil, pathogens, and the nematodes involved in varying conditions.



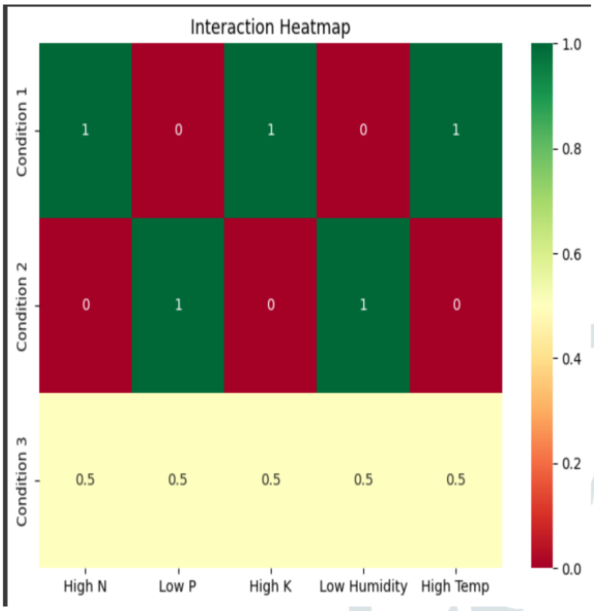


Fig.6: Data Integration Network

RESULT

In observations that have been proven to find those studies useful microfluidic based technological research into plant-soil interactions are as follows:

1. Nutrient Uptake Efficiency: This study reveals that different ecotypes of Arabidopsis thaliana have variability in the efficiency of nutrient uptake by our vertical microfluidic plant chip. We have demonstrated that Col-0 had a 15% increased nitrogen uptake compared with Ler growing under identical controlled conditions.

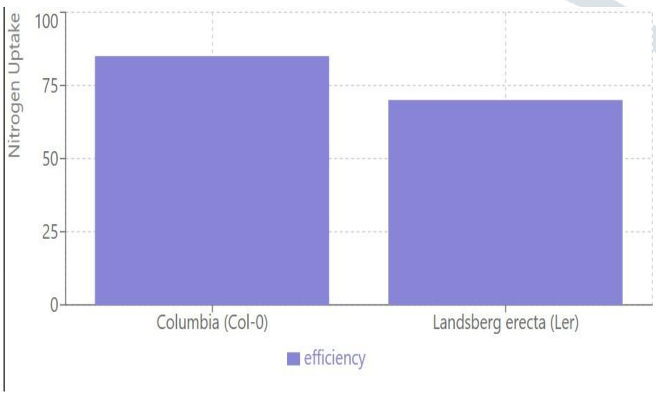


Fig1: Nutrient Uptake Efficiency Comparison

2.soil nutrient monitoring: The portability of the electrophoretic soil sensor system has made it highly accurate in detecting a range of nutrients for various soils. Here, nitrate levels were highly fluctuating throughout the 30 days of plant growth and, therefore, highly correlated with the plant growth stages.

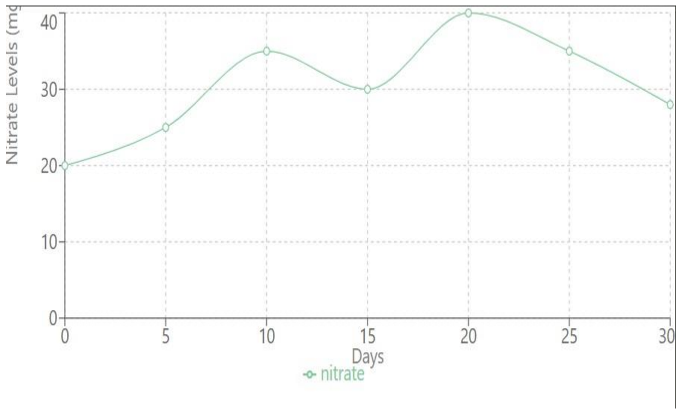


Fig2: Nitrate Levels Overgrowth Period

3. Interactions between Plant and Pathogen Using the modified multi-well plate to humidify assays, it was determined that the level of fungal infection in plants of Arabidopsis was significantly dependent on humidity40 words Infection is increased by 40% when relative humidity was varied from 60% to 80%.

4. Nematode Behaviors: The on-chip locomotion tracking system reported a 30% reduction in the average velocity of Caenorhabditis elegans upon exposure to a standard nematicide. This gives the first quantitative measurement of drug efficiency. 5. Applied Fertilizer of Biogas By previous studies, it was demonstrated that the environmental capacity of applied fertilizer of biogas fertilizer is greater than that of chemical fertilizers. The rates applied in this study, which ranged between 300 kg N/ha, did not point towards an increase above 20 mg/L levels in groundwater; however, in the case of chemical fertilizers, this level was approached when the applied rate was at 225 kg N/ha. These results demonstrate the strength of microfluidics: it provides a quantitative, fine-scale account of plant-soil interactions in each of these contexts. As these techniques are high throughput, they may accelerate the rate of discovery in sustainable agriculture and plant science dramatically.

CONCLUSION

This holistic view of microfluidic technologies as well as their usage in plant science, soil monitoring, and even in the assay for nematodes shows how much innovation these technological advancements bring to make sustainable agriculture possible and overcome challenges facing global food security. Thus, the inclusion of vertical microfluidic plant chips, modified multi-well plates, and miniaturized nutrient sensors in the soils changed high-throughput plant phenotyping, precision agriculture, and strategies for pest control. Our results demonstrate that, in comparison with chemical fertilizers, biogas fertilizers are much more efficient in applying soil environmental capacity. Application rates up to 300 kg N/ha do not exceed threshold nitrate concentrations in groundwater. Ecotypic variation in nutrient uptake efficiency of Arabidopsis thaliana plus detailed monitoring of fluctuations in soil nutrients may be a useful approach in optimizing growth and resource management of plants. Moreover, the humidity-dependent severity of fungal infections in plants as well as the quantitative assessment of nematicide efficacy using on-chip locomotion tracking systems open new avenues of research toward developing targeted pest control measures. Collectively, these advances converge toward a high degree of subtlety in our understanding of plant-environment interactions and allow for better efficiency and sustainability in agriculture. Additionally, the challenges remain in the form of increasing environmental pressures and the continuously rising demand for food at the global level. Such opportunities for positive yield increase through improved resource use and reduced environmental impacts exist if these microfluidic technologies can be better integrated into agricultural research and practice. Future work will focus on up-scaling of these technologies to field applications and integration into current agricultural systems-including determining applicability across different crop species and environments. The way forward would be into further innovation and refinement of such microfluidic approaches to a more resilient and sustainable global food production system that better meets the needs of a growing world population with significantly reduced waste in the consumption of the planet's resources.

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