Summary of the Ph.D. Thesis

Plant-Wearable Electronics for Climate-Smart Agriculture: Toward Energy-Autonomous Bio-Impedance Monitoring Systems

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Summary

The agricultural sector faces unprecedented pressures from climate change, escalating global population, and finite natural resources. A transformative shift towards sustainable practices is crucial to meet future food demand while mitigating environmental impacts. Climate-Smart Agriculture (CSA) represents a comprehensive strategy to enhance agricultural productivity, improve resilience to climate variability, and reduce greenhouse gas emissions. Innovative monitoring technologies are essential for optimizing resource usage and maintaining crop health within this framework.

This Ph.D. research advances CSA by developing plant-wearable electronic systems for in-vivo, real-time monitoring of crop physiological conditions. The systems focus on electrical bio-impedance measurements, a biophysical parameter that non-invasively captures variations in plant water status, metabolic activity, and potential disease onset. Though accurate, traditional electrical impedance spectroscopy tools are impractical for field applications due to their size, cost, and energy demands.

The thesis is structured into several progressive stages. A laboratory-grade monitoring system was initially constructed, utilizing a Keysight 4294A precision impedance analyzer. This setup validated the hypothesis that stem electrical impedance correlates strongly with soil water potential, environmental factors, and diurnal physiological cycles. Data collected from controlled drought stress experiments demonstrated that stem impedance increased under water-deficient conditions and exhibited daily cyclic behavior associated with plant transpiration and metabolic activities.

Subsequently, the research focused on transitioning from bulky laboratory systems to compact, low-power, and field-deployable solutions. Relaxation oscillator circuits were designed to replace the impedance analyzer. These circuits leveraged the plant stem as part of the oscillation feedback network, translating impedance changes into frequency shifts that microcontrollers could easily monitor.

Wireless data transmission was a critical component of system design. Low-Power Wide-Area Network (LPWAN) protocols, particularly LoRaWAN, were selected to enable long-range communication in rural environments with minimal energy consumption. Data acquisition nodes collected plant physiological data and transmitted it to remote servers, facilitating real-time monitoring over extensive agricultural areas.

To further enhance system sustainability, various energy harvesting techniques were explored. Prototypes capable of scavenging solar, wind, and soil-based energy were developed, combined with energy-efficient designs employing Maximum Power Point Tracking (MPPT) algorithms, adaptive sensing intervals, and ultra-low-power modes. These energy-autonomous nodes achieve extended operational lifespans without frequent maintenance or battery replacement, embodying the ”set-and-forget” paradigm critical for large-scale deployments.

Extensive experimental validation was conducted in controlled indoor environments and open-field conditions on diverse plant species, including those with hard and soft stems. Monitoring campaigns revealed that the wearable devices could detect water stress before visual symptoms appeared, allowing farmers to implement timely irrigation strategies and significantly reduce water usage. Additionally, unexpected plant behaviors, such as decay or pathogen attack, were identifiable through variations in the bio-impedance signal.

The work also highlights a complete hardware-software co-design framework, covering aspects from sensor interface design and analog front-end optimization to embedded firmware development and cloud-based data management. Integrating environmental sensor data (light intensity, temperature, humidity, soil water potential) alongside bio-impedance measurements further enriches the diagnostic capability of the system.

In conclusion, this thesis demonstrates that combining real-time electrical bio-impedance monitoring with low-power electronics, wireless communication, and renewable energy harvesting can provide scalable, sustainable, and precise agricultural monitoring systems. The developed solutions contribute directly to the objectives of Climate-Smart Agriculture and pave the way for future digital farming innovations aimed at increasing productivity, conserving resources, and mitigating the impacts of climate change.

Future directions include refining the signal processing algorithms to extract more complex physiological indicators, expanding multi-point bio-impedance mapping capabilities across different plant organs, and further miniaturizing the hardware for seamless integration into diverse crop types. Scaling up deployments to entire agricultural regions through dense IoT networks could revolutionize precision agriculture practices and significantly contribute to global food security and environmental stewardship.

Keywords: Climate-Smart Agriculture, Plant Bio-Impedance Monitoring, Energy Harvesting, Low-Power Electronics, Wearable Plant Sensors.