iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 13 **Issue:** V **Month of publication:** May 2025

DOI: https://doi.org/10.22214/ijraset.2025.71504

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 13 Issue V May 2025- Available at www.ijraset.com

VERDANT TERRA: An Acoustic and AI-Driven Framework for Real-Time Plant Stress Management in Precision Agriculture

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Abstract: Precision agriculture demands innovative solutions for early and accurate plant stress detection to optimize growth and yield. Existing methods often lack real-time capabilities and proactive environmental control. This research presents VERDANT TERRA, an automated plant stress management system utilizing ultrasonic sensors and machine learning (ML). VERDANT TERRA captures stress-induced acoustic emissions from plants, imperceptible to human hearing. These signals are then analyzed by a custom-trained ML algorithm, enabling real-time stress identification and classification. The system integrates with environmental control mechanisms, automatically adjusting parameters like irrigation and lighting based on the detected stress levels. Experimental results demonstrate VERDANT TERRA's efficacy in identifying and responding to various stress factors, including dehydration and nutrient deficiencies, ultimately enhancing plant growth and productivity. VERDANT TERRA offers a cost-effective and scalable solution for precision agriculture, paving the way for sustainable and optimized crop management
Keywords: Precision Agriculture, Acoustic emissions, Plant Stress Detection, Ultrasonic sensors, Machine Learning.

I. INTRODUCTION

Agriculture remains vital to economies like India, but traditional methods struggle to meet growing food demands amid climate unpredictability and resource scarcity. Recent studies reveal that plants emit ultrasonic sounds when stressed, such as during drought or physical damage. By integrating ultrasonic sensors and AI/ML models, the VERDANT TERRA system leverages this phenomenon to detect plant stress and adjust environmental conditions in real time.

The system not only monitors plant stress but also mitigates insect-related irritations and modifies climatic factors based on specific plant requirements. Additionally, with the UN predicting that over two-thirds of the global population will reside in urban areas by 2050, ensuring consistent food supply will be challenging. Controlled Environment Agriculture (CEA) solutions like VERDANT TERRA can play a key role in urban farming, providing year-round fresh produce through automated systems.

This study details the design, implementation, and impact of the VERDANT TERRA system, showcasing how plant bioacoustics and AI can transform agricultural practices.

FRAMEWORKS

The VERDANT TERRA system is a set of five interrelated frameworks that are designed to detect, evaluate, predict and mitigate plant stress by linking acoustic sensing, machine learning algorithms, and automating environmental controls.

The frameworks are modular but functionally integrated, hence enabling functioning all real time monitoring and relief of stress on plants in a controlled agricultural environment.

- Plant Stress Detection Framework (PSDF)
- Data Collection and Analysis Framework (DCAF)
- Environmental Control Framework (ECF)
- Predictive Analysis Framework (PAF)
- User Interface and Reporting Framework (UIRF)

II. WORKING OF FRMAEWORKS

The working of the five different frameworks of VERADANT TERRA is given below:

A. *Plant Stress Detection Framework (PSDF)*

The Plant Stress Detection Framework (PSDF) is the underlying sensing mechanism for the detection of early symptoms of plant physiological stress. It uses ultrasonic microphones with sound detecting capabilities within the range of 20 to 100 kHz, the frequency range in which xylem cavitation events and other mechanical responses to abiotic and biotic stressors occur. The acoustic emissions (AEs) are non-invasive indicators of stress conditions like drought stress, pathogen infection, or mineral deficiency. The PSDF continuously monitors these emissions and presents them to the processing layer for processing.

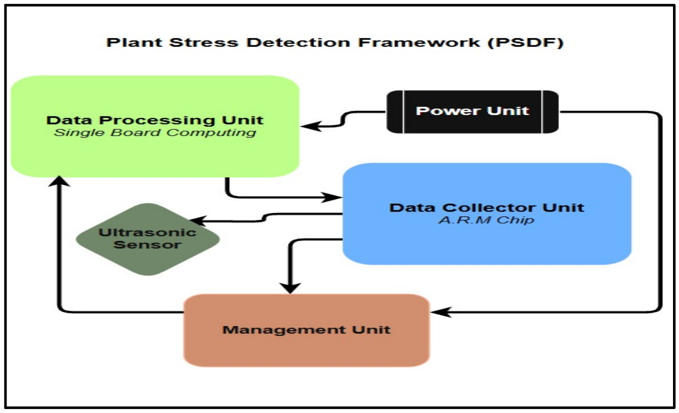


Fig -1: Block Diagram of PSDF Framework

B. *Data Collection and Analysis Framework (DCAF)*

The Data Collection and Analysis Framework (DCAF) is designed to turn raw acoustic signals from the PSDF into meaningful insights about plant health using advanced AI techniques. At its core, the system combines multiple machine learning models to analyze plant stress in a detailed and responsive way.

To begin with, Support Vector Machines (SVMs) are used to make a basic but crucial distinction—whether a plant is stressed or not—by analyzing frequency-based features in the acoustic data.

Once stress is detected, Random Forest classifiers step in to identify what type of stress the plant is experiencing, whether it's due to water shortage, nitrogen deficiency, or a fungal infection.

To understand how these stress conditions develop over time, the framework uses Long Short-Term Memory (LSTM) networks, which are well-suited for time-series analysis. These models help forecast changes in plant health by learning from patterns in historical data. By combining these techniques, DCAF offers a layered, intelligent approach to plant stress monitoring—one that adapts to changing environmental conditions and supports timely, informed decision-making in precision agriculture.

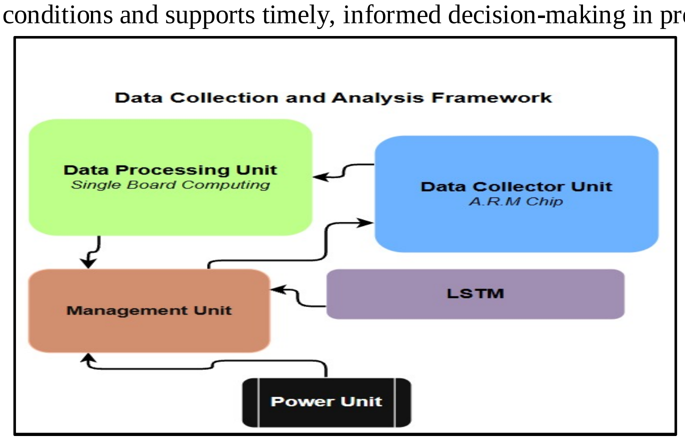


Fig -2: Block Diagram of DCAF Framework

C. *Environmental Control Framework (ECF)*

The Environmental Control Framework (ECF) serves as the actuation module within the closed-loop system, making targeted environmental adjustments in response to stress signals identified through the PSDF-DCAF pipeline. It integrates multiple subsystems that work together to maintain optimal growth conditions and prevent prolonged plant stress.

The UV Light Regulation Subsystem dynamically adjusts ultraviolet radiation exposure to influence photomorphogenic responses, helping plants adapt more effectively under stress conditions. The Temperature Control Unit operates using a Proportional-Integral-Derivative (PID) controller to ensure precise thermal regulation within the growth chambers, promoting stable physiological performance. Complementing these is the Automated Irrigation Subsystem, which modulates sprinkler timing and flow rates based on real-time moisture stress data, thereby keeping soil water potential within ideal physiological thresholds. By continuously responding to environmental deviations, ECF plays a vital role in maintaining homeostasis and mitigating the risk of chronic stress responses, effectively closing the loop between sensing and environmental control.

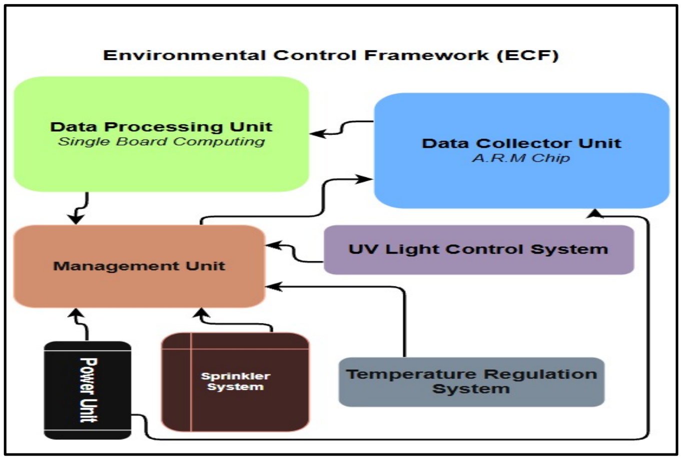


Fig -3: Block Diagram of ECF Framework

D. Predictive Analysis Framework (PAF)

The Predictive Analysis Framework (PAF) functions as the forward-looking component of the system, designed to anticipate plant stress dynamics using historical sensor data and environmental trends. Its primary role is to enable proactive adjustments that minimize the risk of stress before it fully develops. At the core of PAF are LSTM-based deep learning models, which analyze time-series data to forecast the potential onset, duration, and severity of stress events. These models capture complex temporal patterns in plant responses and environmental fluctuations, allowing the system to predict how conditions may evolve. In parallel, Stress Simulation Models are used to run predictive scenarios under varying environmental inputs. This enables the system to test "what-if" conditions and make anticipatory adjustments—such as tuning temperature, light, or irrigation settings—before actual stress occurs. Together, these predictive tools allow PAF to significantly reduce the lag between stress development and system response, supporting a more proactive and resilient approach to environmental control.

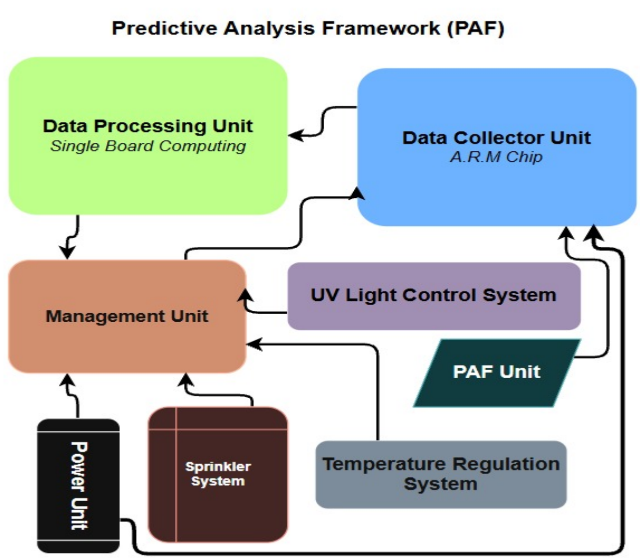


Fig -4: Block Diagram of PAF Framework

E. User Interface and Reporting Framework (UIRF)

The User Interface and Reporting Framework (UIRF) is designed to make plant stress monitoring more accessible and actionable for users. It features a clear and interactive dashboard that displays real-time data on stress levels, acoustic signals, and overall system status, helping users stay informed at a glance.

To ensure timely responses, the system includes an alert module that automatically sends notifications—via email or SMS—whenever critical stress thresholds are crossed. Alongside real-time updates, the framework also generates regular reports that summarize key insights, such as stress classifications, environmental changes, and prediction accuracy.

Built with a user-friendly web interface and supported by a RESTful backend, the UIRF allows for secure remote access and easy integration with farm management tools. Overall, it bridges complex analytics with practical decision-making, supporting efficient and informed action in precision agriculture.

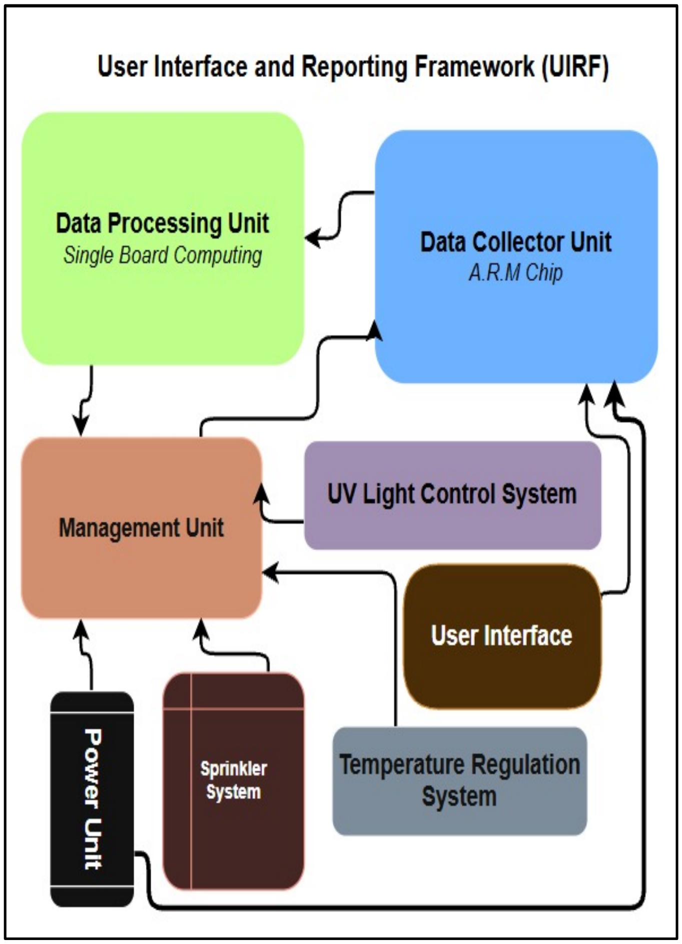


Fig -5: Block Diagram of UIRF Framework

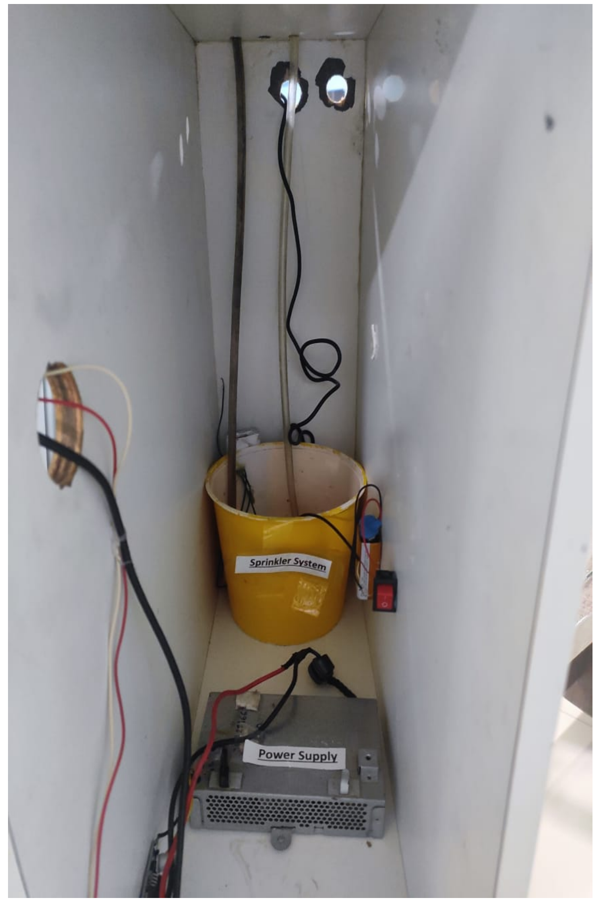
III. CONCLUSIONS

VERDANT TERRA represents a transformative step in precision agriculture by uniting plant bioacoustics, artificial intelligence, and automated environmental control into a cohesive, real-time stress management system. Its modular architecture not only enables early detection and accurate classification of plant stress but also delivers timely, data-driven interventions that enhance crop health and yield. With its predictive intelligence and user-centric interface, VERDANT TERRA offers a scalable, future-ready solution for sustainable farming across diverse agricultural environments.

IV. ACKNOWLEDGEMENT

The authors would like to express their sincere gratitude to Miss Pratiksha Sahu (Engineer and Mentor) for her invaluable mentorship, technical guidance, and provision of essential resources throughout the development of this project.

PROTOTYPE MODEL



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ACKNOWLEDGEMENT

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For providing mentorship and resources for this project.