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Automated Machine Systems for Monitoring Plant Growth and Physiological Stress

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INTRODUCTION & AIM

- Achieving food security for 9 billion people by 2050 requires overcoming a stagnant 1.3% annual crop growth rate.
- The "phenotyping bottleneck" hinders progress because our ability to measure complex traits in real-time lags behind genomic sequencing.
- High-throughput phenotyping (HTP) is essential for identifying superior genetic variations and capitalizing on molecular breeding.
- This study systematically evaluates mechatronic architectures and optical sensors that convert light-plant interactions into physiological data.
- The primary goal is to establish a framework for pre-symptomatic stress detection using engineering-driven machine solutions.

METHOD

This study is a systematic review that evaluates mechatronic architectures and imaging technologies used for non-invasive plant stress monitoring.

It analyzes the integration of optical sensors with automated processing to identify physiological changes across diverse environmental conditions

RESULTS & DISCUSSION

Biophysical Principles of Plant Sensing

- Plants exhibit unique optical properties where healthy tissues interact with electromagnetic radiation differently than infected ones.
- Chlorophyll pigments drive low visible reflectance by absorbing photons in blue and red spectral regions while reflecting green light at 550 nm.
- The "red edge" serves as a critical diagnostic transition between low visible reflectance and high NIR reflectance at approximately 670 nm.
- Scattering at air-cell interfaces within internal leaf tissues causes high NIR reflectance (700–1200 nm), which correlates with biomass and architecture.

Mechatronic Architectures and Operational Stability

- Controlled environment platforms utilize robotics and precise environmental control to assess growth non-destructively.
- Limitations in greenhouses include restricted soil volumes and lower wind speeds, which can alter normal field-like growth patterns.
- Ground-based "phenomobiles" enable detailed plot-level data capture using integrated sensor suites and 3D Time-of-Flight cameras.
- Aerial platforms like UAVs scan hundreds of plots within minutes, overcoming the scale and speed constraints of ground-based systems.

Imaging Technique	**Sensor / Spectrum**	**Phenotypic Parameters**	**Stress Correlation**
Visible (RGB)	CCD/CMOS (400–750 nm)	Projected biomass, leaf area, growth dynamics, and root architecture.	Identifies seedling vigor and monitors leaf senescence under salinity stress.
Fluorescence	Laser/LED (UV/Blue)	Photosynthetic status, quantum yield, and non-photochemical quenching.	Detects metabolic changes and early disease infection before growth declines.
Thermal IR	Microbolometers (3–14 µm)	Canopy temperature and stomatal conductance.	Measures transpiration rates and plant responses to water status.
Spectroscopy	Hyperspectral (350–2500 nm)	Vegetation indices (NDVI), water content, and pigment composition.	Tracks spatiotemporal growth patterns and nutrient levels.

. **Table 1.** Comparative Analysis of Imaging Technologies

CONCLUSIONS

- Automated systems provide the necessary precision to measure complex traits from individual organs to entire canopies.
- Sensor fusion—such as combining thermal and fluorescence imaging—is critical for distinguishing between causal stresses like water deficit and nutrient deficiency.
- Engineering-driven solutions are the primary driver for advancing imaging-based studies and overcoming the phenotyping bottleneck.

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