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Digital technologies to assess and mitigate the abiotic stress in horticultural crops

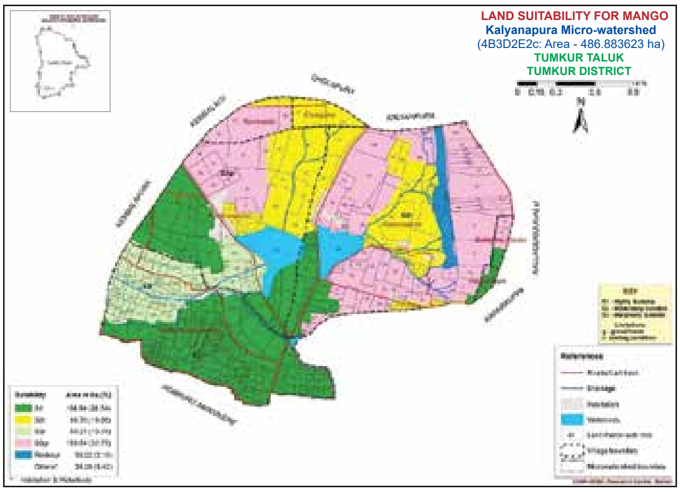
The Indian horticulture industry plays a crucial role in ensuring national food and nutritional security, yet it faces significant challenges from abiotic stressors, including drought, salinity, extreme temperatures, and irregular rainfall, which are exacerbated by climate change. These stress factors negatively affect crop yield and quality, threatening farmers' livelihoods. To mitigate these effects, digital technologies such as remote sensing, the Internet of Things (IoT), machine learning, and drones offer innovative solutions. These technologies enable real-time monitoring, early detection, and targeted interventions to reduce stress and improve crop resilience. Remote sensing and GIS aid in monitoring and managing stress by analyzing environmental factors and crop conditions, while IoT systems optimize irrigation through precise adjustments based on real-time data. Drones equipped with advanced sensors help detect stress and apply interventions like nutrient delivery and water management, particularly in diverse agro-climatic zones. Despite their potential, the adoption of these technologies faces barriers such as high costs, lack of skilled operators, and regulatory challenges. To scale up these innovations, government support and training are crucial. High-throughput phenotyping and imaging technologies further enhance stress management by providing valuable insights into crop health and development. Overall, digital tools are transforming the Indian horticulture landscape, offering significant potential to enhance productivity, sustainability, and resilience against abiotic stresses.

THE Indian horticulture industry is crucial to national food and nutritional security as well as the agricultural economy. However, it faces increasing threats from abiotic stressors such as drought, salinity, extreme temperatures, and irregular rainfall, all of which are exacerbated by climate change. These stressors significantly affect crop yields, putting millions of farmers' livelihoods at risk. Abiotic stresses pose significant challenges to horticultural crops in India by affecting productivity, quality, and sustainability. Drought is a major concern, particularly in arid and semi-arid regions where water scarcity reduces plant growth, fruit quality, and yield. Heat stress, exacerbated by rising temperatures, disrupts plant metabolism, leading to premature leaf senescence and reduced fruit quality, thereby affecting crops such as tomatoes, cucumbers, and strawberries.

Digital technologies offer novel ways to manage abiotic stress challenges and enhance crop resilience. Tools such as remote sensing, the Internet of Things (IoT), machine learning, and decision support systems (DSS) are transforming how farmers monitor and mitigate environmental stress. IoT-based sensors monitor critical factors such as soil moisture and temperature, enabling precise irrigation adjustments to prevent drought stress. Drones equipped with advanced imaging technologies provide real-time, high-resolution data on plant health and soil conditions, allowing for targeted interventions. They are particularly effective in India's diverse agro-climatic zones, helping to optimize resource use and reduce input waste. Additionally, drones with thermal imaging and precision sprayers assist in mitigating heat stress and nutrient deficiencies by delivering localized treatments. Remote sensing, combined with AI and machine learning, further enhances stress management by offering broad landscape-level insights and early detection of stress symptoms. Despite the transformative potential of these technologies, barriers, such as high costs, regulatory hurdles, and the need for skilled operators, remain. Overcoming these challenges through government support and training is essential for scaling up digital tools in Indian horticulture, ultimately improving crop resilience, productivity, and sustainability. Emerging technologies, such as IoT, drones, and precision agriculture, offer potential solutions to these challenges by providing early detection and tailored real-time interventions to help Indian horticulture adapt to environmental stresses and ensure sustainable productivity.

Digital technologies for assessing abiotic stresses

Remote sensing (RS) involves capturing and analysing reflected or emitted energy to gather information on vegetation health, crop conditions, and environmental factors. Utilizing technologies from the ground, air, and space, RS provides multispectral, spatial, and temporal data that aid in crop yield estimation and monitoring. RS applications include crop inventory, production forecasting, leaf area index (LAI) estimation, and drought or flood damage assessment. Geographic Information Systems (GIS) combine spatial data with agronomic information to map stress factors, such as soil salinity or drought-prone areas, facilitating targeted interventions. GIS also enables land suitability assessments, as demonstrated in mango cultivation, by analysing factors such as soil texture and groundwater availability. This helps farmers make informed decisions regarding crop pattern and management. By integrating data over time, GIS allows the tracking of changing stress conditions, identifying trends, and assessing long-term impacts on horticultural crops. High-resolution imagery and thermal monitoring can also assist in the detection of plant stress under varying irrigation regimes. Internet of Things (IoT) systems deploy smart sensors to monitor environmental conditions such as soil moisture, temperature, and humidity in real time. These sensors continuously collect data, enabling early detection of stress indicators. AI and machine learning algorithms analyse data to identify stress patterns, predict severity, recommend timely interventions, optimize crop management, and improve resilience. In addition, machine learning models can forecast future stress events by assessing historical data, weather patterns, and crop growth stages, allowing for proactive and targeted management strategies that enhance crop health and productivity. Agricultural weather stations enable real-time monitoring of production factors and environmental conditions. Equipped with various meteorological instruments and sensors, these stations collect and record key parameters such as temperature, humidity, wind speed, and rainfall. The data are then transmitted in real time to a central database or cloud platform via an automated recording system for analysis and processing.



Typical land resources inventory (LRI) of crop suitability map in Tumkur district of Karnataka

High-throughput phenotyping (HTP) enables rapid, precise, and non-destructive measurements of multiple plant traits. This approach relies on automation, data integration, advanced analytics, imaging platforms, and sensor technologies. Modern HTP systems are fully automated and equipped with advanced sensors, imaging devices, and computational tools for streamlined phenotyping. These platforms employ diverse imaging techniques such as 3D imaging, near-infrared spectroscopy, far-infrared imaging, fluorescence imaging, and hyperspectral imaging. Specialized HTP platforms such as LemnaTec, Phenomobile, and Phenotower are used for enhanced plant phenotyping. The choice of sensors, considering factors such as spectral and spatial resolutions and cost, is crucial for specific applications. RGB images capture three wavebands (Red, Green, and Blue), multispectral images cover several wavebands in the visible and near-infrared regions, and hyperspectral images include hundreds or thousands of continuous wavebands. Each type of sensor offers distinct features, making it essential to assess its impact on plant phenotyping. For optimal results, the use of trait-specific sensors with appropriate algorithms is recommended, as this enhances predictive accuracy and model robustness. The features of the sensors and the phenotypic traits that are studied using these sensors are presented in Table 1.

Crop phenotyping techniques are pivotal for advancing crop breeding by precisely characterizing the traits that are essential for improvement. These techniques have been

Table 1. Utility of sensors and their pros-cons

Sensor type	Plant trait(s)	Pros	Cons
RGB imaging	Yield, biomass, height, LAI, nitrogen, crop vigour etc.	Low price, light weight, work flexibly, easy operation, easy data analysis etc.	Limited imaging information
Multispectral imaging (MSI)	Yield, biomass, LAI, nitrogen, water content, citrus greening diseases etc.	Low price, work flexibly, easy operation, easy data analysis etc.	Less wavebands, no continuous spectrum information etc.
Hyperspectral imaging (HIS)	Biomass, height, LAI, chlorophyll, nitrogen, citrus greening diseases etc.	More wavebands, more images, high resolution etc.	High price, complicated operation and data analysis etc.
Thermal infrared imaging (TII)	Canopy temperature and water status	High accuracy for stress detection	Easily affected by other factors (e.g., weather)
Light detection and ranging (LDR)	Biomass, canopy spread, number of fruits etc.	High precision horizontal and vertical information, effective in deep canopy information, feasibly work at night etc.	High price, complicated data analysis etc.

Table 2. Application of crop phenotyping techniques with respect to crop breeding

Application	Traits
Drought tolerance	Surface temperature and transpiration, canopy and leaf water status, shoot biomass, leaf rolling, and stay-green properties etc.
Salinity tolerance	Surface temperature, transpiration rate, plant growth rate, shoot area etc.
Nutrient deficiency	Photosynthetic status, leaf health status, growth rate, vegetation indices etc.
Disease detection	Colour and morphology, transpiration rate, photosynthetic rate, spectral vegetation indices etc.
Pest resistance	Insect number and behaviour, surface temperature, spectral vegetation indices, chlorophyll fluorescence spectrum etc.
Direct yield estimation	Fruit count, determination of fruit size, fruit density etc.

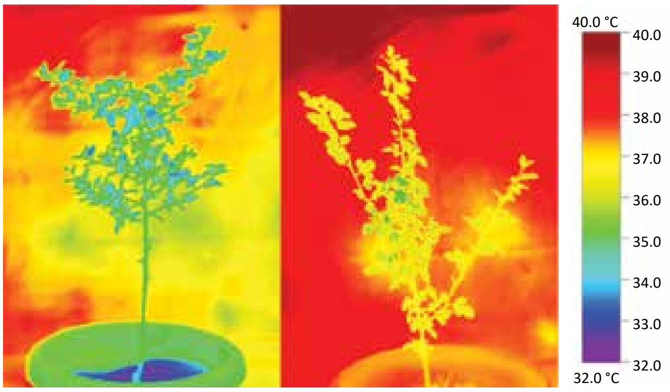
applied in various domains, such as drought and salinity tolerance, nutrient deficiency, disease detection, pest resistance, and yield optimization (Table 2). They enable breeders to assess traits such as surface temperature, transpiration rates, shoot biomass, and more specifically, tailored to specific breeding goals. By providing valuable insights into plant characteristics, phenotyping accelerates the development of superior crop varieties and enhances their resilience and productivity.

Thermal imaging detects infrared radiation to measure canopy temperature, indicating water stress, because plants with reduced transpiration show higher temperatures. It offers high accuracy for real-time stress assessments and can be mounted on drones or ground systems. However, weather conditions may also affect the reliability. Near-infrared (NIR) imaging monitors leaf and soil water content, whereas far-infrared (FIR) imaging measures temperature. Both techniques are valuable for studying drought stress and the traits related to osmotic resistance.

Chlorophyll fluorescence imaging provides information on photosynthetic efficiency, allowing for the detection of stresses that affect photosynthesis, such as light, heat, or nutrient stress. This technique is non-invasive and highly sensitive to early stage stress responses. Image-based technologies provide a non-destructive, accurate, and scalable means for assessing abiotic stress in horticultural crops. By capturing detailed visual and spectral information, these tools help farmers and researchers understand plant health at both macro and micro levels, facilitating early intervention and improving stress management strategies.

Digital technologies for mitigating abiotic stress

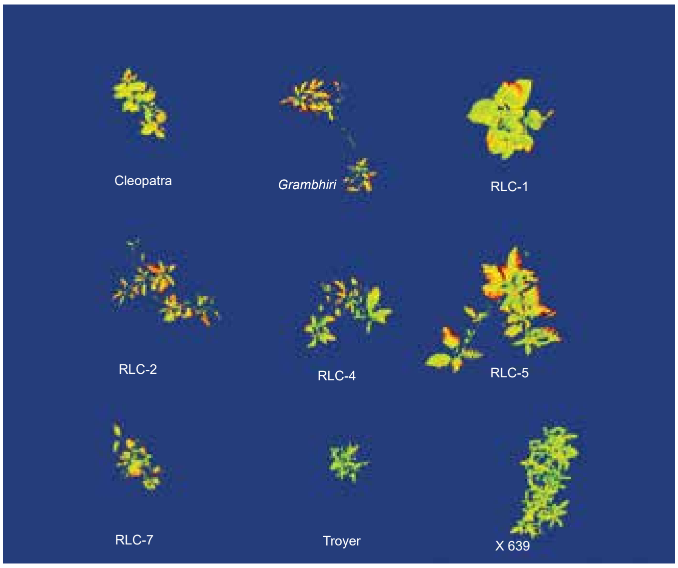
Digital technologies for mitigating abiotic stress in horticultural crops include various tools and methods aimed at optimizing resource use and supporting adaptive crop management. These innovations reduce the impacts of stress factors, such as drought, salinity, and extreme temperatures, thereby enhancing crop resilience and productivity. The key digital technologies employed for this purpose include automated precision irrigation



Comparison of plant canopy temperature under well-watered (left) and water deficit conditions (right)

systems, environmental control systems, image-based technologies, weather-monitoring tools, and drones. Water and nutrients are vital inputs for horticultural crop plants to maintain growth and productivity. Water deficits during critical developmental stages can lead to significant yield losses, making precision-sensor-based irrigation essential. Advanced irrigation systems equipped with IoT sensors and remote sensing data adjust water application rates based on real-time crop needs and environmental conditions. For example, soil moisture sensors can continuously monitor moisture levels and automatically regulate irrigation systems, thereby reducing water and nutrient waste. This efficient use of water helps to alleviate drought stress while conserving limited natural resources.

In controlled greenhouse environments, automated systems regulate the temperature, humidity, and light based on sensor feedback. When temperature sensors detect heat stress, cooling systems can be activated to maintain the optimal growth conditions. Automated shading and ventilation systems further protect crops from heat stress and excessive sunlight exposure. These systems ensure consistent growing conditions, reduce resource consumption, and improve crop quality by utilizing IoT sensors and software to monitor and adjust the environment in real-time. Advanced technologies like



Comparison of whole plant chlorophyll fluorescence during drought stress in citrus genotypes

AI and machine learning can further enhance productivity in automated greenhouses, promoting efficient and sustainable vegetable production.

Thermal cameras can identify hot spots in the field, allowing for targeted cooling interventions, such as misting to mitigate heat stress. Multispectral imaging can reveal nutrient deficiencies or pest infestations, prompting precise foliar application that reduces chemical use and enhances crop resilience. For instance, imaging techniques such as thermal cameras and chlorophyll fluorescence have been used to monitor mango trees for desiccation tolerance. In Okra, studies combining thermal and RGB imaging achieved high accuracy in detecting water stress, demonstrating the effectiveness of these technologies in real-time irrigation management. These image-based approaches support improved water management and stress alleviation strategies for various crops. Automated weather stations and forecasting tools provide critical alerts regarding imminent stress conditions, enabling farmers to take preventive actions. For instance, grape growers can adjust irrigation schedules or apply protective treatments in anticipation of sudden rainfall during the sensitive growth stages. Monitoring microclimatic parameters allows for a better understanding of the factors leading to issues such as berry cracking in grapes, enabling adaptive management strategies to minimize potential losses.

Drones play a multifaceted role in the monitoring and management of abiotic stress. They provide real-time aerial views of crop conditions, facilitating immediate mitigation when stress indicators are detected. Equipped with multispectral or hyperspectral sensors, drones can assess soil moisture and plant health, and guide interventions, such as moisture retention practices. In greenhouse environments, drones assist in scouting plants for symptoms of deficiency, fruit growth, and development. They can automate environmental controls, activate misting systems during high heat, or provide ventilation during extreme humidity, helping maintain optimal conditions. Moreover, drones enhance the precision of nutrient and water application. Studies have shown that drone-facilitated foliar application of micronutrients significantly improves growth and yield compared with traditional methods. Drones quickly scan large areas, identify zones requiring immediate intervention, and efficiently allocate resources to areas experiencing higher stress levels.

SUMMARY

Digital technologies offer significant potential for the assessment and mitigation of abiotic stresses in horticultural crops. These tools provide precise real-time data on plant health and environmental conditions, allowing for early stress detection and targeted interventions. By utilizing remote sensing, IoT sensors, AI, and decision support systems, farmers can implement timely and precise strategies to mitigate the effects of drought, heat, salinity, and other stress factors. These technologies facilitate the rapid, accurate, and comprehensive assessment of plant traits, thereby accelerating the development of stress-resilient fruit varieties and promoting sustainable fruit crop production in the context of climate change. Adopting this multidimensional approach is essential for ensuring food security and long-term success of the fruit crop industry.

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Profitable Nursery through "Mini-Shade Net"

Shri M. Sankara Rao is a marginal farmer, belonging to a remote village of Naiduvalasa of Rambadrapuram Mandal of Vizianagaram district in Andhra Pradesh. He is an ex-trainee of KVK, Vizianagaram. Having gained knowledge and skill in nursery, he established nursery unit with "*mini-shade net*" under the technical guidance of KVK faculty. He raised seedlings of different vegetables and papaya under *mini-shade net* (60 sq m) and produced high quality virus-free papaya seedlings (2,500) and vegetables seedlings, viz. Tomato (5,000), Brinjal (5,000), Chilli (5,000) during May 2021 to October 2021, with which, he received a net income of ₹ 25,700. Farmers from the neighbouring villages got attracted with the benefits gained by protected shade-net nursery production; and accordingly, approached KVK, Vizianagaram for further guidance to adopt the technology.

A view of nursery unit of Shri M. Sankara Rao with mini-shade net

Source: ICAR Annual Report 2022-23