

PHYSIOLOGICAL RESEARCH ON CLIMATE RESILIENCE AND STRESS MITIGATION IN TROPICAL TUBER CROPS: A DECADE OF INSIGHTS AT ICAR-CTCRI



भाकृअनुप- केंद्रीय कंद फसल अनुसंधान संस्थान
श्रीकार्यम, तिरुवनंतपुरम 695017, केरल, भारत
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(Indian Council of Agricultural Research)



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From the Director



It gives me great pleasure to present this bulletin, “Physiological Research on Climate Resilience and Stress Mitigation in Tropical Tuber Crops: A Decade of Insights at ICAR-CTCRI,” which captures the institute's sustained efforts to strengthen tuber crop production under increasing climate variability. Over the past decade, ICAR-CTCRI has combined multi-location field research with controlled-environment climate simulation facilities and modern physiological and molecular tools to generate actionable knowledge for cassava, sweet potato, elephant foot yam, taro, yams, and yam bean. The bulletin highlights validated stress-screening traits, practical interventions such as plant growth regulators and bioinoculants, and progress in identifying climate-resilient varieties and gene-level regulators-evidence that is relevant not only to researchers and students but also to breeders, extension personnel, and policy stakeholders. I extend my congratulations to the authors and all contributing teams and collaborators for presenting these insights in such a clear and practical manner. I am confident that this publication will serve as a valuable reference and road-map for advancing climate-smart tuber crop research and development in the years ahead.

March, 2026


G. Byju
Director

1. INTRODUCTION

Importance of Tropical Tuber Crops in Food and Nutritional Security

Tropical tuber crops-including cassava (*Manihot esculenta*), sweet potato (*Ipomoea batatas*), taro (*Colocasia esculenta*), yam (*Dioscorea* spp.), elephant foot yam (*Amorphophallus paeoniifolius*), and yam bean (*Pachyrhizus erosus*)-constitute a critical foundation for food and nutritional security for millions of people in Asia, Africa, and Latin America. These crops are particularly valuable in marginal environments where cereal crops frequently fail, providing reliable food sources under rain-fed and resource-limited conditions.

Cassava is notably significant as the third most crucial source of calories in tropical regions, following rice and maize. It serves both as a dietary staple and as an essential industrial raw material (FAO, 2013). Sweet potato, recognized for its adaptability and short growing cycle, plays an essential role in combating vitamin A deficiency among vulnerable populations due to its high content of beta-carotene and antioxidants (Low et al., 2009). Additionally, taro and yams occupy an indispensable position in the traditional diets of many indigenous communities, valued for their digestibility, rich mineral content, and balanced glycemic properties.

From a nutritional perspective, tropical tuber crops offer essential dietary components, including complex carbohydrates, vital amino acids, dietary fiber, and micronutrients such as iron, zinc, and potassium. Significantly, biofortified varieties of sweet potato and cassava have been developed to effectively combat micronutrient malnutrition, providing scalable solutions to the global challenge of hidden hunger (Bouis & Saltzman, 2017).

The inherent resilience of tuber crops to both biotic and abiotic stresses positions them strategically for climate adaptation. Their capacity to sustain yields under prolonged drought, degraded soils, or limited agricultural inputs makes them ideal candidates for ensuring food security in the face of changing climatic conditions (Jarvis et al., 2012). Furthermore, their diverse potential uses-including food, animal feed, starch production, alcohol, and pharmaceuticals-significantly enhance their economic value and versatility.

In India, the strategic importance of tropical tuber crops in bolstering food supply, particularly in tribal and upland regions, is increasingly recognized. Research institutions such as ICAR-CTCRI have been pivotal in the development of improved varieties, value-added products, and climate-resilient agricultural practices, enhancing the prominence of these crops within national food security strategies.

In summary, tropical tuber crops are far more than mere subsistence staples. They represent strategic resources critical for sustainable development, uniquely capable of addressing the interconnected goals of nutritional security and climate resilience in an era marked by uncertainty and environmental change.

Vulnerability to Climate Change and Stressors

Despite their inherent resilience, tropical tuber crops are increasingly vulnerable to the intensifying impacts of climate change. Rising temperatures, erratic rainfall patterns, prolonged droughts, unseasonal floods, and increased pest and disease pressures significantly alter their growth dynamics and productivity potential. Although many tuber crops thrive in marginal, stress-prone environments, the compounding effects of extreme climatic events seriously threaten their yield stability and crop quality.

Cassava, for example, demonstrates drought tolerance through deep rooting systems and stomatal regulation. However, prolonged drought during early growth stages can severely impair canopy development and tuber bulking (El-Sharkawy, 2007). Similarly, sweet potato is sensitive to heat stress during tuber initiation and suffers under waterlogged conditions in poorly drained soils. Yam and taro are susceptible to diseases such as anthracnose and leaf blight, whose incidence increases under humid and warming conditions.

These vulnerabilities are further exacerbated by the limited adaptive capacities of traditional varieties, particularly in regions where climate-smart agricultural practices and improved genotypes are not extensively adopted. Moreover, abiotic stresses frequently coincide with biotic challenges, such as cassava mosaic virus (CMD), taro leaf blight, and nematode infestations, creating complex stress scenarios for smallholder farmers.

Given the projected global temperature rise of 1.5-2°C by the end of this century and increased inter-annual rainfall variability in tropical regions (IPCC, 2021), it is imperative to develop climate-resilient crop varieties and tailored management strategies. These efforts are essential to ensure that tuber crops not only survive but also sustain productivity under unpredictable and adverse agro-climatic conditions.

Rationale for Physiological Research at ICAR–CTCRI

Acknowledging the strategic global significance of tropical tuber crops for food security and climate adaptation, the ICAR-Central Tuber Crops Research Institute (CTCRI) has been at the forefront of physiological research over the past decade to proactively address emerging climate-related challenges. The primary objective is to unravel complex plant responses to critical environmental stressors-including drought, submergence, elevated temperatures, and increased atmospheric carbon dioxide concentrations-and to convert this scientific understanding into practical breeding and agronomic interventions.

Physiological research at ICAR-CTCRI emphasizes identifying and characterizing pivotal stress-responsive traits, such as canopy architecture, leaf retention index, chlorophyll fluorescence, stomatal conductance, osmotic adjustment, and water-use efficiency. These physiological traits form reliable selection criteria to screen genotypes, thereby facilitating the development of climate-resilient crop varieties.

To effectively simulate and evaluate crop responses to anticipated climate scenarios, ICAR-

CTCRI has developed specialized research infrastructures, including open-top chambers (OTCs), rainout shelters, and polychambers. These advanced facilities enable precise assessments of crop physiological responses under controlled as well as realistic field conditions. Additionally, multi-location field trials across various agroclimatic zones help validate the consistency and robustness of physiological traits and overall crop performance under diverse environmental stress gradients.

Another essential component of ICAR-CTCRI's research involves exploring the synergistic use of plant growth regulators (PGRs), beneficial soil microbes, and moisture-conserving agronomic practices to enhance stress tolerance through physiological priming. Findings from these studies not only complement breeding initiatives but also significantly inform the creation of region-specific, climate-smart crop management strategies.

By integrating fundamental plant physiology with practical crop-imvment methodologies, ICAR-CTCRI is building a comprehensive foundation for climate-resilient tuber crop agriculture in India and beyond. This research holds particular importance for smallholder and marginal farmers, whose livelihoods are critically linked to these crops amid growing climatic uncertainty.

2. CLIMATE CHANGE AND TUBER CROPS: FROM GLOBAL AND NATIONAL PERSPECTIVE

Overview of Climate Risks in Tropical Agriculture

Agriculture in tropical regions faces heightened vulnerability to climate change due to its inherent sensitivity to rising temperatures, erratic rainfall patterns, increasing frequency of extreme weather events, and intensifying pest and disease pressures. Unlike temperate regions, tropical agricultural systems often operate close to critical physiological thresholds, making them particularly susceptible to even slight fluctuations in climate variables, resulting in significant reductions in crop yields (Lobell et al., 2011). This vulnerability disproportionately affects smallholder farming communities across South Asia and sub-Saharan Africa, where agriculture predominantly relies on rainfed conditions and limited resource availability.

The key climate-induced risks affecting tropical agriculture include:

- **Drought stress:** Occurring during critical growth stages, drought significantly reduces biomass accumulation and tuber yield.
- **Heat stress:** Elevated temperatures impair photosynthetic efficiency and negatively impact reproductive and developmental processes.
- **Waterlogging and submergence:** Excessive water and flooding compromise root health by reducing oxygen availability in poorly drained soils.
- **Pest and disease pressure:** Altered microclimatic conditions contribute to emerging and more aggressive pest and disease outbreaks.
- **Elevated atmospheric CO₂:** Increased CO₂ levels have mixed effects-enhancing photosynthesis in C₃ crops but potentially accelerating crop development, altering nutrient composition, and increasing pest susceptibility.

These climatic challenges are particularly pronounced for tropical tuber crops such as cassava, sweet potato, taro, yam, and elephant foot yam, which are primarily cultivated in marginal and stress-prone agroecosystems. Although these crops possess certain adaptive traits-such as cassava's deep rooting system or taro's tolerance to shade-their productivity is frequently compromised under conditions of prolonged or concurrent stress.

Recent research findings from ICAR-CTCRI corroborate these global concerns with region-specific data. For example, cassava plants exposed to early-season water deficit stress (3-5 months after planting, MAP) showed significant reductions in photosynthetic efficiency (30-48%), stomatal conductance (47-64%), and ultimately, tuber yield, highlighting its particular vulnerability during early bulking stages (More et al., 2020). Similarly, studies on elephant

foot yam demonstrated a severe yield reduction (approximately 78%) when exposed to water deficits between 4-5 MAP, indicating this period as critical for targeted irrigation management (Ravi et al., 2015).

Conversely, elevated atmospheric CO₂ scenarios may present some physiological advantages for certain tuber crops. Studies revealed that sweet potato, yam, and taro exhibit improved photosynthetic rates, enhanced water-use efficiency, and increased tuber yields under elevated CO₂ levels (600-1000 ppm), particularly in high-light environments (Ravi et al., 2017; 2019). However, these benefits are strongly genotype-dependent and may be counteracted by nutrient dilution effects or yield suppression from increased heat stress if not managed effectively.

At the national level, projections indicate that India's tropical agricultural zones could face yield reductions of 10-20% in major crops by 2050, driven primarily by rising temperatures and erratic rainfall patterns (ICAR-NICRA, 2014). they are gaining recognition in India's climate-resilient agricultural strategies owing to their adaptability and comparatively lower input requirements.

Given these risks, integrating climate-smart agricultural practices into tuber crop systems represents both an agronomic necessity and a strategic imperative for ensuring long-term food security. Continuous research emphasizing physiological insights, advanced stress diagnostics, and targeted genotypic selections remains critical to future-proofing tropical tuber agriculture in an era of rapidly evolving climate conditions.

Specific Challenges for Tuber Crops under Climate Change (Heat, Drought, Submergence, and Elevated Co₂)

Tropical tuber crops face distinct and intensifying challenges under climate change scenarios, largely due to the sensitivity of their underground storage organs to changes in soil moisture, aeration, and temperature. Although generally regarded as hardy and adaptable, their productivity and quality are increasingly compromised by four critical climate-induced stressors: heat, drought, submergence, and altered atmospheric CO₂.

Heat Stress

Rising temperatures adversely affect critical physiological processes, including tuber initiation, photosynthesis, and enzyme activities in tuber crops. Elephant foot yam and sweet potato, for example, show inhibited canopy growth and accelerated leaf senescence under prolonged heat stress. It is demonstrated that foliar application of salicylic acid (0.2%) effectively mitigated heat stress in elephant foot yam, increasing yields to approximately 42.5 t/ha compared to untreated controls exposed to high-temperature conditions (More et al., 2017). Without such targeted interventions, heat stress can sharply reduce tuber yields by impairing carbon assimilation and disrupting source–sink dynamics.

Drought Stress

Water scarcity poses a severe threat to tuber crops, particularly during early growth and critical tuber-bulking phases. Drought negatively impacts photosynthesis, leaf area expansion, stomatal functionality, and nutrient uptake (More et al., 2023). Studies reported that cassava subjected to drought stress between 3-5 months after planting (MAP) experienced substantial reductions-30-48% in photosynthesis and up to a 50% decline in root yield (More et al., 2020). Similarly, elephant foot yam exhibited over a 75% yield reduction when drought occurred between 4-5 MAP (Ravi et al., 2015). Consequently, identifying drought-tolerant genotypes and optimizing irrigation schedules during sensitive growth stages are essential adaptation priorities.

Submergence and Waterlogging

Episodes of flooding and poor soil drainage cause hypoxia, adversely affecting root development and tuber growth. Taro and elephant foot yam, though somewhat tolerant to moist conditions, suffer significantly under prolonged submergence, especially in low-lying or high-rainfall regions. Hypoxic conditions lead to root asphyxiation, microbial imbalance, and increased vulnerability to secondary infections, such as *Pythium* rot in taro. Unlike flood-adapted cereals such as rice, most tuber crops possess limited anaerobic metabolic adaptations despite partially aerenchymatous roots, making them vulnerable to prolonged waterlogging events.

Elevated CO₂ Concentrations

Significant alterations in physiological attributes and yield performance of major tropical tuber crops under elevated CO₂ (eCO₂) conditions have been documented through a series of controlled experiments. These studies evaluated crop responses in terms of photosynthetic efficiency, biomass accumulation, and yield under short-term eCO₂ exposure. Notable findings have been reported in sweet potato (*Ipomoea batatas*) (Ravi et al., 2017), elephant foot yam (*Amorphophallus paeoniifolius*) (Ravi et al., 2018), colocasia (*Colocasia* spp.) (Ravi et al., 2019), yam bean (*Pachyrhizus erosus*) (Ravi et al., 2020), and yam (*Dioscorea* spp.) (Ravi et al., 2022). Collectively, these studies demonstrate enhanced photosynthetic efficiency and associated yield responses under elevated CO₂ environments. Enhanced CO₂ generally improves photosynthetic efficiency in C₃ plants, including cassava, sweet potato, taro, and yam. Studies at ICAR-CTCRI using open-top chambers and gas exchange assessments reported increased net photosynthesis rates of 61-74% in sweet potato and yam under elevated CO₂ (1000 ppm; Ravi et al., 2017; 2019). Likewise, yam bean demonstrated a 23% increase in net photosynthesis (P_n) under elevated CO₂ combined with high light intensity (Ravi et al., 2020), indicating that elevated CO₂ may partially offset drought and heat stress by enhancing carbon fixation and water-use efficiency.

However, responses to elevated CO₂ are genotype-dependent. In certain cases, increased

atmospheric CO₂ can cause nutrient dilution, reducing tuber protein and micronutrient concentrations. Furthermore, potential physiological benefits from elevated CO₂ might be diminished under extreme heat or water deficit conditions, due to stomatal closure and enzymatic impairments.

Adaptive and Mitigative Strategies: Relevance and Implementation

The accelerating impacts of climate change necessitate immediate deployment of both adaptive and mitigative strategies, especially for tuber crops central to food security in climate-sensitive regions. Such measures are critical not only for sustaining agricultural productivity but also for safeguarding rural livelihoods, preserving soil health, and maintaining agrobiodiversity.

Adaptation: Enhancing Crop Resilience and System Flexibility

Adaptation measures aim to enhance the plant's tolerance or avoidance of climate-induced stresses. Key adaptive strategies include:

- **Breeding resilient varieties:** Selecting for traits such as deeper rooting systems, increased leaf retention, delayed senescence, and improved water-use efficiency.
- **Trait-based screening:** Evaluating genotypes under controlled environments such as rainout shelters, open-top chambers (OTCs), and temperature-controlled facilities.
- **Precision irrigation management:** Critical water supply during sensitive growth periods (e.g., 3-5 MAP in cassava, 4-6 MAP in elephant foot yam).
- **Application of plant growth regulators (PGRs):** Foliar treatments (e.g., salicylic acid, calcium chloride) to enhance resilience, reduce oxidative stress, and promote recovery from abiotic stress.
- **Integrated pest and disease management:** Proactive strategies targeting emerging biotic threats related to changing microclimates.

Research at ICAR-CTCRI has identified critical genotype × environment interactions, allowing integration of cassava and sweet potato varieties with high photosynthetic efficiency and drought tolerance into breeding pipelines (More et al., 2020; Ravi et al., 2017).

Mitigation: Reducing Agriculture's Environmental Footprint

Mitigation strategies aim to reduce greenhouse gas emissions and enhance carbon sequestration. Relevant mitigative strategies for tuber crops include:

- **Efficient nutrient management:** Minimizing nitrous oxide emissions through site-specific fertilizer application, using slow-release formulations.
- **Utilization of biological agents:** Plant growth-promoting rhizobacteria (PGPRs) to enhance nutrient efficiency and stress resilience, reducing dependence on synthetic fertilizers.

- **Conservation agriculture:** Practices such as minimum tillage and organic mulching, improving soil carbon sequestration and moisture retention.
- **Diversification and intercropping:** Systems such as yam-bean or pulse-tuber intercropping to enhance nitrogen fixation, system resilience, and overall productivity.

Research at ICAR-CTCRI has indicated that elevated CO₂ conditions increase biomass production and root carbon inputs in yam, sweet potato, and taro, indirectly contributing to soil carbon storage (Ravi et al., 2019; Saravanan et al., 2020). Balancing these benefits with nutritional quality and nutrient-use efficiency is essential, offering opportunities to integrate adaptation with mitigation strategies effectively. Developing high-yielding, abiotic stress-tolerant cultivars of tropical tuber crops with enhanced starch content and other beneficial constituents, while simultaneously minimizing anti-nutritional factors, will remain an elusive and challenging task for breeders. This is particularly critical since the consumption of reported anti-nutritional compounds has been associated with several human diseases and disorders.

3. RESEARCH INFRASTRUCTURE AND APPROACH

Field Stations and Controlled Environment Facilities

To advance research on climate-resilient tropical tuber crops, the ICAR-Central Tuber Crops Research Institute (ICAR-CTCRI) has developed a comprehensive research infrastructure that integrates large-scale field stations with modern controlled-environment facilities.

The main campus at Thiruvananthapuram, Kerala, encompasses a 130-acre experimental farm, purposefully designed for multi-season trials, varietal screening, and evaluations under both abiotic and biotic stress conditions. This site also facilitates studies on soil-crop-climate interactions. Complementing this, the 30-acre regional research station in Bhubaneswar, Odisha, offers a contrasting agroclimatic setting, supporting multilocal testing and genotype $\times$ environment interaction ($G \times E$) analyses, particularly relevant to eastern Indian growing conditions.

To investigate the physiological basis of stress tolerance, ICAR-CTCRI has established state-of-the-art controlled-environment facilities that allow precise simulation of climate variables. These include:

- **Open-Top CO₂ Enrichment Chambers (OTCs):** Used to evaluate plant responses to elevated atmospheric CO₂ levels, enabling studies on photosynthesis, biomass accumulation, and tuber yield under simulated future climates.
- **Controlled Environment Greenhouses and Polyhouses:** Equipped to manipulate temperature, humidity, and light, these units support experiments across a range of stress conditions, including drought, heat, and submergence.
- **High-Resolution Analytical and Diagnostic Instruments:**
 - **Portable Photosynthetic System (LI-COR 6800XT):** Enables real-time measurements of photosynthetic rate (Pn), stomatal conductance (gs), transpiration (E), and intercellular CO₂ concentration (Ci).
 - **Plant Canopy Analyzer:** Used for non-destructive estimation of Leaf Area Index (LAI) and monitoring canopy development in both field and greenhouse conditions.
 - **Canopy Temperature Probes:** Facilitate detection of water stress and stomatal behavior through thermal imaging.
 - **Water Potential Console and Osmometer:** Key for assessing plant water relations and osmotic adjustment under drought or salinity.
 - **UV-Visible Spectrophotometer:** Extensively used to quantify chlorophyll content, antioxidative enzyme activity, and other stress-related metabolites.

In addition to these instruments, the institute is equipped with standard physiological, biochemical, and agronomic tools necessary for integrated stress research. This

infrastructure enables both fundamental and applied research and fosters national and international collaborations focused on climate-resilient agriculture.

The integration of precision-controlled experimentation with real-world field validation has led to several landmark findings at ICAR-CTCRI. These include insights into drought physiology in cassava, heat mitigation strategies in elephant foot yam, CO₂ responsiveness in sweet potato and yam bean, and canopy dynamics under submergence in taro.

Experimental Designs, Tools, and Collaborations

The effectiveness of ICAR-CTCRI's physiological research is underpinned not only by its infrastructure but also by rigorous experimental design, advanced analytical tools, and strong collaborative frameworks.

Experimental Designs

A range of statistical designs is employed to suit diverse research objectives, including:

- **Randomized Complete Block Design (RCBD) and Split-Plot Designs** for multifactorial field experiments involving variables like fertility regimes, irrigation schedules, or bio-stimulants applications.
- **Factorial Designs** to investigate interaction effects such as genotype $\times$ drought or CO₂ $\times$ nitrogen interactions on growth and yield.
- **Repeated Measures and Time-Series Designs** to track physiological parameters (e.g., Pn, LAI, canopy temperature) across different growth stages.
- **Simulation Chambers and Microplots** for precise physiological measurements under semi-controlled stress environments.

This methodological flexibility enables robust simulation and analysis of a wide spectrum of abiotic and biotic stress scenarios, facilitating a deeper understanding of crop responses.

Tools for Data Collection and Analysis

Advanced hardware and software tools are seamlessly integrated into the research workflow:

- **Field Instruments:** LI-COR 6800XT and canopy analyzers for high-resolution physiological trait measurements.
- **Software Platforms:** R, SAS, and GenStat for statistical modeling, variance analysis, and mixed-effect model evaluation, especially in multilocational and unbalanced datasets.
- **GIS and Remote Sensing:** Used for spatial mapping of stress distribution and landscape-level crop performance analysis.
- **Molecular Tools:** In collaboration with partner institutes, molecular assays are conducted to assess gene expression and marker-trait associations related to stress responses.

Collaborations and Networking

ICAR–CTCRI actively collaborates with multiple national and international partners to expand the scope and impact of its research. Key partnerships include:

- **ICAR Institutes** (e.g., IARI, IIHR, NRRI) for germplasm sharing, multi-location trials, and integrative research on plant-soil-microbe interactions.
- **State Agricultural Universities (SAUs)** and **Krishi Vigyan Kendras (KVKs)** for field validation and dissemination of climate-smart technologies.
- **International Centers:** Collaborations with CIP (International Potato Center) and IITA (International Institute of Tropical Agriculture) provide access to global expertise, genetic resources, and capacity-building programs.
- **Academic Institutions:** Engagements with Kerala Agricultural University, Indian Institute of Science, and others for joint research on physiological modeling, carbon flux estimation, and biochemical analyses.

These collaborations have resulted in co-authored publications, externally funded projects, joint student supervision, and training workshops-collectively contributing to mainstreaming climate resilience in tropical tuber crop systems.

4. ABIOTIC STRESS RESPONSES: KEY THEMES

4.1 DROUGHT STRESS

Screening Methods and Tolerant Genotypes

Drought stress is one of the most significant constraints on the productivity of tropical tuber crops such as cassava and elephant foot yam (EFY), especially when grown in rainfed or marginal agroecosystems. At ICAR-CTCRI, systematic screening protocols have been established to evaluate genotypic responses to moisture deficit under both field and controlled environments.

For cassava, screening under managed drought involves:

- With holding irrigation during the early bulking phase (3-5 months after planting, MAP),
- Monitoring canopy wilting scores, leaf retention index (LRI), chlorophyll content (SPAD), and stomatal behavior,
- Assessing final tuber yield and storage root bulking efficiency.

Early-bulking genotypes showed better performance under intermittent drought by accumulating significant root biomass before terminal stress onset. High-performing genotypes maintained over 30% higher photosynthetic rate and up to 40% greater storage root biomass than susceptible lines.

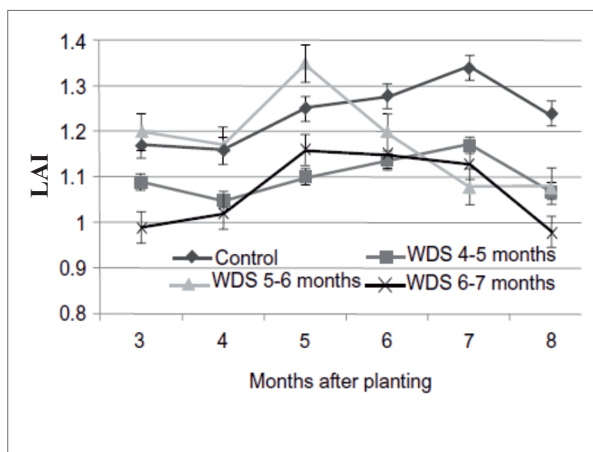


Fig. 1. Leaf Area Index (LAI) as affected by water deficit stress in EFY across different months after planting.

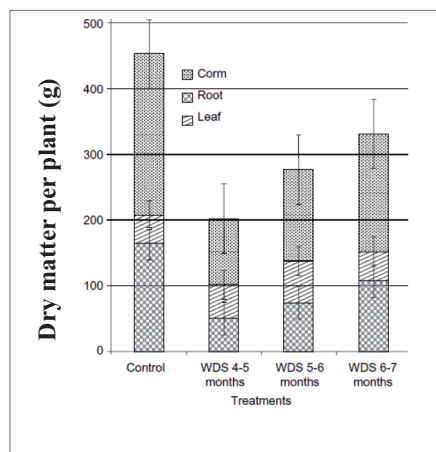


Fig. 2. Total dry matter partitioning (leaf, root, corm) under different drought timings in EFY.

In elephant foot yam, water deficit stress (WDS) was imposed during three critical growth windows: 4-5, 5-6, and 6-7 MAP. The 4-5 MAP period was identified as the most vulnerable

phase. Leaf Area Index (LAI) dropped significantly, with values falling below 1.0 compared to over 1.2 in control (Fig. 1). Total dry matter accumulation was also drastically reduced, with corm yield showing up to 78.5% decline when drought coincided with this sensitive phase (Fig. 2).

Physiological Traits Linked to Drought Tolerance

Multiple physiological and anatomical traits have been correlated with drought resilience in cassava and EFY:

- **Leaf Retention and LAI Maintenance:** Genotypes that sustained higher LAI and delayed senescence exhibited improved drought tolerance and tuber productivity.
- **Photosynthesis and Stomatal Regulation:** Tolerant types maintained higher net photosynthesis ($25\text{--}30 \mu\text{mol CO}_2 \text{ m}^{-2}\text{s}^{-1}$), regulated stomatal conductance efficiently, and adapted to reduced soil moisture by modulating gas exchange dynamics.
- **Osmotic Adjustment:** Accumulation of compatible solutes such as proline and glycine-betaine helped maintain cell turgor and mitigate oxidative stress during drought (Fig. 3).
- **Root System Architecture:** Deeper roots, greater lateral branching, and early root bulking were key traits supporting water uptake and drought avoidance. Advanced phenotyping tools like root crown imaging and shovelomics have been used to assess these traits (Fig. 8).
- **Stem Reserve Mobilization:** Ability to remobilize stem carbohydrate reserves to tubers during stress periods emerged as a critical mechanism supporting sustained yield under drought.

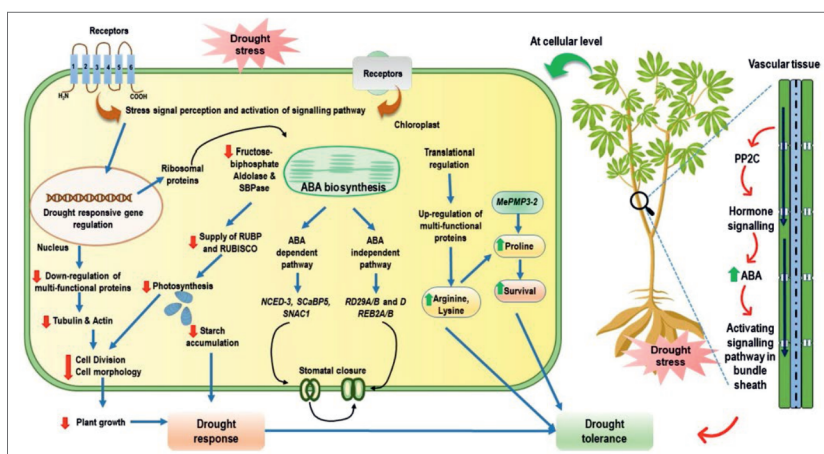


Fig. 3. ABA-mediated physiological and molecular drought stress pathways highlighting the role of stomatal closure, osmolyte accumulation, and stress-responsive gene activation

Field-Level Validations

Multi-season trials conducted in Kerala and Odisha under both natural and simulated drought conditions validated the physiological findings:

- In cassava, genotypes like Sree Jaya, Sree Pavithra, and several advanced clones consistently outperformed standard checks under drought, showing high root bulking indices and superior stress resilience.
- In EFY, precise irrigation scheduling during the 4-5 MAP window reduced yield losses by over 50%, demonstrating the effectiveness of phenology-based water management.

These insights are being actively integrated into ICAR-CTCRI's drought-resilient breeding programs through a combination of conventional selection and trait-based approaches (More et al., 2020).

4.2 HEAT STRESS

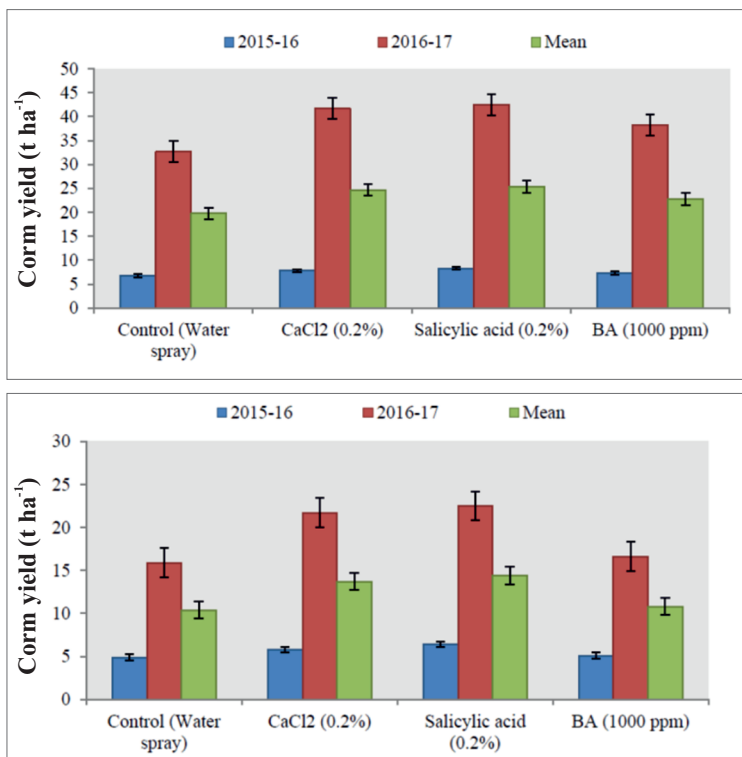
Impact on Tuberization and Biomass

Heat stress-characterized by prolonged exposure to temperatures exceeding 30°C-poses a significant challenge to tuber crops by disrupting physiological processes such as photosynthesis, enzyme function, and assimilate translocation. In crops like sweet potato and elephant foot yam (EFY), elevated temperatures during early growth stages (2-3 months after planting, MAP) are especially detrimental to tuber initiation and bulking.

Controlled environment studies at ICAR-CTCRI using polychambers simulating 32-38°C temperatures revealed:

- **Sweet potato** experienced a 35-44% decline in tuber yield, primarily due to reduced harvest index and starch accumulation.
- **Elephant foot yam** showed early senescence, reduced canopy expansion, and significant leaf drop under heat stress.

However, foliar application of salicylic acid (0.2%) notably mitigated heat-induced damage in EFY, enhancing corm yield by up to 36.4% over two consecutive seasons (Fig. 4 a-c).



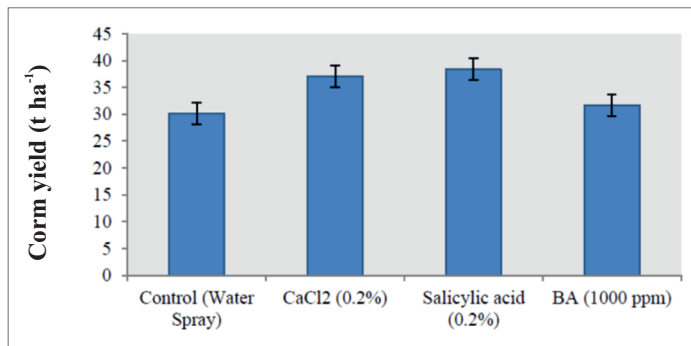


Fig. 4 a-c. Corm yield in EFY under open, non-humidified, and humidified polychamber conditions across treatments (SA, CaCl₂, BA).

Similarly, sweet potato treated with CaCl₂ or salicylic acid under heat stress maintained significantly higher tuber yield and starch content compared to control (Fig. 5). These findings identify the 2-3 MAP window as the most heat-sensitive phase in tuber crops.

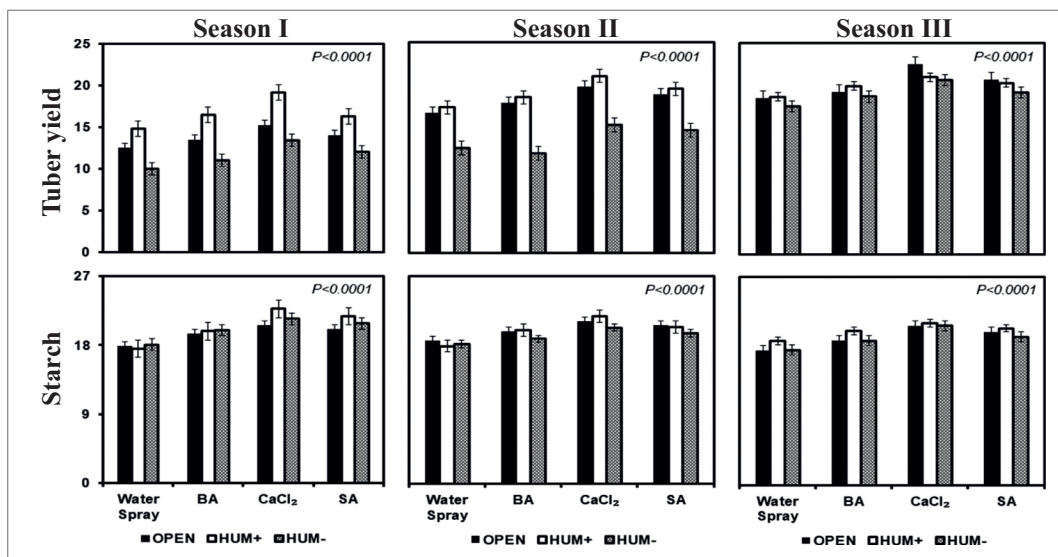


Fig. 5. Tuber yield and starch content under three-season PGR treatments (water, BA, CaCl₂, SA) across varying humidification regimes in sweet potato.

Gene Expression and Hormonal Regulation

The heat stress response in tuber crops is regulated by a complex network of gene expression and hormonal signaling. Research at ICAR-CTCRI highlights the potential of plant growth regulators (PGRs) as physiological modulators to counteract heat stress:

- **Salicylic Acid (SA, 0.2%)** enhanced net photosynthesis (up to $\sim 15.5 \mu\text{mol CO}_2 \text{ m}^{-2}\text{s}^{-1}$) (Fig. 6), increased LAI, and improved RWC and MSI by activating antioxidant defenses and maintaining membrane integrity (Fig. 7).
- **Calcium Chloride (CaCl_2 , 0.2%)** contributed to heat tolerance through calcium-mediated signaling, which stabilized chloroplast structure, improved chlorophyll retention, and supported canopy development.
- **6-Benzyladenine (BA, 1000 ppm)** improved sink strength and delayed senescence, enhancing assimilate partitioning to tubers and increasing harvest index.

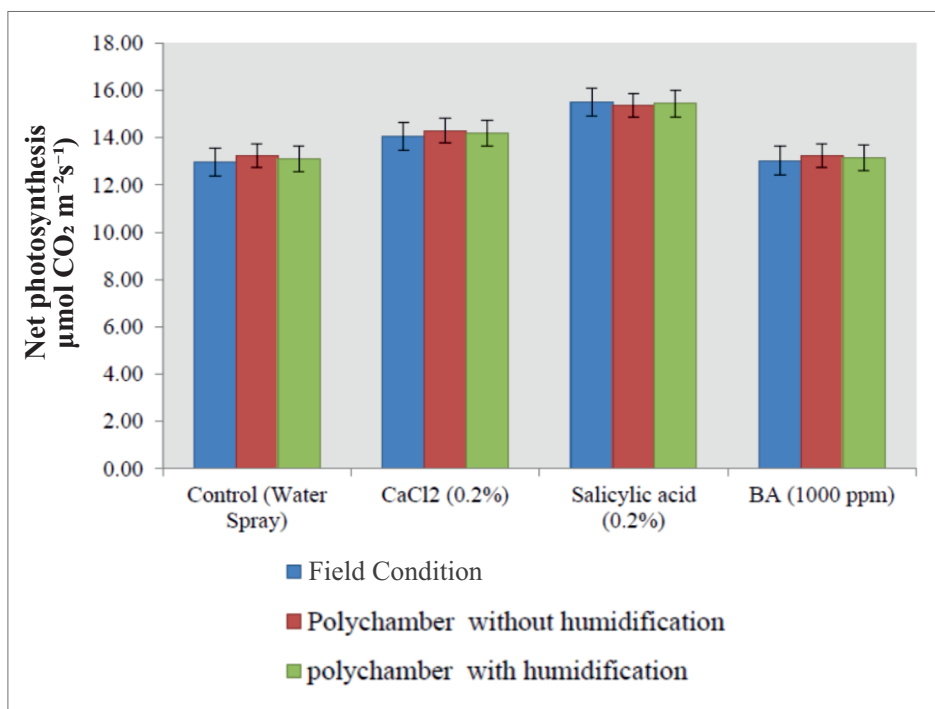


Fig. 6. Net photosynthesis in sweet potato under control, SA, BA, and CaCl_2 treatments across field and polychamber

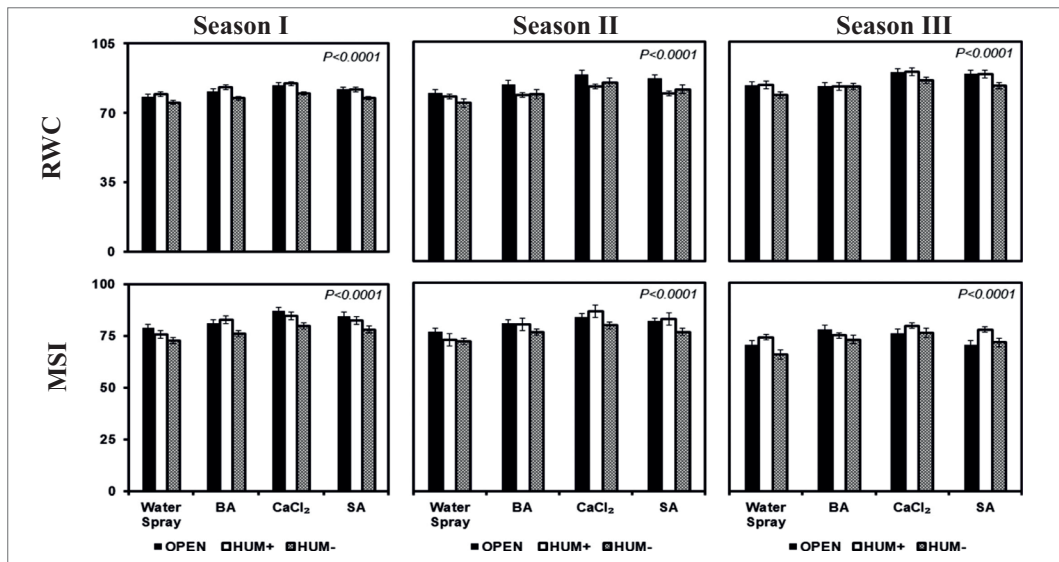


Fig. 7. Relative Water Content (RWC) and Membrane Stability Index (MSI) across seasons and PGR treatments in sweet potato under heat stress.

Although molecular studies on sweet potato under heat are still emerging, the enhanced performance under PGR treatments suggests activation of heat-responsive genes and hormonal pathways that warrant further transcriptomic investigation.

Summary Points

- Tuber crops display critical sensitivity to heat stress during early bulking stages (2-3 MAP).
- Elevated temperatures impair assimilate translocation, photosynthetic efficiency, and storage organ development.
- Salicylic acid, CaCl₂, and BA serve as effective mitigators by regulating key physiological and hormonal pathways.
- Strategic agronomic interventions during critical crop stages can significantly improve resilience under warming climates.

4.3 WATERLOGGING/SUBMERGENCE

Tolerance Screening under Regulated? Submergence

Waterlogging and submergence are important constraint in cassava cultivation, especially in flood-prone regions where stagnant water and hypoxic conditions drastically impair photosynthesis, root respiration, and nutrient transport. To address this, ICAR-CTCRI implemented systematic physiological screening of cassava genotypes under simulated submergence stress to evaluate their tolerance mechanisms. In a field trial, ten cassava genotypes were subjected to two weeks of continuous submergence at 5 months after planting (MAP). Key physiological and biochemical traits-including gas exchange, antioxidant enzyme activity, chlorophyll stability, and osmotic balance-were measured.

Key findings included:

- Tolerant genotypes such as Sree Apoorva, Sree Pavithra and Sree Swarna retained significantly higher chlorophyll content, membrane stability index (MSI), and catalase/peroxidase activity under submergence.
- CMR-2 maintained high chlorophyll under control but suffered severe physiological decline under stress, marking it as highly sensitive.
- Sree Athulya showed reduced chlorophyll levels yet displayed robust antioxidant activity, indicating potential tolerance through ROS-scavenging pathways.

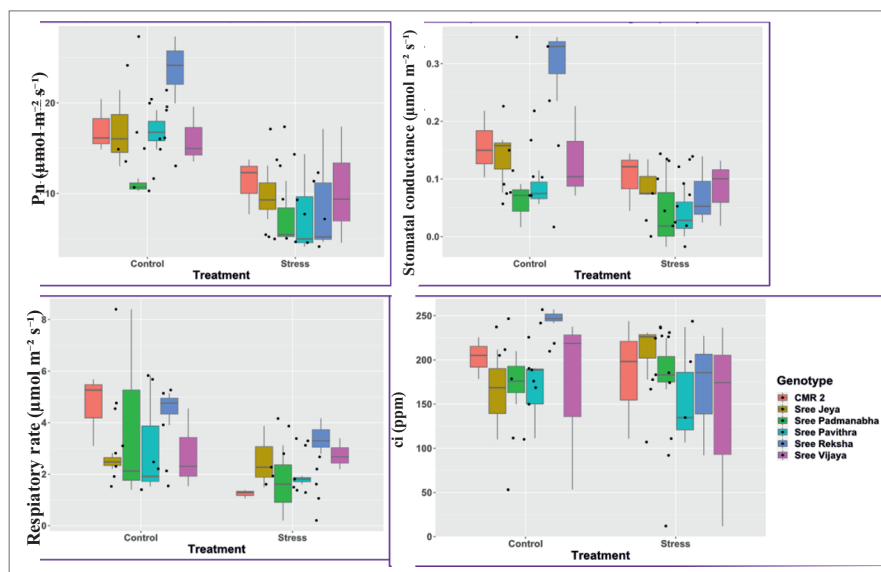


Fig. 8. Net photosynthetic rate (P_n), stomatal conductance (g_s), respiration rate, and intercellular CO_2 concentration (C_i) in cassava genotypes under control and submergence stress.

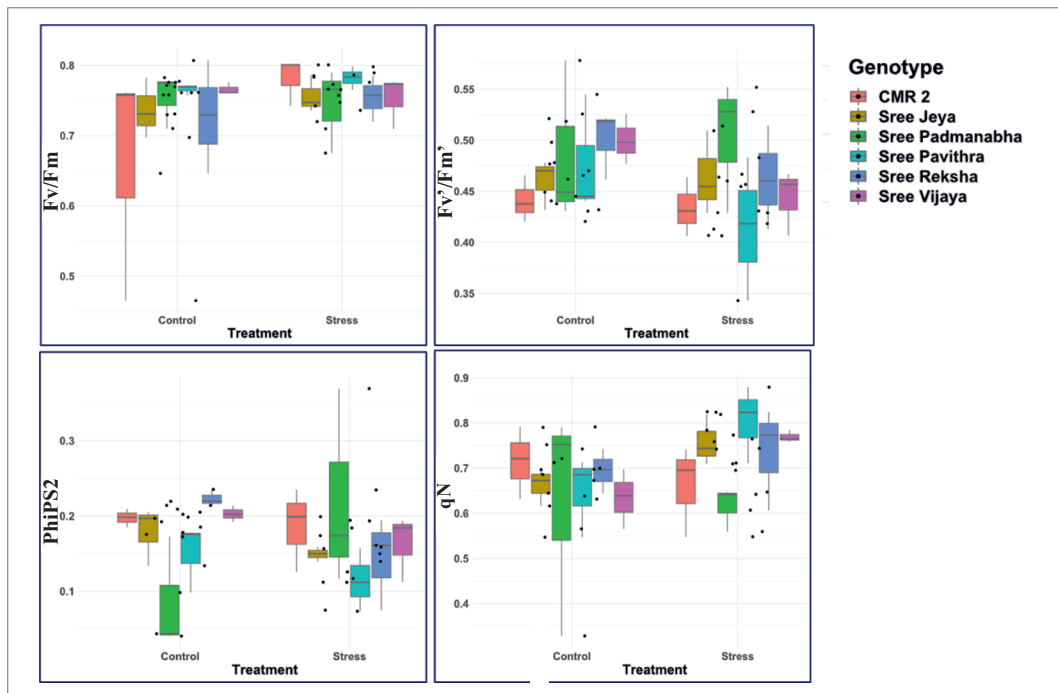


Fig. 9. Chlorophyll fluorescence parameters (Fv/Fm, ΦPSII, qN) showing variability in photoprotection and stress adaptation across genotypes.

Root Traits, Aerenchyma Formation, and Gas Exchange Responses

Submergence creates oxygen-deficient environments, leading to impaired aerobic respiration in roots. Although cassava lacks fully developed aerenchyma like rice, some genotypes exhibit partial anatomical and physiological adaptations.

Notable traits identified in tolerant genotypes:

- **Photosynthetic resilience:** *Sree Apoorva* and *Sree Kaveri* maintained high net photosynthesis ($\sim 20 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$) under stress, in contrast to highly sensitive lines like *Sree Athulya* ($\sim 2 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$) (Fig. 8).
- **Chlorophyll fluorescence (Fv/Fm, ΦPSII):** Moderate decline in tolerant genotypes under submergence indicated active non-photochemical quenching (NPQ) and partial retention of photosystem integrity (Fig. 9).
- **Water status indicators:** MSI and RWC remained high in tolerant lines (e.g., *Sree Apoorva* with MSI $\sim 60\%$ and RWC $\sim 94\%$), reflecting superior membrane integrity and osmotic adjustment (Table 2)

- **Osmolyte accumulation:** Genotypes like Sree Sakthi and Sree Apoorva showed elevated proline and phenolic levels, contributing to oxidative stress mitigation. Positive correlations were noted between phenolic content and DPPH activity ($r = 0.52$), reinforcing their antioxidative role (Fig. 10).

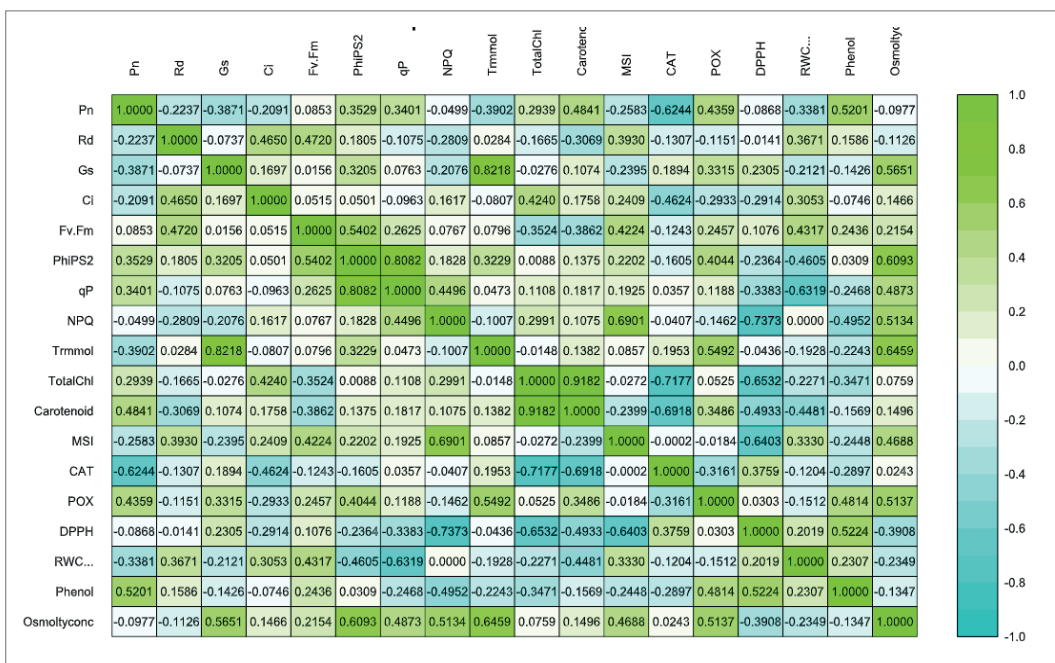


Fig. 10. Correlation matrix of physiological parameters in cassava under control and submergence, highlighting relationships between photosynthesis, membrane stability, and antioxidant traits.

Table 2. Membrane stability index (MSI), Relative water content (RWC) and osmolytic concentrations of ten cassava genotypes under control and submergence treatments.

Treatment	Genotype	Membrane stability index (%)	RWC (%)	Osmolyteconc (mmol kg ⁻¹)
Control	CMR-2	17 ± 0.063 ^k	91 ± 0.97 ^{cd}	520 ± 4.8 ^f
	Sree Athulya	24 ± 0.14 ^{ij}	93 ± 0.16 ^{ab}	510 ± 2.6 ^{fg}
	Sree Apoorva	12 ± 0.43 ⁱ	93 ± 0.45 ^{bd}	670 ± 6.8 ^b
	Sree Jaya	48 ± 0.54 ^{cd}	93 ± 0.4 ^{ab}	590 ± 5.2 ^d
	Sree Kaveri	47 ± 0.35 ^d	95 ± 0.42 ^a	550 ± 1.7 ^c
	Sree Pavithra	23 ± 1.7 ^j	93 ± 0.4 ^{abc}	630 ± 4.8 ^c
	Sree Reksha	29 ± 0.026 ^{gh}	94 ± 0.44 ^{ab}	350 ± 2.9 ^j
	Sree Sakthi	53 ± 0.22 ^b	90 ± 1.1 ^d	760 ± 7.8 ^a

	Sree Swarna	28 ± 0.1^h	93 ± 0.28^{bd}	480 ± 5^{hj}
	Sree Vijaya	26 ± 0.045^{hi}	93 ± 0.36^{ab}	470 ± 2.7^{ij}
Stress	CMR-2	36 ± 0.34^f	78 ± 0.7^g	490 ± 2.9^{gh}
	Sree Athulya	51 ± 0.58^{bc}	94 ± 0.2^{ab}	430 ± 3.2^k
	Sree Apoorva	60 ± 0.084^a	81 ± 0.28^f	600 ± 1.8^d
	Sree Jaya	28 ± 0.22^h	74 ± 0.39^h	510 ± 2.3^{fg}
	Sree Kaveri	31 ± 0.56^g	83 ± 0.18^f	560 ± 3.5^e
	Sree Pavithra	54 ± 0.087^b	81 ± 0.32^f	520 ± 2.6^f
	Sree Reksha	42 ± 0.18^e	82 ± 0.2^f	460 ± 3.2^j
	Sree Sakthi	43 ± 0.64^e	87 ± 0.36^e	530 ± 2.6^f
	Sree Swarna	49 ± 1.3^{cd}	92 ± 0.33^{bd}	550 ± 3.2^e
	Sree Vijaya	48 ± 0.67^d	80 ± 0.45^{fg}	480 ± 2.3^{hi}
	Treatment	<0.01	<0.01	<0.01
	Genotype	<0.01	<0.01	<0.01
P-value	T×G1	<0.01	<0.01	<0.01

Summary

- Submergence stress at 5 MAP revealed Sree Apoorva, Sree Pavithra, and Sree Swarna as relatively tolerant cassava genotypes.
- Physiological traits such as photosynthetic efficiency, chlorophyll stability, antioxidant capacity, and osmotic regulation were key indicators of resilience.
- Managed submergence trials are essential for integrating flood tolerance into cassava breeding programs.
- Correlation analysis confirmed that traits like phenolic content, DPPH activity, and MSI are positively associated with submergence tolerance.

4.4 ELEVATED CO₂ AND CLIMATE PROJECTIONS

Studies on Crop Response to Elevated CO₂

With atmospheric CO₂ concentrations projected to reach 550-700 ppm by mid-century (IPCC, 2021), it is imperative to understand how tropical tuber crops respond to elevated CO₂ (eCO₂) environments. As predominantly C₃ species, these crops generally exhibit enhanced photosynthesis, improved water-use efficiency (WUE), and increased biomass under higher CO₂ conditions, though these benefits are often influenced by nutrient availability and light intensity.

At ICAR-CTCRI, extensive experiments using Open Top Chambers (OTCs) and controlled CO₂ enrichment systems revealed consistent photosynthetic enhancement across several tuber crops:

Crop-Specific Findings

• Sweet Potato

Under 1000 ppm CO₂, net photosynthesis increased by up to 53%, with significant reductions in stomatal conductance (22-38%) and improved WUE. Enhanced leaf area and LAI were also recorded. However, the response was moderated by nitrogen supply, indicating a strong CO₂ × nitrogen interaction (Fig. 11)

• Elephant Foot Yam

Net photosynthetic rate increased by 66%, peaking at 30 $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ under high photon flux density (PPFD). Improvements in LAI and dry matter production indicate strong CO₂ × light interaction (Fig. 12)

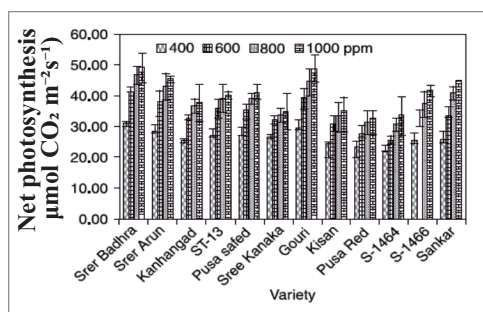


Fig. 11. Net photosynthetic rate in sweet potato under eCO₂ and across nitrogen levels.

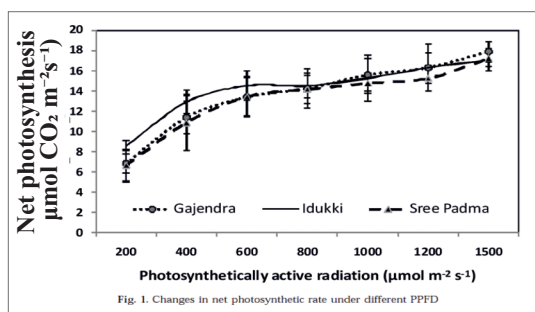


Fig. 12. Photosynthetic rate in EFY under varying light and CO₂ conditions.

- **Taro**

Exhibited the highest relative increase in photosynthesis (~113%) under elevated CO₂ and high light conditions. No signs of photosynthetic downregulation were observed, suggesting that taro maintains carbon assimilation efficiency under prolonged eCO₂ exposure (Fig. 13)

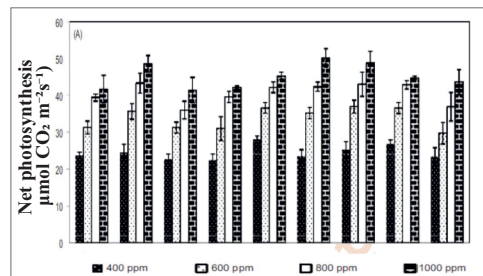


Fig. 13. Net photosynthetic response of taro across a CO₂ gradient (200-1000 ppm).

- **Cassava**

Responded favorably to short-term CO₂ enrichment with a 23% increase in net photosynthesis and elevated intercellular CO₂ concentration (C_i). Although slight reductions in stomatal conductance were recorded, they contributed positively to WUE. Nutrient dilution and sink limitations, however, may moderate long-term benefits.

- **Yam Bean (*Pachyrhizus erosus*)**

Demonstrated a 23% increase in photosynthesis at 600 ppm and above, with a plateauing trend at 800-1000 ppm (Fig. 14). The crop's strong coupling of source (leaf) and sink (tuber) development ensured efficient carbon utilization, with no evidence of photosynthetic acclimation.

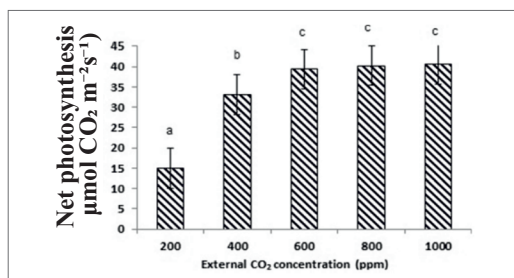


Fig. 14. Net photosynthetic response of yam bean across a CO₂ gradient (200-1000 ppm)

- **Yams (*Dioscorea* spp.)**

Preliminary trials revealed elevated C_i and P_n under high CO₂, with no signs of downregulation. Yam's high biological yield potential (50-70 t/ha) and robust sink strength may protect it from feedback inhibition, making it a promising candidate under future atmospheric CO₂ levels.

Elevated CO₂ and Climate Projections

Varietal Response in Yams Under Elevated CO₂

Controlled-environment studies conducted at ICAR-CTCRI reveal significant varietal variation in photosynthetic response of yams (white and greater yam types) to elevated CO₂ concentrations (400 to 1000 ppm). Seven varieties were assessed across treatments using

parameters such as net photosynthetic rate (Pn), stomatal conductance (gs), intrinsic water-use efficiency (Pn/gs), and transpiration efficiency (Pn/E).

- **Photosynthesis (Pn):** All varieties showed progressive increases in Pn with increasing CO₂ concentration. Sree Shilpa, Sree Priya, and Sree Nidhi recorded the highest rates (~39–41 $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$) at 1000 ppm (Table 3).

Table 3. Net photosynthetic rate of seven yam varieties under different CO₂ concentrations.

Variables	CO ₂ conc.	No. of observations	P_n	g_s	C_i	E	VpdL
White Yam							
	400	n = 52	17 ± 0.42 ^p	0.74 ± 0.081 ^{cg}	340 ± 12 ^{nm}	3.5 ± 0.25 ^j	0.7 ± 0.082 ^{hij}
Sree	600	n = 33	25 ± 0.3 ^{klm}	0.89 ± 0.1 ^{bdef}	500 ± 8.6 ^{kl}	5 ± 0.16 ^{efg}	1 ± 0.12 ^{dg}
Dhanya	800	n = 24	30 ± 0.93 ^{cf}	1.2 ± 0.17 ^{ab}	690 ± 13 ^{fg}	4.9 ± 0.1 ^{efh}	0.88 ± 0.14 ^{efgi}
	1000	n = 32	33 ± 0.7 ^c	1.1 ± 0.1 ^{acd}	890 ± 11 ^{ab}	5 ± 0.2 ^{efg}	0.79 ± 0.11 ^{fij}
	400	n = 27	16 ± 0.23 ^p	1.1 ± 0.065 ^{ad}	360 ± 6.1 ^m	4.7 ± 0.13 ^{ghi}	0.48 ± 0.023 ^j
Sree	600	n = 36	24 ± 0.38 ^{klm}	1.2 ± 0.04 ^{ab}	540 ± 1.2 ^j	5.1 ± 0.063 ^{efg}	0.5 ± 0.021 ^j
Haritha	800	n = 14	26 ± 0.33 ^{hij}	0.95 ± 0.048 ^{acf}	720 ± 4.8 ^{ef}	5 ± 0.052 ^{defhi}	0.59 ± 0.045 ^{hij}
	1000	n = 15	30 ± 0.59 ^{cfg}	0.77 ± 0.074 ^{bdegh}	890 ± 6.5 ^{ab}	5 ± 0.18 ^{defh}	0.75 ± 0.066 ^{fij}
	400	n = 12	22 ± 0.34 ^{ln}	0.67 ± 0.041 ^{deg}	320 ± 4.6 ^{mn}	7.3 ± 0.1 ^{ab}	1.2 ± 0.082 ^{bcd}
Sree	600	n = 16	31 ± 0.29 ^{cf}	0.81 ± 0.033 ^{bdeg}	500 ± 3.7 ^{jl}	7.1 ± 0.13 ^{ab}	0.95 ± 0.048 ^{dgi}
Priya	800	n = 22	37 ± 0.47 ^{ab}	0.65 ± 0.025 ^{ci}	660 ± 4.4 ^{gh}	6.5 ± 0.077 ^{ac}	1.1 ± 0.041 ^{cdg}
	1000	n = 15	39 ± 0.71 ^a	0.66 ± 0.042 ^{cegi}	850 ± 8.7 ^{bc}	6.8 ± 0.23 ^{ac}	1.1 ± 0.05 ^{cdg}
	400	n = 38	19 ± 0.37 ^{no}	0.71 ± 0.02 ^{gh}	330 ± 1.5 ^{mn}	6.9 ± 0.077 ^{ab}	1 ± 0.03 ^{dg}
Sree	600	n = 24	26 ± 0.53 ^{ik}	0.62 ± 0.027 ^{ci}	500 ± 3.3 ^{kl}	7 ± 0.18 ^{ab}	1.2 ± 0.04 ^{cdg}
Swetha	800	n = 17	31 ± 0.71 ^{cf}	0.45 ± 0.019 ^{gi}	640 ± 5.1 ^{hi}	7.4 ± 0.25 ^a	1.7 ± 0.021 ^a
	1000	n = 19	31 ± 0.58 ^{cde}	0.43 ± 0.0088 ^{gi}	830 ± 4.1 ^{cd}	6.9 ± 0.11 ^{ab}	1.6 ± 0.0072 ^{ab}
Greater yam							
	400	n = 30	18 ± 0.55 ^{op}	0.58 ± 0.025 ^{fgi}	330 ± 2.2 ^{mn}	4.9 ± 0.16 ^{efh}	0.89 ± 0.03 ^{efgi}
Sree	600	n = 28	26 ± 0.77 ^{hjk}	1.1 ± 0.1 ^{ad}	520 ± 4.8 ^{lk}	4.8 ± 0.15 ^{ghi}	0.58 ± 0.053 ^{ij}
Karthika	800	n = 34	29 ± 0.6 ^{dghi}	1.3 ± 0.099 ^a	720 ± 4.3 ^e	6.1 ± 0.24 ^{bcd}	0.61 ± 0.047 ^{ij}
	1000	n = 15	31 ± 1.1 ^{efg}	1 ± 0.044 ^{ac}	910 ± 4.5 ^a	6.3 ± 0.063 ^{acd}	0.69 ± 0.036 ^{ad}
	400	n = 6	20 ± 0.43 ^{mnp}	0.54 ± 0.0026 ^{degi}	310 ± 1.8 ^{mn}	7.9 ± 0.16 ^a	1.5 ± 0.029 ^{ad}
Sree	600	n = 21	28 ± 0.93 ^{fij}	0.44 ± 0.025 ^{gi}	460 ± 3.2 ^j	5.6 ± 0.26 ^{cf}	1.3 ± 0.016 ^{ad}
Nidhi	800	n = 23	27 ± 0.38 ^{gik}	0.31 ± 0.017 ⁱ	610 ± 6.6 ^j	3.8 ± 0.18 ^{ij}	1.3 ± 0.02 ^{bcd}
	1000	n = 19	32 ± 0.79 ^{cd}	0.33 ± 0.014 ^{hi}	800 ± 4.9 ^d	3.9 ± 0.13 ^{ij}	1.2 ± 0.012 ^{cdg}
	800	n = 34	28 ± 0.67 ^{efi}	0.46 ± 0.027 ^{gi}	660 ± 4.5 ^{gh}	4.5 ± 0.18 ^{ghi}	1 ± 0.026 ^{dg}
Sree	400	n = 27	19 ± 0.5 ^{np}	0.5 ± 0.025 ^{bi}	310 ± 2.6 ⁿ	6.5 ± 0.2 ^{ac}	1.4 ± 0.031 ^{ac}
Shilpa	600	n = 28	26 ± 0.56 ^{il}	0.61 ± 0.037 ^{ei}	490 ± 5.1 ^{kl}	5.8 ± 0.2 ^{ce}	1 ± 0.043 ^{dg}
	1000	n = 16	33 ± 0.83 ^{bc}	0.49 ± 0.034 ^{fgi}	830 ± 11 ^{cd}	4.7 ± 0.25 ^{efhi}	1 ± 0.021 ^{cdgh}
	Variety (V)		<0.01	<0.01	<0.01	<0.01	<0.01
P-value	CO₂		<0.01	<0.01	<0.01	<0.01	0.24
	V x CO₂		<0.01	<0.01	<0.01	<0.01	<0.01

- **Stomatal Conductance (gs):** Decreased significantly with higher CO₂ in all genotypes, consistent with improved WUE. Kisan, Gouri, and Pusa Red showed the greatest reduction (Fig. 15).

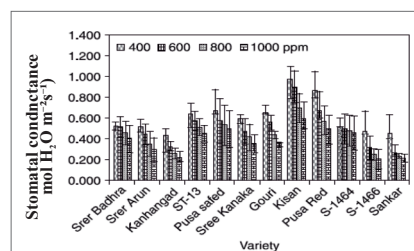


Fig. 15. Variation in stomatal conductance of sweet potato genotypes under 400, 600, 800, and 1000 ppm CO₂ concentrations.

- **Intrinsic Water-Use Efficiency (Pn/g_s):** Improved consistently with rising CO₂, with Sree Nidhi and Sree Shilpa exhibiting the highest values (Fig. 16).
- **Transpiration Efficiency (Pn/E):** Also improved under elevated CO₂. Sree Swetha and Sree Nidhi showed superior values, suggesting genotypic resilience under water-limited high-CO₂ scenarios (Fig. 17).

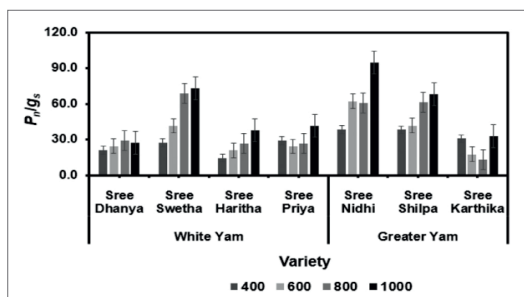


Fig. 16. Changes in intrinsic WUE (Pn/g_s) across yam genotypes under CO₂ enrichment.

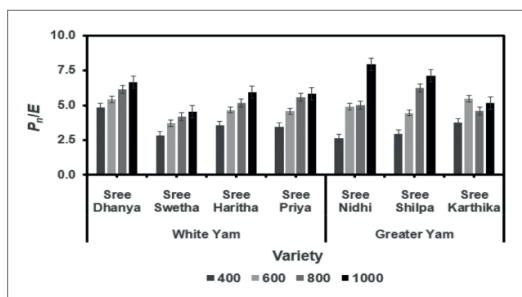


Fig. 17. Transpiration efficiency (Pn/E) response to CO₂ elevation in yams.

Interaction with Temperature and Water Regimes

While elevated CO₂ enhances carbon assimilation in C₃ crops, the magnitude of benefit is influenced by temperature, water availability, and nutrient supply-key variables under changing climate scenarios.

- **Temperature Interaction:** In sweet potato, elevated CO₂ under heat stress resulted in reduced Rubisco activity and lower transpiration rates. Although photosynthesis improved initially, the acclimation was limited at supra-optimal temperatures (~>35°C), leading to diminished yield benefits.
- **Water Stress Mitigation:** In cassava, taro, and yam bean, CO₂ enrichment helped alleviate drought-induced physiological stress:
 - *Cassava:* elevated CO₂ (eCO₂) reduced transpiration by ~20-30%, preserving leaf turgor and tuber yield under moisture deficit.
 - *Taro and Yam Bean:* Osmotic adjustment and higher photosynthetic rates were sustained at 600-1000 ppm CO₂, buffering the effects of soil water stress.
- **Nutrient Limitation Effects:** Sweet potato demonstrated significantly higher Pn and WUE at 800 ppm CO₂ only when grown with optimal nitrogen. Treatments with suboptimal nitrogen failed to capitalize on CO₂ enrichment (Fig. 15, Table 4) (Suresh et al., 2025)

Table 4. Mean P_n across seven yam genotypes under four CO_2 levels. Genotype $\times$ CO_2 interaction was highly significant ($p < 0.01$).

Treatments	P_n		
	Mean $\pm$ std	Min.	Max.
CO_2 concentration (C)			
400	25.99 ± 5.2^c	15.43	34.04
600	37.58 ± 6.2^b	22.11	48.80
800	42.35 ± 6.2^a	30.48	52.21
Variety (V)			
Sree Arun	36.03 ± 8.9^a	17.00	52.21
Sree Kanaka	34.47 ± 9.1^b	15.43	51.00
Nitrogen (N)			
N_0	27.19 ± 7.4^d	15.43	38.00
N_1	32.86 ± 7.2^c	19.65	45.00
N_2	36.63 ± 7.1^b	21.93	47.82
N_3	39.07 ± 8.5^a	25.48	51.95
N_4	40.62 ± 8.5^a	24.15	52.21

Summary

- Most tropical tuber crops show significant physiological gains under eCO_2 , including increased photosynthesis, reduced stomatal conductance, and improved WUE.
- Responses are genotype-dependent and moderated by nitrogen availability and light intensity.
- Taro and yam bean showed the highest gains without signs of photosynthetic downregulation.
- Integration of eCO_2 response traits into breeding pipelines can aid in climate-smart cultivar development.
- Elevated CO_2 enhances photosynthesis and WUE in tropical tuber crops; however, benefits are context-specific and influenced by genotype, temperature, water availability, and nutrient status.
- White and greater yams show strong CO_2 responsiveness, particularly in Sree Nidhi, Sree Shilpa, and Sree Priya.
- Multi-factorial trials integrating $CO_2 \times$ temperature $\times$ water $\times$ nutrition are essential for identifying climate-resilient genotypes.
- Further research on long-term effects, nutrient balance, and sink strength is essential to harness eCO_2 benefits fully.

5. BIOTIC STRESS RESPONSES UNDER CLIMATE VARIABILITY

Climate-Induced Shifts in Pest and Disease Dynamics

Climate change has altered pest–pathogen interactions, contributing to increased incidence and severity of biotic stressors such as Cassava Mosaic Disease (CMD). Rising temperatures, erratic rainfall, and shifts in the population dynamics of the whitefly vector (*Bemisia tabaci*) are accelerating CMD spread and symptom progression in cassava.

Multi-seasonal field assessments at ICAR-CTCRI revealed distinct genotypic differences in CMD response (Fig. 18). Sree Athulya and Sree Swarna exhibited rapid symptom progression and viral load accumulation, with viral load increasing up to 555% from CMD score 1 to 5. In contrast, Sree Vijaya and Sree Vishakam maintained lower viral titers (~62% increase), suggesting intrinsic suppression or delayed replication mechanisms.

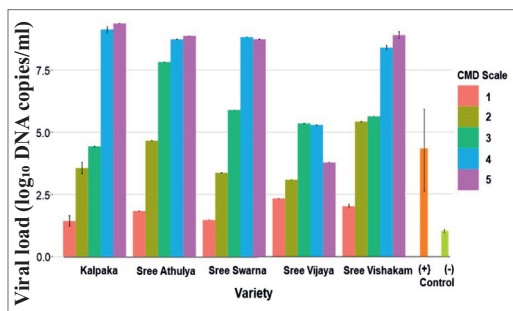


Fig. 18. Viral load ($\log_{10}$ DNA copies/ml) across CMD scores in six cassava varieties.

Impacts on Plant Defense Physiology and Metabolism

CMD significantly suppressed photosynthetic performance:

- Net photosynthesis (Pn): Decreased up to 81% in Sree Swarna, 77% in Sree Athulya.
- Stomatal conductance (gs) and transpiration (E): Declined by 88% and 74%, respectively, under high CMD scores.
- Microscopic analyses revealed stomatal deformities and loss of epidermal integrity, reducing gas diffusion efficiency and CO₂ uptake.

Chlorophyll Degradation and Photochemical Disruption

CMD stress led to severe pigment and chloroplast function decline:

- Total chlorophyll content dropped by 42-64% across varieties, with Sree Athulya showing the highest loss.
- NPQ (non-photochemical quenching) increased notably in tolerant genotypes, e.g., +183% in Sree Vijaya, indicating active energy dissipation.

qP (photochemical quenching) and Φ PSII (quantum yield of PSII) declined steeply in susceptible varieties, signaling impaired light conversion efficiency.

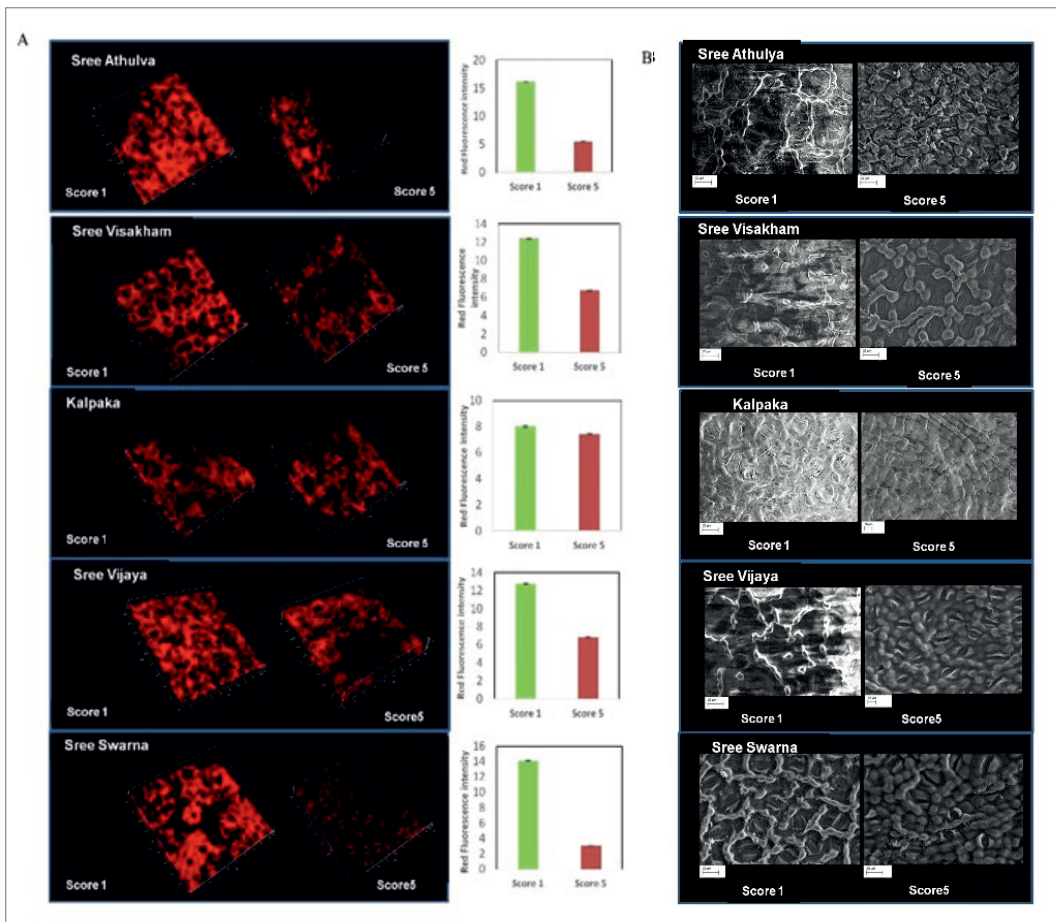


Fig. 19 a. Autofluorescence microscopy indicating chloroplast breakdown., 19 b. SEM visuals confirming guard cell distortion and epidermal collapse

Carbon Partitioning: Sugar and Starch Metabolism

CMD altered source-sink dynamics and phloem function:

- Sugar content in leaves increased sharply at CMD score 5, reaching 9.3 mg/g FW in Sree Swarna and Sree Vishakam, indicating impaired translocation.
- Starch content dropped by up to 70%, reflecting reduced conversion and allocation to storage roots.

These metabolic shifts highlight CMD's interference with carbohydrate processing and transport.

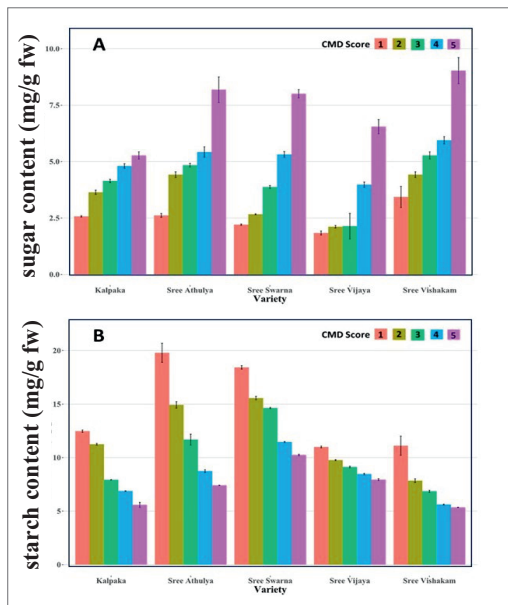


Fig. 20a & 20b. CMD score vs. sugar and starch content across genotypes.

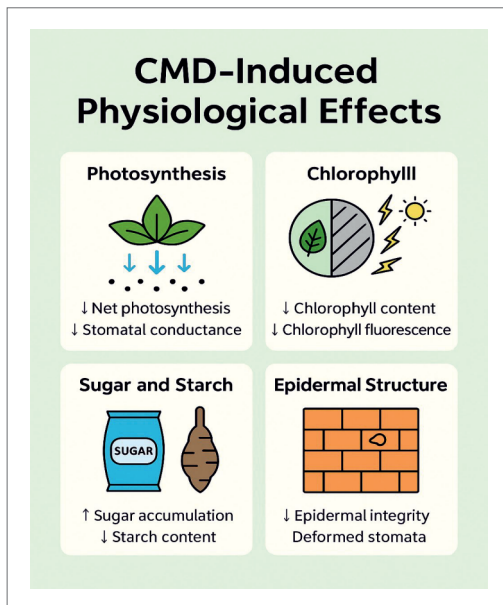


Fig 21. Physiological responses of cassava to CMD

Structural Defense and Genotypic Resilience

- **Sree Vishakam** maintained anatomical integrity of the epidermis and mesophyll under CMD, as visualized through SEM, aligning with stable gas exchange and moderate pigment loss.
- **Sree Athulya**, in contrast, showed pronounced cellular deformation and highest physiological damage scores.

Summary

CMD severely disrupts cassava's physiological and biochemical pathways, reducing photosynthesis, pigment stability, and carbohydrate synthesis.

- **Tolerant genotypes** like Sree Vijaya and Sree Vishakam maintain photosystem functionality, higher NPQ, and structural resilience.
- **Microscopic evidence** supports that epidermal and chloroplast integrity are critical for CMD resistance.
- **Integrated screening protocols** involving qPCR, chlorophyll fluorescence, and gas exchange are essential for CMD phenotyping under climate-vulnerable settings

6. CLIMATE-RESPONSIVE AGRONOMIC AND BIOLOGICAL INTERVENTIONS

6.1 ENHANCING STRESS RESILIENCE USING PLANT GROWTH REGULATORS (PGRS)

Plant growth regulators (PGRs) and biostimulants are emerging as vital components of climate-smart agriculture, enabling physiological fine-tuning to sustain crop productivity under adverse environmental conditions. At ICAR–CTCRI, both biogenic (natural) and synthetic PGRs have been rigorously studied to enhance the resilience of tropical tuber crops, particularly taro and sweet potato.

Biogenic PGRs: Cyanobacterial Auxins in Taro

A pioneering study evaluated auxin (indole-3-acetic acid, IAA) production by five filamentous, nitrogen-fixing cyanobacteria—*Anabaena*, *Aulosira*, *Cylindrospermum*, *Nostoc*, and *Tolypothrix*—after 15 days of culture. Among these, *Nostoc* showed the highest IAA release to the medium (2.53 µg/mL), significantly exceeding the critical difference (CD=1.06 µg/mL) at $P=0.05$ (Table 5).

Cyanobacteria	IAA released to the culture media (µg / ml)
<i>Anabaena</i>	0.04
<i>Aulosira</i>	0.15
<i>Cylindrospermum</i>	0.06
<i>Nostoc</i>	2.53
<i>Tolypothrix</i>	0.21
Control (BG11 medium)	0.00
CD ($P=0.05$)	1.06

Table 5. IAA production by different cyanobacterial strains.

Optimized culture conditions (pH 7.0; 2.75 mg/mL tryptophan) led *Nostoc* to produce up to 8.66 µg/mL IAA, as determined by Salkowski's assay. Application of its culture filtrate markedly enhanced sprouting in taro corms (*Colocasia esculenta* cv. Muktakeshi and Telia) and promoted seedling vigor in cowpea, demonstrating cross-species bioactivity.

This represents a first-of-its-kind approach to using cyanobacteria as a biofertilizer-based growth stimulant for taro, especially in waterlogged agroecosystems (Ashok et al., 2017).

6.2 Synthetic PGRs: CCC and Ethephon in Sweet Potato

In sweet potato (*Ipomoea batatas*), the application of synthetic PGRs—Chlormequat chloride (CCC) and Ethephon (an ethylene-releasing agent)—was investigated to assess their effects on photosynthesis, pigment dynamics, and antioxidant response under climate-induced stress.

Chlormequat chloride (CCC) at 250–500 ppm resulted in:

- Increased chlorophyll-a and carotenoid concentrations (Fig. 22),
- Enhanced photosynthetic rates (P_n up to 27–30 µmol CO₂ m⁻² s⁻¹ across genotypes; Fig. 24a),

- Improved photochemical efficiency (Φ PSII; Fig. 24b),
- Significantly elevated catalase and peroxidase activities (Fig. 23a & 23b), reflecting strengthened oxidative stress defense.

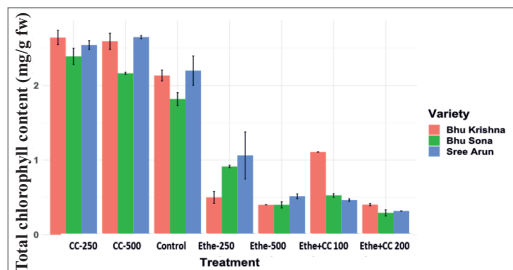


Fig. 22. Total chlorophyll content under PGR treatments in three sweet potato varieties.

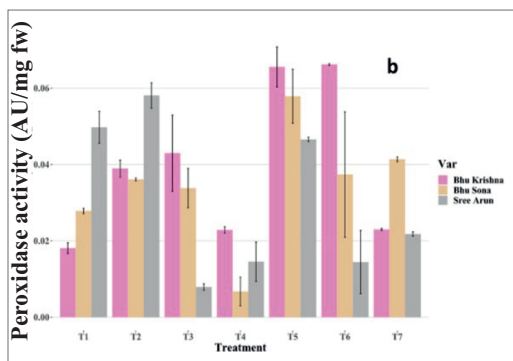
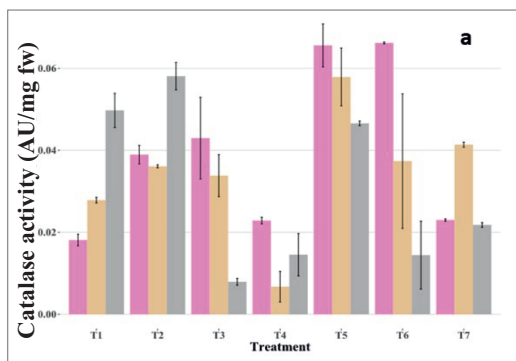


Fig. 23a & 23b. Catalase and peroxidase activity levels across PGR treatments in sweet potato

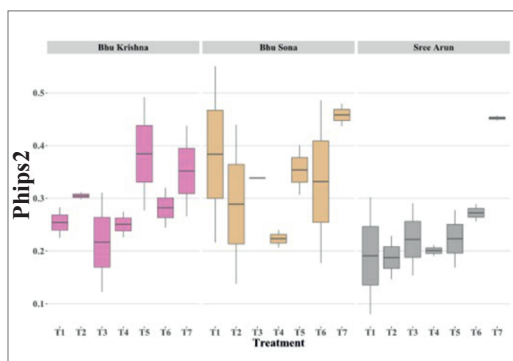
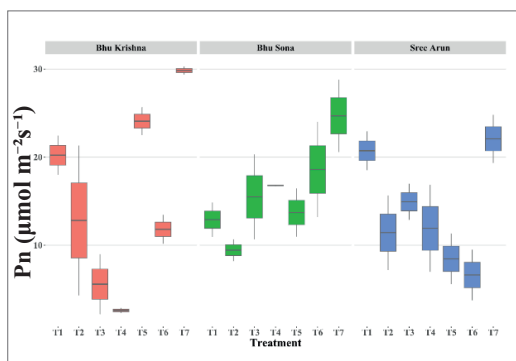


Fig. 24a. Net photosynthesis (Pn) response to PGRs & **24b.** Φ PSII (Photosystem II quantum yield) changes with PGRs in sweet potato

Conversely, Ethephon at higher concentrations (500 ppm) induced premature senescence:

- Caused significant chlorophyll degradation and reduction in gas exchange parameters,
- Elevated ROS levels and catalase activity as a compensatory stress response (Fig. 23 a & b),
- Impaired photosynthesis (Fig 24 a & b) and pigment stability (Fig. 22).

Interestingly, combination treatments (Ethephon + CCC) showed intermediate responses. The T5 treatment (100 ppm of each) yielded balanced photosynthetic performance, higher chlorophyll retention, and moderate antioxidant activation, indicating potential for use under mild stress environments.

Summary

- **Biogenic PGRs**, such as cyanobacterial-derived IAA from *Nostoc*, represent a promising, sustainable input for enhancing taro sprouting and early-stage vigor.
- **Chlormequat chloride (CCC)** improves photosynthetic performance, pigment stability, and enzymatic defense, offering practical utility under drought or temperature stress in sweet potato.
- **Ethephon**, while physiologically active, can exacerbate oxidative stress and reduce productivity when used at high doses.
- Integrated use of PGRs-biological and synthetic-tailored to crop and stress context, holds substantial promise for enhancing tuber crop resilience under evolving climatic scenarios.

6.2 Biochar Research in Tuber Crops - Soil Conditioning and Drought Mitigation

Biochar Preparation from Tuber Crop Residues

At ICAR–CTCRI, a cost-effective double-barrel pyrolysis kiln was developed for biochar production using farm-derived residues such as cassava stalks, yam vines, and arrowroot leaves. These biomass resources, typically discarded or underutilized, were thermochemically converted under oxygen-limited conditions to yield biochar with high agronomic potential. The step-wise production process, from drying of crop residue to ball milling and final packing for field application, is illustrated in Fig. 25.

Feedstock	Biochar Yield	pH
Cassava stalks	20-25%	7-8
Yam vines	20%	7-8
Arrowroot leaves	15%	8-9
Wood residues	~30%	~7.8

This process supports decentralized, smallholder-friendly biochar generation for field-level soil amendment programs.

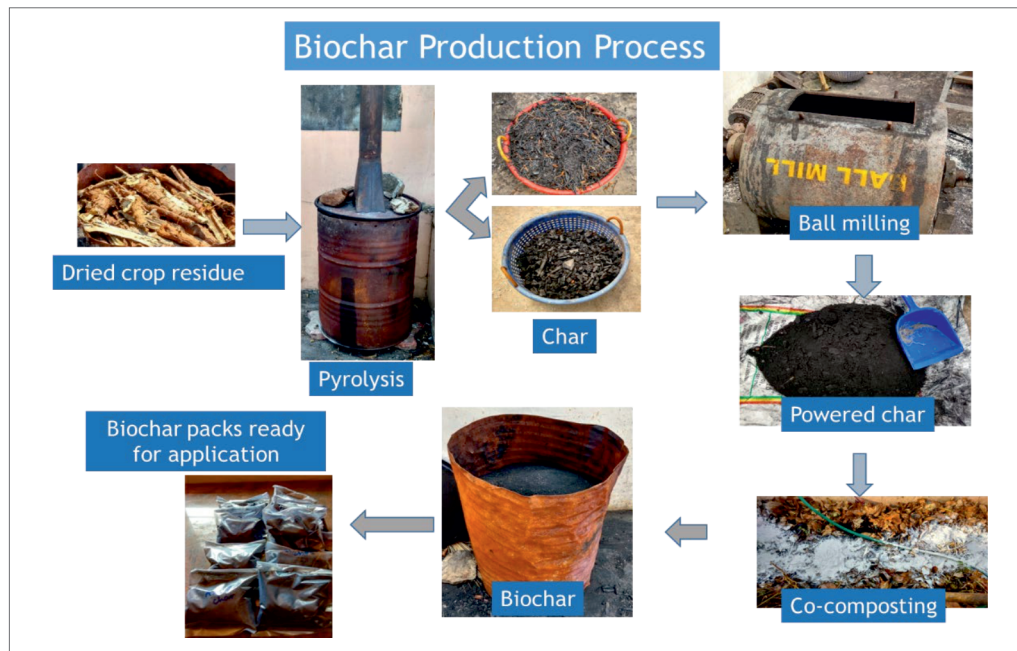


Fig. 25. Biochar preparation from tuber crops residues and its enrichment

Sweet Potato Response to Biochar Under Drought Conditions

A factorial field experiment was conducted using two sweet potato genotypes-Sree Arun and Sree Kanaka-evaluating the effects of three biochar treatments (0%, 2%, 5%) under two irrigation regimes (control and water deficit stress, WDS). Key physiological responses were enhanced under biochar application:

- Photosynthetic rate and stomatal conductance were significantly higher under 2% biochar, especially under WDS, suggesting better CO₂ assimilation and water-use efficiency (Fig. 26).
- Leaf respiration decreased with biochar amendment under drought, indicating reduced metabolic stress (Fig. 26).
- Tuber yield parameters (fresh and dry weight) showed significant improvement across both genotypes, particularly under 2% biochar (up to 47.4% increase in dry matter under stress) (Fig. 27).
- Enhanced non-photochemical quenching (NPQ) in WDS + biochar plots further indicated a stress-primed photoprotective response.

These findings highlight that moderate biochar supplementation improves physiological

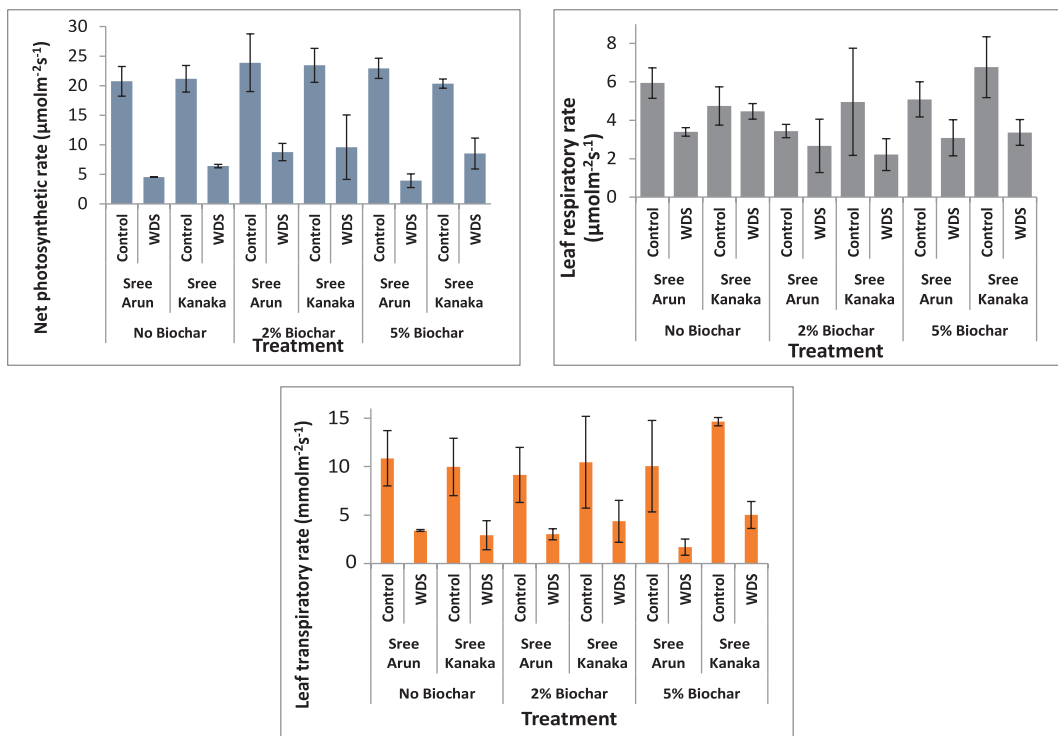


Fig. 26. Changes in photosynthetic gas exchange in sweetpotato varieties a. net photosynthetic rate, b. leaf respiration, c. leaf transpiration with biochar application.

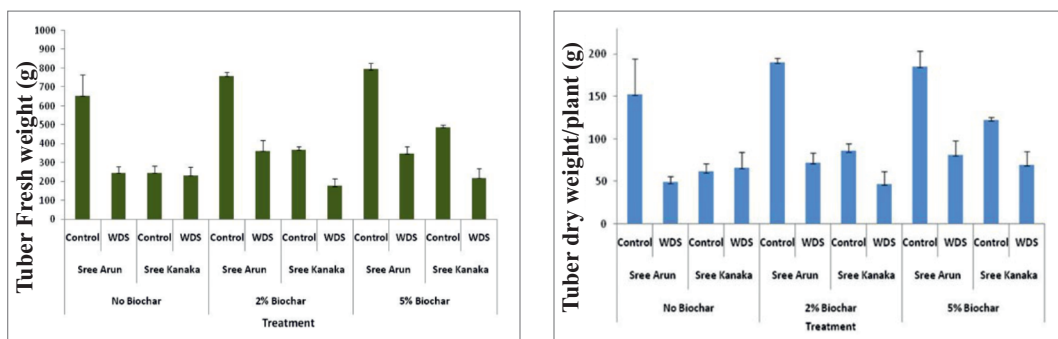


Fig. 27. Changes in tuber a. Tuber Fresh and b. Tuber dry weight characteristics of sweet potato varieties with biochar application

Yam Bean Response to Biochar Application

Yam bean (*Pachyrhizus erosus*) exhibited significant growth stimulation with biochar under both irrigated and WDS conditions:

- Application of 2% biochar led to a 53% increase in yield under drought, and up to 97% under irrigated plots, while 5% biochar provided a moderate yield benefit (13% and 68% under stress and irrigation, respectively) (Fig. 28).
- Enhanced net photosynthetic rate and efficient root-shoot allocation were recorded with biochar, indicating its potential as a soil-conditioning input under variable moisture regimes.

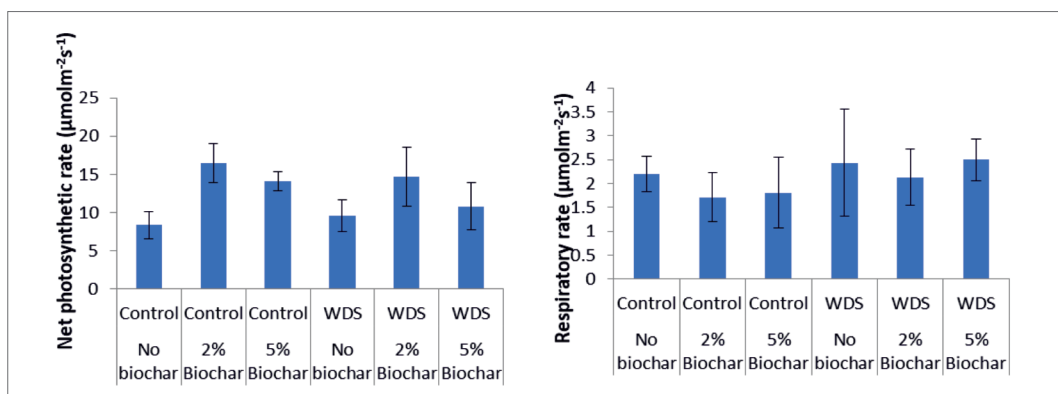


Fig. 28. Changes in photosynthetic gas exchange in yam bean **a.** net photosynthetic rate and **b.** leaf respiration with biochar application.

Summary and Outlook

Biochar derived from cassava and yam crop residues represents a scalable, sustainable solution for improving soil health, nutrient availability, and crop physiological performance under climate stress conditions. Among the tested doses, 2% biochar consistently provided optimal outcomes in terms of plant gas exchange, respiration, tuber biomass, and drought resilience.

Future research will emphasize:

- **Biochar-microbial consortia** for enhanced soil biological activity,
- Long-term impacts on soil carbon dynamics and nutrient cycling,
- Integration of biochar into climate-resilient agroecosystem frameworks for tropical tuber crops.

7. CROP IMPROVEMENT AND GENE EXPRESSION STUDIES

Transcriptomic Insights Under Stress

Genomic and transcriptomic approaches have provided deep insights into the regulatory architecture underlying stress adaptation and storage organ development in tropical tuber crops. Over the past decade, ICAR-CTCRI and collaborating institutions have employed gene expression profiling, microarrays, and functional genomics to unravel key pathways modulating drought tolerance, heat stress responses, and tuber formation, particularly in cassava and sweet potato.

Sweet Potato: Auxin Signaling and Storage Root Development

Storage root formation in sweet potato (*Ipomoea batatas*) is governed by finely tuned hormonal signaling and tissue-specific gene expression. Comparative transcriptomic analysis between storage roots and non-tuberizing fibrous roots revealed marked upregulation of Auxin Response Factors (ARFs), notably ARF2, ARF4, ARF8, ARF10, ARF16, and ARF18, during the early thickening phase. These genes are implicated in cell division, asymmetric patterning, vascular differentiation, and lateral organ development, highlighting their role in establishing tuber architecture.

Downregulation of certain Aux/IAA repressors, such as OsIAA10 and OsIAA30, suggests a de-repression mechanism that allows ARF-mediated transcription to drive tuberization. Notably, ARF4 has been identified as a key regulator of asymmetric patterning, a prerequisite for lateral swelling and storage parenchyma development (Ravi et al., 2017). These results indicate that modulation of the auxin-cytokinin-ethylene axis could enhance root bulking under climate-induced stress scenarios.

Additionally, molecular chaperones play a complementary role in tuber development. Microarray-based transcriptome analysis revealed significant differential expression of chaperone genes, including HSP90, HSP20, and DnaJ family members, in storage roots compared to fibrous roots (Ravi et al., 2020). Specifically, 76 chaperone genes were upregulated and 45 downregulated during tuber formation, underscoring their regulatory role in hormone signaling, protein folding, and stress response during morphogenesis (Fig. 29)

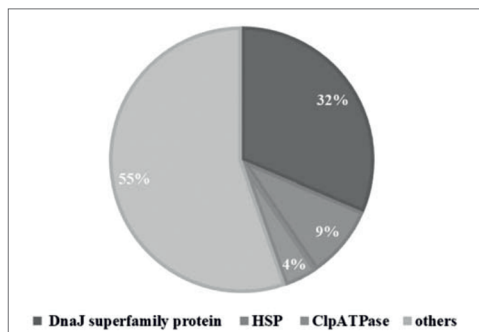


Fig. 29. Details of differential expression of chaperone genes, including HSP90, HSP20, and DnaJ family members, in storage roots compared to fibrous roots in sweet potato

Cassava: Drought-Responsive Gene Networks and Functional Traits

In *Manihot esculenta*, transcriptomic studies have identified several gene families integral to drought resilience. Notably:

- **CC-type glutaredoxins (e.g., MeGRXC3):** Activate transcriptional regulators involved in redox signaling and reactive oxygen species (ROS) homeostasis.
- **MePMP3-2:** A plasma membrane protein induced under PEG and NaCl stress, conferring cellular membrane stabilization.
- **Aquaporins (MePIP2-1, MePIP2-10):** Play a pivotal role in facilitating water transport and maintaining leaf water status during dehydration.
- **Heat shock proteins (MeHSP90.9) and WRKY transcription factors (MeWRKY20):** Cooperatively regulate antioxidant defenses and ABA signaling pathways under combined heat and drought stress.

Transgenic cassava lines overexpressing stress-tolerance genes like cytosolic superoxide dismutase (MeCu/ZnSOD) and catalase (MeCAT1) demonstrated superior water retention, reduced oxidative damage, and improved survival under water-limited conditions.

Summary Highlights

- Sweet potato storage root formation is driven by coordinated expression of auxin-responsive genes (ARFs) and chaperones, particularly HSP90 and DnaJ, with key roles in tissue differentiation and hormonal crosstalk.
- ARF1, ARF4, ARF8, and ARF10 are potential gene targets for genetic enhancement of tuber formation and early bulking.
- In cassava, aquaporins, glutaredoxins, and WRKY modules form a core molecular toolkit enabling adaptation to drought and oxidative stress.
- Integration of physiological trait data with transcriptomic signatures accelerates marker-assisted selection and molecular breeding for climate-smart tuber crop cultivars.

Marker Traits for Resilience

Breeding for climate resilience in tuber crops hinges on identifying reliable phenotypic and molecular traits with high heritability and environmental stability.

Key marker traits in cassava include:

- **Early bulking:** Associated with robust sink strength and efficient carbohydrate partitioning during the critical 3-5 MAP window.
- **Root system architecture:** Traits such as deep root length, higher lateral root density, and root dry weight support efficient water acquisition.
- **Canopy traits:** High leaf retention index (LRI), optimal plant height, and low stomatal

density (in humid zones) contribute to water-use efficiency and stable photosynthesis.

- **Anatomical plasticity:** Enhanced palisade and spongy mesophyll layers, thicker epidermis, and reduced xylem vulnerability promote mechanical and hydraulic stability under drought.

These traits, validated through multi-location trials, serve as key selection indices in advanced breeding pipelines aimed at enhancing resilience to climatic extremes.

Tissue-Specific Expression Studies

Tissue-specific transcriptomic profiling provides critical insights into how distinct organs perceive and respond to environmental stress at the molecular level. In tropical tuber crops, such localized gene expression analysis has revealed spatial differentiation in stress perception, hormonal crosstalk, and developmental signaling, particularly in cassava and sweet potato.

Cassava: Spatial Regulation of Stress Response Networks

In cassava (*Manihot esculenta*), expression profiling under drought and oxidative stress revealed differential gene activation between tissues:

- **Leaf vasculature** emerged as the primary site of stress signal perception, with elevated expression of **ABA biosynthesis genes** (*NCED*, *ABAI*), signal transduction components (*PP2C*, *SnRK2*), and stress-responsive transcription factors such as *MeRAV5*, *MeWRKY20*, and *MeMYB26*. These genes coordinate the early signaling events in response to dehydration and oxidative challenges.
- **Storage roots**, in contrast, exhibited lower levels of ethylene-responsive gene expression, suggesting a **leaf-dominant control mechanism** during drought adaptation. This may reflect a top-down regulatory cascade in which the shoot system modulates sink activity under resource-limited conditions.
- **Antioxidant enzymes**-*SOD*, *CAT*, and *APX*-showed their highest expression in leaves, not only during abiotic stress but also during postharvest physiological deterioration (PPD), indicating their pivotal role in systemic oxidative defense.
- Notably, long non-coding RNAs (lncRNAs), including *DIR*, were identified as novel regulators of drought tolerance by modulating proline accumulation and driving ABA-independent transcriptional reprogramming.

These tissue-specific insights highlight the shoot's regulatory dominance in orchestrating whole-plant stress responses, offering targets for foliar gene editing and transgenic interventions.

Sweet Potato: Root-Zone Specificity in Developmental Regulation

In sweet potato (*Ipomoea batatas*), the contrast between storage roots and fibrous roots reveals critical differences in developmental gene expression under stress:

- A suite of **Auxin Response Factors (ARFs)**, including *ARF4*, *ARF8*, *ARF10*, *ARF16*, and *ARF18*, were upregulated in storage roots, promoting vascular patterning, cell expansion, and early tuber bulking.
- In parallel, the downregulation of Aux/IAA repressors (notably *OsIAA4* and *OsIAA30*) supports sustained auxin activity, facilitating elongation and radial expansion of developing storage organs.
- The tissue-specific expression patterns of these genes provide a strong basis for targeted modulation of tuber initiation pathways, especially under environmental stress, where early root development is critical to yield.

These findings complement earlier transcriptomic work highlighting the centrality of hormonal reprogramming and molecular chaperones during tuber development.

Yam and Taro: Preliminary Molecular Insights

Though less explored, early transcriptomic data from **yam** (*Dioscorea spp.*) and **taro** (*Colocasia esculenta*) suggest notable tissue-specific expression trends:

- In yam, genes related to starch biosynthesis and bulking were activated predominantly in the cortical and cambial tissues, aligning with anatomical zones of carbohydrate storage.
- In taro, exposure to waterlogged conditions induced differential expression between petiole and corm tissues, indicating organ-specific oxidative stress responses and osmolyte regulation pathways suited to localized hypoxia tolerance.

These preliminary findings underscore the need for high-resolution spatial transcriptomic analysis to characterize regulatory gradients within tuber organs.

Summary

- **Leaves act as central regulators** of stress responses in cassava, particularly through ABA synthesis, ROS detoxification, and systemic signaling.
- In sweet potato, tissue-targeted ARF and Aux/IAA gene expression governs the initiation and expansion of storage roots, especially under stress.
- Tissue-specific gene markers and spatially mapped regulatory pathways are critical for precision breeding in tuber crops, ensuring targeted expression without systemic side effects.
- Marker traits such as early bulking, high LRI, root branching, and antioxidant enzyme expression are reinforced by spatial transcriptomic evidence, validating their use in genotype selection.
- Future directions include integration of spatial transcriptomics, anatomical phenotyping, and physiological indices to enable climate-resilient, organ-specific trait engineering in tropical root and tuber crops.

8. CLIMATE-SMART VARIETIES AND THEIR PERFORMANCE

ICAR–CTCRI has systematically evaluated the climate resilience of tropical tuber crop genotypes through a combination of multi-season field trials and controlled-environment experiments. The focus has been on identifying varieties with superior adaptability to drought, heat, submergence, and combined stress conditions, while maintaining photosynthetic stability, physiological plasticity, and yield consistency.

Cassava: Model Genotype for Drought Resilience

Cassava (*Manihot esculenta*) is inherently drought-tolerant, yet significant genotypic variation exists in stress responsiveness. Among tested lines:

- **Sree Reksha** emerged as a drought-resilient genotype, maintaining high photosynthetic rate (P_n), stomatal conductance (g_s), leaf retention index (LRI), and harvest index (HI) under moisture-limited conditions.
- Strong positive correlations were observed between P_n ($r = 0.78$), g_s ($r = 0.76$), leaf area index (LAI), and number of functional leaves with final tuber yield under drought, confirming their value as physiological markers for breeding.
- Due to its canopy vigor, resource use efficiency, and consistent performance, *Sree Reksha* is now considered a benchmark genotype for cassava drought-breeding programs.

Sweet Potato: Heat-Resilient Productivity Through Physiological Intervention

Sweet potato genotypes were evaluated under simulated high-temperature environments (32–37.5°C) using **polychamber experiments**:

- **Sree Arun** demonstrated 22-35% higher tuber yield under CaCl_2 treatment (0.2%) compared to untreated controls, under elevated temperature and variable humidity conditions.
- Foliar application of salicylic acid (SA) and CaCl_2 enhanced photosynthetic rate, relative water content (RWC), and membrane stability index (MSI), mitigating oxidative stress and cellular damage.
- Yield was significantly correlated with LAI, P_n , and harvest index ($r^2 \approx 0.4$), reinforcing the physiological basis for climate-smart varietal selection.

Sree Arun, supported by PGR interventions, is a promising cultivar for heat-prone and humid agroecologies.

Elephant Foot Yam (EFY): Enhanced Resilience with Timely Interventions

Though susceptible to heat, EFY shows strong yield recovery when supported by agronomic interventions:

- In polychamber studies, Gajendra responded well to salicylic acid (0.2%) and CaCl_2 (0.2%), achieving up to 36.4% improvement in corm yield under heat stress.
- This genotype exhibited robust photosynthetic efficiency, chlorophyll retention, and biomass accumulation under elevated CO_2 and high light conditions.
- EFY performance improves significantly with PGR application, controlled shading, and strategic planting during early growth phases, making it suitable for semi-arid to humid tropical regions.

Taro: Cyanobacteria-Aided Growth in Waterlogged Systems

For wetland agriculture, taro genotypes Muktakeshi and Telia were evaluated under high soil moisture and submergence conditions:

- Application of Nostoc-based cyanobacterial biofertilizers improved sprouting percentage, early biomass, and root vigor in both genotypes.
- Enhanced corm development was observed even under excessive moisture, suggesting suitability for low-input, flood-prone ecosystems.
- These findings highlight the potential of biofertilizer-assisted crop establishment in climate-adaptive wetland systems.

9. WAY FORWARD AND RESEARCH PRIORITIE

Field-Validated Climate-Resilient Varieties

Over the last decade, ICAR-CTCRI has prioritized the development and evaluation of climate-smart tuber crop varieties across diverse agroclimatic zones. These varieties have been systematically tested under controlled stress conditions-drought, heat, and submergence-coupled with physiological and biochemical trait analysis to assess their resilience and yield reliability.

Cassava: Drought-Tolerant Genotypes with Stable Productivity

Cassava (*Manihot esculenta*) is inherently drought-tolerant, but genotype-specific variation offers opportunities for targeted improvement. Field trials under soil moisture stress revealed that:

- Sree Reksha and Sree Vijaya consistently maintained higher tuber yield, stomatal conductance (gs), and canopy vigor compared to other varieties (Fig.30).
- Physiological markers such as net photosynthetic rate (Pn), gs, and leaf area index (LAI) were positively correlated with yield under drought ($r = 0.76-0.80$), validating them as useful selection traits.
- Significant genotype $\times$ treatment interaction was observed for gs ($p = 0.03$), indicating inherent differences in stomatal regulation during stress (Fig. 30).
- Varieties like Sree Pavithra and Sree Reksha showed superior photosynthetic efficiency under both control and stress, supporting their recommendation as core drought-tolerant cultivars (Fig. 30).

Sweet Potato: Heat and Water Deficit Resilience Through Physiological Plasticity

In sweet potato (*Ipomoea batatas*), the combination of genotypic adaptation and foliar PGR application proved effective in countering heat and water stress:

- Sree Arun, under foliar calcium chloride (CaCl_2) or salicylic acid (SA) treatments, maintained 22-35% higher tuber yield at elevated temperatures ($32-37.5^\circ\text{C}$), with improved Pn, relative water content (RWC), and membrane stability index (MSI).
- Polychamber trials confirmed that these interventions mitigated heat-induced oxidative damage, maintaining better canopy function and tuber bulking.
- Drought stress led to reductions in stomatal conductance, Pn, and biomass accumulation across genotypes, yet Sree Kanaka and Sree Bhadra sustained higher tuber fresh weight compared to others, illustrating superior conversion efficiency and osmotic adjustment capacity (Fig.31).
- Genotype-specific osmolyte accumulation and photochemical efficiency (ΦPSII) under drought provided further insight into adaptive physiology.

Elephant Foot Yam (EFY): Enhancing Heat Stress Tolerance

Elephant foot yam, though sensitive to elevated temperatures, responded well to PGR-based mitigation strategies:

- Foliar application of 0.2% salicylic acid and 0.2% CaCl_2 significantly improved corm yield by up to 36.4% under simulated heat stress conditions.
- Genotype Gajendra displayed improved chlorophyll retention, photosynthetic rate, and tuber biomass under elevated CO_2 and high PFD environments, as confirmed in polychamber experiments.
- These results underscore the importance of early-stage canopy protection and hormonal support in heat-prone ecologies.

Taro: Low-Input Adaptation to Waterlogging Stress

In wetland agroecosystems, Muktakeshi and Telia taro varieties demonstrated considerable tolerance to waterlogged conditions:

- Application of biofertilizers derived from *Nostoc* cyanobacteria improved sprouting rates and early seedling vigor.
- These varieties retained root vigor and corm expansion under moisture stress, indicating effective stress avoidance mechanisms suitable for monsoon farming systems.

Summary and Outlook

- Sree Reksha (cassava) and Sree Arun (sweet potato) are climate-resilient cultivars with superior physiological plasticity under drought and heat, respectively.
- Strategic use of PGRs, biofertilizers, and timely stress mitigation practices further enhances varietal performance under extreme conditions.
- Genotype $\times$ environment $\times$ management ($G \times E \times M$) synergy is key for stabilizing tuber crop yields in the face of climate uncertainty.
- Figures 30 & 31 illustrate physiological and yield-based responses across cassava and sweet potato genotypes, validating their

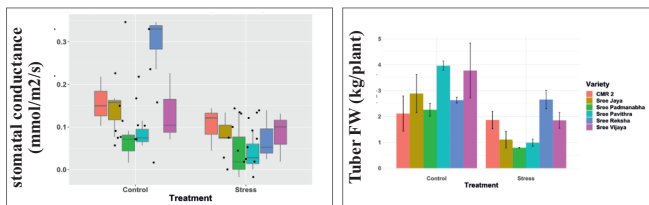


Fig. 30. Changes in stomatal conductance and tuber weight in cassava genotypes under control and drought stress.

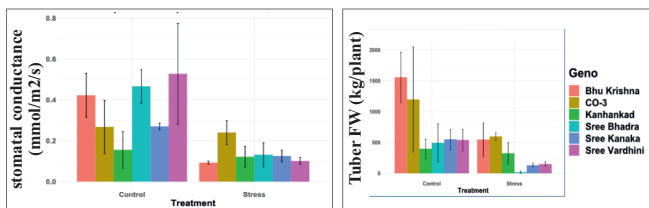


Fig.31. Changes in stomatal conductance and tuber weight in cassava genotypes under control and drought stress.

10. SUMMARY AND CONCLUSIONS

A Decade of Advancing Climate Resilience in Tuber Crops

Over the past ten years, the ICAR-Central Tuber Crops Research Institute (ICAR-CTCRI) has made pioneering contributions toward understanding and enhancing climate resilience in tropical tuber crops. By integrating field experiments, controlled-environment studies, and advanced physiological and molecular tools, the institute has laid a robust foundation for climate-smart research, technology development, and varietal innovation in crops such as cassava, sweet potato, elephant foot yam, taro, yam bean, and yams.

The key highlights of this comprehensive research program include:

- **Simulation of climatic stressors**-such as drought, heat, submergence, and elevated CO₂-using state-of-the-art facilities like open-top chambers, polychambers, and rainout shelters.
- **In-depth physiological and biochemical profiling** under abiotic stress conditions, enabling the identification of critical traits for stress adaptation and selection.
- **Characterization of core stress-responsive parameters**, including stomatal conductance, chlorophyll fluorescence (Fv/Fm, ΦPSII), non-photochemical quenching (NPQ), osmotic adjustment, and leaf area index (LAI).
- **Application of plant growth regulators (PGRs) and bioinoculants**, including cyanobacterial auxins and microbial consortia (PGPR/AMF), to improve tolerance and productivity under stress.
- **Transcriptomic and gene expression studies** that revealed key regulators such as auxin response factors (ARFs), aquaporins, WRKYs, and CC-type glutaredoxins involved in stress mitigation and development.
- **Development and validation of climate-resilient varieties** through multi-location field trials and genotype × environment × management (G×E×M) interaction studies.

Collectively, these initiatives have advanced the scientific understanding of crop-environment-management interactions, resulting in practical innovations and varietal solutions for climate-vulnerable regions.

Key Scientific and Technological Contributions

1. **Physiological Screening Tools:** Identification of robust physiological markers-such as NPQ, WUE, LAI, and stomatal conductance-as indicators of drought and heat resilience, particularly in cassava and sweet potato.
2. **Biofertilizer Innovations:** Validation of *Nostoc*-based cyanobacterial formulations to enhance sprouting, root vigor, and early growth in taro under waterlogged conditions.

3. **Molecular Insights:** Establishment of regulatory links between gene expression and stress responses-especially ARF-Aux/IAA signaling in sweet potato and antioxidant gene modules in cassava.
4. **PGR Strategies:** Optimization of foliar treatments using salicylic acid (SA), calcium chloride (CaCl_2), and chlormequat chloride (CCC) to alleviate heat stress and improve tuber yield in sweet potato and elephant foot yam.
5. **Resilient Varietal Releases:** Promotion of elite, climate-resilient varieties such as **Sree** Reksha (cassava), Sree Arun (sweet potato), and Gajendra (EFY), backed by multi-environment performance data.
6. **Support for Climate Policy:** Contribution of physiological datasets for use in climate adaptation frameworks like State Action Plans on Climate Change (SAPCCs) and the National Mission for Sustainable Agriculture (NMSA).
7. **Research Infrastructure Development:** Establishment of dedicated platforms for climate simulation, high-throughput phenotyping, and gene-trait association mapping in tropical tuber crops.

Reflections

Through dedicated, multidisciplinary research and collaborative partnerships, ICAR-CTCRI has positioned itself at the forefront of climate-resilient agricultural innovation in India's tuber crop sector. This bulletin encapsulates the outcomes of a decade-long scientific journey-offering validated tools, cultivars, and approaches that can inform breeding, agronomy, and policy alike. As the agriculture sector braces for increasing climate variability, the insights and technologies generated through this work underscore the strategic importance of tropical tuber crops in ensuring food, nutritional, and livelihood security. Moving forward, this knowledge base provides a clear roadmap for future research, capacity building, and institutional partnerships aimed at accelerating sustainable agricultural transformation.

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12. APPENDIX A: KEY PHYSIOLOGICAL TRAITS OF TUBER CROPS UNDER STRESS

Crop	Stress Type	Key Physiological Traits
Cassava	Drought	High NPQ, early bulking, high LAI, root length, leaf retention index (LRI), Pn stability
Sweet Potato	Heat & Drought	High osmolyte accumulation, chlorophyll stability, Pn and WUE retention, Aux/IAA expression in storage roots
Elephant Foot Yam	Heat	Improved Pn with SA/CaCl ₂ , canopy temperature regulation, enhanced chlorophyll retention
Taro	Waterlogging	Improved sprouting with Nostoc IAA, root vigor, membrane stability
Yam Bean	Elevated Co ₂	Increased photosynthesis, no downregulation under high PFD, high biomass accumulation
Taro	Elevated Co ₂	113% increase in Pn, stable chlorophyll fluorescence under high light and CO ₂
Cassava	Submergence	High MSI and antioxidant response, chlorophyll retention, altered stomatal behavior
Sweet Potato	PGRs	CCC improved chlorophyll, Pn, antioxidant enzyme activity; Ethephon affected pigment stability

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