Environmental stress responses

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***Abstract*—Hydroponic plants depend on coordinated aerial and root-zone conditions to maintain water balance, gas exchange, metabolism and development. Heat, cold, excessive atmospheric demand and stagnant humid air can disrupt this coordination, but similar visible symptoms may also arise from nutrient imbalance, salinity, oxygen limitation or biological disturbance. This paper synthesises evidence on environmental stress responses in hydroponic plants, with emphasis on stomatal regulation, hydraulic function, root-zone constraints and disease susceptibility. The evidence indicates that high vapour pressure deficit can increase transpirational demand and alter stomatal, photosynthetic and hydraulic responses, whereas humid stagnant air can reduce transpiration-driven transport. Temperature stress may also affect root-zone oxygen status and crop performance. Because environmental, chemical and biological constraints can converge in reduced growth, chlorosis, wilting or poor crop quality, visual symptoms alone do not provide a reliable causal diagnosis. A mechanism-based assessment that integrates climate, solution and root-zone observations is therefore needed to interpret plant stress and manage susceptibility without attributing symptoms to a particular pathogen.**

I. Introduction

Hydroponic cultivation provides direct control over nutrient solution and the aerial environment, but this control does not remove plants from basic physiological constraints. Plant performance depends on the coordination of leaf water loss, root water uptake, oxygen supply and metabolic activity. Root-zone temperature and dissolved oxygen are associated with hypoxia, growth and yield responses in nutrient-film strawberry systems, demonstrating that a plant exposed to atmospheric stress may simultaneously experience reduced root capacity to support transpiration [1]. Environmental stress should therefore be understood as a whole-plant problem, in which the aerial environment and root zone jointly influence the capacity to maintain water and energy balance [2].

The interpretation of environmental stress is complicated by the convergence of symptoms from different causes. Nutrient concentration, electrical conductivity, pH, salinity, substrate water-air balance, temperature, microbial imbalance and pathogen pressure can each affect crop performance in soilless systems [3]. Reduced growth or loss of canopy vigour may thus reflect a climate-related hydraulic response, a root-zone constraint, or both. This uncertainty makes symptom recognition insufficient as a basis for diagnosis and supports an assessment approach that first identifies the physiological process most likely to be limiting plant performance [4].

Environmental stress also develops through interacting rather than isolated variables. Temperature, moisture, aeration, nutrient status, substrate conditions and microbial communities can jointly influence plant responses, while the importance of these factors varies among systems and environments [3]. This paper explains major responses to heat, cold, excessive atmospheric demand and stagnant humid air. It then examines why different mechanisms can produce similar visible effects and how climate stress may influence disease susceptibility without diagnosing specific pathogens [5].

II. Background and Scope

Hydroponic systems concentrate several potential stressors within a tightly managed production environment. Reviews identify pH, electrical conductivity, nutrient formulation, salinity, substrate properties, root-zone oxygenation and pathogen exposure as distinct influences that may produce overlapping growth problems [6]. A plant with poor expansion, chlorosis or reduced vigour cannot therefore be assumed to have a climate problem solely because air temperature or humidity is outside a preferred range. The same response may result from a chemical, hydraulic or biological limitation. This overlap establishes the central analytical need for mechanism-based interpretation [7].

The climate environment also shapes the context in which other constraints act. Temperature and humidity interact with root-zone conditions, nutrient chemistry, pathogen presence and control practices in determining hydroponic system susceptibility [6]. Such interactions do not mean that climate conditions identify a disease. Rather, they indicate that stressful environmental conditions may change plant function and the wider conditions affecting exposure to biological pressures. The relevant question is whether climate stress contributes to a pattern of vulnerability, not whether a visible symptom can confirm a specific causal agent [8].

Evidence from strawberry nutrient-film systems illustrates why this distinction matters. Root-zone oxygen limitation, elevated solution temperature and disease-related processes can generate similar stress responses, despite arising through different pathways [1]. The practical limitation is that a single observation cannot distinguish among these mechanisms. A sound interpretation requires comparison of aerial measurements, root-zone status and the timing of plant responses, particularly when symptoms emerge rapidly after a change in temperature, humidity or water movement [9].

III. Core Concepts and Mechanisms

Temperature stress affects plants through both aerial and root-zone processes. Heat can increase atmospheric demand and respiratory burden, while elevated root-zone temperature

may reduce dissolved oxygen availability and impair root function. In nutrient-film production, the interaction between root-zone temperature, oxygen stress and waterborne disease susceptibility demonstrates that thermal conditions can place plants under combined physiological and biological pressure [1]. Cold presents a different but related constraint because lower temperatures can alter metabolic activity and water-use responses. In both cases, the important mechanism is disrupted coordination between demand in the shoot and supply from the root system [10].

Excessive atmospheric demand is commonly represented by vapour pressure deficit. When the air exerts a strong drying force, plants must regulate stomatal opening to balance carbon dioxide uptake against water loss. Vapour pressure deficit and temperature are directly associated with stomatal, photosynthetic and hydraulic responses [11]. Stomatal closure may conserve water when root supply becomes limiting, but it can also constrain photosynthetic carbon assimilation. A decline in growth under high atmospheric demand may consequently be driven by hydraulic and stomatal limitation even when nutrient concentration and pH remain stable [12].

Stagnant humid air creates an opposing atmospheric condition. High humidity and inadequate air movement reduce the evaporative gradient at leaf surfaces, potentially weakening transpiration-driven water movement through the plant. Soilless production reviews identify temperature, humidity and climate-control conditions as important influences on crop response [13]. The effect should not be simplified as improved hydration, because reduced transpiration can alter the movement of water and dissolved nutrients within the plant. Species, developmental stage, airflow and root-zone condition remain important limitations on generalising a response from one crop or system to another [14].

IV. Evidence Synthesis

The evidence supports analysing environmental stress as a coupled system response. Water quality, temperature, flow, irrigation precision, runoff conditions, pathogen propagules and treatment design can jointly affect exposure and susceptibility in managed crop production [15]. These conditions may operate through different physical and biological mechanisms, yet converge in a crop that appears stressed or grows poorly. When climate stress is suspected, the state of water delivery and root-zone oxygenation should be considered alongside air conditions because each can influence whether plants are able to maintain turgor and nutrient uptake [16].

Nutrient chemistry provides a clear example of symptom convergence. Nutrient imbalance, salinity, osmotic stress, pH and electrical conductivity are distinct causes of decline in hydroponic crops [17]. Excessive atmospheric demand can also reduce leaf expansion and crop vigour when transpirational loss exceeds root supply. Although both situations may produce similar visible responses, their mechanisms differ: one constrains water acquisition through solution properties, while the other increases water loss through the aerial environment. This distinction matters because changes to climate control will not necessarily resolve a chemically induced restriction, and nutrient adjustments will not correct an atmospheric hydraulic imbalance [18].

Differences among cultivation systems reinforce the need to interpret climate in relation to roots. Aeroponic research identifies root temperature, oxygen and carbon dioxide as factors associated with growth responses [19]. The aerial environment may be similar across production systems, yet the physical conditions surrounding roots can differ substantially. These observations support the conclusion that air temperature and humidity measurements alone are inadequate indicators of plant stress. Meaningful interpretation requires information about whether root conditions can sustain the water and metabolic demands imposed by the aerial environment [20].

V. Practical Implications and Limitations

Environmental monitoring is most useful when it supports assessment of susceptibility rather than diagnosis. Reviews of soilless agriculture describe interactions among temperature, humidity, dissolved oxygen, nutrient stress, pathogen risk and system management, while limiting conclusions to monitoring and susceptibility rather than identification of particular pathogens [21]. An observed stress response should therefore prompt examination of several conditions, including air temperature, humidity, dissolved oxygen, solution chemistry and water movement. This integrated approach is more defensible than assigning symptoms to a specific disease or nutrient disorder from appearance alone [22].

Vapour pressure deficit should be interpreted as a dynamic indicator of plant demand rather than as an isolated control target. Its effects on stomatal behaviour, photosynthesis and plant hydraulics depend on temperature and on the capacity of the root system to replenish water [11]. This limits the value of universal environmental set points across crops, growth stages and systems. Validation should assess whether changes in atmospheric demand precede changes in canopy condition, stomatal behaviour or growth, while also checking whether root-zone conditions remained adequate during the same interval [23].

The available evidence also shows that non-climatic stressors can obscure environmental interpretation. Root exudates, autotoxicity, algae, pathogens, nutrient loss, pH shifts, oxygen conditions and treatment chemistry are all identified as potential contributors to reduced growth and plant stress in hydroponic systems [24]. These factors may coexist with heat, cold or humidity stress. The principal limitation is therefore causal ambiguity: a stressed plant may reflect one dominant process or several interacting processes. Time-resolved observations across both air and solution conditions provide the strongest basis for distinguishing plausible mechanisms.

VI. Conclusion

Hydroponic plants respond to physiologically stressful aerial environments through changes in stomatal behaviour, water balance, metabolism and development. Heat, cold, excessive atmospheric demand and stagnant humid air can alter

these responses directly, while root-zone temperature, oxygen, solution chemistry and water movement may amplify or resemble the resulting symptoms [1], [11], [17]. Similar visible symptoms can therefore emerge from different environmental and root-zone mechanisms, making appearance alone an unreliable basis for causal interpretation.

The evidence supports an integrated assessment of climate and root-zone conditions. Temperature, humidity, vapour pressure deficit, dissolved oxygen, solution chemistry and water movement should be considered together when evaluating plant stress and disease susceptibility [6], [15]. The highest-value next work is time-resolved validation that relates environmental change to plant response, enabling management decisions to address the most plausible physiological constraint without treating stress symptoms as a diagnosis.

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