# Temperature effects on plant metabolism

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***Abstract*—Air temperature is a principal determinant of plant performance in controlled hydroponic environments because it influences the rates and coordination of growth, physiology and development. However, the available evidence does not support a universal temperature optimum. Instead, crop responses depend on species, cultivar, developmental stage, lighting, humidity, vapour pressure deficit, nutrient conditions and system design. This paper synthesises evidence concerning the influence of air temperature on plant metabolism, with particular attention to its relationship with leaf temperature and its distinction from root-zone temperature. The evidence indicates that air temperature should be regarded as an interacting environmental regulator rather than an isolated setpoint. It can alter crop growth, yield and developmental timing, while leaf energy exchange links the surrounding air environment to the temperature experienced by photosynthetic tissues. Root-zone temperature remains analytically distinct because it affects dissolved oxygen, root respiration, nutrient uptake and disease-related processes. Consequently, controlled hydroponic systems require crop-specific thermal interpretation, independent specification of aerial and root conditions, and validation under defined environmental combinations.**

## I. Introduction

Air temperature has a central role in controlled hydroponic production because temperature-dependent conditions are associated with changes in crop growth, yield, physiology and development. Reviews of soilless production nevertheless show that these responses differ across crops and growing contexts [1]. Temperature management is therefore not simply a matter of selecting one favourable numerical setpoint. A change in air temperature alters the environmental setting in which plant processes occur, but the resulting response depends on whether light, humidity, vapour pressure deficit and nutrient supply remain compatible with the crop's developmental state. The practical implication is that temperature must be interpreted as part of an interacting crop environment rather than as an independent production input [2].

The need for this broader interpretation is apparent in hydroponic strawberry research, where temperature-related outcomes are linked with oxygen sensitivity, root demand, developmental stage, dissolved oxygen and Pythium biology [3]. These findings concern the root environment, yet they demonstrate a principle relevant to the aerial environment: plant performance reflects the balance among several physiological constraints. This paper examines how air temperature influences the rate and balance of plant processes in controlled hydroponic systems. It distinguishes air and leaf temperature from root-zone temperature, then synthesises evidence on developmental context, environmental interactions and the limits of generalising thermal guidance [4].

## II. Background and Scope

Existing controlled-environment literature places temperature among several interacting sources of variation. Crop type, growth stage, climate, humidity, vapour pressure deficit, nutrient management, system design and operator control can each modify the response observed at a particular temperature [1]. This means that air-temperature effects cannot be inferred reliably from crop performance alone when associated environmental conditions are unspecified. Hydroponics provides considerable control over production conditions, but control does not remove biological variation in demand or environmental variation around the shoot. The relevant analytical task is to identify how air temperature participates in a defined environmental combination [5].

Developmental evidence reinforces this limitation. Studies of flowering regulation describe temperature as integrated with photoperiodic, hormonal and stress-related pathways, with the significance of each pathway varying according to species and developmental condition [6]. Temperature can therefore influence the timing of developmental transitions without providing a complete explanation of them. For hydroponic crops, a temperature regime that supports vegetative performance may not necessarily produce the same response during reproductive development. Air temperature should consequently be aligned with the crop objective and growth phase, rather than evaluated only through immediate biomass or visual condition [7].

Broader phenological synthesis shows that temperature responses differ across taxa, life forms, phenophases, ecotypes, chilling histories, photoperiods and environmental contexts [8]. This evidence rules out a simple temperature-response model that could be transferred unchanged across controlled crops. It also identifies the central scope of the present paper: to explain why air temperature modifies plant metabolism and development while recognising that the observed response remains conditional. The available literature supports careful interpretation of interacting factors, not universal prescriptions for all hydroponic species or stages [9].

## III. Core Concepts and Mechanisms

Air temperature influences plant metabolism within the wider shoot environment, where crop response is shaped by temperature together with vapour pressure deficit, climate context, crop identity, growth stage and management conditions [10]. This relationship is important because a temperature

adjustment may alter the pace of plant activity while other resources remain unchanged. The outcome may therefore vary according to the capacity of the surrounding environment to support that altered physiological demand. In practical terms, air temperature should be considered alongside the conditions that determine leaf microclimate and crop resource balance. The evidence supports comparison among defined production contexts rather than extrapolation from a single system [11].

Temperature-dependent development is also governed by biological integration. Reviews of flowering regulation indicate that developmental competence, species identity, photoperiod, temperature, hormones, vernalisation and stress can all contribute to developmental responses [12]. This means that temperature may alter developmental rate or timing, but the plant's response is mediated through its current biological state and concurrent environmental signals. For a controlled hydroponic crop, the implication is that air-temperature management must be interpreted with reference to the intended developmental outcome. A thermal programme cannot be assumed to have equivalent effects across cultivars, growth stages or lighting programmes [13].

Leaf temperature is a useful conceptual link between air conditions and plant metabolism because leaves exchange energy with their surroundings rather than merely matching recorded air temperature. A controlled-environment lettuce model considered air temperature, crop heat exchange, leaf-temperature-related energy exchange, yield and energy load, while assuming root temperature was equal to air temperature [14]. The assumption provides a useful comparison boundary, but it also illustrates a major limitation in interpretation. Air temperature describes the shoot environment, whereas leaf temperature more directly characterises the thermal state of photosynthetic tissue. Root temperature should be reported separately when its effects are relevant.

## IV. Evidence Synthesis

Evidence from controlled-environment agriculture consistently attributes crop outcomes to interacting environmental and system conditions. Crop characteristics, climate, microclimate, lighting, humidity, vapour pressure deficit, energy conditions and system design are all reported as relevant to performance differences [15]. Temperature is consequently important, but it should not be presented as the only explanatory variable when these conditions co-vary. A measured air-temperature response may reflect altered leaf energy exchange or humidity-related conditions as well as temperature itself. Strong interpretation therefore requires the aerial environment to be characterised sufficiently to distinguish a direct thermal effect from a broader microclimate effect.

Nutrient-related evidence similarly cautions against assigning temperature an explanatory role beyond the available support. Plant nutrient outcomes vary with properties of the growing medium, pH, moisture, management and crop conditions [16]. In bioponic production, crop demand, ammonium sensitivity, microbial processing, pH and temperature conditions also contribute to heterogeneous outcomes [17]. These sources support the conclusion that temperature is embedded in a wider production system, but they do not establish that air temperature alone governs nutrient performance. The analytical implication is that crop response should be attributed cautiously unless aerial and root-zone conditions are independently described.

Respiration research offers a more specific example of how environmental constraints affect metabolism. Under low oxygen, mitochondrial energy generation is impaired, ATP production decreases and metabolic intermediates can accumulate; re-oxygenation may also be associated with reactive oxygen species formation [18]. This evidence concerns hypoxia rather than ordinary air-temperature control and should not be treated as proof of a general air-temperature relationship. Its relevance is that metabolic rate depends on oxygen status as well as thermal conditions. In hydroponics, oxygen-related root-zone processes require separate treatment from the influence of air temperature on shoots and leaves.

## V. Practical Implications and Limitations

Air-temperature management should be crop- and stage-specific because responses to artificial lighting differ across species, cultivars and developmental stages, with temperature acting as an interacting modifier [19]. A thermal setting developed under one spectrum or irradiance regime may therefore not transfer reliably to another crop or lighting treatment. This is especially important where developmental progression is a production objective, since lighting and temperature can both contribute to morphological and physiological responses. The appropriate practice is to document the crop, cultivar, stage and lighting environment when evaluating a temperature programme, rather than claiming that the recorded temperature alone caused an observed response.

Complex nutrient systems provide a further limit to generalisation. Bioponic outcomes can differ with crop demand, ammonium sensitivity, microbial processing, pH and temperature conditions [17]. Such evidence indicates that performance changes may arise from multiple system processes rather than a direct effect of air temperature. It does not justify transferring conclusions from biologically active nutrient solutions to conventional hydroponic systems without validation. Studies that seek to identify air-temperature effects should therefore hold nutrient conditions stable where possible and report the solution context explicitly. This would reduce the risk of conflating aerial metabolic responses with changes originating in nutrient processing.

Root-zone evidence must also be kept distinct from aerial-temperature evidence. Aeroponic research reports that root-environment conditions can affect root area, mineral content and growth, but it provides limited explanation of air-temperature response differences [20]. Comparative temperature research likewise shows that phenological responses vary across taxa, phenophases, ecotypes, chilling histories and photoperiodic contexts [8]. The strongest validation need is therefore independent specification of air, leaf and root-zone temperatures, followed by crop-stage-specific assessment of

physiological and developmental outcomes. Without this separation, apparently simple thermal recommendations remain vulnerable to confounding.

## VI. Conclusion

Air temperature alters the rate and balance of plant processes in controlled hydroponic environments, but the evidence does not support one universal optimum. Crop identity, developmental stage, lighting, humidity, vapour pressure deficit, nutrient conditions and system design shape the response associated with a particular thermal regime [1], [10]. Air and leaf temperatures should be interpreted together when considering shoot metabolism, while root-zone temperature should remain a distinct variable because of its separate links with dissolved oxygen, root respiration, nutrient uptake and disease-related conditions [3].

The highest-value next work is controlled validation that specifies air, leaf and root-zone temperatures independently while documenting crop stage, lighting, humidity and nutrient conditions. Such work would address the principal limitation identified across the evidence base: thermal responses are consistently conditional on plant state and environmental resources, rather than isolated effects of a single setpoint [8], [19].


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