The Path Not Traveled

Rethinking Air Distribution in Canopy-Dominated Environments

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An Engineering Position White Paper on Canopy-Focused Air Distribution in Controlled Environment Agriculture

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Executive Summary

Vertical farms operate under tight financial and biological margins, making climate-control design a strategic decision rather than a mechanical afterthought. This paper argues that conventional room-mixed air delivery, while familiar and capable of producing crops, is an indirect means of managing the dominant heat and moisture loads generated within dense crop canopies. By relying on the room as a mixing chamber, room-mixed systems can obscure the actual air conditions experienced by plants and make it difficult to verify uniform canopy climate control.

Direct-to-canopy air distribution offers a more deliberate alternative. It supplies dry, conditioned air directly to the crop canopy, allows that air to absorb heat and moisture from the canopy, and uses the canopy-leaving air as the primary reference for design, measurement, commissioning, and control. This approach aligns the climate-control system with the location where plant response, transpiration, vapor-pressure management, and crop uniformity are determined.

In the representative example, direct-to-canopy air delivery achieves the same canopy-leaving condition with 30 tons and 6,212 CFM, versus 47 tons and 12,174 CFM for room-mixed delivery—a 36% reduction in calculated CH&D capacity and a 49% reduction in airflow, before considering fan energy, noise, maintenance, and commissioning benefits. In both cases, local canopy air distribution should be delivered uniformly and perpendicularly to the crop canopy to optimize canopy penetration and ensure uniform crop quality.

The findings should be read as engineering evidence from a representative psychrometric comparison, not as a universal savings guarantee. Actual performance will depend on crop architecture, rack geometry, airflow distribution, sensor strategy, equipment configuration, and the effectiveness of room mixing. Savings will vary with room-mixing effectiveness and the efficiency with which direct-to-canopy airflow remains engaged with the crop before leaving the canopy.

CEA climate design should shift from controlling an assumed room-average condition to controlling the canopy air path. Direct-to-canopy delivery offers a clearer, more measurable framework for improving uniformity, reducing excess airflow and capacity, and directly linking HVACD performance to plant-level conditions.

Table 1-Summary of air delivery system strategies

Room-Mixed	Direct-to-Canopy
→CANOPY OUT↘ →CH&D OUT↗ →ROOM-MIXED→ ↗CANOPY IN→ ↘CH&D IN→	**CH&D OUT→CANOPY IN→CANOPY OUT→CH&D IN→**
Figure 1, Figure 2, Figure 3, Table 3, Table 4	Figure 4, Figure 5, Table 5
Supply air is diluted before reaching the crop.	Supply air is delivered directly to the crop.
Canopy leaving air is diluted before reaching the CH&D	Canopy leaving air is delivered directly to the CH&D
47 Tons, 12,174 CFM	30 Tons, 6,212 CFM
Baseline	36% Less Tons, 49% Less Airflow

Another central issue is where the grower's specified temperature and humidity apply in the air path. Assigning 80°F and 60% RH to canopy-entering rather than canopy-leaving air yields materially different psychrometric outcomes; the "Inflection Point," discussed starting on page 11, addresses this issue.

Introduction

Vertical farming's narrow margins make climate-control design a strategic economic decision. Air-distribution choices affect capital cost, energy use, reliability, crop uniformity, and marketable quality. In an industry pressured by farm closures, tighter financing, and high operating costs, inefficient climate-control assumptions can materially affect profitability.

Vertical farms are not conventional comfort-cooling applications. They are typically well-insulated, windowless spaces in which the dominant sensible and latent loads originate within the crop canopy from lighting and transpiration, rather than from the building envelope. Yet much of CEA air-distribution practice still relies on strategies adapted from commercial comfort conditioning, in which the room is treated as the primary mixing chamber and the room-average condition serves as the reference point for design and control.

That assumption deserves closer examination. Room-mixed systems can and do produce crops, but crop production alone does not prove that the air-distribution strategy is optimal. A facility may achieve marketable output while still carrying unnecessary airflow, excess CH&D capacity, higher fan energy, added commissioning complexity, and uneven canopy-level conditions.

Uniformity is central to CEA success. Growers already seek precise, uniform delivery of water, nutrients, and light. Climate should be treated with the same discipline. In a room-mixed system, dry CH&D supply air must blend with humid canopy-leaving air before reentering the crop. If that blending is incomplete, each section of the canopy may receive a different combination of temperature, vapor pressure, and air velocity. The result can be an acceptable room-average condition that masks localized microclimates at the plant level.

This paper compares conventional room-mixed air delivery with a direct-to-canopy strategy that delivers dry, conditioned air directly to the crop canopy and uses canopy-leaving air as the meaningful reference for design, measurement, commissioning, and control. The issue is not whether room-mixed systems can grow crops. They can. The issue is whether a room-average, dilution-based strategy is the best way to manage canopy-dominated sensible and latent loads.

Direct-to-canopy air delivery offers a more deliberate framework. By connecting CH&D equipment directly to the crop air path, it delivers conditioned air where heat and moisture are generated, reduces reliance on uncontrolled whole-room mixing, and makes the canopy—not the room—the primary point of climate-control design. The results are improved crop quality, uniformity, and energy demand.

Engineering Position

This engineering position paper argues that:

1. Crop uniformity improves when air temperature, vapor pressure (VP), and velocity are distributed uniformly and perpendicular to the plant canopy.
2. Crop quality improves when the driest air from the cooling, heating, and dehumidification (CH&D) unit is delivered directly to the plant canopy.
3. HVACD system efficiency improves when controlled from canopy-leaving air conditions because canopy-exit temperature and humidity more directly reflect plant-level activity.

This paper does not argue that room-mixed systems cannot grow crops. They do. The position advanced here is that room-mixed air delivery is less effective at achieving crop uniformity, crop quality, and energy consumption, as well as air volume, because it is an indirect and less measurable strategy for managing canopy-dominated sensible and latent loads efficiently.

Direct-to-canopy air distribution provides a more direct engineering framework by delivering conditioned air to the canopy, while using canopy-leaving air as the primary reference condition, and aligning equipment selection, airflow design, measurement, commissioning, and control with the actual psychrometric process occurring at the crop.

Design Assumptions and Definitions

Key Terms

Grower refers to the team responsible for managing cultivation operations.

CH&D means a cooling, heating, and dehumidification unit that provides all three functions.

HVACD refers to a climate control system of heating, ventilating, air conditioning, and dehumidification.

The room-mixed air distribution strategy describes a system in which the dry air leaving the CH&D unit mixes with humid air leaving the canopy before reentering the canopy and CH&D unit.

The direct-to-canopy air-distribution strategy describes a system in which the CH&D unit supplies dry air directly to the canopy and is the subject of U.S. patent application number 18/639,274. In this paper, the patented Canopy-Direct™ air distribution system is described. The engineering argument rests on the air-path and psychrometric comparison, not the trademark itself.

The evaporation rate is the sum of plant transpiration and any water spillage that is not drained away.

Evaporative cooling is a moisture-driven cooling mechanism that occurs at the leaf surface. When that evaporation is treated as occurring without external heat exchange, it is commonly modeled as an adiabatic cooling process.

Air conditions refer to air velocity, temperature, and humidity, which can be used to calculate other important psychrometric values, such as dew point and vapor pressure.

Canopy-entering air is the conditioned air delivered into the crop canopy before it absorbs heat and moisture from the plants.

Canopy-leaving air is the air state after it exits the canopy, carrying the heat and water vapor generated by plant lighting and transpiration.

> *Note: For design and control purposes, canopy-leaving air is the more meaningful reference because it reveals what occurred within the crop zone. It reflects the combined effects of airflow, transpiration, and heat from lighting that occur dynamically within the plant canopy. Therefore, when referring to canopy air as a control condition, we also mean canopy-leaving air.*

Crop Quality and Uniformity

Superior crop quality depends on the uniform delivery of the required temperature, vapor pressure, and air velocity to the canopy.

Climate affects crop quality and uniformity. **Crop uniformity** happens when a uniform climate is delivered across the growing area. **Crop quality** happens when the uniform climate meets the grower's specifications, ensuring the entire crop meets the desired standards for appearance, yield, flavor, shelf life, and marketability. Uniformity alone does not guarantee quality, but you cannot achieve consistently high crop quality without uniformity.

Crop quality is optimized when the climate system delivers air to the canopy with a consistent, intentionally selected temperature, vapor pressure, and velocity, ensuring each plant experiences the same driving force for transpiration and gas exchange.

Canopy Air Velocity

Currently published recommendations for canopy air velocity range from about 40 to 300 feet/minute (fpm), depending on the source. That broad range itself suggests uncertainty.

Recommendations for canopy air velocity are based on empirical data from traditional room-mixed air-distribution systems, which dominate current practice and therefore constitute most of the available field experience. As a result, the published velocity ranges reflect conditions in which air has already been diluted, redirected, and mixed within the room before reaching the crop. They should not be treated as fixed design rules for direct-to-canopy systems, where drier conditioned air is delivered more intentionally into the canopy air path, and velocities are potentially lower.

Air velocity reduces leaf boundary-layer thickness and improves gas exchange by strengthening leaf-to-air coupling. Lowering the vapor pressure of air delivered to the canopy can have the same effect by increasing the vapor pressure deficit and strengthening the driving force for transpiration. Therefore, the resulting physiological effect cannot be attributed to air velocity alone. In practical terms, delivering lower-velocity dry air to the canopy can produce the same exchange benefits as delivering higher-velocity, more humid air. These two mechanisms can contribute to the same physiological outcome. Therefore, delivering lower-vapor-pressure air directly to the canopy may reduce the air velocity required to achieve a comparable transpiration response.

Vapor Pressure and Vapor-Pressure-Deficit

Vapor pressure (VP) and vapor pressure deficit (VPD) are key grower metrics for assessing how climate conditions drive water movement through the crop. They are typically expressed in kilopascals (kPa). The VPD is calculated as the difference between the vapor pressure of the leaf surface and that of the canopy air conditions specified by the grower. A chart for calculating VPD is shown in Figure 7.

Leaf Surface Temperature

Leaf surface temperature (LST) is typically measured with an infrared thermometer and used to calculate the saturation vapor pressure at the leaf surface. Because an actively transpiring leaf presents a moist evaporating surface, the leaf surface is commonly treated as being at or near 100% relative humidity for VPD calculations. More efficient CEA lighting converts more electrical energy into photosynthetically active photons and produces less waste heat. Reducing both radiant and convective heat transfer to the canopy can lower leaf surface temperature (LST), reduce sensible cooling loads, and improve the stability of vapor pressure deficit (VPD) control.

Because lighting spectra and intensity are typically fixed within a given crop production strategy, bulk VP and VPD metrics remain practical and consistent reference points for system comparison, operational communication, and performance evaluation—particularly when direct LST measurement is unavailable or impractical.

Leaf surface temperature (LST) strongly influences the leaf vapor pressure used in VPD calculations. In practice, LST may range from about 3°F below canopy air temperature in night mode to about 8°F above it in the day mode.

When LST is known, the actual VPD may be calculated. When the value is unknown, VP and VPD are reported as “bulk” values. Bulk leaf VP is calculated from the grower-specified temperature at 100% RH, without accounting for the effect of lighting or evaporative cooling. Figure 7 explains the methods for determining bulk and actual VPD’s.

From a crop-performance standpoint, what matters are the air conditions experienced at the leaf surface, where the boundary layer is formed and where heat, water vapor, and CO^2 exchange occur.

CH&D Reheat Energy

The most prevalent CEA dehumidification systems use a vapor-compression cycle, in which reheating energy is an abundant byproduct and contributes little to operating expenses.

Measurement and Controls

Canopy-leaving air is the most useful practical reference for measurement and control. It reflects the air state after direct interaction with the crop. It captures the combined effects that determine the vapor-pressure environment at the end of the airflow path, where moisture accumulation is greatest.

When the uniformity of canopy air distribution is unreliable, the control strategy should include an array of canopy-leaving air-averaging sensors to provide a signal for operating the CH&D unit.

Across all operating modes and growth stages, the controls must manage canopy-leaving conditions by adjusting supply-air conditions to keep the canopy-leaving air conditions within a tight range.

This reframes room condition as a result rather than the primary design variable. If canopy-leaving air is treated as the true design and control reference, CH&D equipment can be selected and operated around the crop's actual psychrometric load rather than an assumed room condition.

Grower-Provided Design Specifications

Growers provide specifications that define the crop's target climate and load assumptions. These inputs typically include the desired humidity and temperature conditions, lighting load, and expected moisture evaporation rate. The engineer then uses these values to select the CH&D equipment and design the air-distribution system. Table 2 lists the grower-provided specifications used for examples throughout this paper.

Table 2-Grower Specified Data

Canopy Conditions	Value	Units
Altitude	0	ft
Temperature (1)	80°	°F
Relative Humidity (1)	60%	% RH
Maximum Water Evaporation Rate	150	lb./h
Lighting	146,235	Btu/h
Canopy Area	4,286	ft^2

(1) Represents canopy leaving-air conditions and the point of system control.

Building Envelope Loads

In CEA facilities, the dominant sensible and latent loads come from canopy transpiration and grow lighting rather than from the building's envelope. In many cases, the building's envelope loads are only a small fraction of the total load. Nevertheless, the engineer must calculate the summer and winter building-envelope loads separately and add them to the total CH&D capacity. Envelope gains and losses will somewhat influence the room conditions surrounding the canopy, but the canopy itself remains stable because the CH&D unit maintains canopy-leaving air conditions. This approach keeps the analysis focused on the crop-driven psychrometric load while still accounting for building-specific conditions.

The Inflection Point

Interpretation of a Grower's Specification

The Inflection Point occurs when the engineer assigns the grower's specified temperature and relative humidity to a defined location in the air path—either canopy-entering or canopy-leaving air. This single decision establishes the psychrometric basis for airflow, CH&D capacity, sensor placement, and control strategy.

The distinction is critical because air gains both sensible heat from lighting and latent moisture from transpiration as it passes through the crop. As a result, the same specification—80°F and 60% RH—yields materially different engineering outcomes depending on whether it is applied to canopy-entering air (room-mixed air) or canopy-leaving air.

The key question is not whether a room sensor reads 80°F and 60% RH, but where those conditions are intended to exist within the air path. If the grower intends to define the condition of the air after it has passed through the canopy, then the specification must be treated as canopy-leaving and not as room-mixed or canopy-entering air.

A common error arises when this specification is instead interpreted as canopy-entering (or room-mixed) air. This misinterpretation is understandable, as grower specifications typically specify only temperature and relative humidity without indicating the intended location.

As illustrated in Figure 1 and Table 3, the system, under this mistaken assumption, appears to satisfy the requirement: maintaining 80°F and 60% RH at the entering-air point, removing 150 lb./hr of moisture, and requiring approximately 30 tons of CH&D capacity. However, when the resulting canopy-leaving condition is calculated, the relative humidity is approximately 91%, which significantly alters the vapor-pressure environment experienced by the crop and promotes the development of mold and mildew. The system satisfies the interpreted condition, but not the grower's actual intent.

When the specification is correctly assigned to canopy-leaving air, the required system capacity increases substantially. As shown in Figure 3 and Table 4, the corrected interpretation raises CH&D capacity from 30 tons to 47 tons and increases airflow from approximately 6,212 CFM to 12,174 CFM. Correcting this misinterpretation after design or installation would entail high costs.

This divergence defines the Inflection Point: the grower's specification remains unchanged, but the engineering solution shifts dramatically once the condition is assigned to its correct location in the air path. Because room-mixed systems have been the prevailing design approach in vertical farming, this error is most likely to occur in their application and evaluation.

The implication is straightforward: every CEA design must explicitly define where the humidity and temperature specifications apply before finalizing system capacity, airflow, controls, sensor placement, and air distribution strategy. The engineer must then quantify the psychrometric consequences of that choice.

All parties should standardize climate specifications to mean canopy-leaving air.

Figure 1-Room-Mixed Psychrometric Chart with Canopy Entering Air Control

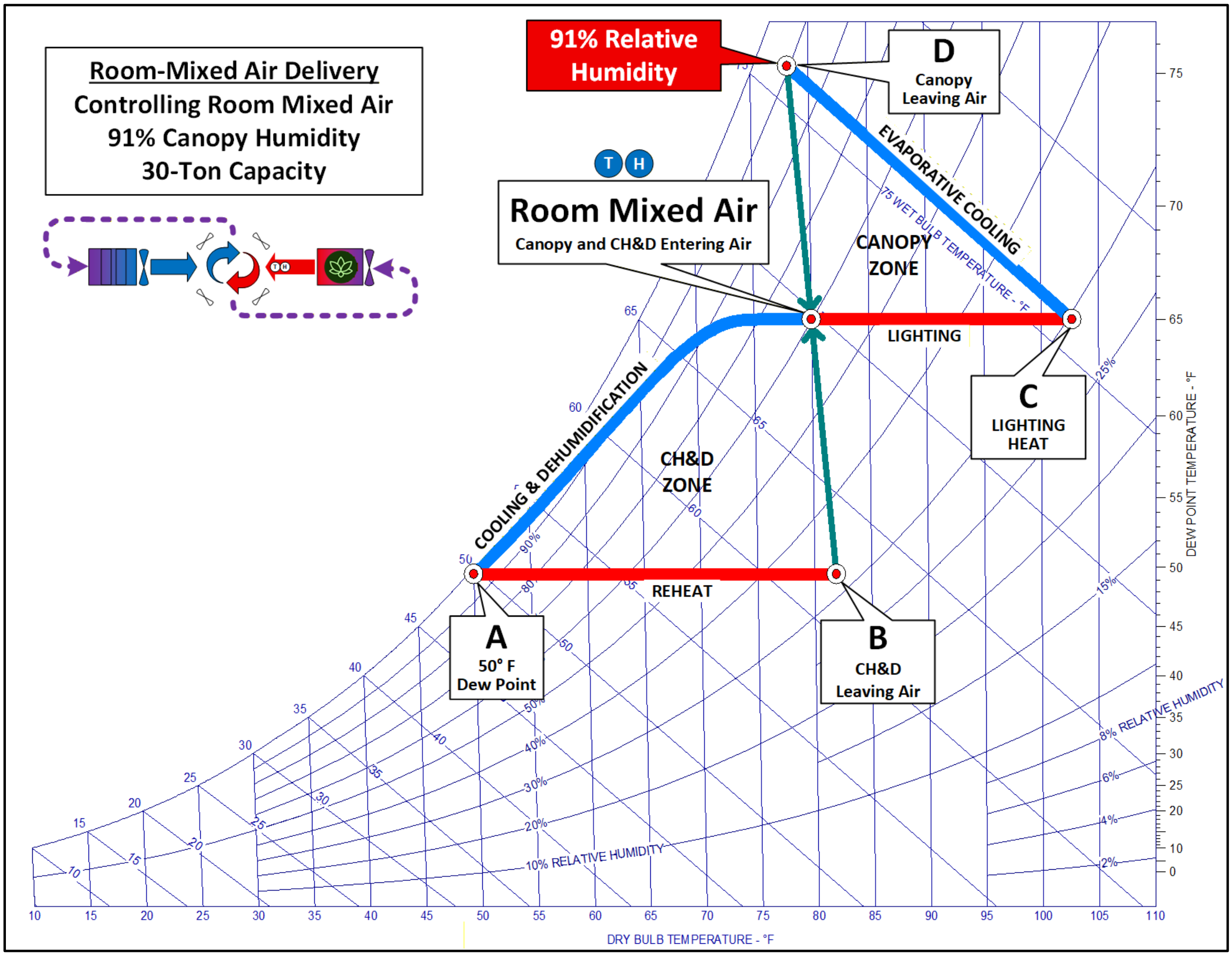


Table 3-Room-Mixed Psychrometric Values with Canopy Entering Air Control

CONDITION	SYMBOL	UNITS	CH&D UNIT		ROOM MIXED AIR	CANOPY	
			A	B		C	D
			COOL & DEHUMID	REHEAT		LIGHTING HEAT	EVAP. COOLING
Dry Bulb	t_db	°f	50.00	81.85	80.00	102.65	78.15
Dew Point	t_dp	°f	49.46	49.46	64.88	64.88	75.18
Relative Humidity	%	%	98%	32%	60%	30%	*91%*
Sat. Partial Pressure	p_ws	kPa	1.23	3.72	3.50	7.09	3.29
Partial Pressure	p_w	kPa	1.20	1.20	2.10	2.10	2.98
Humidity Ratio	W	grains/lb. (da)	52.33	52.33	92.09	92.09	132.07
Enthalpy	h	btu/lb. (da)	20.10	27.85	33.63	39.19	39.43
Specific Volume	v	f^3/lb. (da)	13.00	13.82	13.89	14.48	13.97
Process Energy Change	q_s	Btu/h	-357,256	204,666	0	146,235	6,172
Humid/Dehumid	$\dot{m}_w$	lb./hr (H_2O)	-150	0	0	0	150
Air Volume	Q	acfm	5,723	6,047	12,195	6,336	6,149

SUMMARY - Bulk VPD = 0.31 kPa Tons = 30 SHR = -0.08

A negative SHR indicates high latent heat, with evaporative cooling dominating the process.

Comparative Analysis: Room-mixed vs. Direct-to-canopy

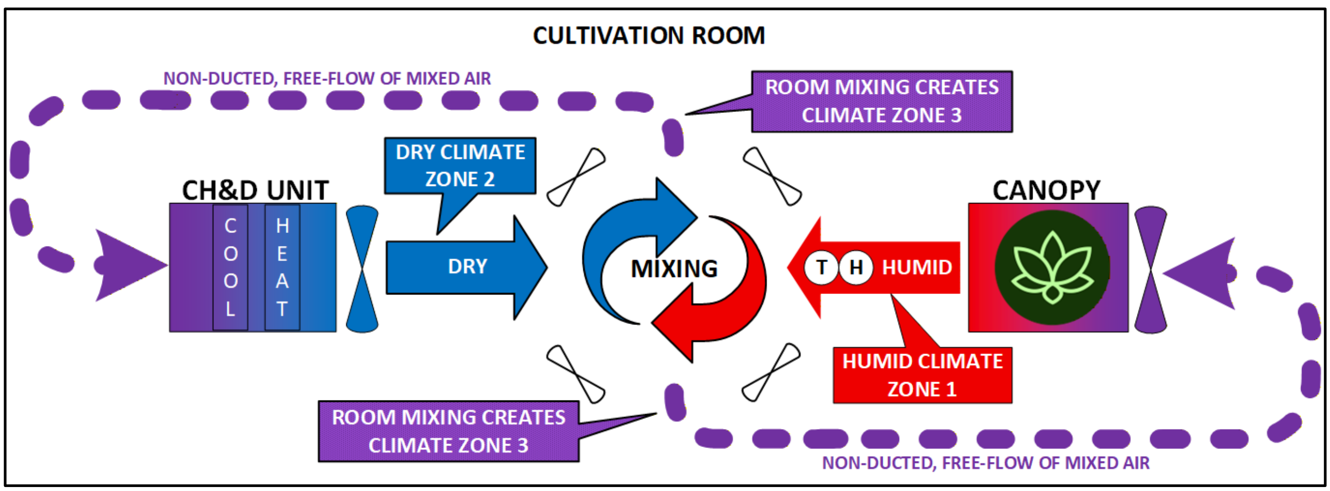
The following psychrometric comparison applies the stated canopy conditions, altitude, lighting load, and evaporation rate to show how each air-distribution strategy changes system capacity, airflow, and control implications. The results illustrate the engineering consequences of the design principles used in this representative example; actual facility savings may be higher or lower depending on crop architecture, rack layout, room-mixing effectiveness, and commissioning quality.

Room-Mixed Air Delivery

Design Summary: A three-step process cools, dehumidifies, and reheats air in the CH&D unit, then delivers it directly to the cultivation space, where it mixes with humid air leaving the canopy. The mixed air then returns to the canopy and the CH&D unit for reprocessing.

Figure 2 illustrates a room-mixed air-delivery strategy in which the CH&D unit is separated from the crop canopy by the room air volume. In this arrangement, the CH&D unit does not deliver conditioned air directly to the canopy. Instead, dry air leaving the CH&D unit is discharged into the room, where it mixes with warmer, more humid air leaving the canopy. The resulting room air mixture then becomes the air entering both the canopy and the CH&D unit. This creates three distinct climate states.

Figure 2-Room-Mixed Air Delivery Schematic with Canopy Leaving Air Control



Room-Mixed Climate Zones

Humid Climate Zone 1 represents the humid air conditions leaving the canopy, as specified by the grower.

Dry Climate Zone 2 represents the dry air conditions leaving the CH&D unit, as calculated by the engineer.

Room-Mixed Climate Zone 3 represents the mixed air entering the canopy and CH&D unit, as calculated by the engineer to achieve the conditions that leave the canopy in Humid Climate Zone 1.

Room-Mixed Psychrometrics

Figure 3-Room-Mixed Psychrometric Chart with Canopy Leaving Air Control

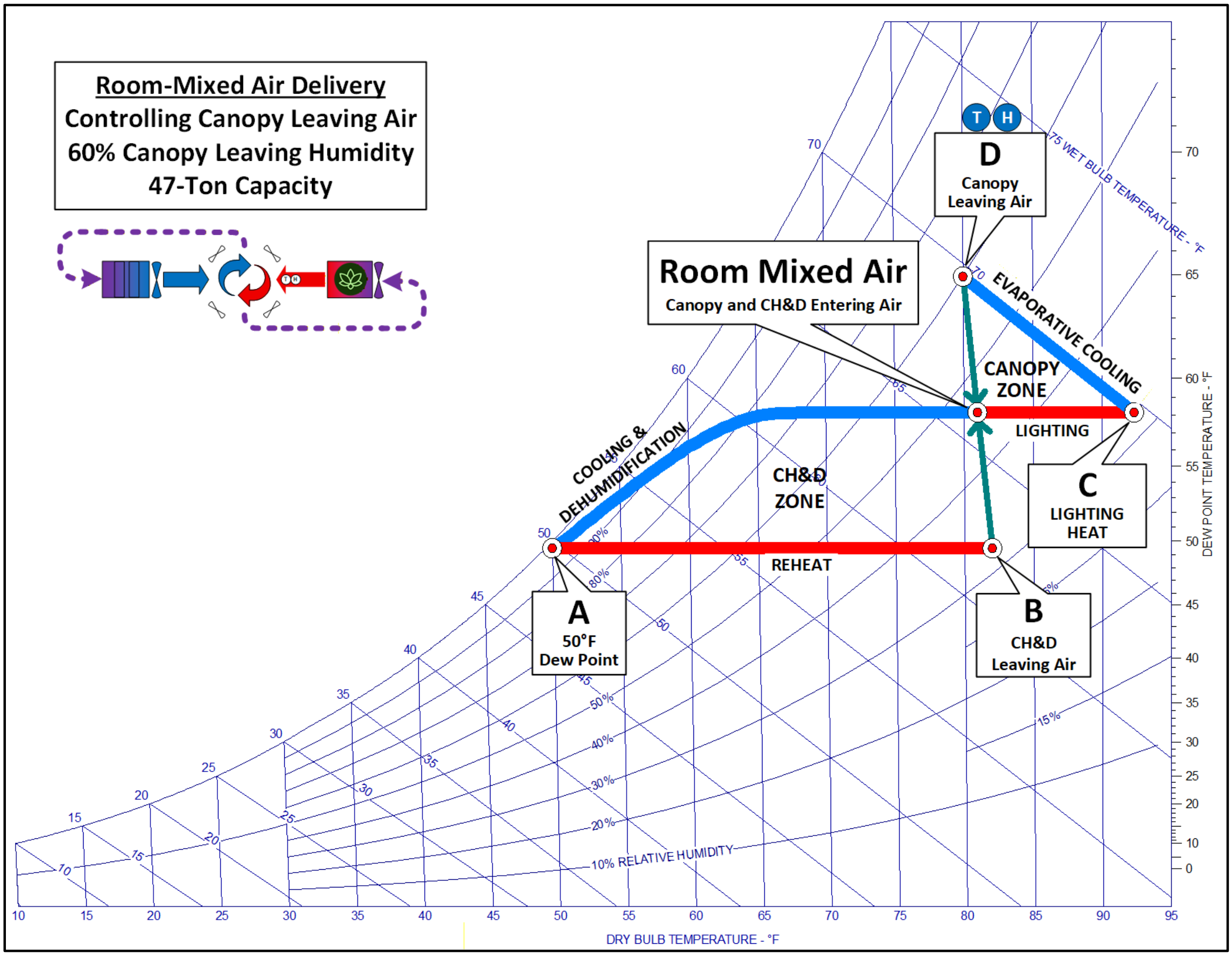


Table 4-Room-Mixed Psychrometric Values with Leaving Air Control

CONDITION	SYMBOL	UNITS	CH&D UNIT		ROOM MIXED AIR	CANOPY	
			A	B		C	D
			COOL & DEHUMID	REHEAT		LIGHTING HEAT	EVAP. COOLING
Dry Bulb	t_db	°f	50.0	82.0	81.0	92.3	80.0
Dew Point	t_dp	°f	49.5	49.5	58.1	58.1	64.9
Relative Humidity	%	%	98%	32%	46%	32%	60%
Sat. Partial Pressure	p_ws	kPa	1.23	3.73	3.61	5.18	3.50
Partial Pressure	p_w	kPa	1.21	1.21	1.65	1.65	2.10
Humidity Ratio	W	grains/lb. (da)	52	52	72	72	92
Enthalpy	h	btu/lb. (da)	20.11	27.90	30.76	33.52	33.63
Specific Volume	v	f^3/lb. (da)	13.00	13.82	13.86	14.15	13.89
Process Energy Change	q_s	Btu/h	-564,356	412,708	0	146,235	5,316
Humid/Dehumid	$\dot{m}_w$	lb./hr (H_2O)	-150	0	0	0	150
Air Volume	Q	acfm	11,487	12,174	24,447	12,461	12,273
SUMMARY - Bulk VPD = 1.4 kPa Tons = 47 SHR = -0.09							
A negative SHR indicates high latent heat, with evaporative cooling dominating the process.							

The Limitations of Room-Mixed Air Distribution

The psychrometric analysis in Figure 3and Table 4 assumes that dry CH&D supply air and humid canopy-leaving air blend into one uniform condition before reentering the canopy and returning to the CH&D unit. In practice, complete and repeatable blending is difficult to achieve because the room, rack geometry, canopy exhaust, bypass airflow, fan placement, and local obstructions all influence what air mixture reaches each part of the crop.

This is the central limitation of room-mixed air distribution: it relies on the room itself to serve as the mixing chamber. Supplemental fans may reduce local variation, but they add airflow, fan heat, energy use, noise, maintenance, capital cost, and commissioning complexity without proving that each canopy zone receives the intended temperature, vapor pressure, and velocity.

As a result, responsibility for achieving uniformity often shifts from the engineer's defined air path to the grower's field adjustments. Growers may add or reposition fans based on observations and local measurements, but averaged sensor readings may still mask canopy zones that are above or below the intended target.

The practical consequence is that room-mixed delivery must condition a blended room-air state rather than leaving air directly at the canopy, and the plants receive a higher vapor pressure, which is compensated for by higher system air volume. To achieve the same canopy-leaving condition, the system compensates with more airflow, lower supply-air humidity, larger CH&D capacity, higher fan energy, increased first cost, more noise, added maintenance, and greater crop-performance risk.

Room-mixed systems are conventional, familiar, and capable of producing crops. Their limitation is not failure but reliance on an indirect, dilution-based, and difficult-to-verify air pathway, where plant response is governed at the canopy level.

Third-party vendors such as Vertical Air Solutions, PIPP Horticulture, FabricAir, and DuctSox have developed local canopy air delivery systems that supply air perpendicularly and uniformly to a crop. These products represent the first step in improving the performance of all air distribution systems.

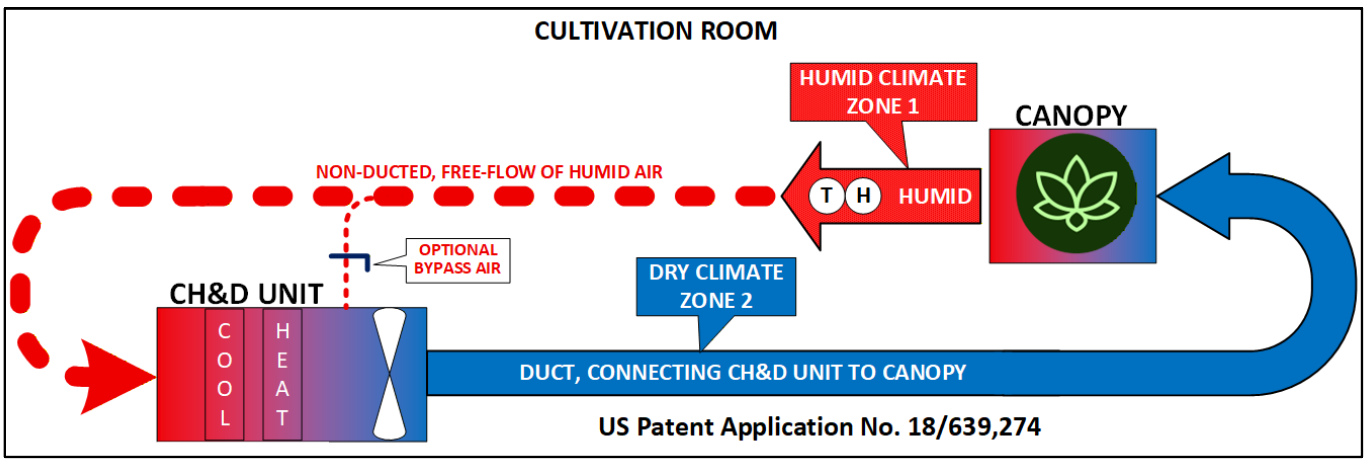
Direct-to-Canopy Air Delivery

Design Summary: A simple two-step process cools, dehumidifies, and reheats air in the CH&D unit, then delivers it directly to the canopy, where it absorbs heat and humidity before returning to the CH&D unit for reprocessing.

Figure 4 illustrates a direct-to-canopy air-distribution strategy. This strategy delivers dry, conditioned air directly from the CH&D unit to the plant canopy. This intentional and measurable air path—CH&D unit → canopy → return—delivers conditioned air where heat and moisture are generated. By reducing reliance on whole-room mixing, the direct-to-canopy approach makes the canopy, rather than the room, the primary point of design, measurement, and control.

The key advantage is that the CH&D unit-leaving air condition is also the canopy-entering air condition, while canopy-leaving air provides the meaningful reference for load calculations, measurements, and control. This creates a clear connection between equipment performance and the vapor-pressure, humidity, and airflow conditions that govern transpiration in the crop canopy.

Figure 4-Direct-to-Canopy Air Delivery Schematic with Leaving Air Control



Direct-to-Canopy Climate Zones

Humid Climate Zone 1 represents the air condition leaving the canopy, as specified by the grower.

Dry Climate Zone 2 refers to the air conditions as they leave the CH&D unit and enter the canopy. The engineer calculates this based on the maximum transpiration rate and the lighting wattage needed to achieve the conditions in the Zone 1 selected by the grower.

Direct-to-Canopy Psychrometrics

Figure 5-Direct-to-Canopy Psychrometric Chart with Canopy Leaving Air Control

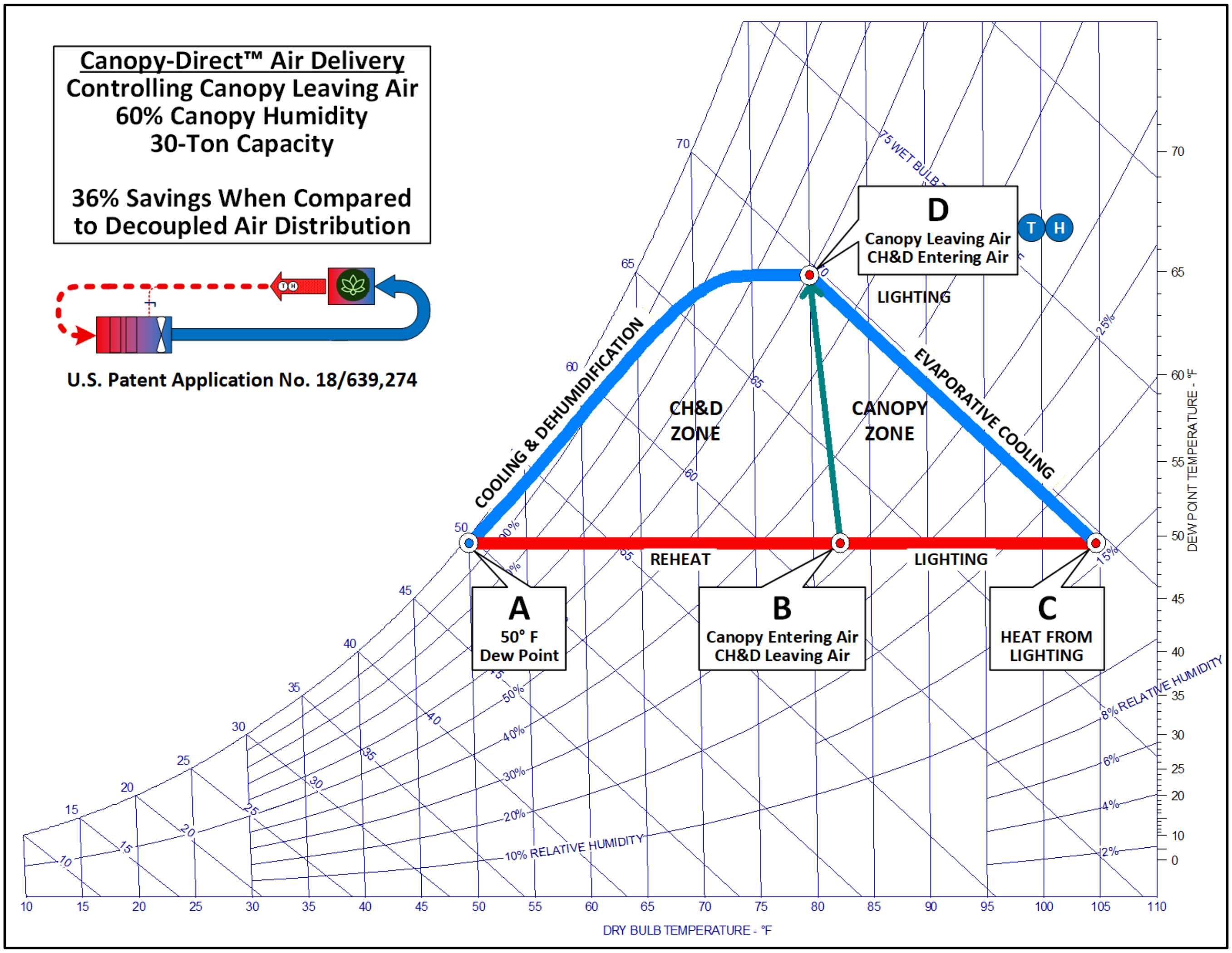


Table 5-Direct-to-Canopy Psychrometric Values with Canopy Leaving Air Control

CONDITION	SYMBOL	UNITS	CH&D UNIT		CANOPY	
			A	B	C	D
			COOL & DEHUMID	REHEAT	LIGHTING HEAT	EVAP COOLING
Dry Bulb	t_db	°f	50.0	82.4	104.7	80.0
Dew Point	t_dp	°f	49.5	49.5	49.5	64.9
Relative Humidity	%	%	98%	32%	16%	60%
Sat. Partial Pressure	p_ws	kPa	1.23	3.78	7.54	3.50
Partial Pressure	p_w	kPa	1.21	1.21	1.21	2.10
Humidity Ratio	W	grains/lb. (da)	52.45	52.45	52.45	92.23
Enthalpy	h	btu/lb. (da)	20.12	28.01	33.43	33.65
Specific Volume	v	f^3/lb. (da)	13.00	13.83	14.40	13.89
Process Energy Change	q_s	Btu/h	-364,640	212,579	146,235	5,826
Humid/Dehumid	$\dot{m}_w$	lb./hr (H_2O)	-150			150
Air Volume	Q	acfm	5,840	6,212	6,467	6,275
SUMMARY - Bulk VPD= 1.4 kPa Tons= 30 SHR = -0.11						
A negative SHR indicates high latent heat, with evaporative cooling dominating the process.						

The Practical Direct-to-Canopy Solution

Direct-to-canopy air distribution connects the CH&D unit to the plant canopy and delivers dry, conditioned air to the canopy, where heat and moisture originate. The CH&D unit conditions the canopy directly, applying the full dehumidification potential at the load's generation point.

The direct-to-canopy example in Figure 5 and Table 5 requires about 49% less airflow and 36% less CH&D capacity than the room-mixed example. These results are specific to the representative assumptions used here; actual savings will vary with facility design, crop conditions, and the effectiveness of room mixing.

Direct-to-canopy air distribution also enhances the control strategy's effectiveness through an intentional air path: the system uniformly delivers conditioned air to the canopy, resulting in uniformly conditioned air leaving the canopy that provides primary feedback for assessing plant microclimates and CH&D equipment performance. Commissioning is still required, but the control aim is clear, easier to verify, and directly tied to canopy performance.

Multiple sensors verify uniformity rather than averaging it. The direct-to-canopy system makes sensor placement less arbitrary because the air path is more predictable. This supports tighter canopy humidity control, improved VPD management, reduced risk of mold and mildew, reduced unnecessary turbulence and noise, and lower energy, maintenance, and capital and operating costs.

The design goal is to minimize dry-air spillage back into the room and to provide sufficient, uniform airflow to efficiently control canopy temperature, VP, and VPD. The design prioritizes local air delivery methods around canopy performance over whole-room mixing.

A direct-to-canopy system simplifies the air-distribution problem by reducing it to two meaningful climate states: conditioned air entering the canopy from the CH&D unit, and air leaving the canopy after absorbing heat and moisture from the crop. Eliminating the third, blended mixed-room condition removes much of the ambiguity that complicates measurement, control, and equipment selection in room-mixed systems.

A practical approach is to deliver conditioned air through strategically placed canopy outlets, allowing the driest air to penetrate the foliage uniformly. This shortens the vapor-removal path and makes the canopy—not the room—the primary control target.

Data Center Analogy

Data-center cooling offers a useful engineering parallel: when heat loads became concentrated, designers moved from generalized room mixing to targeted supply and controlled return paths. Vertical farms face a different load source—the crop canopy—but the same thermodynamic principle applies: deliver conditioned air where heat and/or moisture are generated, measure conditions after the load is absorbed, and avoid relying on an uncontrolled room average.

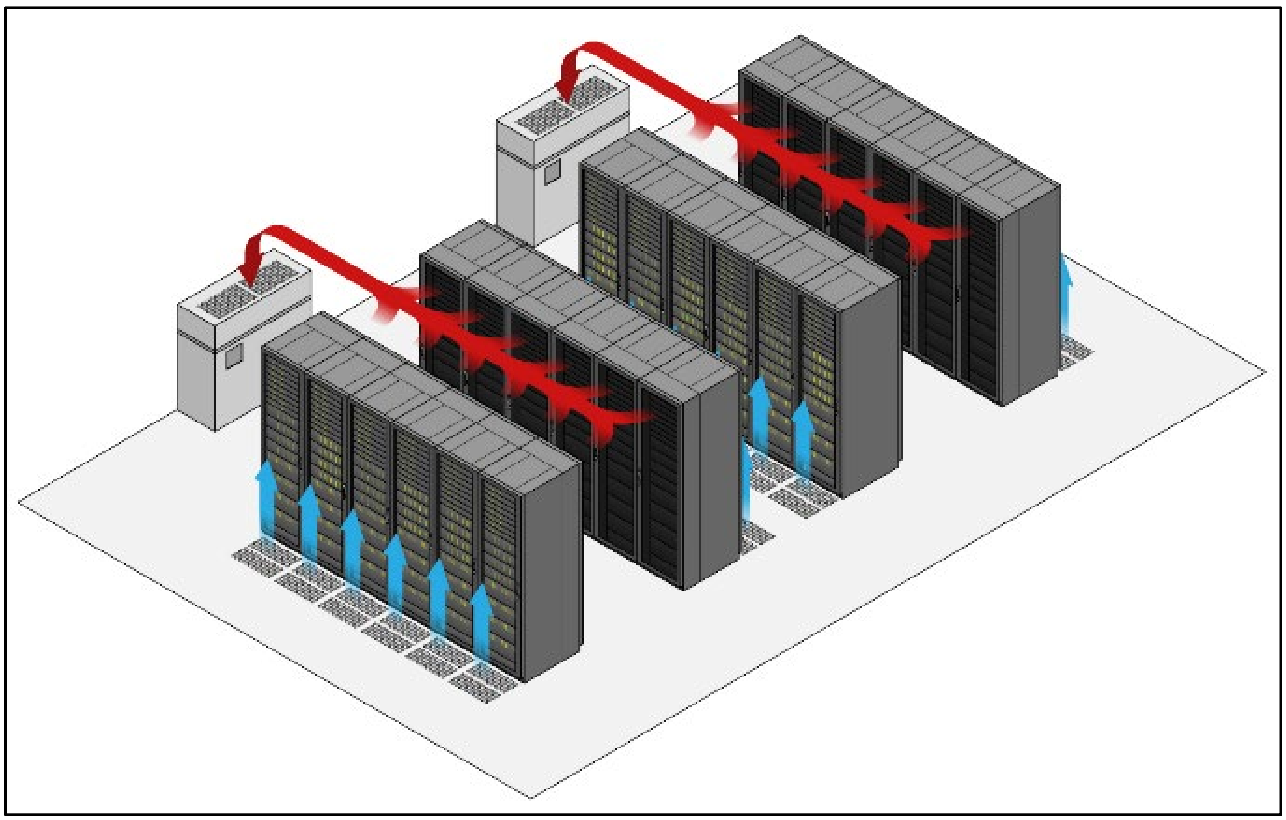
Early data centers cooled the entire room, intending that enough cold air and sufficient mixing would keep equipment in acceptable condition. As power density increased, that assumption became less reliable.

Raised-floor systems improved delivery by bringing cold air closer to the equipment, but they still depended heavily on room-level mixing and average space conditions.

Rack-mounted servers exposed the weakness of that approach: some racks received excess cold air while others developed hot spots. The solution was a hot-aisle/cold-aisle design that separated supply and exhaust air, creating a defined path from the cooling unit to the load and back.

That shift—from mixing the room to controlling the air path—is the relevant lesson for CEA. Direct-to-canopy applies the same logic to vertical farms: supply dry conditioned air directly to the canopy, prevent unnecessary dilution, and use the air leaving the canopy as the meaningful reference for design and control before returning to the CH&D unit.

Figure 6-Hot / Cold Aisle Strategy for Data Centers



Canopy-Level Microclimates - A Distributed Mass Transfer Process

In a direct-to-canopy system, the driest air produced by the conditioning, heating, and dehumidification (CH&D) unit is delivered directly and uniformly perpendicular to the crop canopy rather than being mixed into the room first. As this air enters the foliage, it immediately disrupts the humid boundary layers that naturally form around leaves, exposing them to air with a substantially lower vapor pressure. This creates a strong local driving force for transpiration and moisture removal where it is needed most: the leaf surface.

A common concern is that the air gradually becomes wetter as it absorbs moisture from the crop, thereby reducing its ability to support downstream transpiration. This concern is valid when air follows a long horizontal path through the canopy. However, when dry air is distributed uniformly across the entire crop surface and allowed to escape horizontally after passing through the foliage, the airflow behaves very differently. Rather than a single continuous stream becoming progressively saturated, many small airflow pathways operate simultaneously throughout the crop.

Each local region of the canopy receives freshly conditioned air directly from the supply system. The air absorbs moisture from nearby leaves over a relatively short travel distance before moving toward the return path. As a result, moisture loading is localized, and the increase in humidity ratio along any individual airflow path remains limited. The canopy effectively functions as thousands of parallel heat- and mass-transfer zones, each independently exchanging heat and moisture with the passing air.

In this arrangement, the moving air acts as a transport mechanism, continuously carrying transpired water vapor away from the foliage and toward the CH&D unit. The objective is not to keep the air unchanged as it passes through the crop, but rather to ensure that it remains sufficiently below leaf-surface vapor pressure throughout its path to sustain healthy transpiration. The gradual increase in humidity ratio is therefore evidence that useful moisture is being removed.

Viewed this way, the crop canopy becomes an active component of the dehumidification system rather than merely an occupant of the conditioned space. The canopy extracts the available latent capacity from the incoming air, while the CH&D unit removes the collected moisture and restores the air's drying potential. By directly coupling the foliage to the dehumidification process, direct-to-canopy airflow promotes more uniform microclimatic conditions, improves heat and mass transfer at the leaf surface, and may allow the facility to achieve superior crop conditions without requiring uniformly low humidity throughout the entire room.

Plants live by diffusion. Water vapor leaves the leaf, and CO_2 enters the leaf because concentration differences exist. Fick's Law states that the rate of this exchange depends on the gradient and the resistance between the leaf and the surrounding air. Direct-to-canopy air distribution improves plant performance by reducing resistance and maintaining gradients where they matter most—directly at the leaf surface. Also, CO_2 may be introduced into the CH&D unit and uniformly distributed with dry air.

> *With a direct-to-canopy approach, field adjustments and fine-tuning are reduced to canopy-level air-volume adjustments.*

Conclusion

Table 6 compares the practical engineering implications of the two air distribution choices.

Table 6-Engineering Comparison of Direct-to-Canopy and Room-Mixed Air Delivery

Performance Outcome	Direct to Canopy	Room Mixed	Basis / Reason
Can be engineered to meet a specified canopy-leaving air condition	✓	✓	A room-mixed strategy can be designed to meet the same canopy-leaving humidity and temperature targets by increasing the air volume.
Can remove the specified latent load	✓	✓	A room-mixed strategy can be designed to meet the latent load by increasing the tonnage.
Produces crops when properly designed and commissioned	✓	✓	Room-mixed systems can produce crops; the distinction lies in the crops' quality and uniformity.
Reduces individual rack-level canopy microclimates	✓	✓	Using local canopy-level air distribution, both systems can reduce individual rack-level microclimates.
Reduces canopy-level microclimates for the entire crop in a room	✓		With the room-mixed air system, each rack can experience varying degrees of mixing, leading to different crop outcomes.
Reduces system tonnage	✓		The direct-to-canopy system reduces tonnage by 36%, compared with the room-mixed system.
Reduces airflow volume	✓		The direct-to-canopy system reduces air volume by 49% compared with the room-mixed system.
Provides a reliable strategy for system control	✓		The direct-to-canopy system provides a uniform, well-defined air path, making measurement and commissioning more reliable.
Delivers the driest air directly to the canopy	✓		The direct-to-canopy system delivers dry, conditioned air uniformly to the canopy air path.
Reduces dilution between the CH&D supply air and the canopy	✓		Room-mixed delivery intentionally blends supply air with the room before it reaches the crop; Direct-to-canopy shortens that path.

Checkmarks indicate outcomes each strategy can reasonably support when properly engineered.
Blank cells do not mean the outcome is impossible; they indicate that the comparison shows a stronger or more direct advantage for the other strategy.

The engineering comparisons in Table 6 shows that direct-to-canopy air delivery is more than an alternate duct arrangement; it is a different design framework for canopy-dominated environments. By connecting the CH&D unit directly to the crop canopy and distributing its air uniformly, the system delivers conditioned air where heat and moisture are generated, uses canopy-leaving air as the control reference, and reduces the uncertainty created when the room serves as the primary mixing chamber.

In room-mixed systems, it has been unofficially reported that aiming dry CH&D supply airflow toward the canopy can improve crop and equipment performance. When that air is intentionally aimed at the crop, however, the design is no longer purely room-mixed; it becomes a hybrid that partially couples CH&D discharge to the canopy air path—making direct-to-canopy delivery the logical next step.

The analysis demonstrates a clear engineering and economic consequence: to achieve the same canopy-leaving condition, the room-mixed case requires approximately 12,174 CFM and 47 tons of CH&D capacity. In comparison, the direct-to-canopy strategy requires approximately 6,212 CFM and 30 tons. That represents a 36% reduction in calculated CH&D capacity and a 49% reduction in required air volume, before accounting for additional savings from reduced ancillary fan energy, fan equipment, noise, maintenance, and room-mixing complexity. These values are derived from the representative design example presented in this paper and should not be interpreted as universal savings for all facilities. Actual savings can be greater or less, depending on the degree of room mixing.

The broader implication is that CEA air distribution should be designed around the crop's actual psychrometric process rather than a room-average condition that may conceal local microclimates. Room-mixed systems can grow crops, but they remain indirect, dilution-dependent, and difficult to measure at the point where plant responses occur. Direct-to-canopy design provides a clearer, more measurable, and potentially lower-cost path to uniform canopy climate control.

Design Implications and Future Work

Future work should validate direct-to-canopy performance under representative crop densities, lighting loads, airflow rates, rack layouts, and production cycles. The most useful studies should compare room-mixed and direct-to-canopy systems by measuring canopy-entering and canopy-leaving temperature, vapor pressure, air velocity, crop uniformity, energy use, and commissioning requirements.

In practical design terms, growers should explicitly define humidity and temperature targets as canopy-leaving conditions and understand how those conditions differ from those of the canopy-entering air. In room-mixed systems, room air and canopy-entering air are essentially the same, so the engineer must translate the grower's canopy-leaving target into the required canopy-entering air condition.

The remaining implementation question is local canopy airflow. CH&D airflow alone may be sufficient, while adjustable bypass air, as shown in Figure 4, can help commissioning and crop trials identify crop-specific air-volume targets that vary by crop type and outlet-to-canopy distance.

Figure 7-VPD Calculating Table

Controlled Environment Agriculture (CEA)

By: Walter Stark Consulting

VAPOR PRESSURE TABLE

ROOM OR LEAF °F	ROOM RELATIVE HUMIDITY %																															LEAF %	ROOM OR LEAF °F
	40%	41%	42%	43%	44%	45%	46%	47%	48%	49%	50%	51%	52%	53%	54%	55%	56%	57%	58%	59%	60%	61%	62%	63%	64%	65%	66%	67%	68%	69%	70%	100%	
	VAPOR PRESSURE kPa																																
95	2.25	2.31	2.36	2.42	2.48	2.53	2.59	2.65	2.70	2.76	2.81	2.87	2.93	2.98	3.04	3.10	3.15	3.21	3.26	3.32	3.38	3.43	3.49	3.55	3.60	3.66	3.71	3.77	3.83	3.88	3.94	5.63	95
94	2.18	2.24	2.29	2.35	2.40	2.46	2.51	2.56	2.62	2.67	2.73	2.78	2.84	2.89	2.95	3.00	3.06	3.11	3.17	3.22	3.27	3.33	3.38	3.44	3.49	3.55	3.60	3.66	3.71	3.77	3.82	5.46	94
93	2.12	2.17	2.22	2.28	2.33	2.38	2.43	2.49	2.54	2.59	2.65	2.70	2.75	2.80	2.86	2.91	2.96	3.02	3.07	3.12	3.17	3.23	3.28	3.33	3.39	3.44	3.49	3.54	3.60	3.65	3.70	5.29	93
92	2.05	2.10	2.15	2.21	2.26	2.31	2.36	2.41	2.46	2.51	2.56	2.62	2.67	2.72	2.77	2.82	2.87	2.92	2.97	3.03	3.08	3.13	3.18	3.23	3.28	3.33	3.39	3.44	3.49	3.54	3.59	5.13	92
91	1.99	2.04	2.09	2.14	2.19	2.24	2.29	2.34	2.39	2.44	2.49	2.54	2.59	2.64	2.68	2.73	2.78	2.83	2.88	2.93	2.98	3.03	3.08	3.13	3.18	3.23	3.28	3.33	3.38	3.43	3.48	4.97	91
90	1.93	1.98	2.02	2.07	2.12	2.17	2.22	2.26	2.31	2.36	2.41	2.46	2.51	2.55	2.60	2.65	2.70	2.75	2.79	2.84	2.89	2.94	2.99	3.04	3.08	3.13	3.18	3.23	3.28	3.32	3.37	4.82	90
89	1.87	1.91	1.96	2.01	2.05	2.10	2.15	2.19	2.24	2.29	2.33	2.38	2.43	2.47	2.52	2.57	2.61	2.66	2.71	2.76	2.80	2.85	2.90	2.94	2.99	3.04	3.08	3.13	3.18	3.22	3.27	4.67	89
88	1.81	1.86	1.90	1.95	1.99	2.04	2.08	2.13	2.17	2.22	2.26	2.31	2.35	2.40	2.44	2.49	2.53	2.58	2.62	2.67	2.71	2.76	2.81	2.85	2.90	2.94	2.99	3.03	3.08	3.12	3.17	4.52	88
87	1.75	1.80	1.84	1.88	1.93	1.97	2.02	2.06	2.10	2.15	2.19	2.24	2.28	2.32	2.37	2.41	2.45	2.50	2.54	2.59	2.63	2.67	2.72	2.76	2.81	2.85	2.89	2.94	2.98	3.02	3.07	4.38	87
86	1.70	1.74	1.78	1.83	1.87	1.91	1.95	2.00	2.04	2.08	2.12	2.17	2.21	2.25	2.29	2.34	2.38	2.42	2.46	2.51	2.55	2.59	2.63	2.67	2.72	2.76	2.80	2.84	2.89	2.93	2.97	4.25	86
85	1.64	1.69	1.73	1.77	1.81	1.85	1.89	1.93	1.97	2.02	2.06	2.10	2.14	2.18	2.22	2.26	2.30	2.34	2.39	2.43	2.47	2.51	2.55	2.59	2.63	2.67	2.71	2.76	2.80	2.84	2.88	4.11	85
84	1.59	1.63	1.67	1.71	1.75	1.79	1.83	1.87	1.91	1.95	1.99	2.03	2.07	2.11	2.15	2.19	2.23	2.27	2.31	2.35	2.39	2.43	2.47	2.51	2.55	2.59	2.63	2.67	2.71	2.75	2.79	3.98	84
83	1.54	1.58	1.62	1.66	1.70	1.74	1.77	1.81	1.85	1.89	1.93	1.97	2.01	2.04	2.08	2.12	2.16	2.20	2.24	2.28	2.31	2.35	2.39	2.43	2.47	2.51	2.55	2.58	2.62	2.66	2.70	3.86	83
82	1.49	1.53	1.57	1.61	1.64	1.68	1.72	1.75	1.79	1.83	1.87	1.90	1.94	1.98	2.02	2.05	2.09	2.13	2.17	2.20	2.24	2.28	2.31	2.35	2.39	2.43	2.46	2.50	2.54	2.58	2.61	3.73	82
81	1.45	1.48	1.52	1.55	1.59	1.63	1.66	1.70	1.73	1.77	1.81	1.84	1.88	1.92	1.95	1.99	2.02	2.06	2.10	2.13	2.17	2.20	2.24	2.28	2.31	2.35	2.39	2.42	2.46	2.49	2.53	3.61	81
80	1.40	1.43	1.47	1.50	1.54	1.57	1.61	1.64	1.68	1.71	1.75	1.78	1.82	1.85	1.89	1.92	1.96	1.99	2.03	2.06	2.10	2.13	2.17	2.20	2.24	2.27	2.31	2.34	2.38	2.41	2.45	3.50	80
79	1.35	1.39	1.42	1.46	1.49	1.52	1.56	1.59	1.62	1.66	1.69	1.73	1.76	1.79	1.83	1.86	1.90	1.93	1.96	2.00	2.03	2.07	2.10	2.13	2.17	2.20	2.23	2.27	2.30	2.34	2.37	3.39	79
78	1.31	1.34	1.38	1.41	1.44	1.47	1.51	1.54	1.57	1.61	1.64	1.67	1.70	1.74	1.77	1.80	1.83	1.87	1.90	1.93	1.97	2.00	2.03	2.06	2.10	2.13	2.16	2.19	2.23	2.26	2.29	3.28	78
77	1.27	1.30	1.33	1.36	1.39	1.43	1.46	1.49	1.52	1.55	1.58	1.62	1.65	1.68	1.71	1.74	1.77	1.81	1.84	1.87	1.90	1.93	1.96	2.00	2.03	2.06	2.09	2.12	2.16	2.19	2.22	3.17	77
76	1.23	1.26	1.29	1.32	1.35	1.38	1.41	1.44	1.47	1.50	1.53	1.56	1.59	1.62	1.66	1.69	1.72	1.75	1.78	1.81	1.84	1.87	1.90	1.93	1.96	1.99	2.02	2.05	2.08	2.12	2.15	3.07	76
75	1.19	1.22	1.25	1.28	1.30	1.33	1.36	1.39	1.42	1.45	1.48	1.51	1.54	1.57	1.60	1.63	1.66	1.69	1.72	1.75	1.78	1.81	1.84	1.87	1.90	1.93	1.96	1.99	2.02	2.05	2.08	2.97	75
74	1.15	1.18	1.20	1.23	1.26	1.29	1.32	1.35	1.38	1.41	1.43	1.46	1.49	1.52	1.55	1.58	1.61	1.63	1.66	1.69	1.72	1.75	1.78	1.81	1.84	1.86	1.89	1.92	1.95	1.98	2.01	2.87	74
73	1.11	1.14	1.16	1.19	1.22	1.25	1.28	1.30	1.33	1.36	1.39	1.41	1.44	1.47	1.50	1.53	1.55	1.58	1.61	1.64	1.66	1.69	1.72	1.75	1.77	1.80	1.83	1.86	1.89	1.91	1.94	2.77	73
72	1.07	1.10	1.13	1.15	1.18	1.21	1.23	1.26	1.29	1.31	1.34	1.37	1.39	1.42	1.45	1.47	1.50	1.53	1.55	1.58	1.61	1.64	1.66	1.69	1.72	1.74	1.77	1.80	1.82	1.85	1.88	2.68	72
71	1.04	1.06	1.09	1.11	1.14	1.17	1.19	1.22	1.24	1.27	1.30	1.32	1.35	1.37	1.40	1.43	1.45	1.48	1.50	1.53	1.55	1.58	1.61	1.63	1.66	1.68	1.71	1.74	1.76	1.79	1.81	2.59	71
70	1.00	1.03	1.05	1.08	1.10	1.13	1.15	1.18	1.20	1.23	1.25	1.28	1.30	1.33	1.35	1.38	1.40	1.43	1.45	1.48	1.50	1.53	1.55	1.58	1.60	1.63	1.65	1.68	1.70	1.73	1.75	2.50	70
69	0.97	0.99	1.02	1.04	1.07	1.09	1.11	1.14	1.16	1.19	1.21	1.23	1.26	1.28	1.31	1.33	1.36	1.38	1.40	1.43	1.45	1.48	1.50	1.52	1.55	1.57	1.60	1.62	1.65	1.67	1.69	2.42	69
68	0.94	0.96	0.98	1.01	1.03	1.05	1.08	1.10	1.12	1.15	1.17	1.19	1.22	1.24	1.26	1.29	1.31	1.33	1.36	1.38	1.40	1.43	1.45	1.47	1.50	1.52	1.54	1.57	1.59	1.61	1.64	2.34	68
67	0.90	0.93	0.95	0.97	0.99	1.02	1.04	1.06	1.08	1.11	1.13	1.15	1.17	1.20	1.22	1.24	1.27	1.29	1.31	1.33	1.36	1.38	1.40	1.42	1.45	1.47	1.49	1.51	1.54	1.56	1.58	2.26	67
66	0.87	0.89	0.92	0.94	0.96	0.98	1.00	1.03	1.05	1.07	1.09	1.11	1.13	1.16	1.18	1.20	1.22	1.24	1.27	1.29	1.31	1.33	1.35	1.38	1.40	1.42	1.44	1.46	1.48	1.51	1.53	2.18	66
65	0.84	0.86	0.89	0.91	0.93	0.95	0.97	0.99	1.01	1.03	1.05	1.08	1.10	1.12	1.14	1.16	1.18	1.20	1.22	1.24	1.26	1.29	1.31	1.33	1.35	1.37	1.39	1.41	1.43	1.45	1.48	2.11	65

1. **Using the canopy-leaving air conditions, select the cell where the humidity and temperature converge. (Example: 80°F/60% converge at 2.10 kPa, canopy vapor pressure).**

2. **Select the leaf vapor pressure in the 100% RH column, using the measured or anticipated LST. (Example: for an LST of 82°F, the leaf VP is 3.73 kPa; for bulk VPD, the LST is 80°F, and the leaf VP is 3.50.)**

3. **Subtract the canopy VP from the leaf VP to obtain the VPD (Example: VPD = 3.73 – 2.10 = 1.63 kPa; For Bulk VPD 3.50 – 2.10 = 1.40 kPa.)**