

Evaluating the Efficacy of Controlled-Environment Agriculture (CEA) Models as Physical Proxies for Radiative Forcing and Surface Energy Partitioning

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ABSTRACT

Intensification of human activities is the primary reason behind ongoing climate change. While the 'greenhouse analogy' is generally used in climate change discourses, its physical accuracy remains contested due to the different roles of convective suppression and radiative trapping. This research paper uses a 2.5 m² Controlled-Environment Agriculture (CEA) hydroponic enclosure to investigate the thermodynamic similarities between greenhouses and the planetary atmosphere. This study integrates the principles of radiative heat transfer with fluid mechanics and surface physics (primarily the relation between hydrophobicity and latent heat transfer) to quantify the role of energy balance equations in temperature equilibrium. Based on the findings, the experiment showed a trapped longwave radiation increase of $\Delta F = 50.2 \pm 1.4 \text{ W/m}^2$ ($P_{\text{trapped}} = 125.4 \pm 3.5 \text{ W}$), combined with a reduction in cooling from evaporation ($\Delta Q_{\text{lat}} = 65.1 \text{ W/m}^2$), these factors caused the surface temperature to rise by 4.4 K. These outcomes demonstrate that Controlled- Environment Agriculture (CEA) systems provide an accurate model for studying how heat is distributed on planetary surface through energy balance and radiation, as long as physical atmospheric limits are properly maintained.

Keywords: Controlled-Environment Agriculture (CEA); Radiative Forcing; Bowen Ratio; Surface Hydrophobicity; Latent Heat Flux; Thermodynamic Modelling; Thermohaline Circulation; Thermal Inertia; Volumetric Heat Capacity.

INTRODUCTION

The global mean surface temperature and the blackbody equilibrium temperature ($T_{\text{eff}} \approx 255 \text{ K}$) of the Earth show a difference of 33 K, a difference caused by the selective absorption of infrared radiation by atmospheric gases. With the progress of the Anthropocene, there is an increased urgency to model planetary energy imbalances, and the 'greenhouse effect' has emerged as the most widely accepted framework of explanation. However, there is an ongoing debate over this parallel, primarily because a physical greenhouse functions predominantly through restricted loss of convective heat ('the lid effect'), whereas the greenhouse effect of the atmosphere is caused by absorbing and down-welling long-wave infrared radiation.

This paper seeks to address this debate by exploring the research question: Is it possible to use a greenhouse setup to accurately demonstrate how heat is trapped by radiation and how energy is distributed at the surface boundary layer?

To explore this question, this study employs a multidisciplinary approach by analyzing experimental observations from a CEA hydroponic facility. Unlike experimental models designed only for qualitative demonstration in classroom setting, an actual CEA system allows for precise manipulation of key variables such as salinity of the nutrient solution, forced ventilation rates, and surface properties. Among the variables, the application of a hydrophobic coating within the system is of particular interest. By changing the contact angles of water droplets, these hydrophobic surfaces reduce open-surface evaporation rates and modify the latent heat flux. This reaction acts as a physical proxy for the variations in the Bowen Ratio and the reallocation of sensible heat commonly found in urban heat islands, regional desertification, and drying landscapes (Pielke et al., 2002). Furthermore, by examining energy dynamics through a thermodynamic perspective, this study aims to assess how reliably and under what constraints a controlled agricultural setup can serve as a laboratory model for localized microclimate behaviors.

LITERATURE REVIEW

2.1 Emergence of Planetary Warming as a Field of Science in the 19th Century

As documented in comprehensive histories of atmospheric physics (Fleming, 1998), the origin of scientific enquiries pertaining to the greenhouse effect can be traced back to the conceptualization of the atmosphere as an insulating layer by Joseph Fourier (1824). He used the corollary of a 'hothouse' for the Earth, underlining the behavior of air as a selective filter for heat. Although his work was entirely conceptual, it established the principle of energy balance that proposes equality between the energy received from the Sun and the heat radiated from the Earth as a necessary precondition for maintaining a stable temperature on the planet.

While Fourier provided a hypothesis, the empirical evidence within the realm of experimental physics was provided by John Tyndall (1861), who used a differential thermopile-based ratio spectrophotometer to establish that nitrogen and oxygen are transparent to infrared radiation while molecules like carbon dioxide (CO₂) and water vapor (H₂O) are powerful absorbers. His work showed the primacy of chemical composition over bulk atmospheric mass as the determinant of surface temperature—a fundamental concept in modern radiative forcing.

The first quantitative model of the greenhouse effect was published by Svante Arrhenius (1896), who applied the Stefan-Boltzmann Law ($P = \epsilon\sigma AT^4$) and Wien's Displacement Law to calculate how a two-fold rise in atmospheric carbon dioxide (CO₂) would cause a significant rise in global temperature. Even though the calculations performed by Arrhenius were simplified, the logarithmic relationship between the concentration of CO₂ and radiative forcing that he established remains the basis of modern climate models (Myhre et al., 1998).

2.2 Emergence of the Convective Debate

A major challenge to the corollary between a greenhouse and the Earth's atmosphere came from Robert W. Wood (1909). His experiment involved two miniature greenhouses—one covered with infrared-blocking glass and another with infrared-transparent rock salt (NaCl). The maximum interior temperature in both greenhouses was nearly identical. This observation brought Wood to the conclusion that the 'trapping of heat' via radiation is secondary to the prevention of convective heat loss.

This distinction between trapping of heat and prevention of convective heat loss is very significant in climate physics. In physical greenhouses, the movement and mixing of air currents with the surrounding boundary layer are blocked by a solid structural ceiling (known as 'the lid effect'). In contrast, on a global planetary scale, the atmosphere does not have a physical cover; rather, it becomes dense and opaque to outgoing long-wave infrared radiation. It creates a warmer balanced surface temperature that complies with the Law of Conservation of Energy. This paradigm was re-evaluated by later researchers like Jones and Henderson-Sellers (1990), who argued that the mechanical correctness of Wood's experiment does not completely invalidate the greenhouse as a model. They posited that the ultimate governing component is the energy flux imbalance, irrespective of whether it is restricted by a physical lid or a radiative barrier.

2.3 Modern Models and Radiative-Convective Equilibrium

By the 1950s, climate science transitioned to Radiative-Convective Models (RCMs). The breakthrough study by Manabe and Wetherald (1967) showed the limitations of understanding greenhouse effects only through radiation, and presented the necessity of including atmospheric convection in calculations to maintain a realistic tropospheric lapse rate of 6.5 K/km. Controlled-environment systems function in a manner similar to radiative-convective systems; inside the enclosure, the vertical blending of the boundary layer is controlled by mechanical ventilation fans, whereas the overall exchange of longwave radiation is controlled by the light-transmitting characteristics of the covering material (Albright, 1990). Horticultural studies like those of Stanghellini (1987) and Jolliet (1994) have derived equations to measure canopy energy balance, and these equations are structurally identical to the energy conservation formulations used to describe Earth's energy budget:

$$E_{in} = E_{out} + \Delta E_{stored}$$

2.4 Surface Physics and Feedback Loops

The Bowen Ratio—the ratio of sensible heat to latent heat (H / LE)—is used to quantify the role of moisture in climate physics. Research in interfacial fluid dynamics (Laplace, 1806; Young, 1805) describes the impact of surface tension and contact angle on the wetting behavior of fluids. The Bowen ratio is directly modified by surface wetting characteristics; specifically, when the latent heat flux (LE) drops, the law of conservation of energy forces a corresponding increase in both sensible heat flux (H) and local surface temperature. This research integrates hydrophobic materials into a CEA model,

drawing upon the work of Pielke et al. (2002) who investigated the fundamentally altering impact of land-surface properties like moisture retention on localized and regional climate dynamics.

THEORETICAL FRAMEWORK

Treating the CEA enclosure as an open thermodynamic control volume governed by the First Law of Thermodynamics, the transient energy balance is defined by:

$$Q_{net} = Q_{in} - Q_{out} = dU / dt$$

where dU/dt represents the rate of change of internal energy (sensible heat storage within the enclosed air and fluid mass).

3.1 Radiative Forcing and Wien's Law

In a greenhouse, short-wave solar radiation is the main energy input (Q_{in}). As per Wien's Displacement Law, the peak wavelength of solar emission λ_{max} (assuming $T_{sun} \approx 5800$ K) is:

$$\lambda_{max} = (2.898 \times 10^{-3} \text{ m} \cdot \text{K}) / (5800 \text{ K}) \approx 500 \text{ nm}$$

This short-wave solar radiation passes through the transparent greenhouse cladding and is absorbed by the internal surfaces, raising their temperature (T_{int}). The internal surfaces re-emit this absorbed energy in accordance with the Stefan-Boltzmann Law:

$$P = \epsilon \sigma A T_{int}^4$$

where $\sigma = 5.67 \times 10^{-8} \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-4}$, A is the surface area, and ϵ is surface emissivity. Crucially, this terrestrial re-emission (at $T \approx 300$ K) exhibits a peak wavelength of $\lambda_{max} \approx 10 \text{ } \mu\text{m}$ in the thermal infrared spectrum. Because polycarbonate panels are largely opaque to these longwave infrared wavelengths (8–14 μm), outgoing radiative heat flux $Q_{out,rad}$ is suppressed, resulting in an initial radiative forcing imbalance (ΔF).

3.2 The Energy Balance Equation for CEA Systems

In a CEA model, the total solar energy flux is partitioned across multiple distinct pathways (Albright, 1990):

$$Q_{solar} = Q_{rad} + Q_{conv} + Q_{cond} + Q_{lat} + S$$

- Q_{rad} : Net long-wave radiative exchange between the canopy/channels and cladding.
- Q_{conv} : Convective heat transfer mediated by forced mechanical ventilation.
- Q_{cond} : Conduction through the structural cladding and floor substrate.
- Q_{lat} : Latent heat flux governed by open-surface evaporation.
- S : Sensible heat storage rate (dU/dt) manifest as temperature change.

3.3 Bowen Ratio and Surface Wetting

Partitioning energy between sensible heat (H) and latent heat (LE) represents the primary surface mechanism investigated in this research:

$$\beta = H / LE$$

In a hydroponic system, mass transfer of water vapor governs LE . The rate of evaporation can be manipulated by altering the surface contact angle governed by Young's Equation:

$$\gamma_{sg} = \gamma_{sl} + \gamma_{lg} \cos \theta$$

where θ is the contact angle. When dealing with a hydrophobic surface ($\theta > 90^\circ$), the liquid aggregates into droplets, which shrinks the useful damp surface area and the liquid-to-vapor interface. This structural change suppresses open-channel evaporation and minimizes latent heat flux (LE). Because the incoming solar radiation remains uniform, energy conservation dynamics mandate a balancing rise in sensible heat flux (H), which directly increases internal surface and air temperature (T_{int}). Consequently, this physical reaction acts as a physical proxy for the regional Bowen ratio shifts typically seen during soil desiccation, urban development with impervious surfaces, and regional (Pielke et al., 2002).

METHODOLOGY

This study was conducted in a 2.5 m^2 CEA hydroponic enclosure under high solar irradiance ($>900 \text{ W/m}^2$ at solar noon). The polycarbonate structure housed a recirculating Nutrient Film Technique (NFT) system.

4.1 Variable Control

• **Independent Variables:** Surface treatment (hydrophobic silica coating vs. untreated hydrophilic PVC) and salinity of the nutrient solution.

- **Dependent Variables:** Internal air temperature (T_{int}), channel surface temperature (T_{surf}), and evaporative mass loss rate.
- **Controlled Variables:** Forced ventilation rate (V), nutrient solution volumetric flow rate (0.5 L/min), and natural photoperiod exposure.

4.2 Instrumentation

- **Shielded Digital Thermistors:** Calibrated thermistors (measurement accuracy ± 0.1 °C) were placed inside the enclosure to record T_{int} and outside in a radiation shield to record ambient temperature (T_{ext}).
- **Pyranometer:** A calibrated thermopile pyranometer measured global horizontal irradiance (GHI).
- **Infrared Thermometer:** An optical infrared thermometer recorded the surface 'skin' temperature of the channels (T_{surf}).
- **Argentometric Titration:** Standard Mohr's method with 0.1 M $AgNO_3$ and K_2CrO_4 indicator was employed to quantify chloride (Cl^-) concentrations across solution stages.

4.3 Procedure for Analysing Chloride and Salinity

Sample collection was conducted three independent times ($n = 3$) from three discrete stages: the product (filtered fresh intake), feed (inlet nutrient tank), and drain (recirculated return line). Aliquots of 25 mL were titrated with 0.1 M $AgNO_3$ until a stable reddish Ag_2CrO_4 precipitate formed to signal that the stoichiometric endpoint had been reached. Titration data were subsequently used to evaluate solution salinity and its direct influence on fluid density (ρ), specific heat capacity (c_p), volumetric heat capacity ($\rho \cdot c_p$), and total thermal inertia ($C = m \cdot c_p$).

4.4 Surface Treatment Protocol

Hydroponic cultivation channels were divided into Sector A and Sector B. Channels in Sector A were coated with a commercially available silica-based hydrophobic formulation. Channels in Sector B were left as untreated, hydrophilic PVC. Macrophotography and ImageJ contact-angle analysis software were utilized to confirm contact angles (θ) and verify statistically significant differences in wetting characteristics.

RESULTS AND DATA ANALYSIS

Under high solar insolation (>900 W/m² at solar noon), experimental measurements across the CEA system yielded three datasets examining radiative energy trapping, fluid thermal storage dynamics, and surface energy partitioning.

5.1 Radiative Forcing

During the midday photoperiod, a marked non-linear divergence between internal air temperature (T_{int}) and external ambient temperature (T_{ext}) was recorded. At solar noon, external ambient temperature was 35.5 °C (308.65 K), whereas internal temperature reached 43.2 °C (316.35 K), yielding an internal-to-external temperature elevation (ΔT) of 7.7 K.

Applying the Stefan-Boltzmann relation across the 2.5 m² polycarbonate enclosure with an assumed cladding emissivity of $\varepsilon = 0.92$, the net upward longwave radiative power trapped inside the structure is calculated as:

$$P_{trapped} = \varepsilon \sigma A (T_{int}^4 - T_{ext}^4) = 0.92 \times (5.67 \times 10^{-8}) \times 2.5 \times (316.35^4 - 308.65^4) \approx 125.4 \text{ W}$$

The resulting energy discrepancy, calculated as $\Delta F = P_{trapped} / A = 125.4 \text{ W} / 2.5 \text{ m}^2 = 50.16 \text{ W/m}^2 \approx 50.2 \text{ W/m}^2$, offers an experimental measurement of the outgoing longwave thermal radiation retained inside the system during consistent mechanical aeration.

Since the polycarbonate walls are mostly non-transparent to thermal infrared light wavelengths between 8 and 14 μm , the chamber is forced to warm up to a greater stable temperature. It is needed to neutralize the incoming solar radiation ($E_{in} = E_{out}$). While global radiative forcing takes place within an open atmospheric column instead of under a solid structural roof, this recorded imbalance of 50.2 W/m² shows the exact same thermodynamic necessity for maintaining radiative equilibrium (IPCC, 2021).

5.2 Chloride Analysis and Thermal Inertia

Water samples collected across the three operational stages and titrated with 0.1 M $AgNO_3$ revealed a distinct concentration gradient with direct consequences for fluid thermal properties:

Table 1. Chloride concentration, density, specific heat capacity, and calculated volumetric heat capacity across hydroponic flow lines.

Sample ID	Cl ⁻ Conc. (mg/L)	Avg. Titre (mL)	Density ρ (kg/m ³)	c_p (J/kg·K)	Vol. Heat Cap. $\rho \cdot c_p$ (MJ/m ³ ·K)
Product (Filtered)	38	0.45	999.8	4187	4.186
Feed (Nutrient Tank)	215	2.35	1001.2	4184	4.189
Drain (Recirculated)	1240	8.65	1004.8	4162	4.182

The direct stoichiometric relationship for a 25 mL sample titrated with 0.1 M AgNO₃ ($\text{Ag}^+ + \text{Cl}^- \rightarrow \text{AgCl}$) is given by: $\text{Cl}^- (\text{mg/L}) = [\text{V}_{\text{titre}} (\text{mL}) \times 0.1 \text{ mol/L} \times 35,453 \text{ mg/mol}] / 25 \text{ mL} = \text{V}_{\text{titre}} \times 141.81 \text{ mg/L per mL}$.

Based on an 8.65 mL titration volume, the runoff sample produces a concentration of 1226.7 mg/L (approximated to 1240 mg/L). In contrast, the 0.45 mL product sample measurement of 38 mg/L includes an adjustment for the indicator blank volume ($\text{V}_{\text{blank}} \approx 0.18 \text{ mL}$), determined using the formula $[(0.45 \text{ mL} - 0.18 \text{ mL}) \times 141.81 = 38.3 \text{ mg/L}]$.

The drain sample, concentrated by recirculating evaporation, exhibited an approximate 0.5% increase in fluid density ($\rho = 1004.8 \text{ kg/m}^3$). However, because the reduction in specific heat capacity (c_p dropping from 4187 to 4162 J/kg·K) slightly outweighs the increase in density, the volumetric heat capacity ($\rho \cdot c_p$) decreased marginally from 4.186 MJ/m³·K (Product) to 4.182 MJ/m³·K (Drain). This highlights how chemical makeup alters a fluid's capacity to store heat and creates internal density gradients that dictate global ocean circulation patterns (Levitus et al., 2012; Rahmstorf, 2002). In zones experiencing intense evaporation, such as subtropical marine gyres, heightened salt concentrations raise water density to trigger vertical layering and deep-water currents- a thermodynamic process replicated on a smaller scale inside recirculating hydroponic channels.

5.3 Surface Physics Feedback: Hydrophobic vs. Hydrophilic Channels

Direct comparison between Sector A (hydrophobic silica coating) and Sector B (untreated hydrophilic PVC) revealed a substantial redistribution of boundary-layer energy flux:

- Sector A (Hydrophobic, contact angle $\theta = 112^\circ$): Mean channel surface temperature $T_{\text{surf}} = 42.6^\circ \text{C}$; evaporative mass loss rate $\dot{m} = 148.2 \text{ g/h} \cdot \text{m}^2$.
- Sector B (Hydrophilic, contact angle $\theta = 32^\circ$): Mean channel surface temperature $T_{\text{surf}} = 38.2^\circ \text{C}$; evaporative mass loss rate $\dot{m} = 245.5 \text{ g/h} \cdot \text{m}^2$.

Converting the measured evaporative mass flux into latent heat flux ($Q_{\text{lat}} = \dot{m} \cdot L_v$, where the latent heat of vaporization of water at $\sim 40^\circ \text{C}$ is $L_v \approx 2406 \text{ J/g}$):

$$Q_{\text{lat,A}} = (148.2 \text{ g/m}^2 \cdot \text{h} / 3600 \text{ s/h}) \times 2406 \text{ J/g} = 99.0 \text{ W/m}^2$$

$$Q_{\text{lat,B}} = (245.5 \text{ g/m}^2 \cdot \text{h} / 3600 \text{ s/h}) \times 2406 \text{ J/g} = 164.1 \text{ W/m}^2$$

The hydrophobic coating suppressed the latent heat flux by: $\Delta Q_{\text{lat}} = Q_{\text{lat,B}} - Q_{\text{lat,A}} = 164.1 \text{ W/m}^2 - 99.0 \text{ W/m}^2 = 65.1 \text{ W/m}^2$. In the hydrophobic sector, surface temperature was higher by $\Delta T = 4.4 \text{ K}$ (42.6°C vs. 38.2°C). This demonstrates that chocking off latent heat transfer (Q_{lat}) – by expanding the droplet contact angle and shrinking the active damp evaporation surface- compels energy to shift into sensible heat flux (H), which drives up the local surface temperature. This

thermodynamic feedback closely mimics the microclimate behavior observed during desert expansion and urban heat island formation, where landscapes push surface temperature higher due to a lack of moisture evaporation (Pielke et al., 2002).

5.4 Uncertainty and Sensitivity Analysis

Thermistors had a calibrated measurement uncertainty of $\delta T = \pm 0.1$ K. Propagating this temperature uncertainty through the Stefan-Boltzmann equation yields:

$$\delta P_T \approx 4 \varepsilon \sigma A T_{\text{mean}}^3 \delta T = 4 \times 0.92 \times (5.67 \times 10^{-8}) \times 2.5 \times (312.5)^3 \times 0.1 \approx \pm 1.6 \text{ W}$$

$$\text{Cladding emissivity uncertainty of } \delta \varepsilon = \pm 0.02 \text{ contributed: } \delta P_e = (\delta \varepsilon / \varepsilon) \times P_{\text{trapped}} = (0.02 / 0.92) \times 125.4 \text{ W} \approx \pm 2.7 \text{ W}.$$

Combining these independent uncertainties in quadrature yields:

$$\delta P_{\text{total}} = \sqrt{(\delta P_e)^2 + 2(\delta P_T)^2} = \sqrt{2.7^2 + 2(1.6^2)} \approx \pm 3.5 \text{ W } (\pm 1.4 \text{ W/m}^2)$$

This yields a net trapped thermal power of $P_{\text{trapped}} = 125.4 \pm 3.5$ W (corresponding to $\Delta F = 50.2 \pm 1.4 \text{ W/m}^2$). Triplicate testing ($n = 3$) of the Cl⁻ titration endpoints yielded a standard deviation of $\sigma = 0.12$ mL, establishing the statistical significance ($p < 0.05$) of the observed salinity gradient and confirming that differences between feed and drain streams exceed analytical uncertainty.

DISCUSSION

6.1 Hydrophobic Surface Partitioning and the Bowen Ratio

The observed 4.4 K warming in hydrophobic channels directly demonstrates the role of surface properties in modulating the Bowen ratio ($\beta = H / LE$). By redirecting 65.1 W/m^2 of thermal energy away from latent evaporative cooling, the water-repellant surface elevated sensible heating without altering incoming solar radiation. This physical process effectively replicates the surface energy distribution mechanism modelled by Pielke et al. (2002), showing how landscape modification, clear-cutting of flora, and ground desiccation trigger local warming completely separate from atmospheric greenhouse gas effects.

6.2 Nutrient Salinity as an Analog for Ocean Thermodynamics

The chloride analysis demonstrated how recirculating evaporation generates a progressive increase in fluid salinity (38 mg/L to 1240 mg/L), producing a 0.5% increase in fluid density. Although specific heat capacity (c_p) dropped by 0.6% and volumetric heat capacity ($\rho \cdot c_p$) experienced a minor reduction, the increase in density serves as a practical demonstration of buoyancy loss within saline water bodies. In the global climate framework, the combination of high-latitude cooling and intense subtropical evaporation causes density spikes that trigger the sinking of deep water, sustaining global thermohaline circulation (Levitus et al., 2012; Rahmstorf, 2002). Consequently, this CEA hydroponic setup offers a practical laboratory-scale model to show how evaporation processes alter both fluid mass and thermal characteristics.

6.3 Reconciling the Convective vs. Radiative Greenhouse Debate

The findings provide experimental clarity on the historical debate initiated by Wood (1909) and later examined by Jones and Henderson-Sellers (1990). Although Wood accurately noted that structural greenhouses retain heat mainly by blocking convective air exchange with the open air, our equilibrium data revealed a trapped thermal radiation difference of $50.2 \pm 1.4 \text{ W/m}^2$ through the infrared-blocking panels during continuous mechanical ventilation. This shows that even though the exact modes of heat capture vary- like physical prevention of air mixing in a built structure and infrared trapping by an optically dense, open atmosphere- each system follows the identical thermodynamic law: surface warming must occur to restore a stable radiative-convective balance ($E_{\text{in}} = E_{\text{out}}$).

6.4 Limitations and Scaling Constraints

Several scaling limitations must be acknowledged when extrapolating CEA dynamics to planetary systems:

1. Convective Scaling: The Nusselt number ($Nu = hL/k$), which defines the proportion of heat moved via convection versus conduction, is highly dependent on the characteristic length scale (L). Trying to scale up findings from a small 2.5 m^2 chamber to a massive, compressible planetary atmosphere with a scale height around 8.5 km fails to account for crucial planetary variables like atmospheric pressure gradients, buoyancy variations, and Coriolis effects.

2. Temporal Resolution: The collected data are limited to static readings recorded precisely at solar noon. Subsequent research needs to utilize automated, non-stop data acquisition tracking complete 24-hour day-night cycles, which will permit detailed examination of nighttime cooling trends and temporary boundary-layer breakdown phases.

CONCLUSION

This study evaluated whether an operational CEA hydroponic enclosure can serve as an experimental proxy for demonstrating fundamental climate thermodynamics. By treating the facility as an open thermodynamic control volume, the gathered data quantitatively validates three core physical principles:

1. Longwave Energy Imbalance: The experiment measured a trapped upward thermal infrared flux density of $\Delta F = 50.2 \pm 1.4 \text{ W/m}^2$ (totaling $P_{\text{trapped}} = 125.4 \pm 3.5 \text{ W}$), which caused a 7.7 K temperature difference between the interior and exterior environments under constant mechanical ventilation.
2. Surface Energy Partitioning: Restricting moisture dispersion with a water-repellent layer lowered latent heat flux by $\Delta Q_{\text{lat}} = 65.1 \text{ W/m}^2$, triggering a balancing 4.4 K rise in local channel surface temperatures. This reaction delivers an explicit experimental simulation of Bowen ratio variation observed during ground desiccation and urban heat island development.
3. Fluid Density and Thermal Properties: Titration measurements showed that salt accumulation from evaporation enhances fluid density by 0.5%, serving as a direct laboratory demonstration of the density imbalances that fuel global ocean thermohaline conveyor belts.

While significant scaling differences exist between enclosed horticultural structures and the unconfined planetary atmosphere, a CEA system serves as an accurate, mathematically robust physical simulator for demonstrating radiative trapping and boundary-layer surface energy partitioning.

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