

Optimization of Design and Operational Parameters for GREENBOX Farming System

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Abstract

As global population growth and urbanization intensify, food security faces significant challenges. GREENBOX technology, a modular, thermostatic indoor farming system, was developed at the University of Connecticut to enhance urban food production capacity within warehouse environments. This study developed a dynamic simulation model of the GREENBOX-warehouse system in MATLAB, using coupled energy and mass balances to optimize environmental conditions for Butterhead Rex lettuce (*Lactuca sativa*) and Cannabis crops. The model's performance was validated against empirical data, accurately predicting seasonal temperature and humidity with Mean Absolute Errors (MAE) of 0.8°C - 1.4°C and 3.5% - 6.2%, respectively. Subsequent optimization using Particle Swarm Optimization (PSO) identified a critical thermal transmittance (U-value) of 3.68 Wm⁻²K⁻¹ that balances material volume and thermal stability. Ideal lighting configurations were determined at 11.84 W for lettuce and 35.5 W for cannabis to achieve target PPFD levels. Optimized ventilation rates were established at 0.0132 m³s⁻¹ (standard structure for short crops) and 0.0363 m³s⁻¹ (tall crop version) to effectively manage latent heat. To ensure industrial scalability, warehouse-level HVAC requirements were standardized on a volumetric basis: 0.00011 - 0.00016 m³m⁻³s⁻¹ for air flow, 2.00 Wm⁻³ for cooling, and 1.91 Wm⁻³ for heating. These quantitative benchmarks provide a prescriptive framework for the construction and operation of GREENBOX indoor farming units in a warehouse environment, making the model a practical tool for applying the GREENBOX technology in urban controlled environment agriculture (CEA).

Keywords

Controlled Environment Agriculture (CEA), Dynamic Modeling,

1. Introduction

Global population growth and rapid urbanization are intensifying the need for sustainable and reliable food production. As the world population is projected to reach 9.78 billion by 2064, with nearly two-thirds living in cities, controlled environment agriculture (CEA) has become increasingly important for producing food efficiently and independently of outdoor climate constraints [1] [2]. These demographic and environmental pressures highlight the critical role of indoor food-production systems that can deliver predictable yields in space-limited urban regions.

CEA systems, such as vertical farms, plant factories, and growth chambers, allow precise regulation of temperature, humidity, lighting, CO₂ concentration, and nutrition supply. Recently, GREENBOX technology was developed to allow effective production of leafy vegetables in urban settings. GREENBOX units are environmentally controlled modular facilities with LED lighting and hydroponic platforms for vegetable production in urban residential and warehouse environments. Previous studies have shown that GREENBOX technology can produce lettuce and other leafy vegetables in warehouse conditions with a productivity comparable to large CEA facilities, such as greenhouses, in both quantity and quality [3]-[5]. As a new technology for indoor farming, GREENBOX units are individually controlled with fully automatic operation capabilities, can be stacked up or aggregated to form any scale of production capacities, can be hosted in new and used warehouses or other structures, and therefore have a high potential in producing fresh food in highly populated urban areas while reducing transportation and storage costs. However, the wide and practical application of GREENBOX technology remains limited because optimal design and operational parameters have not yet been established through extensive studies.

Numerous modeling studies have used coupled energy and mass balance frameworks to characterize microclimate dynamics and optimize environmental control in greenhouses and large plant production factories [6] [7]. Researchers have demonstrated the importance of accurately modeling humidity, latent heat, and transpiration processes, which strongly influence climate stability and energy use [8] [9]. Growth-chamber studies further show that insulation, LED heat emission, and airflow patterns significantly affect microclimate uniformity and thermal loads [10] [11]. Collectively, this body of work demonstrates that successful simulation requires representing multiple interacting physical processes, rather than simplifying system behavior to individual components.

Despite these advances, relatively few studies have examined compact modular CEA facilities like GREENBOX units deployed inside warehouse environments.

In these settings, the microclimate is dominated by electrical lighting, strong insulation, minimal solar gain, and coupling with indoor air rather than outdoor conditions. Moreover, most existing models assume steady-state behavior or analyze isolated subsystems, with limited work combining full dynamic energy-mass balance modeling and optimization for small-scale CEA units [12]. As highlighted in Benke and Tomkins [13], modular indoor farming systems are likely to play a significant role in future urban food supply chains. Yet, their environmental control requirements remain insufficiently characterized. This gap underscores the need for validated dynamic modeling frameworks that can support design optimization and scalable deployment. It is hypothesized that such knowledge can be obtained by tailoring existing model frames for GREENBOX units. We propose that physics-based models, by explicitly representing conduction, convection, infiltration, LED heat emission, and crop transpiration, can reveal how these interacting processes govern thermal and humidity dynamics inside modular units and serve as a vital tool for practical design and operation. We further hypothesize that such a model, once validated, can be utilized to systematically derive the optimal operational configurations that are currently missing from the literature.

To test these hypotheses, a model was developed incorporating conduction, convection, infiltration, ventilation, LED heat loads, and crop transpiration for GREENBOX units hosted in a general warehouse environment. Data from previous experimental studies [3] [4] were used to evaluate the model's performance. Following validation, Particle Swarm Optimization (PSO) was applied to identify optimal ventilation rates, insulation properties, and lighting configurations. The resulting optimized parameters provide practical design guidance for deploying GREENBOX systems in warehouse-based operations and highlight the key trade-offs among insulation, airflow, and lighting that govern microclimate stability. Although GREENBOX units were selected as the physical platform, the modeling and optimization approaches developed here are broadly applicable to similar modular CEA systems.

2. Research Objective

The primary objective of this study was to optimize the design and operational parameters of the GREENBOX farming system to facilitate wider practical application. Specifically, we aimed to:

- 1) Develop a Dynamic Simulation Model: Create a model to simulate the microclimate and plant growth inside GREENBOX units and the environmental variables inside the hosting warehouse. This model is based on coupled energy and mass balance equations and incorporates key parameters essential for the optimal growth of both short vegetables (lettuce) and tall crops (cannabis).
- 2) Evaluate Model Performance: Assess the model using data collected in a series of experimental studies with lettuce, focusing on overall performance and its applicability to real-world warehouse conditions.
- 3) Generate Optimal Design Standards: Use the validated model to generate

specific design and operational parameters—such as insulation levels and ventilation rates—necessary for successful GREENBOX plant production in urban warehouse environments.

3. Materials and Methods

This section describes the GREENBOX and warehouse systems, focusing on their structure, crop selection, and energy/mass balances. It further explains the model's implementation and its role in optimizing design and operational parameters. Specific details regarding coding, parameterization, and model structure are provided by Zhuo [14].

3.1. System Structure

3.1.1. GREENBOX Units

The GREENBOX is a thermally insulated, climate-controlled cultivation system developed at the Yang Laboratory, University of Connecticut. Designed as a modular unit for warehouse-based production, each GREENBOX features an insulated enclosure, an LED lighting array with white ones for heating and red and blue ones for photosynthesis (controlled separately), a hydroponic growing platform, and a fan and air inlet/outlet for ventilation to regulate air exchange with the warehouse. Environmental sensors provided continuous monitoring of internal temperature and relative humidity.

As shown in **Figure 1**, the system was designed with dimensions optimized for pallet-lift operations in warehouse environments, as established in previous work [3]–[5], in two configurations. The standard model measured 1.0 m (H) $\times$ 1.2 m (W) $\times$ 1.5 m (L) and was sized for short-stature crops such as lettuce. The high-version model measured 2.0 m in height to accommodate tall crops, such as cannabis. In both configurations, the internal architecture included a height-adjustable LED mounting system, an exhaust port, and a nutrient delivery platform. Together, these components enabled precise regulation of the thermal environment, lighting, and humidity.

3.1.2. Warehouse Configuration

The warehouse served as the macro-scale thermal boundary for the system, representing contemporary small-scale facilities typically ranging from 5,000 to 15,000 ft² with vertical clearances between 10.5 and 12 m [15]. This study assumed a warehouse area of 5,000 ft² (≈ 465 m²) with dimensions of 31 m $\times$ 15 m $\times$ 12 m, utilizing standard steel framing and insulated metal panels. The warehouse was assumed to have basic lighting, heating, and ventilation facilities, in addition to electricity and water. The internal layout consisted of 15 rack structures arranged in a 3 $\times$ 5 grid, with each rack layer holding 8 GREENBOX units. The facility could support up to 11 vertical layers for the standard units (totaling 1,320 units) or 5 layers for the high-version model (totaling 600 units) due to the increased vertical requirements.

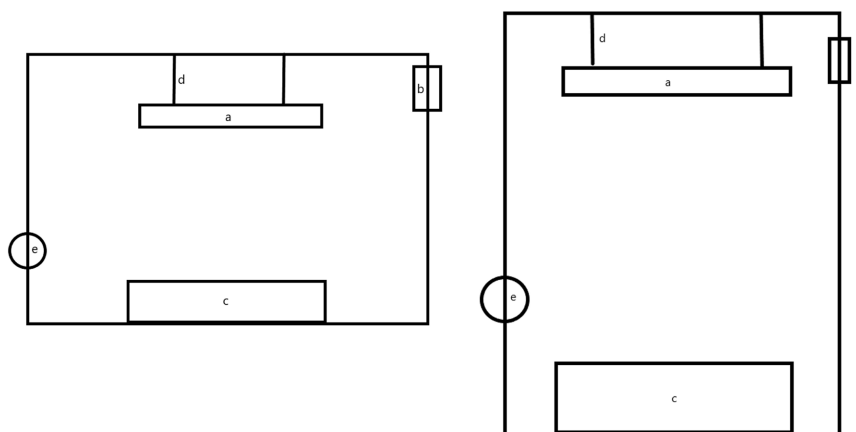


Figure 1. Structural schematics of the modular cultivation units: (Left) standard GREEN-BOX configuration and (Right) high version GREENBOX variant for tall crops. The dimensions are described in the text.

3.2. Crop Selection

Two distinct crops were selected to evaluate the system's versatility. Lettuce was selected for the short crop. Lettuce thrives in temperatures between 17°C - 29°C and relative humidity (RH) of 40% - 60% [16]. The recommended daily light integral (DLI) was $6.5 - 9.7 \text{ mol m}^{-2}\text{d}^{-1}$ [17], corresponding to approximately $75.2 - 112.3 \mu\text{mol m}^{-2}\text{s}^{-1}$, or $37.2 - 55.6 \text{ W m}^{-2}$ or $37.2 - 55.6$ [18].

For tall vegetation, cannabis was selected for the model. The optimal temperature range for cannabis is 25°C - 30°C [19]. While young plants require approximately 75% RH, this should be adjusted to 55% - 60% during growth and flowering stages [20]. Mature heights range from 34 to 65 cm [21]. While a Photosynthetic Photon Flux Density (PPFD) of $900 \mu\text{mol m}^{-2}\text{s}^{-1}$ produces sturdier plants, a level of $600 \mu\text{mol m}^{-2}\text{s}^{-1}$ (equivalent to 196.2 W m^{-2}) was used in this study, which was recommended for enhancing airflow and reducing pest risks [22].

3.3. Modeling of the GREENBOX Units

3.3.1. Dynamic Energy Balance

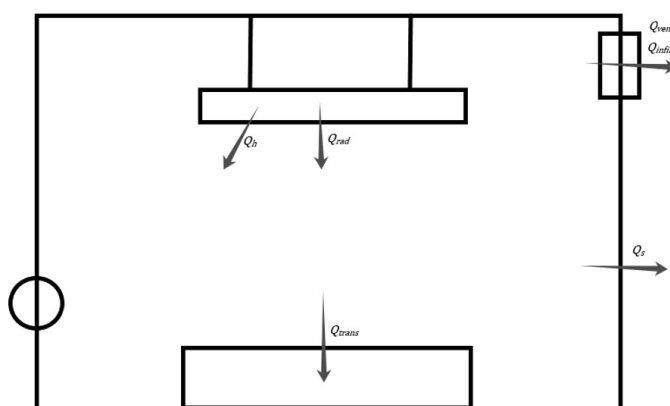


Figure 2. Conceptual diagram of the energy balance and heat transfer mechanisms for the GREENBOX unit.

The energy exchange within the GREENBOX units was modeled based on fundamental heat transfer principles, including conduction, convection, and radiation (**Figure 2**). The system interacts with the surrounding warehouse environment primarily through the structural walls and ventilation outlets.

The dynamic energy balance for an individual GREENBOX unit is governed by the following first-order differential equation:

$$\rho C_p V_b \frac{dT_i}{dt} = Q_h + Q_{rad} - Q_{infil} - Q_{vent} - Q_{trans} - Q_s \quad (1)$$

Where:

Q_h : heating energy from white LED lights (W);

Q_{rad} : thermal radiation from Red and Blue LED lights (W);

Q_{infil} : energy loss due to infiltration (W);

Q_{vent} : energy loss through active ventilation (W);

Q_{trans} : latent heat consumption via crop transpiration (W);

Q_s : sensible energy loss through the unit walls (W);

T_i : air temperature inside the GREENBOX unit (K);

ρ , C_p , V_b : air density (kg m^{-3}), specific heat ($\text{J kg}^{-1}\text{K}^{-1}$), and unit volume (m^3).

The net energy contribution of a single unit to the warehouse environment is represented by the sum of the terms within the parentheses, termed Q_b . While Q_h , Q_{rad} , and Q_{vent} were derived from manufacturer specifications, Q_{infil} was calculated assuming an air change rate of 0.3 h^{-1} [23]. Sensible heat loss (Q_s) was determined using the overall thermal transfer coefficient (U -value) and the temperature gradient between the internal and external environments. Latent heat (Q_{trans}) was calculated as a product of the transpiration rate (M_{trans}) and the latent heat of vaporization of water. The calculation of the transpiration rate was described in the next session.

3.3.2. Dynamic Mass Balance

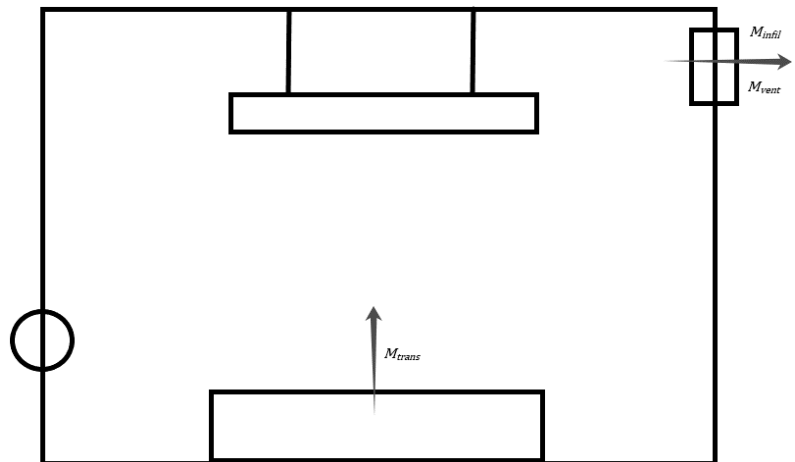


Figure 3. Conceptual diagram of vapor mass balance and moisture flux for the GREEN-BOX unit.

In this system, relative humidity was a critical controlled variable; ventilation is triggered by both temperature and humidity thresholds to maintain optimal growth conditions. The vapor exchange processes (**Figure 3**) are described by the following mass balance equation:

$$\rho V_b \frac{dW_i}{dt} = M_{trans} - M_{vent} - M_{infil} \quad (2)$$

Where:

W_i : specific humidity of the internal air (kg kg^{-1});

M_{trans} : crop transpiration rate (kg s^{-1});

M_{vent} , M_{infil} : vapor loss via ventilation and infiltration (kg s^{-1}).

The net vapor mass exchange of the GREENBOX unit with the warehouse (M_b) is the sum of these three terms. M_{vent} and M_{infil} were determined by the air exchange rates and the humidity difference between the GREENBOX and the warehouse.

For lettuce, the transpiration rate, M_{trans} was estimated using an empirical model based on leaf area index (LAI) data from Ankit *et al.* [3] [4]:

$$M_{trans} = \begin{cases} \frac{0.0563}{1 + e^{(-1.0046(LAI - 0.9381))}} & \text{when LED turns on} \\ \frac{0.0461}{1 + e^{(-1.0046(LAI - 0.9381))}} & \text{when LED turns off} \end{cases} \quad (3)$$

where LAI was estimated using a curve fitting of the experimental data.

For cannabis, canopy development and water use were simulated using the radiation-driven model proposed by Lisson *et al.* [24]. This model utilizes intercepted photosynthetically active radiation (PAR) and vapor pressure deficit (VPD) to determine dry-matter production (DM) and daily transpiration rate:

$$M_{trans} = DM * \frac{VPD}{TE} \quad (4)$$

where TE represents crop-specific transpiration efficiency.

3.4. Modeling of the Warehouse System

3.4.1. Dynamic Energy Balance

The warehouse energy balance accounts for the collective thermal load of the GREENBOX units, structural heat transfer, and the operational HVAC systems (**Figure 4**). The dynamic energy state of the warehouse is described by the following first-order differential equation:

$$\rho C_p V_w \frac{dT_w}{dt} = nQ_b - Q_{ws} - Q_{w,infil} - Q_{w,vent} + Q_{wh} - Q_{wc} \quad (5)$$

Where:

n : number of GREENBOX units within the warehouse;

Q_b : energy gain from a single GREENBOX unit (W), calculated from equation (1);

Q_{ws} : sensible heat loss through the warehouse structure (W);
 $Q_{w,infil}$, $Q_{w,vent}$: energy losses due to infiltration and ventilation, respectively (W);
 Q_{wh} , Q_{wc} : energy input/removal by the heating and cooling systems (W);
 T_w : air temperature inside the warehouse (K);
 V_w : volume of the warehouse (m^3).

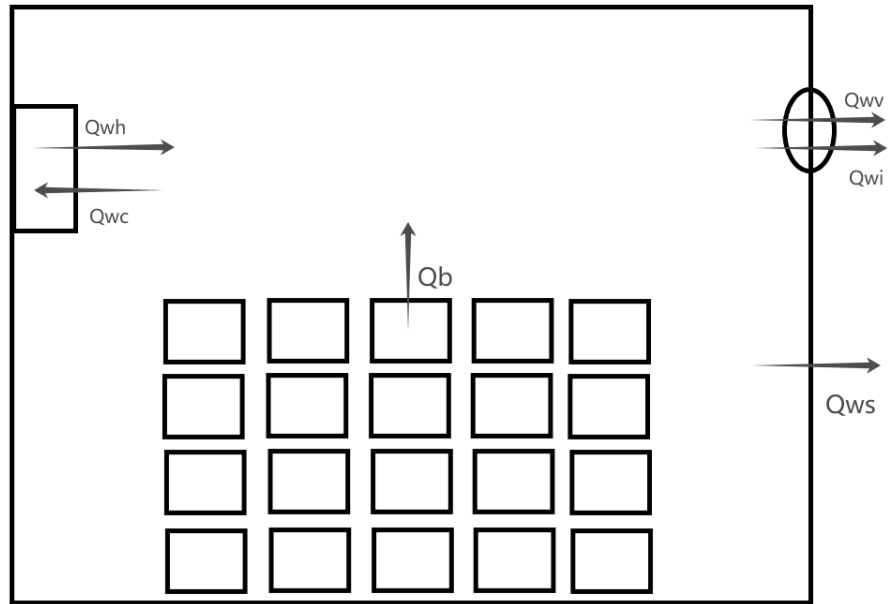


Figure 4. Illustration of the energy balance for the warehouse, including coupling with the internal GREENBOX units and external boundary conditions.

For this simulation, all GREENBOX units were assumed to operate under identical conditions, allowing the total biological/mechanical load to be scaled linearly (nQ_b). Structural heat loss (Q_{ws}) was calculated using the U -value of the warehouse materials and the temperature gradient between the interior and the external ambient air. The energy losses due to ventilation and infiltration were calculated from the flow rate or natural warehouse leakage rate, according to Robert *et al.* [25] and The Engineering Toolbox [26], respectively. The heating and cooling loads of the warehouse were calculated from the specifications of the operational HVAC systems. In accordance with the assumption that no phase changes occur within the warehouse volume (outside of the sealed units), latent heat terms were excluded from the warehouse-level equation.

3.4.2. Dynamic Mass Balance

For the warehouse structure, water vapor is primarily introduced through the GREENBOX units and lost through ventilation and infiltration, as illustrated in **Figure 5**. The following first-order differential equation was used to describe the dynamic mass model for the warehouse.

$$\frac{dW_w}{dt} = \frac{1}{\rho \cdot V_w} (n \cdot M_b - M_{wv} - M_{wi}) \quad (6)$$

Where:

M_b = net water vapor gained from an individual GREENBOX unit, kg;

M_{wv} = vapor mass loss due to the ventilation, kg;

M_{wi} = vapor mass loss due to the infiltration, kg;

W_w = specific humidity of air inside the warehouse; kg kg⁻¹; and

V_w = volume of the warehouse; m³.

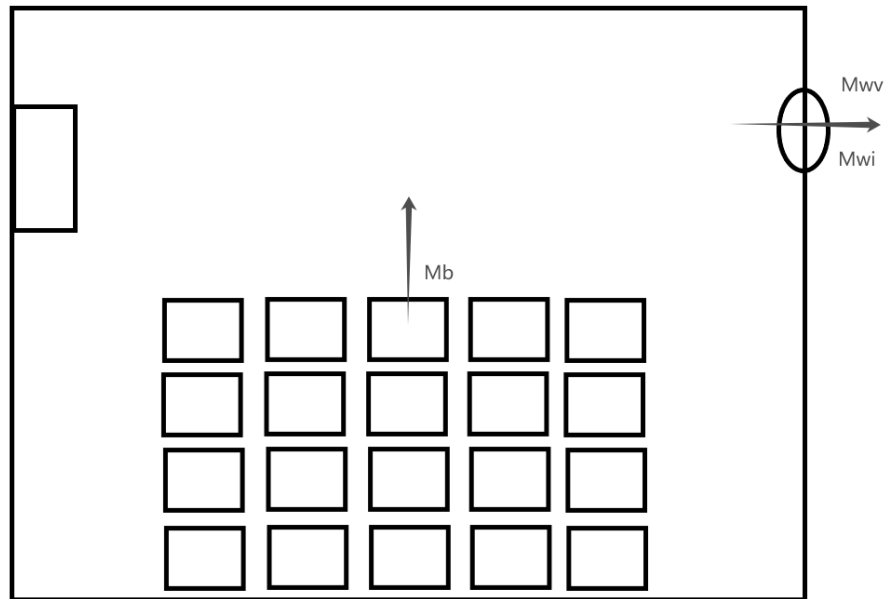


Figure 5. Illustration of the vapor mass balance for the warehouse, representing the moisture exchange between the GREENBOX units and the outside air mass.

Similar to the energy equation, we assumed that the vapor load was the same across all GREENBOX units and calculated the total water vapor input for the GREENBOX units as the product of the number of units and the vapor mass from an individual unit. The vapor exchange of the warehouse with the outside air by ventilation and infiltration was assumed to be proportional to the specific humidity difference between the warehouse and the outside air, regulated by a ventilation rate and a constant infiltration flow rate, similar to the treatment of the energy terms.

3.5. Model Implementation

The dynamic simulation model was implemented in MATLAB as a system of four coupled first-order ordinary differential equations representing the temperature and specific humidity of both the GREENBOX units and the warehouse. The simulation utilized an explicit forward-Euler integration scheme with a 1 s time step to advance the state variables from the initial transplant date. Model inputs included air thermophysical properties, structural dimensions, thermal properties, infiltration and ventilation rates, and LED lighting specifications. Boundary conditions were provided by hourly outdoor weather data, which were linearly interpolated to a one-second resolution to drive the simulation. At each time step, energy and mass

balance equations for both zones were solved simultaneously to ensure consistent interactions between ventilation, infiltration, transpiration, and heat loads.

Control logic was embedded within the simulation loop to manage LEDs and HVAC systems via a piecewise on-off strategy based on crop-specific requirements. For lettuce, Red and Blue LEDs operated on a 16-hour photoperiod, while cannabis followed an 18-hour vegetative and 12-hour flowering schedule. Ventilation fans and HVAC systems were triggered when temperature or relative humidity (RH) exceeded upper thresholds—27°C or 60% RH for lettuce, 28°C or 60% RH for cannabis, and 25°C or 60% RH for the warehouse. These systems were deactivated once conditions fell below lower limits of 23°C/45% RH, 25°C/55% RH, and 24°C/40% RH, respectively. Supplemental white LEDs and warehouse heating were triggered whenever temperatures fell below these minimum set-points. Additional crop-specific parameters needed for the modules were provided in Zhuo [14]. The simulation produced time-resolved outputs of temperature, humidity, and energy-related variables, which served as the dataset for subsequent model validation and system optimization.

3.6. Model Validation

The dynamic model was validated using empirical data collected from four lettuce production cycles conducted across the spring, summer, autumn, and winter of 2020-2021. Each experimental cycle lasted approximately 30 days, during which air temperature and relative humidity (RH) were recorded at one-minute intervals. These measurements were obtained using calibrated sensors installed within both the GREENBOX unit and the surrounding headspace of the Agricultural Biotechnology Laboratory (ABL) at the University of Connecticut. Because the warehouse component of the model was parameterized specifically to the thermal and hygrometric characteristics of the ABL headspace, these experimental measurements provided the necessary boundary conditions for validating the coupled GREENBOX-warehouse simulation.

Validation was performed exclusively on the lettuce cycles, as cannabis was not included in the original experimental dataset. Throughout all four seasons, operational settings remained consistent, including a 16-hour photoperiod, on-off ventilation control with hysteresis, and fixed nutrient and planting schedules. Model performance was evaluated by comparing simulated temperature and RH values against the corresponding measured data for each season. To quantify accuracy, the mean absolute error (MAE) and root mean square error (RMSE) were calculated separately for both the GREENBOX and warehouse environments.

The accuracy of the model was assessed against established engineering criteria for controlled environment systems, where deviations of approximately $\pm 2 - 3^\circ\text{C}$ and $\pm 5 - 10\%$ RH are generally considered acceptable for maintaining crop performance and control reliability [7]-[9] [11]. Accordingly, the model was deemed accurate based on threshold targets of an MAE less than 1.5°C and 7% RH, and an RMSE less than 2.0°C and 10% RH. These metrics ensured that the simulation could reliably predict

environmental dynamics across diverse seasonal boundary conditions.

3.7. Optimization

Particle Swarm Optimization (PSO) was employed to identify the combination of design and operational parameters that most effectively stabilized the GREENBOX microclimate while minimizing deviations from temperature and humidity targets. PSO was selected for its ability to efficiently navigate the nonlinear, high-dimensional solution spaces characteristic of dynamic climate models [27] [28]. The optimization goal was to obtain an optimal range of design and operational parameters for minimizing environmental variance to provide the ideal conditions within the GREENBOX units required for plant growth. The process focused on three primary decision variables: thermal insulation properties, ventilation strategies, and LED lighting configurations, which represent the principal factors influencing sensible and latent heat transfer within the system.

In the PSO framework, a population of particles explored the parameter space by iteratively updating their positions and velocities based on individual and collective performance. For each candidate solution, the coupled GREENBOX-warehouse simulation was executed to quantify microclimate stability based on deviations from target conditions. Each particle retained its personal best position (pbest), while the swarm tracked the global best solution (gbest). Guided by these two attractors, particles adjusted their trajectories to converge toward an optimal parameter set.

The algorithm was implemented in MATLAB with fixed target conditions of 27°C and 60% RH for the GREENBOX, and 28°C and 55% RH for the warehouse. These fixed setpoints facilitated a more direct practical application than the ranges used in the initial simulation. The swarm consisted of 50 particles executed over 200 iterations. To balance global exploration and local convergence, inertia weights were modulated between 0.4 and 1.2, while cognitive and social adjustment weights were both set to 2.0 [27].

Parallel computing was applied to enhance computational efficiency. Performance was evaluated via a custom cost function quantifying deviations from target levels. Upon convergence, optimal solutions were identified and normalized, allowing for the simultaneous optimization of thermal, ventilation, and lighting variables while capturing their interactive effects on microclimate stability.

4. Results and Discussion

4.1. Model Performance

The performance of the dynamic model was evaluated by comparing simulation results with experimental data collected from short-crop lettuce production. Air temperature and relative humidity (RH) were analyzed for both the GREENBOX units and the warehouse environment across four seasons: spring, summer, fall, and winter. The time-series comparisons (**Figures 6-9**) demonstrated that the model effectively reproduced diurnal and seasonal variations and responded to operational changes, such as lighting and ventilation transitions, in a manner con-

sistent with observed data.

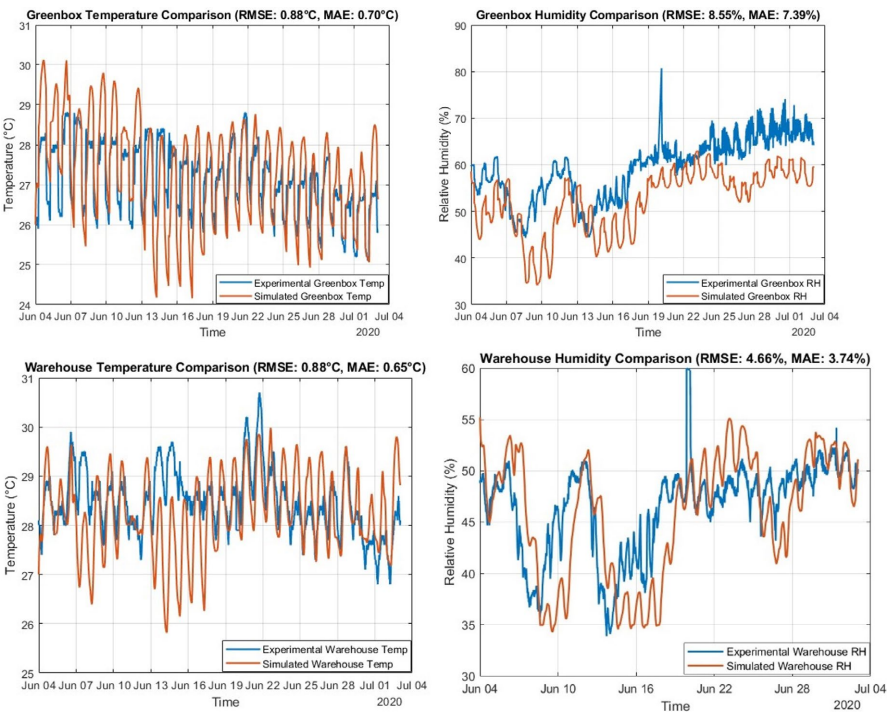


Figure 6. Comparison of experimental and simulated air temperature and relative humidity within the GREENBOX units and in the warehouse headspace during the spring validation cycle.

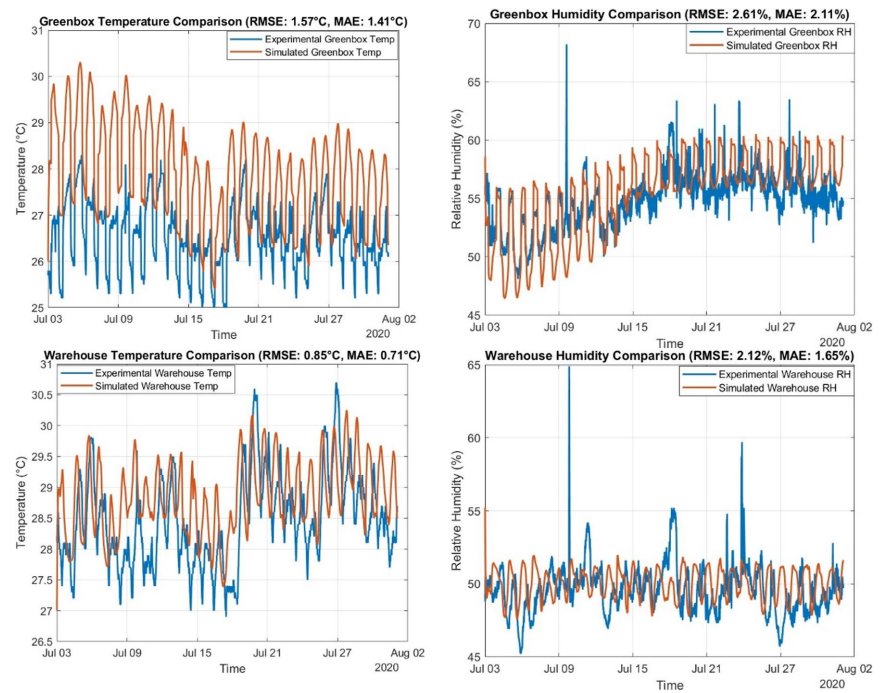


Figure 7. Comparison of experimental and simulated air temperature and relative humidity within the GREENBOX units and in the warehouse headspace during the summer validation cycle.

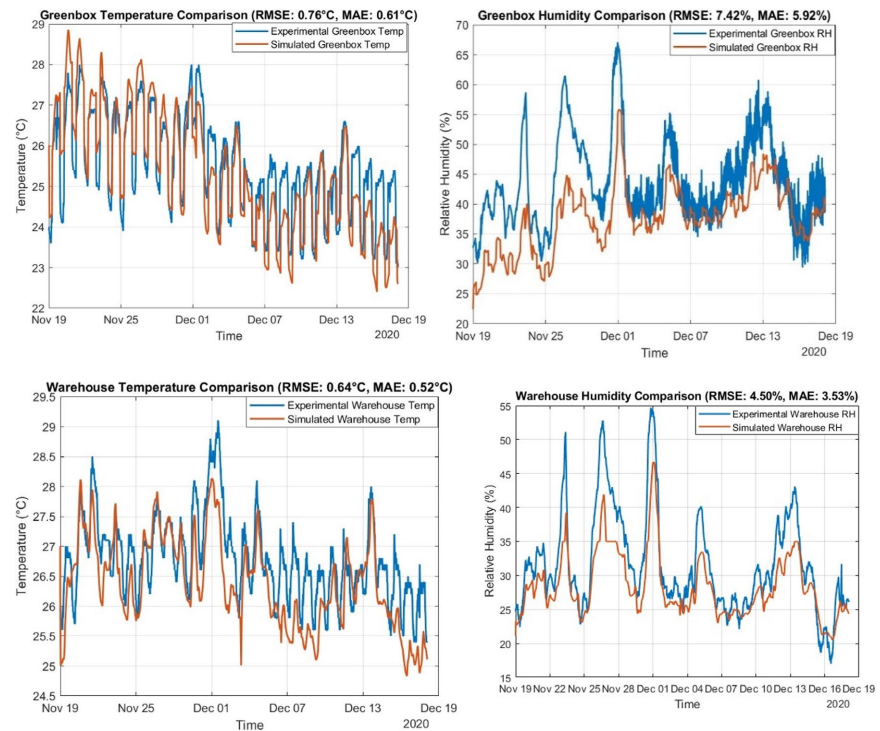


Figure 8. Comparison of experimental and simulated air temperature and relative humidity within the GREENBOX units and in the warehouse headspace during the fall validation cycle.

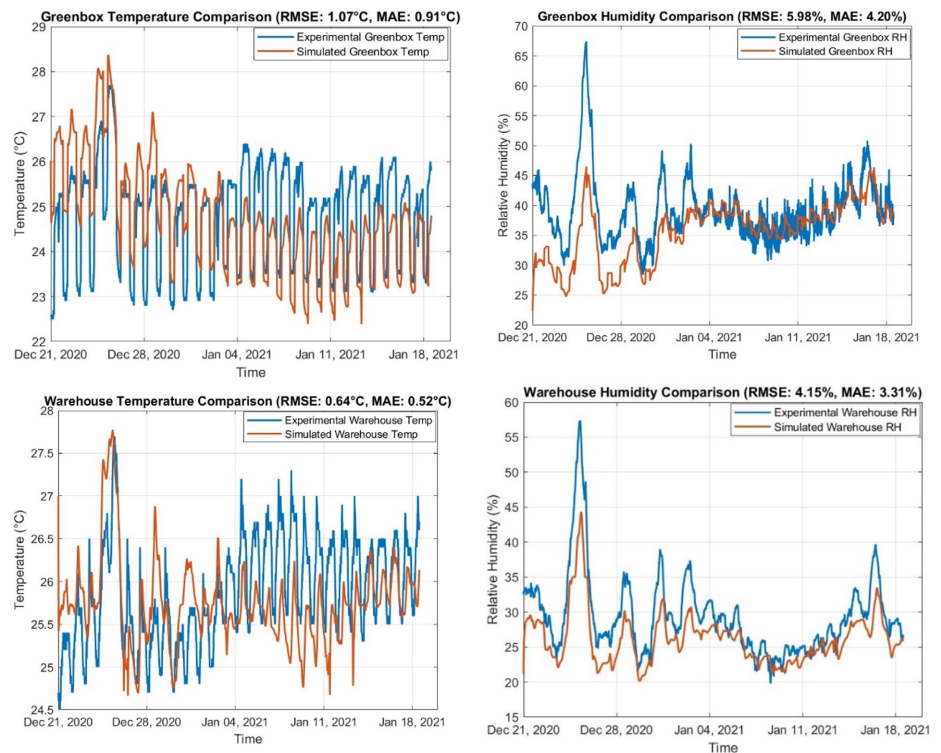


Figure 9. Comparison of experimental and simulated air temperature and relative humidity within the GREENBOX units and in the warehouse headspace during the winter validation cycle.

Statistical accuracy was quantified using Mean Absolute Error (MAE) and Root Mean Square Error (RMSE) for both environments. As detailed in the validation metrics (**Tables 1-2**), all statistical values fell within the predefined acceptable ranges, except for the relative humidity in the Spring cycle, attributed to an incidental surge of relative humidity as shown in **Figure 6**. These results indicated that the model reliably captured the thermal and hygrometric dynamics of the coupled system, confirming its suitability for evaluating design parameters, analyzing operational scenarios, and conducting subsequent optimization via Particle Swarm Optimization (PSO).

Table 1. Mean Absolute Error (MAE) for simulated temperature (°C) and relative humidity (%) across four seasonal validation cycles in the GREENBOX and warehouse environments.

Environment	Variables	Spring	Summer	Fall	Winter
GREENBOX	Temperature	0.70	1.41	0.61	0.91
GREENBOX	Relative Humidity	7.39	2.11	5.92	4.20
Warehouse	Temperature	0.65	0.71	0.52	0.52
Warehouse	Relative Humidity	3.74	1.65	3.53	3.31

Table 2. Root Mean Square Error (RMSE) for simulated temperature (°C) and relative humidity (%) across four seasonal validation cycles in the GREENBOX and warehouse environments.

Environment	Variables	Spring	Summer	Fall	Winter
GREENBOX	Temperature	0.88	1.57	0.76	1.07
GREENBOX	Relative Humidity	8.55	2.61	7.42	5.98
Warehouse	Temperature	0.88	0.85	0.64	0.64
Warehouse	Relative Humidity	4.66	2.12	4.50	4.15

4.2. Optimization Results

The Particle Swarm Optimization (PSO) identified parameter combinations that significantly enhanced microclimate stability compared to the baseline configuration. These findings are categorized into unit-specific design settings and standardized warehouse environmental requirements. **Tables 3-4** summarize the design and operational parameters used for the standard and high versions of the GREENBOX units and the warehouse, while **Table 5** presents the standardized ventilation, cooling, and heating capacities required for warehouse climate control.

The optimization identified distinct configurations for the standard and high versions of the GREENBOX units, as detailed in **Table 3** and **Table 4**. With the fixed dimensions of the boxes, the algorithm consistently converged toward an optimal U-value range of $3.68 \text{ W m}^{-2}\text{K}^{-1}$, indicating that moderate to high insulation is essential for mitigating conductive heat loss.

The optimal maximum ventilation rate was identified as 0.013 and $0.036 \text{ m}^3\text{s}^{-1}$

for the standard and high versions, respectively, which effectively managed the latent heat loads generated by crop transpiration. The optimal LED mounting height was found to be about 0.44 m and 0.76 m above the plant canopy. Furthermore, the lighting configurations favored intermediate LED power levels with a moderate sensible heat fraction, balancing photosynthetically active radiation (PAR) with internal thermal equilibrium.

Beyond unit-level design, the optimization established standardized environmental loads required for the warehouse to support stable GREENBOX operations. As summarized in **Table 5**, these capacities were normalized on a volumetric basis to ensure scalability across different building dimensions.

The standardized ventilation rate was determined to be 0.00011 - 0.00016 $\text{m}^3\text{m}^{-3}\text{s}^{-1}$. Thermal conditioning requirements were similarly normalized, resulting in a cooling capacity of 2.00 Wm^{-3} and a heating capacity of 1.91 Wm^{-3} . These metrics provide a prescriptive engineering framework for sizing the infrastructure necessary to maintain a consistent warehouse environment.

Table 3. Optimized design parameters of GREENBOX.

Parameter	Standard version	High version	Units
Dimensions (H × W × L)	1 × 1.2 × 1.5	2 × 1.2 × 1.5	m
LED height above canopy	0.44	0.76	m
Thermal conductance	3.68	3.68	$\text{W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$

Table 4. Optimized operational parameters of GREENBOX and the warehouse.

Parameter	Standard version	High version	Units
LED power (Blue: Red)	11.84	35.50	W
White light power	6.38	6.38	W
GREENBOX ventilation rate	0.013	0.036	$\text{m}^3\cdot\text{s}^{-1}$
Warehouse ventilation rate	0.611	0.945	$\text{m}^3\cdot\text{s}^{-1}$
Warehouse cooling system	11170	11170	W
Warehouse heating system	10680	10680	W

Table 5. Standardized ventilation rate, cooling, and heating capacities per unit volume for climate control in the warehouse.

Parameter	Standard version	High version	Units
Ventilation rate	0.00011	0.00016	$\text{m}^3\cdot\text{m}^{-3}\cdot\text{s}^{-1}$
Cooling capacity	2.00	2.00	$\text{W}\cdot\text{m}^{-3}$
Heating capacity	1.91	1.91	$\text{W}\cdot\text{m}^{-3}$

4.3. Discussion

4.3.1. Model Performance and Numerical Deviations

While the model successfully replicated seasonal environmental patterns, specific

discrepancies were observed during rapid transitions. Temperature deviations increased during LED switching intervals, likely due to simplified representations of wall thermal inertia and LED sensible heat fractions. Furthermore, relative humidity was occasionally underestimated during peak transpiration periods. This was attributed to the use of a generalized transpiration rate derived from prior empirical literature rather than dynamic, real-time physiological measurements.

Operational modeling further contributed to minor fluctuations. The use of an on-off control strategy with hysteresis—rather than proportional control—led to occasional overshoots and undershoots in temperature and humidity when ventilation states changed. Additionally, the assumption of constant infiltration rates did not account for real-world pressure differences or door movements. Despite these inherent simplifications, the high correlation between predicted and measured values provided a robust foundation for system optimization.

4.3.2. Optimization and System Parameters

The results across **Tables 3-5** demonstrate that effectively controlling the microclimate of the GREENBOX units and the warehouse environment requires a strategic combination of thermal resistance and high-capacity ventilation. In warehouse environment, the steady-state temperature difference between the air inside and outside the GREENBOX units might be small, the fluctuations in both the warehouse and the GREENBOX units may be significant due to various heating/cooling loads and ventilation operations. The convergence of optimal U-values ($3.68 \text{ W m}^{-2} \text{ K}^{-1}$) confirms that while insulation is critical for thermal stability, it must be paired with high-capacity ventilation ($0.013 - 0.036 \text{ m}^3 \text{ s}^{-1}$) to prevent moisture and latent heat accumulation.

The transition to volumetric scaling offers a more reliable engineering metric than traditional area-based measurements. Because warehouse HVAC demands are governed by the total air mass, a function of ceiling height, this approach ensures the design framework remains scalable across diverse building geometries. The industrial warehouse varies in size and configuration, and it is possible that the system is too large for indoor farming operations. Therefore, our study is limited to standard warehouse size (approx 500 m^2 in floor area) with normal HVAC equipment.

4.3.3. Practical Application and Scientific Context

This study extends previous CEA modeling by treating the warehouse as a coupled air mass rather than a static boundary. Unlike traditional greenhouses that ventilate to the outdoors, the GREENBOX utilizes “indoor-indoor” air exchange, effectively using the warehouse as a thermal buffer. Our identified U-values and ventilation capacities align with established literature [9] [11] while introducing new insights into the dynamics of small, insulated modular systems.

Lighting also emerged as a significant thermal driver. Intermediate LED power levels minimized cooling demand by balancing photosynthetically active radiation (PAR) with beneficial sensible heat gain. These findings reinforce the neces-

sity of co-optimizing lighting and HVAC parameters [29] to maintain thermal equilibrium.

4.3.4. Limitations and Future Directions

Limitations of this work include simplified transpiration modeling and constant infiltration assumptions, common challenges noted in recent CEA studies [30] [31]. The abrupt transitions caused by on-off control logic suggest that future research should incorporate proportional or predictive control frameworks [32]. The work was validated only for lettuce. Caution should be taken for studies involving tall plants. Nevertheless, the standardized benchmarks developed here provide a scalable modeling approach and actionable guidance for the practical deployment of GREENBOX systems in industrial environments.

5. Summary and Conclusions

This study established and validated a dynamic simulation model of the GREENBOX system, integrating energy and mass balance equations to predict microclimate conditions across diverse seasonal scenarios. Calibrated with empirical data from a standard unit, the model demonstrated high predictive fidelity with low MAE and RMSE values, confirming its reliability in capturing the system's thermal-hygrometric dynamics. Optimization via Particle Swarm Optimization (PSO) identified a critical wall U-value of $3.68 \text{ W m}^{-2} \text{ K}^{-1}$ to balance material volume with thermal insulation. For lettuce, the optimal configuration utilized 11.84 W LED power at 0.44 m ($200 \mu\text{mol m}^{-2} \text{ s}^{-1}$), while cannabis required 35.5 W at 0.757 m ($600 \mu\text{mol m}^{-2} \text{ s}^{-1}$). Optimized ventilation rates were established at $0.013 \text{ m}^3 \text{ s}^{-1}$ (Standard) and $0.036 \text{ m}^3 \text{ s}^{-1}$ (high version) to maintain target temperature and humidity levels. To ensure scalability, warehouse-level climate control capacities were normalized volumetrically. These benchmarks— $0.00011 - 0.00016 \text{ m}^3 \text{ m}^{-3} \text{ s}^{-1}$ for ventilation, 2.00 W m^{-3} for cooling, and 1.91 W m^{-3} for heating—allow for consistent deployment across varying warehouse sizes. In conclusion, this research provides a validated, optimized framework for precise environmental control for GREENBOX farming in an urban warehouse environment. The established quantitative benchmarks offer a robust foundation for customizing system design. Future work should focus on expanding crop types, integrating real-time automation, and incorporating renewable energy strategies to enhance system sustainability.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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