

INTERMITTENT AIRFLOW TO PREVENT TIP BURN AND MAXIMIZE COST SAVINGS
IN VERTICAL FARMS

By

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ABSTRACT

Controlled environment agriculture (CEA) and the technology integral to creating highly customizable and optimal environments for the plants grown within have given growers the opportunity to greatly increase production yields while simultaneously decreasing resource input. Vertical farming, in particular, allows for significant improvements in yield, quality, and consistency of harvests, while also greatly reducing the spacial requirements necessary for plant cultivation. Though this agricultural method is exemplary in its goals to maximize resource use efficiency, leafy greens such as lettuce grown in this environment are susceptible to the physiological disorder of tip burn. Tip burn in leafy greens manifests itself as visible necrosis of plant leaf tips and is caused by calcium deficiency within the plant. This calcium deficiency can be the result of accelerated growth conditions within the vertical farm, nutrient deficiencies within the fertilizers provided, or lowered transpiration due to a lack of airflow within the system. Suboptimal airflow at the leaf canopy leads to the formation of a thick boundary layer across the leaf surface, stifling the exchange of gases between the leaf and the surrounding environment. To encourage airflow and reduce tip burn occurrences, prior research has shown that vertical airflow blowing down, perpendicular to the plant canopy and leaf surfaces at a speed of $0.3\text{-}1.0\text{ m s}^{-1}$ can mitigate tip burn within a hydroponic system. The lack of research into this topic can be partly explained by the high variability within the vertical farming community, as there is very little standardization in the commercial vertical farming production system designs and practices. This study, conducted at the University of Arizona Controlled Environment Agriculture Center (UA CEAC), incorporated vertical airflow techniques and control strategies to determine the possible electrical energy savings associated with intermittent airflow as a method to reduce electrical energy costs. Within the UA CEAC's vertical farm, oakleaf lettuce

(cv. Rouxai) was grown for 28 days under a daily light integral (DLI) of $13 \text{ mol m}^{-2} \text{ d}^{-1}$, with three treatment levels of airflow; constant vertical airflow for all 28 days (Control), constant vertical airflow for the final 14 days of growth (Treatment 1), and vertical airflow during the photoperiod (16 hours per day) for the final 14 days of growth (Treatment 2).

The primary focus of this study was to explore the efficacy of intermittent airflow on mitigating tip burn in hydroponically grown lettuce in a vertical farm setting, ultimately allowing growers to maximize electrical use efficiency with respect to fan electrical consumption. Using a tip burn rating system ranging from 0 (no tip burn occurrence) to 5 (severe visual necrosis of leaves), both the number of tip burn occurrences, as well as the severity of the occurrence were recorded to determine the most efficient method of airflow distribution. Both treatments (Treatment 1 and Treatment 2) performed comparably with the goal of mitigating the widespread occurrence of tip burn within the sampled crop, with Treatment 1 performing the best. Based on the rating system employed, tip burn ratings of 0-2 are still considered marketable heads of lettuce, since their tip burn is very minimal and would be unnoticeable by consumers. Ratings of 3 and higher are considered to be wastes, as they would be unmarketable for growers, and thus represent a loss in marketable yield. Tip burn was shown to occur in 11.1% of control plants, 19.4% in Treatment 1, and 37% in Treatment 2 plants. Of these occurrences, the control had 0% waste, Treatment 1 showed 3.7% of the harvest wasted, and Treatment 2 had 6.5% of the harvest over the established rating threshold. Broken down further, 9.3% of the plants within the Control had a tip burn rating of 1, while 1.9% had a tip burn rating of 2. In Treatment 1, 10.2% had a tip burn rating of 1, 5.6% tip burn rating of 2, 1.9% tip burn rating of 3, and 1.9% tip burn rating of 4. Treatment 2 was observed to have the following breakdown; 21.3% had a tip burn rating of 1,

9.3% had a tip burn rating of 2, 3.7% had a tip burn rating of 3, and 2.8% had tip burn 4. A tip burn rating of 5 was not present throughout any of the treatment levels.

CHAPTER 1: INTRODUCTION

1.1 Background

1.1.1 Controlled Environment Agriculture

As the world population continues to increase and settle within the boundaries of large metropolitan cities, environmental stressors come to the forefront to a more significant degree. Rising urbanization rates decreased arable land, and shortages in critical resources like food and water drive the continued evolution and progress in the field of Controlled Environment Agriculture (CEA). Controlled Environment Agriculture represents the future of resource-efficient farming, allowing growers to optimize the plant environment to sustain high yields, a high degree of repeatability in both quality and yield, and resource efficiency through reductions in water, space, and fertilizer use. One method of CEA that has proven its worth is hydroponic greenhouse crop cultivation, where farmers have been able to consistently demonstrate the ability to produce higher yields with better quality than that of traditional field agriculture (Barbosa, et al., 2015). The advantages of CEA also allow for crop cultivation in places with unsuitable conditions for field agriculture, providing a solution to feed those living within the increasingly common phenomena of “food deserts” in communities worldwide with fresh produce that would ordinarily not be present (Dutko, Ver Ploeg, & Farrigan, 2012).

1.1.2 Vertical Farming

Taking into account the progression seen in Controlled Environment Agriculture and greenhouse technology, there still remains a noticeable issue with rising populations in both the United States and the world overall. The world population is estimated to reach 9.7 billion by 2050 (United Nations, 2017), and 68% of this massive population is expected to reside in urban

areas by the same year (United Nations, 2018). Because of this unprecedented growth, agricultural methodology must find a way to keep pace with the continuous rise in human population, and find a solution to production in urban settings, since that is where the majority of the population lives. With fresh and sustainably grown food becoming a priority in more and more homes, vertical farming provides an answer to this growing question. By creating a growing environment specifically tailored to the needs of the plant, vertical farming is able to optimize the growing process to excel in both resource and spatial use efficiency when compared to other forms of Controlled Environment Agriculture. Utilizing multi-tiered indoor hydroponic or aeroponic agricultural methods, multiple levels of plants are able to be stacked on top of each other, allowing for a significant boost to the possible planting density of a facility. Relying upon completely controllable components like LED light fixtures, temperature controls, and other manipulated environmental conditions, vertical farms are capable of operating entirely independently of the outside environment, further improving on the benefits of greenhouse agriculture. With commercial vertical farm companies repurposing old warehouses within metropolitan areas, the issue of feeding the rising populations in urban settings can be better addressed while simultaneously avoiding high transportation costs.

1.1.3 Optimising Plant Growth

With indoor crop cultivation methods seen in vertical farming, the plant-growing environment has the ability to be tailored to the specific needs of the plant in question. Because a multitude of crops can be grown in this setting, the environment can be altered to match the needs of the crop in question, lending to vertical farming's great versatility in output. Among these controllable environmental factors are light quality and quantity, temperature, humidity, nutrient solution, and carbon dioxide content in the air. Manipulating and optimizing these

factors to best suit the needs of the crop in production is a vital contributor to the benefits of vertical farm agriculture moving forward in society.

Among the factors optimized for accelerated growth within a vertical farm, humidity and temperature play a significant role. In general, higher air temperatures contribute to increased photosynthetic ability which translates to higher crop yields due to increased biomass production (Thompson, et al., 1998). Controlling the humidity of the growing environment is also a crucial factor in the growing process, as too high of a humidity inhibits gas exchange between the plant and its environment and could also lead to fungal development, while too low of a relative humidity can cause drought stress reactions in a plant, such as stomatal closure to preserve interior water reserves (Kroggel & Kubota, 2017). While manipulating these variables is an important part of optimizing the environment, the dependence on electricity to power the HVAC heating and cooling, as well as dehumidification can lead to significant expenditures, one of the main bottlenecks in the proliferation of vertical farming. To circumvent this issue, it is crucial for growers to take into account the value of their crop and the electrical use efficiency (EUE) of their system as a whole.

The lighting environment is also a very critical aspect of indoor crop cultivation. Because vertical farming does not afford the plants any natural sunlight, the photoperiod, spectrum, and intensity are all dictated by growers to ensure the most efficient use of their resources and maximize output. LED lights are commonly used to supply artificial lighting in vertical farm settings for leafy greens. Using LEDs, growers are able to select the wavelengths most beneficial to the plants being grown, from the Photosynthetically Active Radiation (PAR) spectrum which includes wavebands of length 400-700 nm, with new research further expanding this range to 400-750 nm as the effects of far red light begin to show beneficial effects to crop growth (Zhen

& Bugbee, 2020). There are two main ways to quantify the availability of light to a plant, the Photosynthetic Photon Flux Density (PPFD) and the Daily Light Integral (DLI). The PPFD represents the instantaneous quantity of photons per second a plant receives, measured in $\mu\text{mol m}^{-2} \text{s}^{-1}$, while the DLI represents the total photons a plant receives over the course of a day, measured as $\text{mol m}^{-2} \text{d}^{-1}$. The DLI is the totality of the PPFD throughout the day and is a factor of both lighting duration (photoperiod) and intensity. A DLI of $13 \text{ mol m}^{-2} \text{d}^{-1}$ has been found to increase crop yields, while also keeping the risk of tip burn within leafy greens to a minimal value (Caplan, 2018).

Carbon dioxide concentration and nutrient solution are also important factors to control in an indoor agriculture environment. Higher CO_2 concentrations within a plant environment help to boost the photosynthetic rate of the plants inside, helping to encourage accelerated crop growth and raise the threshold of attainable harvest biomass. Supplementing CO_2 to a level of 850 parts per million (ppm) has been shown to yield the best results, as going beyond this point increases the occurrence of tip burn and diminishes the effect on transpiration for the leafy greens (Caplan, 2018). The nutrient solution sustaining the plants inside an indoor vertical farm is tasked with providing the plants with all of the essential nutrients required for healthy growth in ideal concentrations. Directly monitored and controlled through sensors and pumps, the root zone environment and available nutrients to the plant support the accelerated growth rate that characterizes indoor agriculture. Due to the sterile nature of the vertical farm environment, infiltration of pests and insects is also an infrequent issue, lowering the need for pest management through pesticides or integrated pest management (IPM). Combining the knowledge of plant physiology and the capability of sensors and controls to maintain an optimized environment, vertical farms can produce significantly more fresh produce with better

spatial and resource use efficiency than greenhouses or traditional field agriculture, at the detrimental cost of increased energy consumption due to the significant reliance on electrical power (Graamans, et al., 2018).

1.1.4 Leaf Boundary Layer

The boundary layer over a plant's leaf is a unique factor that must be considered in Controlled Environment Agriculture production, an issue that is not present in traditional field agriculture. The leaf boundary layer is described as a layer of stagnant air surrounding the leaf of a plant and greatly affects the ability of the plant to exchange gases with its environment. With a thick boundary layer, the stomata on the leaf's surface in charge of facilitating gaseous intake and output are stifled, leading to lowered rates of plant transpiration, and negatively impacting the overall health of the plant (Runkle, 2016). To remedy this issue, airflow must be mechanically stimulated within an indoor planting environment to mix the air and disrupt the stagnation of air around the leaf surface. Without the addition of airflow to the indoor system, the plants become increasingly stifled in their ability to release water vapor into the surrounding environment. Failure to expel water vapor from stomata leads to a reduction in water uptake in the plant, an essential process for bringing nutrients into the plant as well. With this lowered rate of water and nutrient uptake, crop deficiencies can establish themselves and deteriorate the health and visual perception of a crop (Kitaya, et al., 2000).

1.1.5 Tipburn in CEA

Accompanying the accelerated growth rate and increased biomass production achieved by indoor controlled environment cultivation, the physiological disorder called tip burn is also a factor to consider. Tip burn is a calcium deficiency affecting the younger developing leaves of leafy greens, as weak cell walls, a symptom of inadequate calcium uptake, cause the laticifer

cells to rupture (Collier & Tibbitts, 2011). The manifestation of this deficiency culminates in the necrosis of new leaf growth in leafy greens, resulting in a brown or black leaf tip showing signs of crinkling, representing something similar to burnt paper. This is a significant detriment to leafy green production within a vertical farm, because lettuce, as with most leafy greens, is normally consumed raw, and as such needs to be aesthetically pleasing to the consumer. Damaged produce showing signs of tip burn will negatively impact growers as they will be unable to sell the product affected by this deficiency. A further consideration affecting the proliferation of tip burn is the rapid growth that is made possible by the optimized growing environment present within a vertical farm. Because accelerated cellular expansion encourages tip burn, it can be much more commonly seen in older crops, especially in CEA settings where an increased growth rate is established and maintained (Saure, 1998).

Nutrient uptake is the key point of stress within the growing lifecycle of leafy greens in an indoor vertical farm because as the plant grows, the meristem has gradually decreasing ventilation. This lowered ventilation rate causes the boundary layer around the plant leaf to establish a microclimate with increased temperature and relative humidity, stifling the leaf and precluding adequate gas exchange (Caplan, 2018). The reduced transpiration rate caused by the thick boundary layer combined with increased nutrient requirements necessary to sustain accelerated growth leads to an overall increase in tip burn occurrence (Kitaya, et al., 2003; Goto & Takakura, 1992). The issue of a thickened and sustained boundary layer can be overcome through airflow within the vertical farm environment to disrupt the boundary layer and promote adequate rates of gas exchange. The re-establishment of proper gas exchange for the leafy greens in an indoor cultivation setting allows for uninhibited nutrient uptake for the plant, allowing necessary elements to carry out their functions. Providing proper mixing of the air in the indoor

environment allows plant cell walls to be formed in the proper manner, leading to the establishment of healthy new leaves without the necrotic appearance of tip burn. All forms of airflow provided to plants are not equally as effective however, as vertical airflow directed down onto the leaf canopy was shown to be significantly more effective at mitigating tip burn than horizontal airflow directed over the top of the canopy surface (Kaufmann, 2023).

1.1.6 Energy Use in Vertical Farming

Consumption of electrical energy is one of the most significant limiting factors in the widespread implementation of vertical farms across the world. Because all environmental conditions like lighting, temperature, and humidity are not naturally occurring within an indoor environment as they are in a greenhouse or field agriculture, the electrical consumption of an indoor plant system is greatly exacerbated. Reliance on artificial lighting, heating and cooling, constant dehumidification, and a comprehensive sensor array contributes to an overall greater electrical consumption need than hydroponic greenhouses, even those with climatic controls (Graamans, et al., 2018; Zhang & Kacira, 2020). Whereas both traditional field and greenhouse agriculture can utilize surrounding environmental conditions to save energy with lighting or temperature regulation, this is not the case for an indoor cultivation system. These two factors, lighting and temperature control are the most expensive components of indoor agriculture operations (Zeidler, Schubert, & Vrakking, 2015).

Where all lighting within a vertical farm must be artificially supplied, this is not the case in greenhouse production. Lighting in a greenhouse is provided naturally by the sun, and at most, supplemental lighting may be needed to further expand the photoperiod. This photoperiod expansion is dependent on crop DLI needs as well as the location and orientation of the greenhouse, since these factors dictate the quantity of light afforded to the plants within.

Temperature control within a vertical farm is also artificially done using a closed system HVAC. Heating and cooling in a greenhouse can be stimulated through the opening and closure of ventilation flaps, the operation of exhaust fans, or other methods like evaporative cooling and hot water pipes. The air mixing caused by exhaust fans or natural air movement throughout a greenhouse also helps to break up the boundary layer and promote homogeneity within the aerial growing environment. Interior lighting systems within a vertical farm also radiate heat, further contributing to costly spending to maintain a suitable interior environment.

1.2 Literature Review

1.2.1 Tipburn Reduction

Mitigating the effects of tipburn on leafy greens in a controlled environment setting is the priority of many research studies and the resulting papers from the experiments. The physiological defect that causes a decrease in calcium uptake to leaf tips is an especially significant factor when it comes to commercial leafy greens, since for the most part, these are produce that are consumed raw. For this reason, an aesthetically pleasing head of lettuce is essential for the profits of sellers nationwide, as the color and texture defects are much harder to ignore when the lettuce is being consumed fresh.

Studies into the reduction of tipburn have explored multiple avenues of mitigation, one of which being the electrical conductivity (EC) of the nutrient solution used to irrigate the plants during growth. One such paper written by Uttara Samarakoon and Jack Palmer explored the relationship between tipburn occurrence and different EC levels of 1.4, 1.6, 1.8, and 2.0 $\text{mS}\cdot\text{cm}^{-1}$. Through this research, it was found that increasing the EC in the nutrient solution beyond the recommended 1.8 $\text{mS}\cdot\text{cm}^{-1}$ did not result in any significant reduction of tipburn. The logic

behind this study was built around the hypothesis that increasing the salt content of the nutrient solution could potentially yield higher rates of calcium uptake in the lettuce. Conversely, the results of the experiment showed that increasing the EC to $2.0 \text{ mS}\cdot\text{cm}^{-1}$ “did not contribute to additional uptake of most of the essential elements” (Samarakoon, et al., 2020), and in fact resulted in extra nutrients remaining in the solution, ultimately “leading to fertilizer waste if the nutrient solution is not reused” (Samarakoon, et al., 2020). Applying a lower EC solution to the lettuce resulted in lowered yield with respect to the usable biomass of the lettuce, another factor that is important to both growers and sellers. Overall, this study showed that neither increasing nor decreasing the EC in the lettuce nutrient solution from $1.8 \text{ mS}\cdot\text{cm}^{-1}$ was a suitable solution for reducing tipburn in lettuce grown in a controlled environment setting.

Another factor related to the formation and spread of tipburn within leafy greens is the accelerated rate of growth they are subjected to in controlled environment agriculture (CEA) (Cox, Mckee, & Dearman, 1975). Because CEA is focused on optimizing the environment to best suit the needs of the plant, the plants are pushed to their physiological limit with respect to environment temperature, carbon dioxide (CO_2) availability, nutrients, and humidity. This increased growth rate is correlated to an increase in tipburn development, as the plants are grown with higher levels of stress than would normally be present in traditional field agriculture (Frantz, et al., 2004). Attempts to use temperature as a deterrent for tip burn have also been explored and resulted in the findings that a lower temperature causes a delay in tipburn symptom onset, while an increased temperature accelerates the occurrence of tip burn (Cox, et al., 1975) because the temperature has an “effect on vapor pressure deficit around the meristem and effect on growth rate” (Frantz, et al., 2004). In the case of reducing the temperature in the growing environment, this results in a decreased growth rate for the lettuce, putting them under less stress

than a more accelerated life cycle. Figure 1 further illustrates the relationship between environmental temperature and the timing of tipburn occurrences.

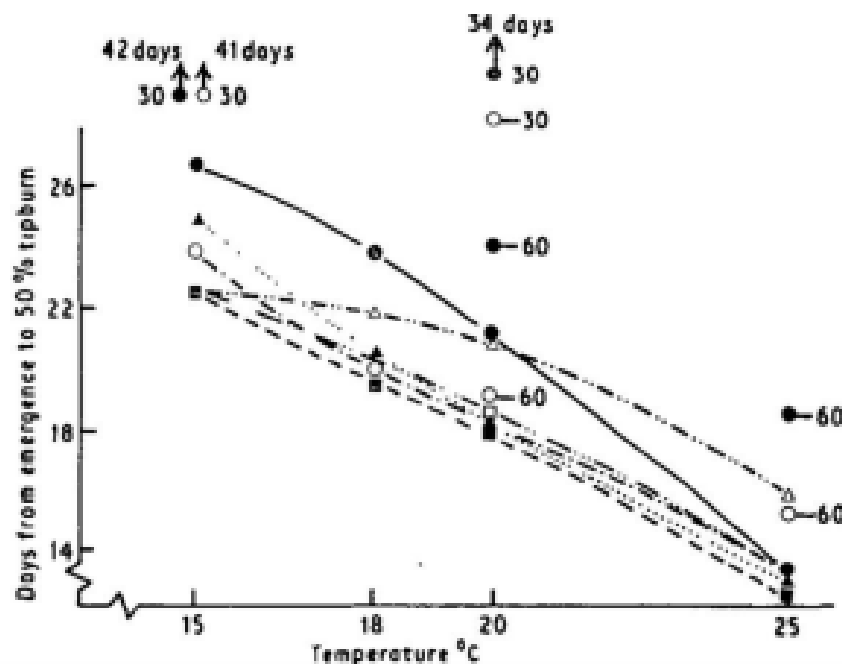


Figure 1: Effects of temperature on tipburn development in 6 lettuce cultivars at 120 W m⁻² (Cox et al., 1976).

Aside from temperature, other environmental factors the lettuce is exposed to, such as CO₂ and lighting also play a part in tipburn occurrence and severity. According to a study conducted by Caplan (2018), lettuce plants grown in an environment with elevated carbon dioxide levels displayed a higher growth rate, which also contributed to earlier occurrences of tipburn. As the growth rate of the lettuce increases, the plant meristem is encroached upon and crowded, causing a suffocating mix of high temperature and relative humidity in the microclimate of the plant growing point (Caplan, 2018). This effect causes a thick boundary layer over the meristem of the lettuce plant, preventing it from exchanging gases and transpiring in an efficient manner, leading to deterioration of the cell wall and the accompanied failure to uptake calcium into leaf tips (Caplan, 2018). This effect can be somewhat controlled through

airflow directed into the core of the plant (Goto & Takakura, 1992; Goto & Takakura, 1992; Frantz, et al., 2004), a concept that is also explored in deeper detail in this paper. Lighting is also a major factor in the growth rate of lettuce, and the resulting tipburn that accompanies this acceleration. Increasing the intensity of the lighting supplied to the plants also increases the rate at which tipburn appears in the growing process (Sago, 2016), and since this is a cumulative effect, severity is increased by the time of harvest (Cox, Mckee, & Dearman, 1975). It has been found that a daily light integral (DLI) within the range of 11-13 mol m⁻² d⁻¹ (Caplan, 2018) is optimal for maximum crop yield (*cv. Fairly*) while also maintaining minimum tipburn occurrence. Further manipulation of light in CEA showed that tipburn reduction in leafy greens could be achieved through decreasing the day/night cycle assuming the same DLI is maintained (Goto & Takakura, 1992). This approach has been found to be slightly flawed by others, however, as the shorter dispersed photoperiods interfere with proper climate control and nutrient uptake of the crops.

Production of leafy greens comes with a focus on the fine balance between yield and quality. As detailed in the studies above, sacrifices to quality can be made for increased crop yield or sacrifices to crop output can be made in the pursuit of higher-quality crops. Changing the growing environment of the leafy greens in question has significant and measurable effects on the overall crop output in a controlled environment setting, and it is a balance that growers constantly need to contend with. Rather than changing the environmental conditions within a CEA setting, exploration into tipburn-resistant cultivars would also be a strong solution to the problem. Having a cultivar of lettuce specifically bred for controlled environment purposes would allow growers to reduce the current overall tradeoff between yield and quality when it comes to leafy greens, ultimately achieving the goal of maximizing profits.

1.2.2 Mitigation by Airflow Over Leaf Boundary Layer

In order to maintain proper homeostasis, plant leaves need the ability to freely exchange gases with their environment, by both absorbing carbon dioxide and expelling water vapor. To accomplish this task, a thin boundary layer is preferred, as this facilitates the best exchange of gas. The boundary layer is the layer of stagnant air around the leaf surface (Runkle, 2016) that impedes airflow and exchange to the leaf itself, effectively suffocating the plant. A thick boundary layer corresponds to a microclimate with higher increased temperature and humidity within the core of the developing leafy green. Because nutrient uptake is tied to the release of water vapor, diminishing the plant's ability to expel water decreases the nutrient uptake efficiency of the plant, leading to defects like tip burn.

In a closed agriculture environment such as an indoor vertical farm, natural airflow is not a factor that can be relied upon to reduce the boundary layer and facilitate transpiration from the leaf surface. For this reason, airflow must be specifically added to the system to encourage this process, a process researched by Goto and Takakura. Their findings showed that airflow to the inner developing leaves of butterhead lettuce (*Lactuca sativa*) was an effective method of mitigating tipburn while also allowing the plants to grow at an accelerated rate (Goto & Takakura, 1992). This is because “an increase in transpiration from the leaves encouraged water and calcium uptake by the root and increased calcium concentration in the leaves” (Goto & Takakura, 1992). As shown in Figure 2 below, it can be seen that airflow during the photoperiod or dark period already shows a massive 64% reduction in tipburn occurrence, while consistent all-day airflow fully eliminated tipburn from the sample population. Being able to produce healthy plants in an accelerated growth environment such as a vertical farm plant factory is

imperative to the success of the controlled environment agriculture industry, and providing artificial airflow is a way to ensure the crop output remains high quality.

TABLE 1. Effects of air supply to inner developing leaves on tipburn development and growth of lettuce

Treatment Time	Percentage of Tipburned* Plants (%)	Leaf Age at Tipburn Emergence*‡	Fresh Weight* (g)	RGR* (day ⁻¹)	Water Content† (%)	Chlorophyll Content† (µg / cm ²)
All-day	0	–	93.3	0.198	95.9	24.8
Light period	33	26.7	84.9	0.174	95.5	24.6
Dark period	33	29.0	83.4	0.167	95.5	24.5
Control	97	19.5	76.7	0.162	95.0	27.4

Lettuce was harvested on the same day.

* Average of 12 plants.

† Average of 5 plants.

‡ Average of tipburned plants.

Figure 2: Effects of air supply to inner developing leaves on tipburn development and growth of lettuce (Goto & Takakura, 1992)

To gain further insight into the most effective airflow technique to mitigate tipburn through targeting airflow, other researchers looked into the optimized airflow speeds that would accomplish this task. Using an infrared gas analyzer to monitor gas exchange rates, it was found that “the net photosynthetic rate and transpiration rate increased significantly as the air current speeds increased from 0.01 to 0.2 m s⁻¹” and that the transpiration rate further gradually increased as air current speeds went from 0.2 to 1.0 m s⁻¹ (Kitaya, et al., 2000). These data points express the importance of proper airflow into and around a leaf canopy, as the transpiration rate and net photosynthetic rate are two factors that tie directly into the health and growth rate of a plant in production. As indicated in Figure 3 below, increased air current speeds led to a direct

decrease in boundary layer resistance, making it easier for the plants to transpire and exchange gases with the environment. As a result, the net photosynthetic rate and transpiration rate were proportionally increased as the boundary layer resistance was decreased, contributing to an overall healthier plant output, the goal of controlled environment agriculture.

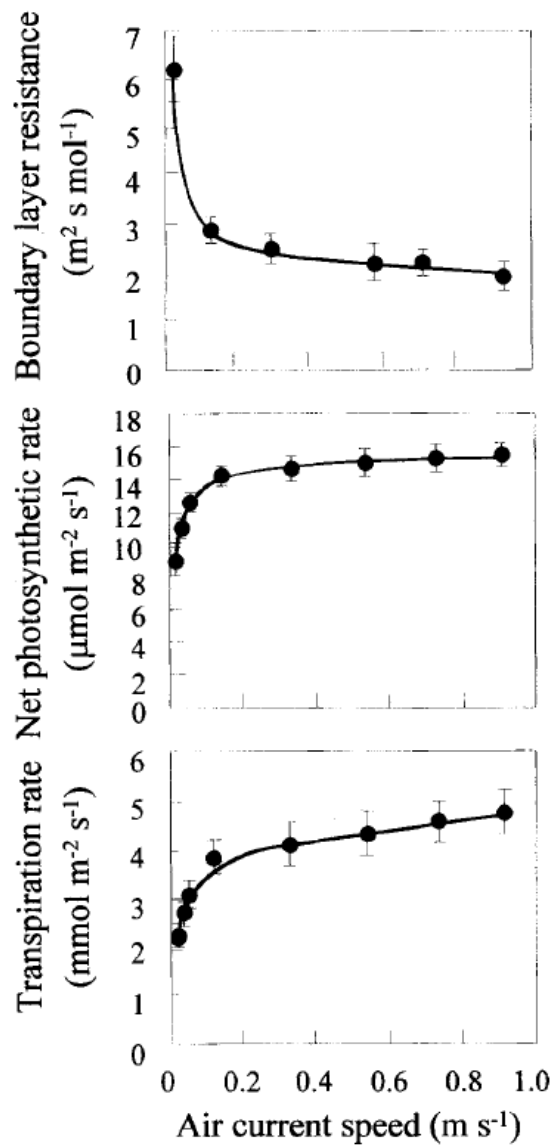


Figure 3: Effects of air current speeds on leafy boundary layer resistance, net photosynthetic rates, and transpiration rates in sweet potato leaves (Kitaya, Tsuruyama, Shibuya, Yoshida, Kiyota, 2003)

1.2.3 Airflow Distribution Optimization

Along with the accelerated growth rate that characterizes controlled environment agriculture, another key feature in the discussion of vertical farm plant factories is the consistency of product output coming from the operation. Growers are focused on both high-quality produce, but also a high degree of consistency between harvests, that way the customer always knows what to expect. Producing an available, high-quality, and readily repeatable crop harvest is the main goal of CEA growers, as these are the building blocks for success in the industry. In order to accomplish consistency in crop output and quality, the environmental conditions surrounding the plant also need to be held consistent for all the plants growing in the facility. In the case of controlled environment agriculture, these conditions include uniformity in lighting, temperature, humidity, and airflow, as well as other smaller components that make up the controls in CEA. To avoid tipburn in leafy greens, the uniformity in the airflow distribution applied to the plants is a matter of great significance, and studies have been conducted in this space to determine the best method to achieve this goal.

As previously explored by researchers studying the effects of air current speed on leafy green gas exchange, it was experimentally concluded that the optimal air current speed applied to leafy greens is within the range of $0.2\text{-}1.0\text{ ms}^{-1}$ (Kitaya, et al., 2003). This information on its own is significant to the controlled environment space, but applying the concept on a consistent basis to all the plants growing in a given greenhouse or vertical farm is another feat. In order to ensure each plant receives a standardized level of airflow strong enough to mitigate tipburn, the physical airflow delivery system must be optimized in a way that can effectively reach all plants within the system. Wells and Amos (1994) were focused on creating a uniform environment for plants within a closed greenhouse, with the end goal of uniform crop production. This was a main focus

of research because “low natural air infiltration can result in significant vertical and horizontal stratification of temperature, humidity, and carbon dioxide concentration”, all of which lead to inconsistent crops in both size and quality (Wells & Amos, 1994). To accomplish uniform airflow within the closed environment, design guidelines for a perforated polyethylene duct were established that included the number of ducts in the system, the relative position of the ducts to the crops, duct dimensions, static pressure within the duct, the number of discharge holes, and the dimensions of said discharge holes (Wells & Amos, 1994). These variables were compiled into a list of derived equations to compute the airflow necessities of a closed system and the procedure necessary for defining the use of perforated ducts in a controlled environment setting.

To accurately create an environment with airflow known to be optimal in every area, computational fluid dynamics (CFD) is necessary. Being able to model the interactions the air will have with both the environment and plants in the system is a very important task and one that takes multiple variables into account. CFD analysis and design is a cornerstone for determining and improving the airflow conditions within a vertical farm plant factory because the airflow to the plants is such a significant part of the production process. Modeling air as a fluid in a controlled environment utilizes the Navier-Stokes equations, quantifying the changes in mass, momentum, and energy of the fluid flow to accurately predict the outcome and capabilities of air ducts installed within the system (Norton & Sun, 2006). Many further research experiments have been carried out to apply this work to other controlled environment spheres, for example optimizing the airflow distribution in multi-layered vertical farm plant factories.

Using the previously mentioned computational fluid dynamics principles for airflow ducts within a controlled environment space, a 2016 study from the University of Arizona CEAC used the CFD program FLUENT to model the airflow of a single-level $1.52 \text{ m} \times 1.52 \text{ m} \times 0.3 \text{ m}$

vertical farm (Zhang et al., 2016). This study sought to build upon the principles described by Amos and Wells (1994) and find the optimal design of airflow delivery for the vertical farm system. As shown below in Figure 4, the model chosen was a perforated tube placed above the plant canopy supplying vertical airflow to the underlying plants via rows of three perforated holes at prescribed angles and distances from one another.

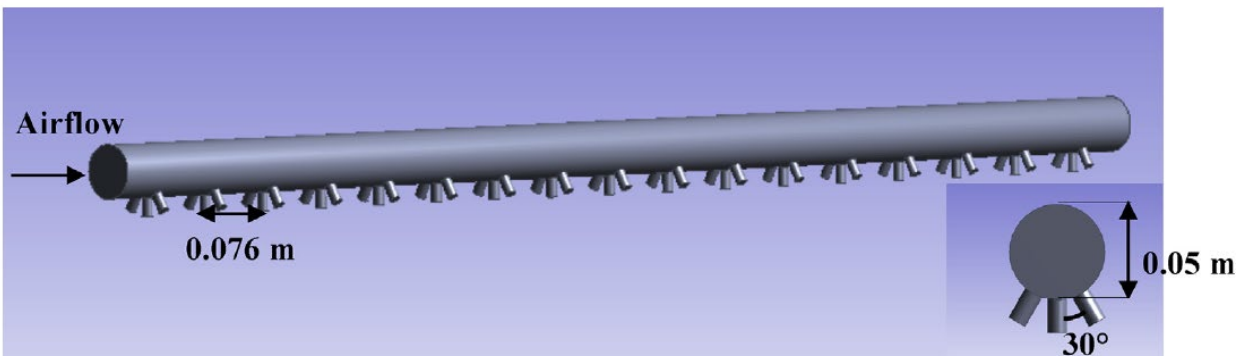


Figure 4: Design of perforated air duct for vertical airflow in a vertical farm (Zhang et al., 2016)

This duct design was chosen in order to promote more uniform airflow to the plants underneath the duct via the rows of three discharge holes, as well as to maintain a consistent aperture ratio of 1.5 to keep uniformity throughout the polyethylene duct (Zhang, et al., 2016). During the course of this project, four vertical airflow treatments and a control were compared, with the goal of finding the orientation with the lowest possible coefficient of variation (CV). Each of the treatments used the duct shown in Figure 4, but with different spacings and number of ducts per growing level, while the control level had no ducting at all, and therefore no augmented airflow past the natural airflow from the HVAC system within the vertical farm. Of the four variations in duct spacing observed, the lowest CV was observed in Case 2, with a CV of 44%, and an average air velocity of 0.42 m s^{-1} which also happened to be the highest air velocity of the group as well. this treatment was composed of two air ducts evenly spaced from the middle of

the modeled environment, providing the growing area with the most uniform airflow profile of the group. In contrast, the configuration (Case 4) that employed four evenly spaced air ducts had a CV of 45% and an average air velocity of 0.28 m s^{-1} , meaning it performed worse despite the fact there were more ducts and seemingly more airflow. The reason behind the decrease in efficiency when using four air ducts instead of two is that having too many air ducts results in disruptions in the airstream discharge holes pointing in opposite directions, ultimately creating a decreased average velocity for the growing environment (Zhang, et al., 2016) as illustrated in Figure 5 below.

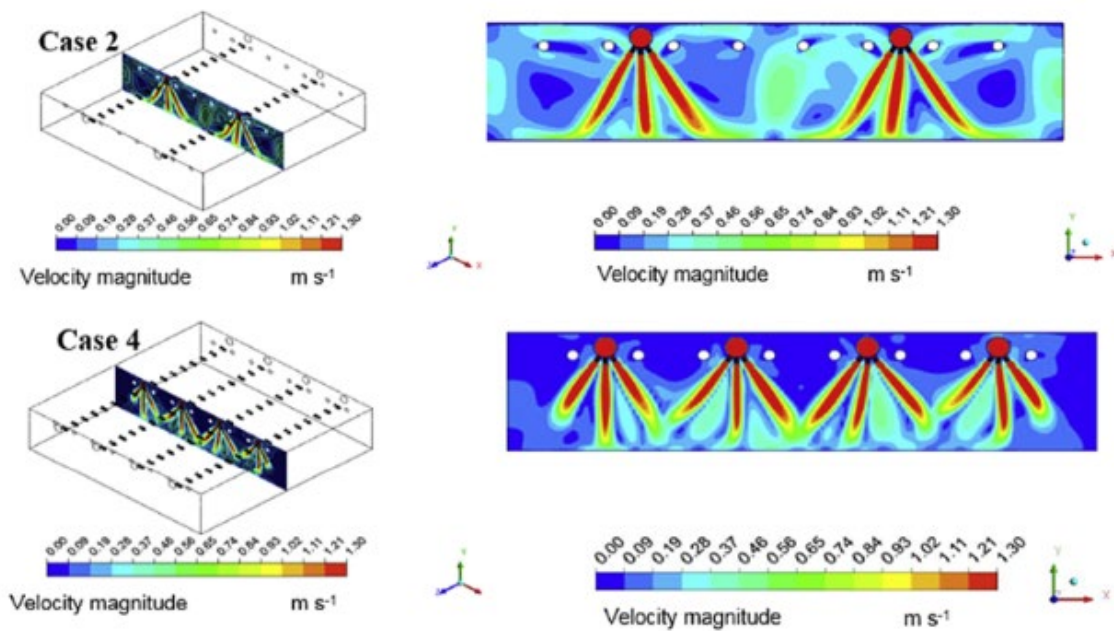


Figure 5: Duct configuration with the most uniformity (top) compared with duct configuration with the greatest number of ducts per level (bottom) for CFD analysis with a vertical farm (Zhang et al., 2016)

Modeling vertical airflow systems through computational fluid dynamics is a very helpful tool in determining the most ideal conditions based on theory and mathematical principles. It is important, however, to then implement these models in a real scenario to observe how effective the method truly is. Experimental data may differ from theoretical data because of real-world

effects that cannot be modeled, like the cycling of the HVAC systems or the physical plant leaf surfaces within the vertical farm chamber. For this reason, even though modeling and CFD analysis is a strong tool in airflow optimization, it also needs to be experimentally verified to confirm the duct efficiency and uniformity in a closed agriculture environment.

1.2.4 Vertical Airflow to Reduce Tipburn

As previously explained, providing CEA-grown leafy greens with adequate airflow is vital to mitigating tipburn and preserving the quality output of the harvest. To properly achieve this goal, it was found that a combination of factors needed to be at play. When brought to the basics of supplemental airflow to facilitate healthy plant transpiration and avoid tipburn, the two main necessities are an air velocity within the range of 0.2-1.0 m s⁻¹ (Kitaya, et al., 2000) and a uniform air distribution system, in this case using perforated polyethylene ducting (Zhang, et al., 2016). In a vertical farm environment, supplemental airflow can be provided to the plants in two ways, either through horizontal airflow over the top of the plant canopy, or vertical airflow that supplies air directly into the lettuce meristem. Horizontal versus vertical airflow delivery affects not only the plant health through production but also plays a part in the overall design of the vertical farm itself, since the ducting and fan placement need to be planned carefully to be implemented in a small area high-efficiency environment such as a vertical farm.

To decide between horizontal (HAF) and vertical airflow (VAF), the mechanics of air movement in real life need to be compared to that of the theoretical models. Through modeling, horizontal airflow was shown to provide uniform airflow across the top of the leaf canopy (Kitaya, et al., 2000), but also struggled to supply adequate airflow to the inner core of the lettuce plants, while also requiring a higher air velocity to be effective (Chang & Miller, 2004). Horizontal airflow may also be rendered ineffective as plants continue to grow and the canopy

becomes thicker because as the plant canopy expands, a wind barrier is created that disturbs the uniform sheet of air supplied from the horizontal airflow ducts, resulting in sporadic and turbulent airflow applied to the plants. Because vertical farm plant factories are so highly focused on repeatability and consistent quality, this is an option that is not acceptable to growers or their customers. Using horizontal airflow blowing over the leaf canopy was found to result in a “decreasing gradient from the blower toward the opposing end of the level”, with the highest velocity nearest to the duct discharge holes and the slowest on the far side away from the duct (Kaufmann, 2023). Because of this decreasing air velocity gradient, the resulting harvest showed lowered levels of tipburn near the fan outlet, but increasingly higher rates as the air speeds died down further away from the discharge points (Kaufmann, 2023).

Comparing the effects of vertical and horizontal airflow supplied to lettuce cultivars of Klee and Rouxai, it was found that vertical airflow was significantly more effective in mitigating tipburn, both by delaying the initial onset (Figure 6) and significantly lowering the severity of the instances that did occur (Figure 7). The vertical airflow perforated tubes designed to supply air directly to the meristem of the lettuce (Zhang, et al., 2016) were shown to be more effective than horizontal airflow at both daily light integrals (DLI) explored within this experiment, one at 15 $\text{mols m}^{-2} \text{d}^{-1}$ and the other at 13 $\text{mols m}^{-2} \text{d}^{-1}$. As shown below in Figure 6, independent of both the daily light integral and lettuce cultivar, the vertical airflow method was more effective in delaying the onset of tipburn in the plants. This is an important finding, as tipburn is an irreversible process, meaning that once it starts, it will only spread throughout the plant. Delaying its onset will result in an overall healthier plant since the disease will have less time to develop the later it is introduced. The efficiency of vertical airflow in mitigating tipburn is also highlighted in Figure 7 at both DLI levels. Focusing on the tip burn-resistant Rouxai cultivar, at a

daily light integral of $15 \text{ mols m}^{-2} \text{ d}^{-1}$, 75% of plants experienced tipburn with horizontal airflow, while 29% experienced tipburn using vertical airflow. This trend is also present at $13 \text{ mols m}^{-2} \text{ d}^{-1}$, where the data showed tipburn occurrences of 65% for horizontal airflow and 13% for vertical airflow. Combining the delayed onset of tipburn with the lowered observation count while using vertical airflow, the overall average severity of the disease was also significantly lowered when utilizing VAF over HAF. At DLI $15 \text{ mols m}^{-2} \text{ d}^{-1}$, the Rouxai lettuce grown with horizontal airflow had 34% of their leaves burned, while vertical airflow had 3% tipburned leaves on average. At a DLI of $13 \text{ mols m}^{-2} \text{ d}^{-1}$, 25 % of HAF leaves were burned, while only 2% of VAF leaves had damage (Kaufmann, 2023).

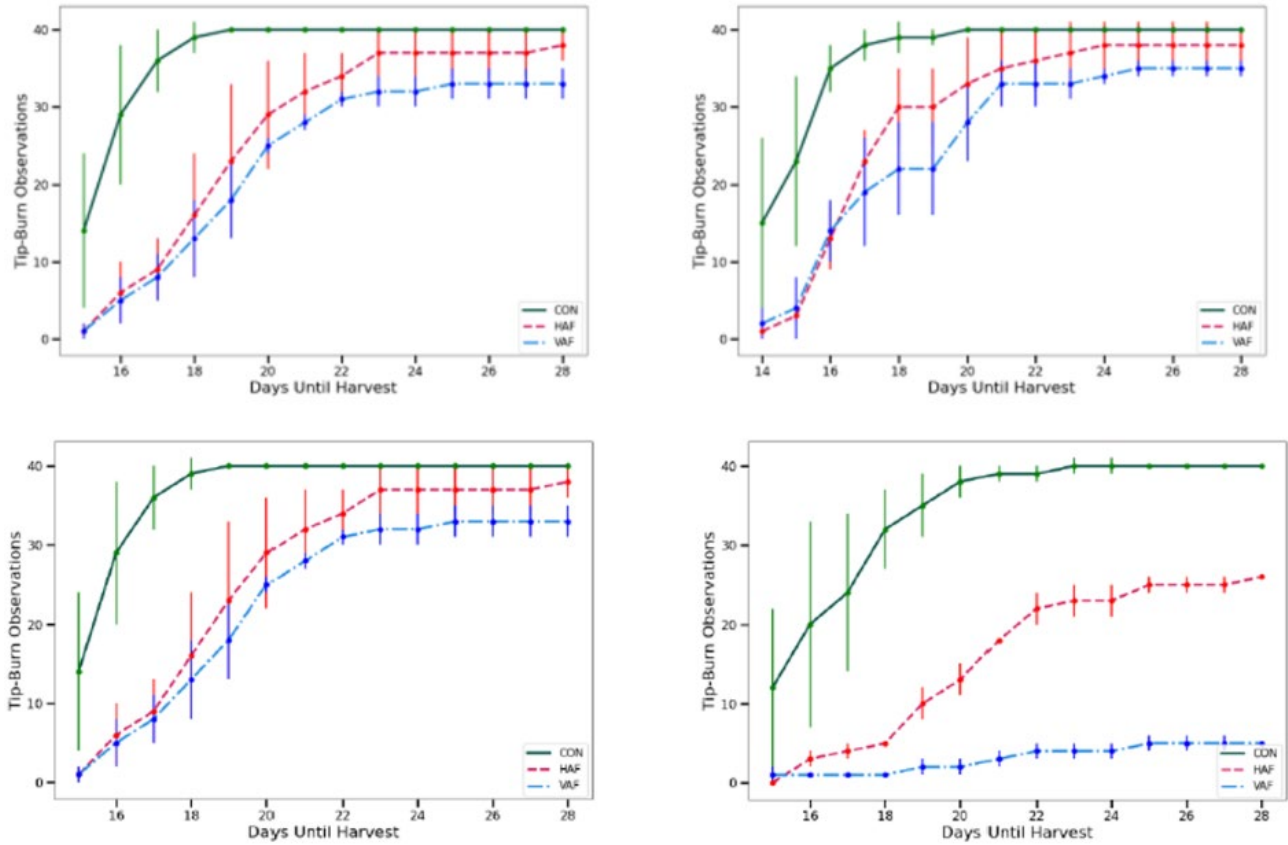


Figure 6: Average number of tipburn occurrences for Klee (left) and Rouxai (right) lettuce cultivars for days until harvest at DLI of 15 mol m⁻² d⁻¹ (top) and 13 mol m⁻² d⁻¹ (bottom) comparing horizontal (red) and vertical (blue) airflow. (Kaufmann et al. 2023)

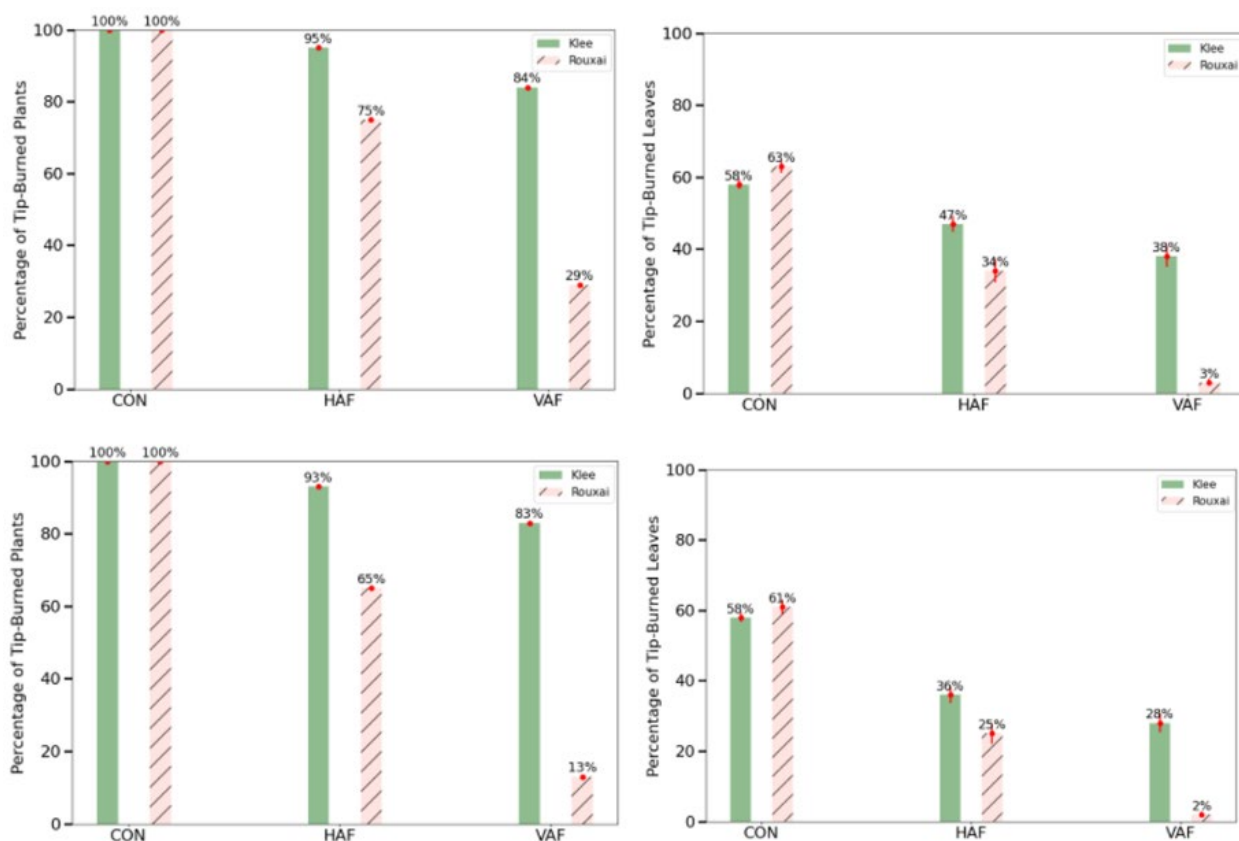


Figure 7: Average percent of plants showing tipburn (left) and average number of tip-burned leaves per plant (right) at DLI 15 mol m⁻² d⁻¹ (top) and DLI 13 mol m⁻² d⁻¹ (bottom) when comparing horizontal (HAF) and vertical (VAF) airflow (Kaufmann et. al, 2023)

Comparing the results of using horizontal and vertical airflow to mitigate tipburn in Rouxai lettuce, it is clear that vertical airflow is significantly superior to other methods and more effective. The ability to blow air at the optimized velocity of 0.2-1.0 m s⁻¹ (Kitaya, et al., 2000) directly into the plant meristem rather than over the top of the leaf canopy is shown to accomplish the task at hand much better than its competitor, resulting in plants with significantly decreased tipburn severity and overall occurrence.

1.2.5 Energy Use Efficiency in Vertical Farming

One of the greatest barriers to entry for large-scale commercialization of vertical farming is the electrical energy required to run the facility, and the costs attached to the energy load. The factors that make the vertical farm plant factory so efficient in growing plants also serve as a hurdle by requiring large amounts of electricity to operate. Compared to traditional field agriculture or greenhouse agriculture, vertical farms consume the most energy, due to the fact that it is an entirely closed system. Reliance on energy for lighting, temperature, humidity, sensors, irrigation, airflow, and the multitude of smaller components within the plant factory make the overall process highly energy dependent, especially compared to other forms of agriculture.

In the pursuit of high profit margins while keeping quality consistent, resource use efficiency, especially that of paid resources like electricity, is a significant factor to be considered. In a study comparing the resource use efficiency of plant factories and greenhouses located in different regions (the Netherlands, United Arab Emirates, and Sweden), it was found that “plant factories outperform even the most efficient greenhouse” (Graamans, et al., 2018) when considering the resource input per kilogram of harvest. This finding, however, was mainly due to the fact that plant factories are incredibly efficient with respect to water, carbon dioxide, and land area, but not so much with purchased energy. Because greenhouses are able to utilize the free energy from the sun for photosynthesis, the requirements for purchased energy fall mainly to heating and other components, while vertical farms require large amounts of electricity for lighting in addition to all other variables within the system. Comparing the electrical use efficiency for one kilogram of dry-weight lettuce, an energy input of 247 kWh, while the most energy-intensive greenhouse in the study required 211 kWh to produce one kilogram dry-

weight lettuce (Graamans, et al., 2018). Despite the disparity in electrical consumption between plant factories and greenhouses, arguments can be made for the year-round consistent efficiency of a plant factory. As shown below in Figure 8, greenhouses, independent of their location, suffer fluctuations in production as a function of dry weight throughout the year, while plant factories are able to maintain the same level of maximum production all year. With greenhouses only meeting the plant factory level during the summer months with their greatest level of production, it is clear that vertical farms are able to outperform greenhouses on a production consistency level, despite their added energy input demands.

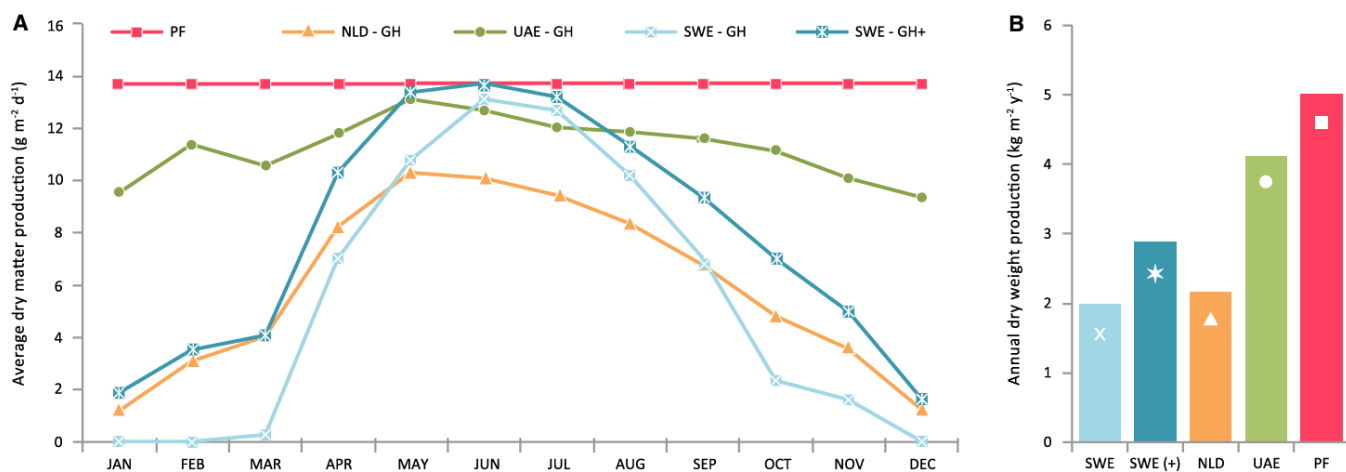


Figure 8: (A): Average daily dry matter production in grams per square meter per day for plant factories versus greenhouses in multiple locations. (B): Total annual dry weight production in kilograms per square meter per year.

(Graamans et al. 2018)

The elevated electrical requirements of plant factories directly contribute to higher operational costs for the system overall. For agriculture in Southern Arizona, it was found that energy costs average 17.1 cents per kWh during peak summer hours, 12.9 cents per kWh for off-peak summer hours and winter hours, and 11.6 cents per kWh for off-peak winter hours (Caplan, 2018). These values apply only to Southern Arizona however, as energy prices vary in different

regions, and overall operational costs will also depend on a system's location, size, crop being produced, and the growing methods used within. A study looking into the energy use efficiency for two greenhouse cases and two plant factory cases used a simulation to compare the annual lettuce biomass yield and energy consumption (Zhang & Kacira, 2020). The energy consumption analysis took into account lighting, heating, and cooling for six geographic locations with different climates, including Duluth, Minnesota; Seattle, Washington; Phoenix, Arizona; Miami, Florida; Abu Dhabi, UAE; and Riyadh, KSA. The study found that plant factories in cold climates using high-efficiency LED lighting were superior to greenhouses, with the two plant factory cases producing a resource efficiency of 0.13 kg kWh^{-1} and 0.14 kg kWh^{-1} , while the greenhouse cases produced 0.10 kg kWh^{-1} and 0.11 kg kWh^{-1} respectively (Zhang & Kacira, 2020). In high-light locations, however, the greenhouses were more energy efficient than the plant factory cases, the highest of which being an energy use efficiency of 0.35 kg kWh^{-1} (Zhang & Kacira, 2020). Increasing the energy use efficiency of plant factories as a whole is a main focus in the field, as maximizing this value through minimizing energy use will save the vertical farming industry massive amounts of money. This aim is the drive behind the present study and many others, looking into how to minimize the time of use for different controls strategically within the plant factory while also keeping harvest quality at the highest level.

1.2.6 Viability of Large-Scale Vertical Farming

The viability of large-scale vertical farms as a whole is another significant factor that must be considered when looking into resource use efficiency optimization. While attempting to mitigate the barrier to entry in this field by lowering operational costs, it must first be taken into account whether or not plant factories make commercial sense, or if they are only viable in small-scale applications like a research laboratory. In these terms, viability is determined by the

economic feasibility of vertical farming to see if they are a sustainable market rather than just a drain of resources. Large communities across the world share a common struggle in feeding their occupants fresh produce, a problem that continues to feed itself and only worsens. While the stress on arable land continues to increase with increasing food demands, urbanization is simultaneously subtracting the amount of available land to set up large-scale agriculture. Because of this relationship, as cities and communities continue to grow and urbanize, a move needs to be made to a form of agriculture that does not require arable land or large amounts of space, such as vertical farms and plant factories.

In a feasibility analysis conducted by He Zhang and their team, it was found that the breakeven point for a vertical farm was on average 11.5 years, a number that could increase or decrease depending on the size of the operation and the maintenance practices being conducted (Zhang, Asutosh, & Hu, 2018). This study was performed by implementing vertical farms in a Chinese university to provide fresh produce for its canteens and then running an economic analysis of what the school saved over time. After the breakeven point was reached, annual profits of \$92,000 were expected, and similar models using the central limit theorem could be created for other institutions of different sizes and demands (Zhang, Asutosh, & Hu, 2018). This economic analysis also does not take into account the savings on transportation costs that would also accompany the proliferation of indoor vertical farms. Having access to fresh produce within city limits is a crucial next step as society continues to expand and farmland is consumed. Requiring minimal real estate but retaining a high planting density, plant factories are readily able to be implemented in urban landscapes such as New York City or Chicago, where conditions may not necessarily support a greenhouse or field agriculture. Having the ability to grow plants

independent of the outside environment, soil condition, or any other limiting factor is a significant reason for the expansion of the vertical farming industry.

These results are similar to the findings of another study which found that through analysis of the net present value (NPV), internal rate of return (IRR), and the payback period of an indoor vertical farm in Aarhus, Denmark, the vertical farm was able to recoup losses to investors in a much more efficient way than standard greenhouses, even in lower population-dense areas (Despoina Avgoustaki & Xydis, 2020). The study found that for basil production, the average annual harvest of basil for the greenhouses in question was 16,875 kilograms per year, while indoor urban vertical farms were able to produce an average of 33,750 kilograms of basil per year. When comparing the same crop side by side between greenhouses and vertical farms, having double the production from a vertical farm is a very significant benefit to consider, when taking into account how much more business that affords to the grower. As shown in the table below (Table 1), the operational costs for producing basil in an indoor urban vertical farm also come out to less than that of a greenhouse. While the electrical consumption of the vertical farm is significantly higher than that of the greenhouse, significant savings were found in the real estate lease, heating costs, water, and nutrients (Despoina Avgoustaki & Xydis, 2020).

	GH		IUVF	
	Annual Cost (€)	Total in %	Annual Cost (€)	Total in %
Real estate lease	43,058	28.4%	7087	4.7%
Lights electricity	13,443	8.9%	49,290	32.6%
Ventilation electricity	35	0.2%	520	0.3%
Electricity demand charge	6050	4%	13,897	9.2%
Heating cost (NG)	26,603	17.6%	15,805	10.4%
Water	1677	1.1%	882	0.6%
Nutrients	1149	0.8%	574	0.4%
Seeds	7031	4.6%	7031	4.6%
Package	556	0.4%	2511	1.7%
Labor	53,200	35.1%	53,200	35.1%
Total OPEX	152,802		150,800	

Table 1: Operational expenditures (OPEX) for a greenhouse (GH) and indoor urban vertical farm (IUVF) (Avgoustaki and Xydis, 2020)

Though the two studies reach a similar conclusion in favor of vertical farming viability, they differ in the methodology used to arrive at this conclusion. In the study by He Zhang, vertical farms were implemented to be the sole crop source of the university's canteens, allowing a direct comparison to be made between the price of importing all of the fresh produce and producing the crops themselves. This analysis was also based upon the knowledge that universities have diversified streams of income, and can thusly afford to miss out on profits for a short time before starting to make their money back. The main objective of this study was to determine how long that payback period was and to see if stresses on land availability and resources could be decreased. In the paper by Despoina Avgoustaki, economic analysis was conducted on pre-existing greenhouses and vertical farms, so there was no direct change in the procedure for these places. Also, the variables in question were different, as the analysis was focused on the economic markers of a viable product, not the time it takes for the overall project to become profitable. By focusing on the IRR, NPV, and payback period, the researchers presented the final data in terms of what a prospective investor or business owner would be

concerned with, instead of an institution that can afford to take a decreased profit line for at least 10 years before seeing any money inflow.

Analyzing the profitability of vertical farms and the practices that can be taken to lower costs is another crucial part of the progression of vertical farming in the future, and a central focus for the current experiment to lower operational costs through airflow. A policy paper by James and Stephen Eaves concluded that the profitability of a vertical farm and greenhouse facility in Quebec, Canada are very similar when considering that each facility has a growing space of 1,171 m² (Eaves & Eaves, 2018). This is very important in the overall literature about vertical farms because the previous consensus was that vertical farms are significantly more expensive to run than greenhouses, and as such do not provide the same level of profitability that traditional greenhouses do. However, this conclusion is only the beginning of the analysis, because as outlined in their conclusion section, the data gathered does not account for the rapid and continuous advancements in LED lighting efficiency, the impact of building insulation in colder (and warmer) environments, and the differences in ventilation and cooling methods for different vertical farms. Because of these omissions in analysis, it can be confidently assumed that the gross profit comparison of \$184,920 for the greenhouse and \$194,334 for the vertical farm is an underestimate and that the gap between the two could potentially be wider. The policy paper conducts a one-to-one analysis, providing a breakdown of the cost for equipment, operation, lighting infrastructure, real estate, heating costs, and profits for greenhouses and vertical farms. This method of comparison allows for direct and clear lines to be drawn between the two agricultural methods and decisions to be made about which is the ideal method for certain situations. The study concluded that while vertical farms had a higher capital expense of \$587,527 when compared to the \$480,060 for a greenhouse, losses were recouped in the

decreased annual operational costs of \$282,303 for the vertical farm and \$291,717 per year to run the greenhouse in question (Eaves & Eaves, 2018). The overall culmination of the study showed that vertical farms had a similar but slightly higher gross profit margin of \$194,334, while greenhouses had a gross profit of \$184,920 per year (Eaves & Eaves, 2018).

Acknowledging the cost similarities between vertical farms and greenhouses is a key step in moving the industry forward, as the lowered property costs and steady progression in technology play a more significant role in the economics of purchasing and running a vertical farm.

1.2.7 Stomatal Activity in Leafy Greens

Similar to the way humans breathe, stomata allow plants to exchange gases with the environment, keeping the internal condition of the plant optimized. The stomata on a plant are small pores on the leaf surface that have the ability to open and close via guard cells, in order to regulate the plant's internal water and CO₂ levels (Caplan, 2018). Controlling the exchange of water vapor and carbon dioxide between the plant and the environment makes the stomata vital for plant health, and the activity of these pores dictates the efficiency of photosynthesis for the plant since transpiration is the “driving force for absorption and transportation of water and nutrients throughout the plant” (Caplan, 2018). The stomatal aperture is the amount at which the stomata are open, and the aperture also contributes to the stomatal conductance, which is the rate of diffusion of carbon dioxide into the plant and water vapor out of the plant.

Through evolution, plants have gained the ability to control the stomatal aperture, and thus the stomatal conductance, based on their circadian rhythm, allowing them to capitalize on the period in which they can perform photosynthesis, but conserve energy during the dark period. Throughout the day, the stomatal aperture dynamically adjusts to the environmental conditions surrounding the plant, following a generally rhythmic pattern. Throughout the photoperiod, the

plants' stomatal aperture continues to increase, reaching a “maximum in the middle of the light period, then decreased again before the dark period when it was minimal” (Kim, et al., 2004). This ramping up and shutting down process reveals a relationship between the photoperiod and stomatal aperture, as shown in Figure 9. Throughout the analysis of four different light qualities; (A) red and blue LEDs; (B) red and blue LEDs with green fluorescent lamps; (C) green fluorescent lamps; and (D) cool white fluorescent lamps (Kim, et al., 2004), it is apparent that independent of light quality there remains a general trend of maximum stomatal conductance during the middle of the photoperiod, and minimum conductance values during the dark period.

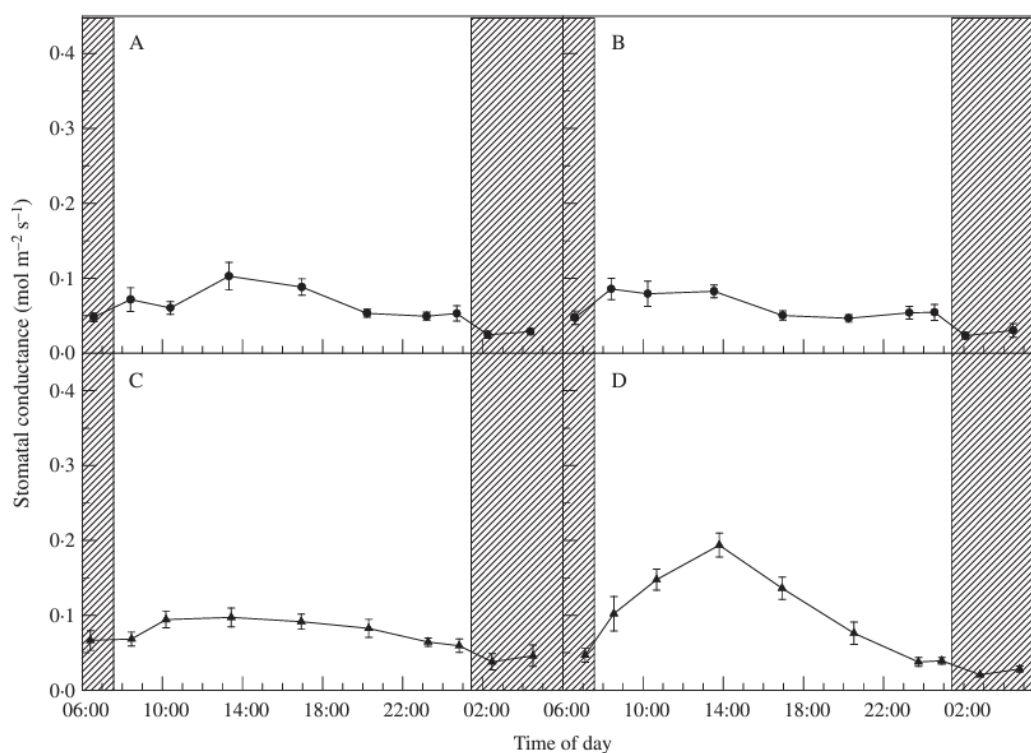


Figure 9: Stomatal conductance of lettuce leaves grown under 4 different light qualities with an 18-hour photoperiod (Kim, et al., 2004)

The stomata of leafy greens also respond to environmental conditions other than light, such as the CO₂ present in the environment. In controlled environment agriculture, especially

vertical farm plant factories focused on building the optimal environment for plant growth and yield, the carbon dioxide levels are often supplemented at a level higher than ambient atmospheric CO₂ would normally be. Helping to maximize the growth rate of leafy greens, CO₂ supplementation is also a contributing factor in the acceleration of tipburn symptoms for plants. As has been long recognized in the CEA field, “growth at increased atmospheric CO₂ often leads to substantial decreases in leaf conductance” (Field, Jackson, & Mooney, 1995). This decrease in leaf conductance means the lettuce is not able to efficiently transpire and exchange gases with the environment, leading to deficiencies in vital nutrients and calcium uptake. The release of water vapor from the plant to the exterior environment helps to promote the uptake of new water into the plant, carrying with it the nutrients that are necessary for the health of the plant (Caplan, 2018), so stifling this process will have a detrimental effect on overall plant function.

While the main objective in controlled environment agriculture is to optimize environmental conditions for growing the crop at hand, this may be another setback in the pursuit of tipburn mitigation. Luxuriant plants are those which are grown in an environment containing no limiting factor, simply put the ideal conditions (Saure, 1998). This perfection in environmental conditions such as nutrient availability, CO₂, lighting, temperature, and humidity causes the plants within the CEA system to grow an increased susceptibility to stress since they are not acclimated to any stressful conditions (Saure, 1998) throughout their life. However, plants grown in controlled environments can be strategically exposed to stress conditions by environmental control applications to enhance certain quality attribute outcomes from the production. Plants in natural conditions are required to endure stress from the natural environment such as interrupted photoperiods, sub-optimal temperatures, atmospheric CO₂ levels, and other stressors that occur in the world on a daily basis. Because the plants grown in a

plant factory are not exposed to these conditions, when they eventually encounter stress conditions in the environment, the plant has no practiced defense mechanism to protect itself, if strategically used leading to enhancements in plant quality attributes (e.g. vitamins, secondary metabolites, antioxidants, phenolics).

The conditions sought after and created within the sphere of a controlled environment agriculture plant factory are the driving factor of both the massive yields that come from the process, but also the physiological drawbacks of growing leafy greens in this manner. The stomata on leaf surfaces are in charge of regulating the gas exchange between the plant and its surrounding environment, but the conductance of the stomata is affected by almost every factor optimized in CEA. Because the life support systems within plants contain many dynamic processes, changing the environmental factors the plants are exposed to has a significant impact on the health of the plant in question. Optimizing the growth conditions within a vertical farm while also maintaining an optimal level of transpiration through maximized stomatal aperture is the key to balancing output yield, with enhanced resource use efficiencies, and production quality for growers in CEA.

1.3 Objectives

The primary objective of this study was to evaluate the efficacy of intermittent vertical airflow to mitigate lettuce tip burn and determine potentials for increased electrical use efficiency for fans within a vertical farm. The airflow methods incorporated in this study were established from previous experimentation on the application of different airflow treatments (no airflow, vertical airflow, and horizontal airflow) to mitigate tip burn in *Lactuca sativa* inside an indoor vertical farm. The effects of the treatments on the lettuce (*cv.* Rouxai) were determined by monitoring the fresh weight of edible biomass at harvest and the severity of the tip burn necrosis

visible on the leaf tips. A cost-savings analysis, based only on electrical energy used to control airflow, was also conducted to represent the potential savings for growers by incorporating intermittent airflow into similar systems.

1.4 Author's Role in the Research Effort and Publication

Erick Dzeketey was the sole individual responsible for the research presented in this thesis document. He formulated, designed, and executed an experiment spanning two trials in the UA Vertical Farm facility at the University of Arizona's Controlled Environment Agriculture Center. Erick managed the complete lettuce cultivation process, executed all data collection and subsequent analysis, and interpreted all results. The airflow distribution system incorporated into the research endeavor was based on the physical design established in previous research (Kaufmann, 2023), which in turn was grounded by calculations of greenhouse airflow systems (Wells & Amos, 1994) and Computational Fluid Dynamic (CFD) models (Zhang & Kacira, 2016) conducted at the University of Arizona. Integrating the physical design and theory, Dzeketey produced additional air ducts and implemented them into the system himself.

This research endeavor was a part of the OptimIA project, a multi-university (University of Arizona, Ohio State University, Michigan State University, Purdue University) collaboration in conjunction with the USDA with the primary goal of increasing the profitability, feasibility, and sustainability of indoor agriculture in the United States. This research was sponsored by the USDA-SCRI project, award number: 2019-51181-30017

CHAPTER 2: PRESENT STUDY

2.1 Overall Summary

This experiment was conducted within the University of Arizona's UAg Vertical Farm at the Controlled Environment Agriculture Center, in the main growth chamber. Inside the growth chamber, two identical growing towers were utilized to compare the treatment effects. Each tower had dimensions of 2.44 m by 2.22 m, using a deep water culture hydroponic technique to irrigate the plants, while the lighting was artificially provided through fixed spectrum LEDs set to deliver a daily light integral (DLI) of $13 \text{ mol m}^{-2} \text{ d}^{-1}$. The chamber had a planting density of 50 plants per square meter, totaling 144 plants per level, with the exterior two guard rows exempt from data analysis.

The research focused on the effect of intermittent airflow as a method to maximize fan electrical use efficiency within an indoor vertical farming system, while simultaneously mitigating tip burn within the crop. The crop grown during this experiment was lettuce (*Lactuca sativa*) of the oakleaf variety (*cv.* Rouxai), consistent through all treatment levels. Within each three-tiered growing tower, each level was exposed to a unique treatment, including the Control (vertical airflow for all 28 days of growth), Treatment 1 (vertical airflow for the final 14 days of growth), and Treatment 2 (vertical airflow during the photoperiod for the final 14 days of growth). The vertical airflow systems and duct work were designed on the basis of prior research and calculations using computational fluid dynamics to model the distribution of different airflow techniques within an indoor plant factory. Air velocity at the canopy surface was confirmed through hotwire anemometer readings to be between $0.45 - 0.75 \text{ m s}^{-1}$, values chosen within the established range of $0.3-1.0 \text{ m s}^{-1}$ known to disrupt and reduce the formation of a thick boundary layer in leafy greens. To confirm the uniformity of the aerial environment, a heat map

was created for each level of both grow towers to accurately and quickly confirm the homogeneity output by the fan/duct system.

Depending on the treatment applied to the plant, the consistency of the airflow environment was manipulated to observe the effects on tip burn rates. In the control levels, the fans were operational for all 28 days of growth from transplant to harvest within the growth chamber. Plants under Treatment 1 conditions received continuous vertical airflow starting from day 14 (halfway through the growth chamber life cycle) until the harvest date, while Treatment 2 plants received airflow for 16 hours per day (6:00 am to 10:00 pm) for the final 14 days of growth within the chamber. Each individual growth tower within the chamber contained one treatment per level, resulting in two replications of each treatment. After 28 days inside the growth chamber, the plants from both growth towers were harvested and data collected included fresh weight and a tip burn rating ranging from 0 to 5. A tip burn rating of 0 meant there was no instance of tip burn on the lettuce head, while a rating of 5 indicated severe necrosis evident throughout the entire plant. A rating of 3 and above was considered to be a loss to the grower, as the tip burn symptoms after that point would be obvious to consumers. The internal conditions of the vertical farm growth chamber were closely monitored, with the following setpoints; atmospheric carbon dioxide was maintained at 1000 parts per million (ppm), DLI was set to $13 \text{ mol m}^{-2} \text{ d}^{-1}$ with a 16-hour photoperiod, humidity was controlled within the range of 65%-75%, and a photoperiod/dark period air temperature setpoints of 23° C and 19° C was established, respectively. The root zone environment utilized a modified Hoagland solution with the electrical conductivity (EC) set to 1.8 dS m^{-2} and a pH setpoint of 5.8, as well as a dissolved oxygen content of 4 – 7 ppm.

The goal of this study was to establish a methodology for indoor vertical farm growers to minimize operational costs in the plant cultivation process by maximizing electrical use efficiency in the aerial environment. Optimizing the electrical use of the airflow systems within an indoor plant factory is one of the necessary components to make vertical farming a financially viable future for agriculture. Due to the independence of the system from external environmental conditions, all interior environmental control is reliant on the consumption of electricity. Decreasing the operational costs of running the facility directly translates to higher profits for growers, enabling the proliferation of vertical farms in more settings. The findings of this study can also be used in future endeavors to serve as a baseline for co-optimization of other variables within the growing space, such as carbon dioxide or lighting. Energy conservation while continuing to mitigate the effects of tip burn was a main focus of this experiment, as maintaining high-quality produce is another significant priority for growers. In totality, the focus of this experiment was to reduce input costs to the system, with reductions in electrical energy used to control airflow, for growers without compromising yield or quality for consumers downstream.

2.2 Overall Conclusions and Recommendations

The results of this experiment expressed that increasing resource use efficiency comes with sacrifices to yield quality, as seen by the differences in the three treatment levels. The Control treatment, applying vertical airflow for 28 days (transplant to harvest) resulted in 11.1% of the total harvest showing signs of tip burn, but only to slight levels, as 0% of the harvest was considered waste. Treatment 1 plants were exposed to vertical airflow for 24 hours a day for the final 14 days of the growing cycle which resulted in 19.4% of the overall yield showing tip burn, 3.7% of which was considered waste. Treatment 2 plants received vertical airflow for 16 hours per day for the final 14 days of growth, resulting in 37% of the plants showing tip burn

symptoms, with 6.5% of the total harvest displaying severe enough tip burn symptoms to be considered waste. In this case, a lettuce head was considered waste if it received a qualitative ranking of 3/5 or higher when ranking the tip burn necrosis at leaf tips. All vertical airflow treatments achieved uniform airflow in the known tip burn mitigation range of $0.3 - 1.0 \text{ m s}^{-1}$, measured and confirmed by an omnidirectional anemometer. The lettuce cultivar Rouxai was used in this experiment, and exposed to a 16-hour photoperiod with a DLI of 13. Overall, the data showed that decreasing the total operation time of the vertical airflow fans resulted in higher rates of tip burn necrosis, but at rates that may be considered negligible to growers.

Along with reducing tip burn occurrences in lettuce, the other priority in this experiment was to maximize electrical cost savings during the operation of the vertical farm. In this aspect, Treatment 2 performed the best, affording the user 66.7% energy savings when adopting this style. The fans in Treatment 2 were operational for 224 hours through the 28-day growing cycle, saving 448 hours when compared to the Control group. Treatment 1 achieved 50% energy savings, as the fans were operational for 336 hours throughout the 28-day cycle. Control fans ran for the length of the experiment (672 hours), and as such were the baseline, resulting in 0% cost savings. The electrical cost savings associated with Treatments 1 and 2 provide insight into the benefits of intermittent airflow as an effective method to mitigate tip burn and promote a healthy aerial environment in an indoor agriculture environment. The plants in the Treatment 2 levels also experienced slightly higher biomass accumulation than that of the Control or Treatment 1 plants, another minor consideration for growers looking to maximize the biomass output of their yield.

Using this study as a foundation to build, future research could go down many avenues. Using similar methods as performed in this experiment, exploring the co-optimization of

environmental variables would be another way to further optimize indoor agriculture for operational cost reduction. Utilizing intermittent airflow with other factors like lighting changes, atmospheric carbon dioxide manipulation, temperature management, light quality, and considering crop growth stage could be paths for future research towards resource use savings through advanced environmental controls. Dynamic controls of set points within the vertical farm, including changing the environmental and root zone conditions based on the age of the plant is also a possible next step to further reduce the cost of operating a closed indoor system such as the one used in this experiment. As part of the data collection of future projects, incorporating nutrient analysis and consumer opinions on “acceptable” levels of tip burn would also serve to advance knowledge on the topic, since nutritional value and aesthetics are two large priorities for consumers when purchasing vegetables like lettuce. Focusing on profitability while retaining high-quality harvests was the defining point of this research endeavor, and continuing this work could take many forms.

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APPENDIX A

Intermittent Airflow to Reduce Tip Burn and Maximize Cost Savings in Vertical Farms

Intermittent Airflow to Reduce Tip Burn and Maximize Cost Savings in Vertical Farms

Abstract

Controlled environment agriculture (CEA) and the technology integral to creating highly customizable and optimal environments for the plants grown within have given growers the opportunity to greatly increase production yields while simultaneously decreasing resource input. Vertical farming, in particular, allows for significant improvements in yield, quality, and consistency of harvests, while also greatly reducing the spacial requirements necessary for plant cultivation. Though this agricultural method is exemplary in its goals to maximize resource use efficiency, leafy greens such as lettuce grown in this environment are susceptible to the physiological disorder of tip burn. Tip burn in leafy greens manifests itself as visible necrosis of plant leaf tips and is caused by calcium deficiency within the plant. This calcium deficiency can be the result of accelerated growth conditions within the vertical farm, nutrient deficiencies within the fertilizers provided, or lowered transpiration due to a lack of airflow within the system. Suboptimal airflow at the leaf canopy leads to the formation of a thick boundary layer across the leaf surface, stifling the exchange of gases between the leaf and the surrounding environment. To encourage airflow and reduce tip burn occurrences, prior research has shown that vertical airflow blowing down, perpendicular to the leaf surface at a speed of $0.3\text{-}1.0\text{ m s}^{-1}$ can mitigate tip burn within a hydroponic system. The lack of research into this topic can be partly explained by the high variability within the vertical farming community, as there is very little standardization in the commercial vertical farming production scope. This study, conducted at the University of Arizona Controlled Environment Agriculture Center (UA CEAC), incorporated vertical airflow techniques to determine the possible energy savings associated with intermittent airflow as a method to reduce operational costs. Within the UA CEAC's vertical

farm, oakleaf lettuce (*cv. Rouxai*) was grown for 28 days under a daily light integral (DLI) of $13 \text{ mol m}^{-2} \text{ d}^{-1}$, with three treatment levels of airflow; constant vertical airflow for all 28 days (Control), constant vertical airflow for the final 14 days of growth (Treatment 1), and vertical airflow during the photoperiod (16 hours per day) for the final 14 days of growth (Treatment 2).

The primary focus of this study was to explore the efficacy of intermittent airflow on mitigating tip burn in hydroponically grown lettuce in a vertical farm setting, ultimately allowing growers to maximize fan electrical use efficiency. Using a tip burn rating system ranging from 0 (no tip burn occurrence) to 5 (severe visual necrosis of leaves), both the number of tip burn occurrences, as well as the severity of the occurrence were recorded to determine the most efficient method of airflow distribution. Both treatments (Treatment 1 and Treatment 2) performed well with the goal of mitigating the widespread occurrence of tip burn within the sampled crop, with Treatment 1 performing the best. Based on the rating system employed, tip burn ratings of 0-2 are considered marketable heads of lettuce, since their tip burn is very minimal and unnoticeable by consumers. Ratings of 3 and higher are considered to be wastes, as they would be unmarketable for growers, and thus represent a loss. Tip burn was shown to occur in 11.1% of control plants, 19.4% in Treatment 1, and 37% in Treatment 2 plants. Of these occurrences, the control had 0% waste, Treatment 1 showed 3.7% of the harvest wasted, and Treatment 2 had 6.5% of the harvest over the established rating threshold. Broken down further, 9.3% of the plants within the Control had a tip burn rating of 1, while 1.9% had a tip burn rating of 2. In Treatment 1, 10.2% had a tip burn rating of 1, 5.6% tip burn rating of 2, 1.9% tip burn rating of 3, and 1.9% tip burn rating of 4. Treatment 2 was observed to have the following breakdown; 21.3% had a tip burn rating of 1, 9.3% had a tip burn rating of 2, 3.7% had a tip burn

rating of 3, and 2.8% had tip burn 4. A tip burn rating of 5 was not present throughout any of the treatment levels.

Introduction

Throughout history, successful civilizations and population growth have always been intimately tied to the availability and success of agriculture. Beginning with the independent establishment of agriculture in multiple isolated regions between 10,000 and 4,000 years ago, the multiple significant population jumps can be closely correlated with major agricultural advancements at the same time (Taiz, 2013). Feeding growing populations has been a consistent goal since the first domestication of wild crops, and this has stayed consistent through to modern day. With already massive urban populations growing at an immense rate and expected to continue at this speed or more, a form of accessible and local agriculture needs to be established in big cities to keep people healthy while keeping food costs reasonable. With an estimated 89% of the US population expected to live in urban areas by 2050 (Michigan, 2023), access to fresh produce is an urgent concern that requires swift action. Vertical farming presents a very real solution to this problem, as “producing fresh greens and vegetables close to these urban populations could help meet growing global food demands in an environmentally responsible and sustainable way by reducing distribution chains to offer lower emissions, providing higher nutrient produce, and drastically reducing water usage and runoff” (Federman, 2018).

The answer to this predicament is vertical farming, a method of high-density agriculture that allows up to 10-20 times the yield that can be obtained per acre of normal field agriculture (Ling & Altland, 2023) for plants such as leafy greens, but in significantly less space. This is done by arranging hydroponic grow beds in a multi-tiered fashion, creating towers of grow beds that allow for much greater spatial use efficiency than that of single-level greenhouses or

traditional field agriculture. Vertical farms can be implemented in any environment, as they are a completely self-sufficient closed system and do not rely on outside conditions such as weather, sunlight availability, or temperature to efficiently operate. For this reason, emerging companies have been able to repurpose former warehouses and other out-of-use buildings by outfitting them with state-of-the-art vertical farms that can feed the surrounding cities without taking up the massive amount of space and resources that a traditional farm would require. The significant production output of vertical farms also comes with the additional benefit that they are incredibly resource efficient, allowing for the recycling of nutrients and water to greatly lower the overall footprint of production. This method of farming will be the future of urban agriculture and provide urban communities with fresh, reliable produce grown locally, further driving down potential transportation or refrigeration costs that would otherwise be necessary for the transport of the produce.

The reason vertical farming is not already a widely implemented technique is that it is very expensive due to its high consumption of electricity. Because the system does not rely on any outdoor conditions, every single aspect of the plants' environment is controlled through a system of sensors that then feed into lighting, heating, cooling, and humidity. Because all of these processes require electricity, the monthly cost to run a vertical farm makes it very unattractive to investors who are mostly focused on profit and the bottom line. This high operational cost is offset overall, however, because in terms of "economic sustainability, vertical farming has a myriad of benefits over rural farming" (Mir, et al., 2022). These benefits arise in many different ways that can be categorized as environmental, social, and economic benefits. Utilizing the ability to reliably produce high-quality crops year-round, independent of exterior weather conditions, reduced costs in resource use, and lowered transportation requirements,

vertical farms stand as a long-term positive addition to most communities, helping to reduce the effects of food deserts in growing urban landscapes. Along with the continual rise in population, there is a simultaneous decrease in arable land, going from 5,200 m² of arable land per person in 1950, to 2,200 m² per person in 2010, to an estimated 1,700 m² per person by 2050 (Mir, et al., 2022). Utilizing the design benefits of vertical farming, a method of agriculture that does not require any degree of arable land will be a requirement moving forward as space decreases and the need for spatial use efficiency begins to increase.

While resulting in increased operational costs, the control capabilities within a vertical farm to create a highly specified and optimized environment for the plants inside is also one of the biggest strengths of the agriculture method. Growers are able to truly optimize their production and tailor their products to an exact quality based on manipulation of interior conditions. Precise control over light intensity, light quality, airflow, temperature, humidity, plant nutrients, and carbon dioxide availability within the vertical farm gives growers the ability to accelerate plant growth, resulting in overall higher yields with a high degree of repeatability and dependability of the product. When comparing the annual output of a hydroponic greenhouse to that of conventional field agriculture, one study showed that the greenhouse was able to produce $41 \pm 6.1 \text{ kg m}^{-2} \text{ y}^{-1}$, while field agriculture could only produce $3.9 \pm 0.21 \text{ kg m}^{-2} \text{ y}^{-1}$ of produce (Barbosa, et al., 2015), showing the massive improvements controlled environment agriculture can have on crop yields. When it is taken into account that vertical farms can produce even more than a hydroponic greenhouse, the production benefits are only increased. Vertical farms also provide the ability to compartmentalize in case of pest infiltration to reduce crop loss, have a footprint a fraction of the size of a greenhouse, can be placed in an urban or remote area without arable land, and can produce crops with higher quality and consistency than that of greenhouse

or field agriculture (Eaves & Eaves, 2018). Vertical farms provide the ideal solution to the majority of the problems faced by increased urbanization worldwide, and could very well serve as the main source of fresh produce moving forward as arable land decreases while food demands increase at the same time.

While there are many clear benefits resulting from the versatility and specialization of vertical farming, there are also drawbacks due to the growth rate the plants are forced to endure and the internal conditions of the vertical farm. The same factors that make vertical farming so flexible to implement anywhere in the world, also contribute to some of the issues with the method of agriculture. Being a completely closed system and isolated from environmental conditions and infiltration also precludes the vertical farm from benefiting from natural processes that are present in both greenhouse and field agriculture. In the production of leafy greens specifically, this presents a problem when considering the fact that vertical farms have no natural airflow in the system. In a greenhouse or field, this is not a problem, as wind naturally blows through the ventilation openings in the greenhouse structure, or just passes over the leaves naturally in a field. This is not the case for vertical farms which are entirely sealed from the outside world, and this manifests itself in a calcium deficiency called tipburn. Without a fan system in place specifically meant to stimulate internal airflow, the only movement of air within a vertical farm is tied to the heating and cooling system, an air exchange that does not facilitate air velocities within the suggested range of $0.3 - 1.0 \text{ m s}^{-1}$, resulting in a thick boundary layer over the leaf of the plant, reducing the ability of the lettuce to exchange gases with its environment (Ahmed, Yu-Xin, & Qi-Chang, 2020). Stifling the gas exchange into and out of the leaf stomata inhibits the uptake of calcium by the lettuce leaf, resulting in leaves that appear brown or black and crispy to the touch, appearing to be burned. To counteract this issue, efforts

have been taken inside vertical farms to facilitate stronger airflow to reduce the boundary layer thickness over the leaf surfaces, ultimately aimed at mitigating the problem of tipburn entirely.

Research into the most efficient ways to combat tipburn has taken routes to explore mitigation through the manipulation of several internal factors within the vertical farm. The exploration most relevant to this project explored the effect of vertical and horizontal airflow supplied to plants during the course of their growing cycle within the vertical farm. Comparing the efficacy of vertical and horizontal airflow to thin the leaf boundary layer and ultimately reduce tipburn occurrences was done through both modeling and experimental confirmation. Through computational fluid dynamics (CFD), a model was constructed, showing that the most efficient application of air within a vertical farm would be delivered vertically, through a polyethylene tube with several rows of three perforations blowing directly into the plant centers, allowing for turbulent airflow at the canopy level, disrupting the boundary layer and allowing gas exchange into and out of the lettuce stomata (Zhang & Kacira, 2016). This CFD model was then tested in a physical vertical farm, comparing the efficacy between no supplemented airflow, horizontal airflow, and vertical airflow. This study showed that when using the perforated tubes to deliver vertical airflow to the lettuce heads, the average tipburn severity decreased from 63% in the control group with no airflow to 3% when using vertical airflow (Kaufmann, 2023). This sizable reduction in tipburn severity and appearance represents a significant step forward in the mitigation of tipburn in closed plant systems, a major drawback of vertical farming for leafy greens. Providing customers with aesthetically pleasing produce directly correlates to higher profits for growers, and correspondingly lower losses due to plant waste when discarding affected lettuce heads.

Building off of this discovery, the primary objective of this research endeavor is to determine the efficacy of intermittent airflow to mitigate tip burn and evaluate the potentials to further increase cost savings for vertical farm growers. In the foundational experiment, the air circulation fans for vertical airflow were operated both during the light and dark periods for the plants, for the entire duration of growth within the vertical farm. Because all of the control methods within a vertical farm are run on electricity, minimizing the operational time of any of these controls will lead to direct savings for the grower. In this research experiment, the effects of decreased fan duration were explored, taking into consideration the quality of the plants at the time of harvest. With the primary objective of keeping plant quality consistent while also running the circulation fans for a minimal time, two treatments were established and explored. With the control being constant airflow for the entire lifecycle of the lettuce, the two treatments to compare were as follows: Treatment 1 utilized continuous airflow during light and dark periods for the final two weeks of the lettuce life cycle, while Treatment 2 ran the circulation fans only during the photoperiod for the final two weeks of growth within the system. It was hypothesized that either of the treatments would help reduce or mitigate tip burn while offering direct cost savings in operational costs by reducing operational time for airflow fans for vertical farm growers, and providing vertical farms with new methodologies in tipburn mitigation while also limiting electrical use.

Materials and Methods

1. Research Facility, Sensors, Instrumentation, Data Collection

The facility utilized for this experiment was located at the University of Arizona's Controlled Environment Agriculture Center's vertical farm, also called the UAg Vertical Farm. The UAg Vertical Farm consists of two neighboring growth chambers and a computer control

room used to monitor interior environmental conditions. Each grow chamber is identical, with proportions of 6 m × 6 m (36 m²), while the control room has an area of 27 m². Inside each chamber stands two three-tiered deep water culture growing racks, with each level covering 2.44 m × 1.22 m, capable of growing 144 plants at a plant density of 50 plants m⁻². Each of the individual growing racks uses a recirculating hydroponic growing technique to allow the growth of 432 plants per rack, with the plants inserted in styrofoam rafts floating on the surface of the nutrient solution. Supplying the water and nutrients to the system, each grow rack contains a 1134 liter reservoir at the base, attached to an inline water pump (Little Giant, 1/8 hp) capable of moving the solution to each of the three levels in the rack. The pump runs continuously throughout the growing cycle and maintains a water level of 7.62 cm, managed by a standpipe at the outlet of each level.

Inside the control room, growth chamber environmental conditions are monitored and controlled by a CR6 Campbell Scientific datalogger (Logan, UT, USA), which takes and displays both instantaneous (every 5 seconds) and averaged (every 900 seconds) readings that are monitored on the control room computer. Each of the growth chambers contains an external environmental sensor array including two aspirated temperature and relative humidity sensors (HMP600, Vaisala, Vantaa, Finland) at canopy height on each of the two grow racks, one carbon dioxide sensor (Vaisala GMP-222, Vantaa, Finland), and two Quantum sensors (S-120, Apogee Instruments, UT, USA) to monitor the light intensity within the chambers. The root zone environment is monitored through a dissolved oxygen sensor (DO1200-T, Sensorex, CA, USA) inserted into the outlet standpipe, as well as a pH sensor (HI 100, Hanna, RI, USA) and an electrical conductivity (EC) sensor (OMEGA CDE- 100-1, Hanna, RI, USA) inserted into the manifold at the return side of the plumbing for each of the growing racks. Setpoint control is

conducted through the CR6 datalogger and Campbell Scientific relay switch (SDM-CD16AC), which allows for automatic control of the carbon dioxide, pH, and EC within each of the growing towers. To supplement the carbon dioxide inside each growing chamber, tubing, and solenoid valves were used to control the injection of CO₂ from high-pressure tanks stored outside of the facility (UN ISO 9809-1 250 CF).

To accurately control the pH and EC of the root zone environment, an injector system custom-made using peristaltic pumps (FPU-401, Omega, Norwalk, CT, USA) drew nutrient solution from A and B and acid-concentrated stock tanks and deposited the solution into the 1134 L base reservoirs of each grow tower depending on need. The dissolved oxygen supply was maintained through the continuous operation of an air compressor (Gast DOA, 1/8 hp, Benton Harbour, MI, USA) that was then diffused into the base reservoirs using air stones (Pentair air diffuser, 9mm). To monitor and maintain the individual microclimate within each growing tray, Fine T type thermocouples (T-36X, ThermoWorks, American Fork, UT, USA) were installed at the canopy height of each growing level, connected to a datalogger (CR-1000, Campbell Scientific, Logan, UT, USA).

Within the UAg Vertical Farm, both chambers have their own independent climate control systems that can be independently controlled for the chamber's environmental needs. The HVAC system maintains an air temperature setpoint through the operation of a heat pump (GPH14H, Goodman, Waller, TX, USA), controlled by a wall-mounted thermostat. The system allows for the internal air within the chamber to be constantly circulated, creating a homogenized aerial environment, for both temperature and humidity. Humidity is controlled through a dehumidifier (CFT4.0D, Colzer, Villeurbanne, France), maintaining an internal relative humidity of less than 75%. The system ran on a 16-hour photoperiod, with electrical lighting provided by

Heliospectra helioSPEC Izar LED (output of $2.8 \mu\text{mol J}^{-1}$) from 6:00 A to 10:00 PM daily. Each rack contained 12 light fixtures with variable light intensity but set to a constant PPFD of $225 \mu\text{mol m}^{-2} \text{s}^{-1}$ with a photoperiod of 16 hours for a DLI of $13 \text{ mol m}^{-2} \text{d}^{-1}$. The spectrum output of these lights was measured to be approximately 65% red, 14% blue, 10% green, and 11% far red as measured by a spectroradiometer (PS-300, Apogee Instruments, Logan, UT, USA).

2. *Vertical Airflow Systems*

The vertical airflow (VAF) system integrated into the growth chamber was present at all growing levels of the experiment and was designed to maximize internal pressure within the duct, leading to maximized exit velocity from the outlet holes, as shown in Figure 10 below. The construction of the VAF systems included a 0.10 m PVC pipe header that then split into three 1.2 m ducts made from 0.10 clear polyethylene tubing. The perforations on the underside of the duct allow for three rows of air jets to distribute wider airflow coverage at the canopy surface than would be possible by placing a duct between each set of light strips. The aperture ratio of the air distribution system was aligned to maintain uniform airflow along the length of the air duct (2018)(Wells & Amos, 1994).



Figure 10: The vertical airflow system installed within the growth chamber.

To maintain uniform air distribution throughout the system, each air duct was perforated with three rows of 30 holes with a diameter of 0.35 cm each. This made 90 air distribution jets per air tube. The alignment of the perforations was such that the center row would deliver air directly downward onto the top of the crop, while the adjacent perforations in each row discharged the air at a 30° angle from the center. Each PVC header duct was connected to an 8-inch inline duct fan (Cloudline Pro S8, AC Infinity, Walnut, CA, USA) with an output of 807 cubic feet of air per minute through a 0.10 m aluminum flexible duct and a 0.2 x 0.1 flexible reducing coupling (The Plumber's Choice, Phoenix, AZ, USA). Each individual grow level contained two VAF systems, each providing airflow to half of the cultivation area. Because the fans were of variable speed, each fan was set to a power level outputting an average of 0.6 m s^{-1} to maintain airflow homogeneity as measured by a Hotwire Anemometer (Model 8475, TSI, Shoreview, MN, USA).

Each airflow treatment contained two repetitions, and treatments were assigned to each level of the growing rack to avoid duplication. Rack 2 Level 1 (top) was assigned as Control, Level 2 (middle) as Treatment 1, and Level 3 (bottom) as Treatment 2. On Rack 1, Level 1 (top) was Treatment 1, Level 2 (middle) was Treatment 2, and Level 3 (bottom) was dedicated to the Control as shown below (**Error! Reference source not found.**). The airflow distribution fans associated with Treatment 2 were connected to outlet timers (T319 Timer Outlet, TOGOAL) to ensure precise start and end times of fan operation.

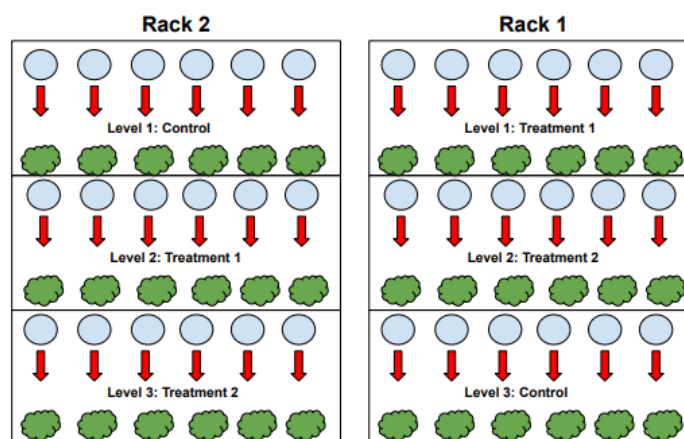


Figure 2. The experimental layout of treatments for air distribution in the growth chamber.

3. Crop Production

The trial conducted was composed of six total growth levels, with each treatment replicated twice with lighting set to 13 DLI. Each growing level had a total of 144 plants, with the center 80 plants being collected for data analysis, excluding the two rows and columns of the exterior edge acting as guard rows. Each level was prescribed an airflow treatment, with one Control, Treatment 1, and Treatment 2 per rack. Each trial showed two replications of each treatment. The lettuce (*Lactuca sativa*) cultivar observed in this trial was of the oakleaf variety (cv. Rouxai). The lettuce spent the duration of its life cycle in the UAg Vertical Farm from

seeding to harvest. During the 14-day germination period, the seedlings were supplied a nutrient solution consisting of a modified Hoagland solution at half-strength with a pH range between 5.8 and 6.0 and a lighting intensity of $200 \mu\text{mol m}^{-2} \text{s}^{-1}$. This procedure continued until the seedlings produced the third true leaf, indicating they were ready for transplant into the main growth chamber. After transplant, the plants spent 28 days in the treatment racks until harvest, with 144 seedlings planted on each level for a plant density of 50 plants m^{-2} .

During the trial, the DLI was kept consistent at $13 \text{ mol m}^{-2} \text{ d}^{-1}$ during the 16-hour photoperiod, providing an 8-hour dark period. The environmental conditions were also kept consistent throughout the duration of the trial, with an air temperature of 23° C during the photoperiod and 19° C during the dark. Supplemental carbon dioxide was added to the system to maintain levels of 1000 ppm for the 28 days of growth within the chamber, and relative humidity was controlled to a range of 65%-75%. The root zone environment consisted of a full-strength application of the modified Hoagland solution with an electrical conductivity (EC) of 1.8 dS m^{-1} and a pH of 5.8. Plants in the designated Control levels were subjected to vertical airflow for 24 hours each day for the 28 days spent inside the growth chamber. Plants experiencing Treatment 1 received vertical airflow for 24 hours each day starting on Day 14, while Treatment 2 plants received vertical airflow during the photoperiod (16 hours per day) from Day 14 until harvest.

4. Data Collection

To ensure homogeneity of the airflow environment, omnidirectional anemometer readings were taken at every point on each grow level. At each point on the growing level, three measurements were taken with the hotwire anemometer (Model 8475, TSI, Shoreview, MN, USA) in both planting areas and interstitial spaces, averaged together, and then compiled into a colored heat map representing the airflow velocity distribution of each level at canopy height

(~15 cm above plant raft). This map confirmed adequate airflow at every point within the growing area, ensuring each plant collected for analysis received the proper treatment effects.

Plants located on the exterior two rows at the perimeter of each grow level were designated guard row crops, meaning they were not sampled for data collection. Each airflow treatment level contained 80 plants eligible for data collection, and within those 80 plants, a random sampling of 54 plants were chosen to be analyzed for tip burn severity. This random sampling was determined by using the statistical programming language R to acquire the minimum necessary sample size through a power analysis following an analysis of variance (ANOVA). The plants chosen were then randomly selected through the `sample()` function, creating a unique sampling pattern for each level to encompass all possible occurrences within the population.

Throughout the 28-day growing period, each plant was inspected daily for the first instance of tip burn and marked on a tip burn map to show the progression of the disorder. The tipburn analysis was based on the appearance of necrotic damage on the leaf tips of the lettuce plants and monitored for its spread after the first instance. During harvest, fresh weights were documented, and the tip burn severity was documented on a qualitative scale from 0-5, with each numerical rating carrying a meaning. A rating of 0 meant no tip burn was present on the plant at all. Rating 1 was reserved for plants with minuscule instances of tipburn to a degree that is not at all noticeable to a significant degree and only detected in small quantities on a small minority of leaves. Rating 2 was categorized by barely noticeable tipburn that would still constitute a marketable crop with tip burn affliction being unnoticed by the majority of consumers. Ratings 3 and 4 become progressively noticeable, with tip burn spreading to more leaves within the plant, obvious to the average consumer. A rating of 5 on the tipburn scale indicates a lettuce head fully

consumed with necrotic damage, and entirely unmarketable. The threshold of marketability was drawn between ratings 2 and 3 to present an aesthetically pleasing head of lettuce to consumers. During harvest, the location of all tip-burned lettuce heads was also recorded and documented.

5. *Statistical Analysis*

To determine the effect of the intermittent airflow treatments on the lettuce fresh weight and tip burn severity, ANOVA tests were performed with $\alpha = 0.05$. The analysis of variance was accompanied by a Tukey Kramer Honest Significant Different (HSD) test to ascertain which of the three treatments (Control, Treatment 1, and Treatment 2) were significantly statistically different from each other. During harvest, a sample size of 54 out of 80 viable plants was selected from each growing level (108 total from each treatment) to be a representative sample size using a power test to confirm the testing power of 0.95. The sampling within each growing level was randomized using the random sampling function in R Studio with no replacements, ensuring each treatment level received completely random sampling.

Results and Discussion

1. *Air Velocity Profile*

To confirm the airflow environment of each treatment level was within the ideal velocity range to mitigate tipburn ($0.3 - 1.0 \text{ m s}^{-1}$), an omnidirectional hotwire anemometer was deployed at canopy level (15 cm above the floating raft). Aerial velocity measurements were taken at each point (planting and non-planting spaces) for each level, and the data were arranged in a heat map (Figure 11) to visualize the velocity distribution for air within the space eligible for data collection. Each treatment occurred once per grow tower, for two iterations overall within each experiment. Control 1, located on Level 3 (bottom) of Rack 1 (nearest to the control room) had

an average vertical airflow velocity of $0.83 \pm 0.21 \text{ m s}^{-1}$ with a coefficient of variance (CV) of 0.26. Control 2, located on Rack 2 Level 1 (top level of the rack nearest to the back wall) had an average velocity of $0.70 \pm 0.18 \text{ m s}^{-1}$ (CV = 0.26). plants exposed to Treatment 1 were located on Rack 1 Level 1 (top) and Rack 2 Level 2 (middle). At these locations, the aerial environment had a velocity of $0.69 \pm 0.14 \text{ m s}^{-1}$ (CV = 0.20) and $0.80 \pm 0.14 \text{ m s}^{-1}$ (CV = 0.17) respectively. The first iteration of Treatment 2 was located on Rack 1 Level 2 with an average velocity of $0.74 \pm 0.20 \text{ m s}^{-1}$ (CV = 0.27), while the second was on Rack 2 Level 3 with an average velocity of $0.87 \pm 0.20 \text{ m s}^{-1}$ (CV = 0.23).

Due to the tunability of the duct fans used in this experiment, the homogeneity of the aerial environment was further confirmed by tuning each fan to output a velocity within the range of $0.45 - 0.75 \text{ m s}^{-1}$. Scaling the velocity output of each fan allowed for a uniform blowing environment at each level, leaving the treatment levels as the only remaining variability. Within each growing level, there was an even distribution of airflow observed in the heat maps, indicating that there was no discernable gradient or airflow concentration at any point. The location of the perforated tubes distributing the airflow also did not appear to play a part in the airflow distribution, aiding in the consistency of air velocity for the entire planting area. To ensure proper interpretation of the airflow environment at each point, three readings were averaged at every space on the board, allowing for the incorporation of all possible wind profiles the omnidirectional anemometer can receive. Airstreams from the vertical airflow ducts were directed in three directions, two pointing diagonally downward, while the middle hole pointed straight down. The interaction of these air streams further assisted in air mixing and homogenizing the overall plant airflow environment.

Rack 2 Level 3 (Bottom); Treatment 2: VAF During Photoperiod After 2 Weeks																					
1																					
2																					
3	1	0.57	0.73	0.89	1.03	0.89	0.94	0.78	0.82	0.98	0.89	0.73	0.80	0.78	0.83	1.29	1.21	0.85	0.80	0.69	0.67
4	2	0.67	0.83	0.69	0.89	0.85	0.86	0.78	0.77	0.78	1.14	0.74	0.82	0.88	1.18	1.10	0.80	0.68	0.67	0.69	0.61
5	3	0.63	0.68	0.67	0.90	0.76	0.78	0.77	0.78	0.80	1.03	0.81	0.83	1.09	1.03	0.99	0.79	0.59	0.55	0.67	0.74
6	4	0.59	0.66	0.73	0.79	0.90	0.74	0.76	0.82	0.84	0.80	0.93	0.78	1.19	1.08	1.06	0.84	0.76	0.55	0.58	0.66
7	5	0.66	0.64	0.83	0.75	0.99	0.72	0.85	0.87	1.05	0.79	1.07	0.83	0.94	1.10	1.13	0.86	0.93	0.67	0.48	0.50
8	6	0.72	0.71	0.86	0.74	1.22	0.87	0.85	0.94	0.94	0.88	1.06	0.88	0.81	1.04	1.06	1.01	0.91	0.67	0.61	0.61
9	7	0.72	0.75	0.97	0.90	1.28	1.05	0.92	1.28	0.99	0.93	1.11	1.11	1.28	1.13	1.12	1.16	0.83	0.59	0.55	0.56
10	8	0.82	0.85	0.96	1.20	1.18	1.12	1.07	1.19	1.28	0.99	0.92	1.13	1.79	1.35	1.00	0.91	0.84	0.58	0.63	0.71
11																					
12																					
black	plant		2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
blue	no plant		AVG		0.87	STDV		0.20	CV	0.23											

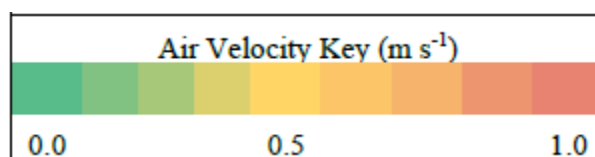


Figure 11. Example of One Level of the Omni-Directional Airflow Heat Map Created for All Treatments Measured at Canopy Height 15 cm.

2. Growth Environment

The internal environment of the growth chamber was continuously monitored and controlled throughout the growth cycle (28 days) of the lettuce (*cv.* Rouxai) used in this experiment. Temperature data for individual levels were collected through thermocouples placed at canopy height for the duration of the experiment, providing insight into the individual microclimates of each growing level.

Table 2. Average Electrical Conductivity, pH, Relative Humidity, Carbon Dioxide, and Daily Light Integral Measured through the 28-day Growing Period.

EC (dS m ⁻²)	pH	CO ₂ (ppm)	RH (%)	DLI (mols m ⁻² d ⁻¹)
Rack 1	7.2	998.7	68.7	13

Rack 2	6.7	998.7	67	13
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Table 3. Average Temperature Measured At Canopy Height of Each Treatment Level Throughout the 28-Day Growing Period.

Rack 1 Level	Average Temperature (°C)	Rack 2 Level	Average Temperature (°C)
1 (Top)	22.4	1 (Top)	18.6
2 (Middle)	20.7	2 (Middle)	20.6
3 (Bottom)	20	3 (Bottom)	20.8

330 Gallon Solution = 1.8 EC			
TANK 1		TANK 2	
Ca(NO ₃) ₂	0.783 kg	KNO ₃	0.325 kg
CaCl ₂ ·6H ₂ O	0.172 kg	KH ₂ PO ₄	0.238 kg
Iron chelate EDTA (Sprint 330)	16.706 GRAMS	MgSO ₄ ·7H ₂ O	0.363 kg
		MICRONUTRIENTS	
		Manganese sulfate (32%)Mn	1.527 g
		Zinc sulfate (36%)Zn	0.859 g
		Copper sulfate (25%) Cu	0.181 g
		Solubor (20.5%)B	1.527 g
		Sodium molybdate (40%)Mo	0.115 g
5 Gallon Stock Tank			
	for	1 concentration:	200 x
	divisor:	2.5 concentration:	80 x
TANK 1		TANK 2	
Ca(NO ₃) ₂	0.236 kg	KNO ₃	0.098 kg
CaCl ₂ ·6H ₂ O	0.052 kg	KH ₂ PO ₄	0.058 kg
Iron chelate EDTA (Sprint 330)	5.041 GRAMS	MgSO ₄ ·7H ₂ O	0.110 kg
		MICRONUTRIENTS	
		Manganese sulfate (32%)Mn	0.461 g
		Zinc sulfate (36%)Zn	0.259 g
		Copper sulfate (25%) Cu	0.055 g
		Solubor (20.5%)B (Sodium Tetrat	0.461 g
		Sodium molybdate (40%)Mo	0.035 g

Figure 12: Modified Hoagland Solution Provided to the Lettuce (cv. Rouxai) Throughout the Germination Stage (Bottom) and Main Growth Stage (Top).

Table 4: Parts per Million (PPM) of Each Nutrient Salt Supplied to Each Nutrient Reservoir During the Germination Period (Left) and the Main Growth Stage (Right), as Part of the Modified Hoagland Solution.

Germination		Main Growth	
Element	Total PPM	Element	Total PPM
Ca	44.352	Ca	178.287
N	35.848	N	144.147
O	208.504	O	854.300
H	6.743	H	27.546
Cl	11.115	Cl	44.562
C	1.162	C	4.669
Fe	0.540	Fe	2.171
K	36.034	K	155.351
P	8.719	P	43.365
Mg	7.164	Mg	28.656
S	9.556	S	38.225
Mn	0.111	Mn	0.445
Zn	0.069	Zn	0.278
Cu	0.014	Cu	0.058
B	0.064	B	0.259
Mo	0.011	Mo	0.043
Na	0.039	Na	0.158

3. Tip Burn

In the data collection of this experiment, tip burn occurrences were measured through two metrics. The first observation method for tip burn quantification acknowledged whether or not tip burn was present at all on the head of lettuce (Figure 13). In the plants sampled, 12 Control plants showed signs of tip burn necrosis. Treatment 1 and Treatment 2 tip burned plants totaled 21 and 40 plants respectively. These values as a percentage of the total harvest showing tip burn symptoms are displayed in Figure 14. The data indicates that 11.1% of the Control group, 19.4% of the Treatment 1 group, and 37% of the Treatment 2 overall harvest showed signs of tip burn. These percentages do not necessarily indicate losses for the growers, however, as very small instances of tip burn were taken into account in these totals but would not appear visible to the

common consumer. To better account for the variability in tip burn severity, observations included ranking the visible tip burn necrosis on a scale of 0 – 5 (Figure 15), with a rating of 0 indicating no tip burn was present, while a rating of 5 designated a plant with tip burn necrosis affecting the high majority of the lettuce leaves (Figure 16 and Figure 17). The onset of tip burn symptoms occurred through a similar timeline for all treatments, with the differences being the severity and quantity of tip burn throughout the treatment levels. Each treatment utilized vertical airflow in an attempt to disrupt the boundary layer around the plant leaf to encourage transpiration and facilitate the normal uptake of key nutrients such as calcium from the nutrient solution into the plant. The Control level plants showed tip burn in 12 out of 108 samples analyzed, with the average rating of tip burn within those 12 being 1.2 out of 5. The composition of ratings for the Control group was 10 plants of rating 1, and 2 plants of rating 2. Plants exposed to vertical airflow after two weeks (Treatment 1) had 21 plants showing tip burn, with an average rating of 1.8 out of 5. The average rating was composed of 11 plants rated at 1, 6 plants rated at tip burn level 2, and 2 plants rated at tip burn levels 3 and 4 each. Treatment 2 plants, exposed to vertical airflow for 2 weeks exclusively during the photoperiod experienced the most tip burn, with 40 out of 108 plants showing signs of tip burn. Of the 40 plants, the average rating was 1.7, with 23 plants rated at tip burn level 1, 10 at level 2, 4 at level 3, and 3 plants at tip burn level 4.

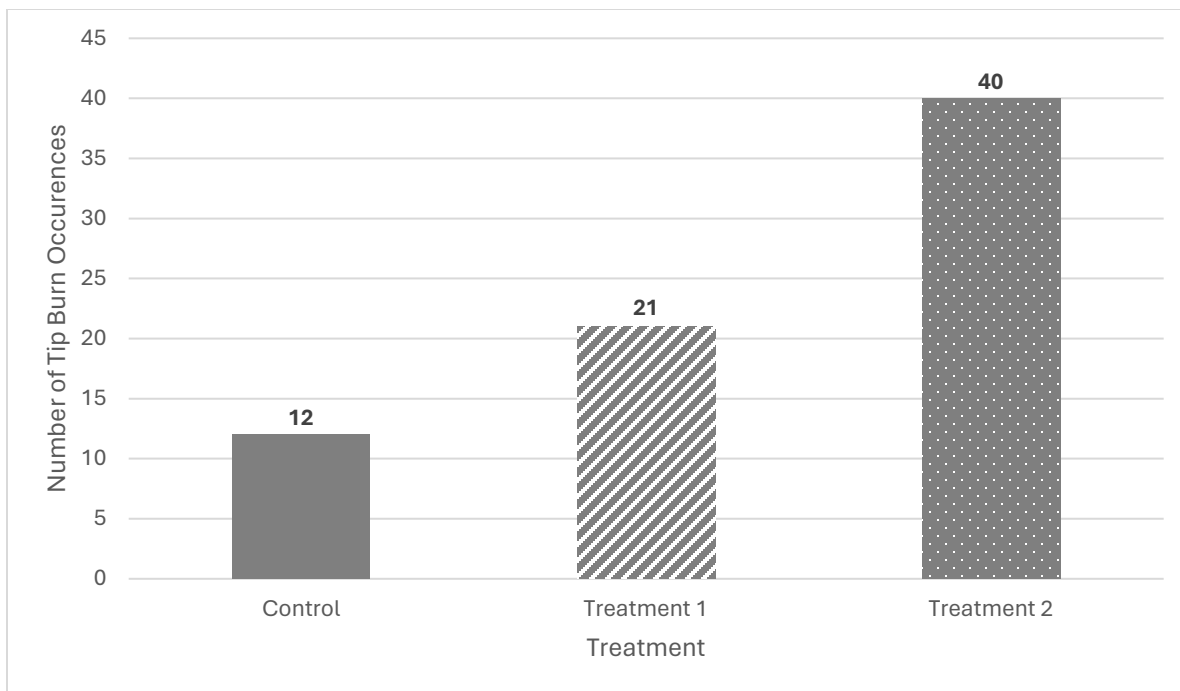


Figure 13. Number of Plants Exhibiting Tip Burn Symptoms in Lettuce (cv. Rouxai) After Harvest for Each Treatment.

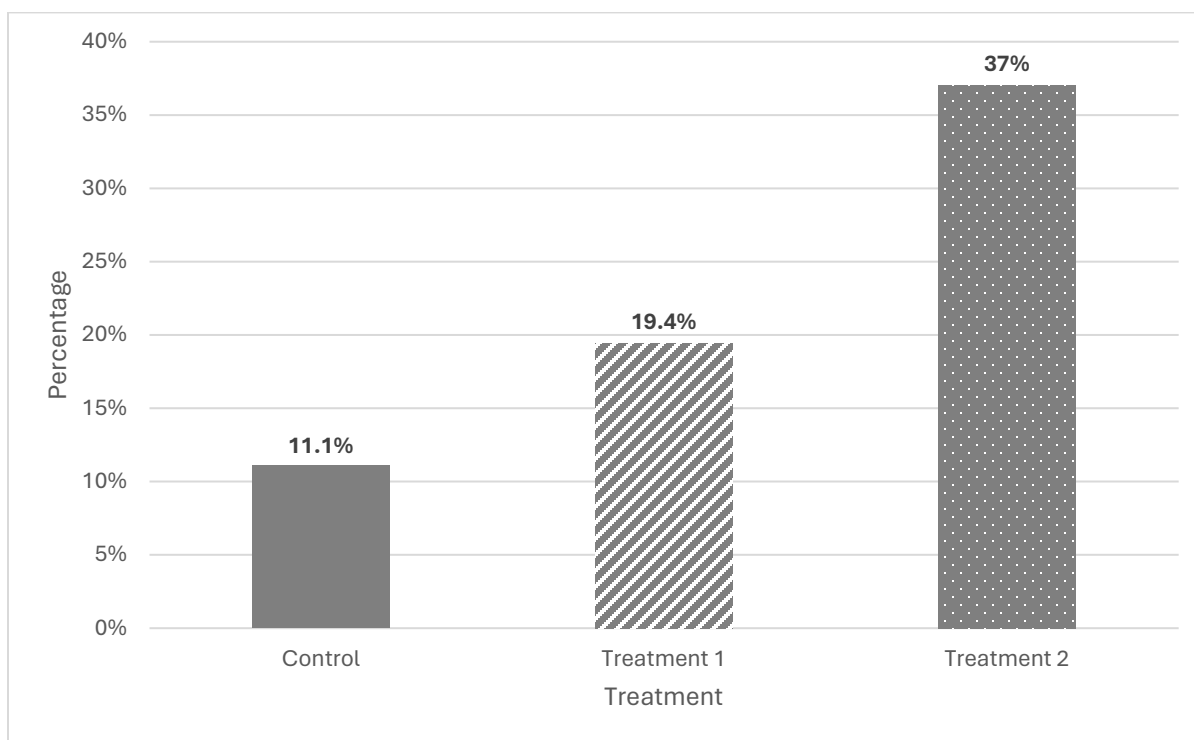


Figure 14. Percentage of Total Harvest Exhibiting Tip Burn Symptoms in Lettuce (cv. Rouxai) After Harvest for Each Treatment

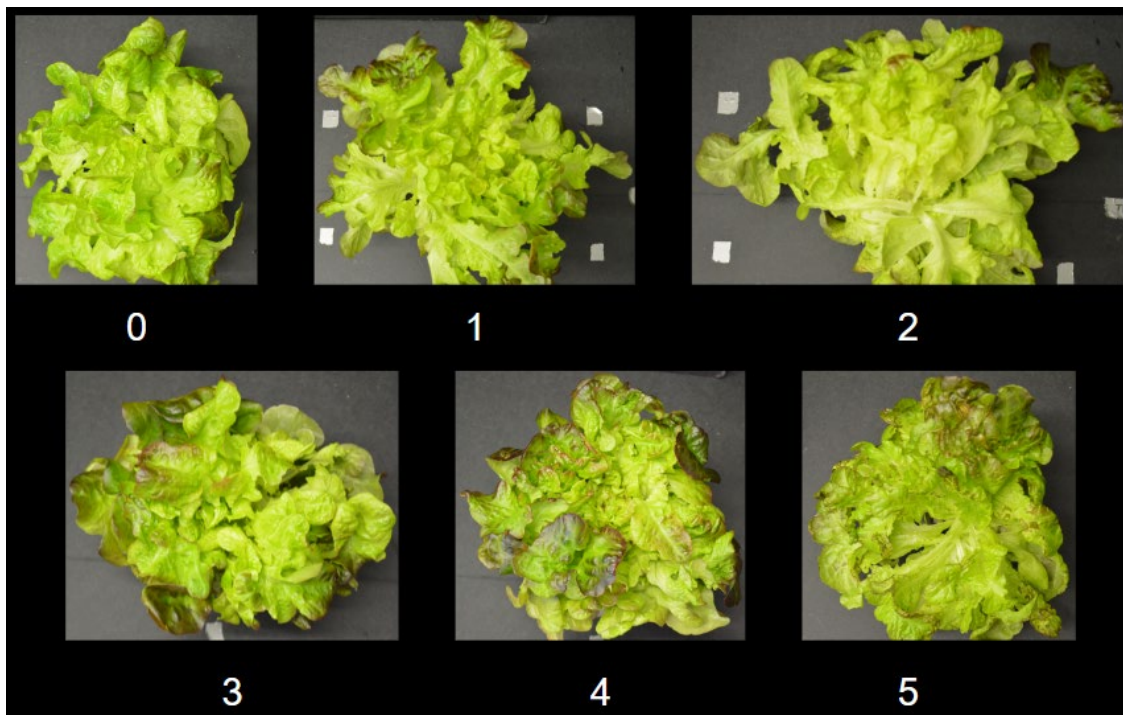


Figure 15. Visual Representation of Heads of Lettuce (cv. Rouxai) Experiencing Tip Burn From Rating Level 0-5 After 28-Day Growing Cycle. Pigmentation Visible on the Exterior Leaf Edges Is Due to the Natural Coloration of Rouxai Lettuce, Not Tip Burn Symptoms.

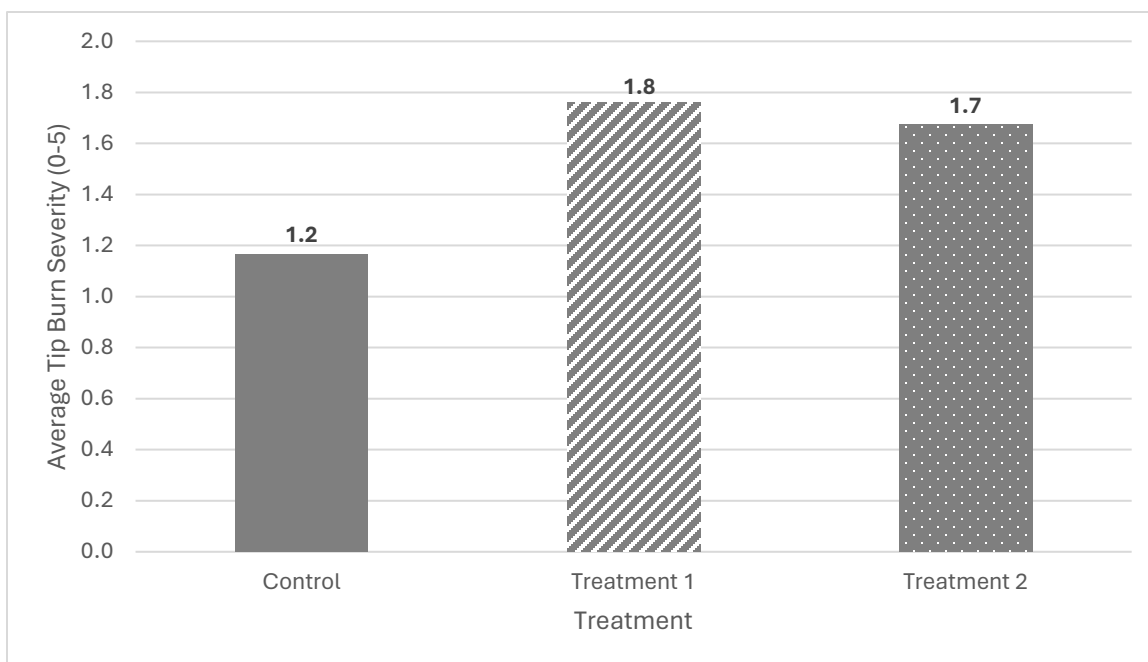


Figure 16. Average Rating of Tip Burn Severity for Plants Exhibiting Tip Burn Symptoms for Each Treatment.

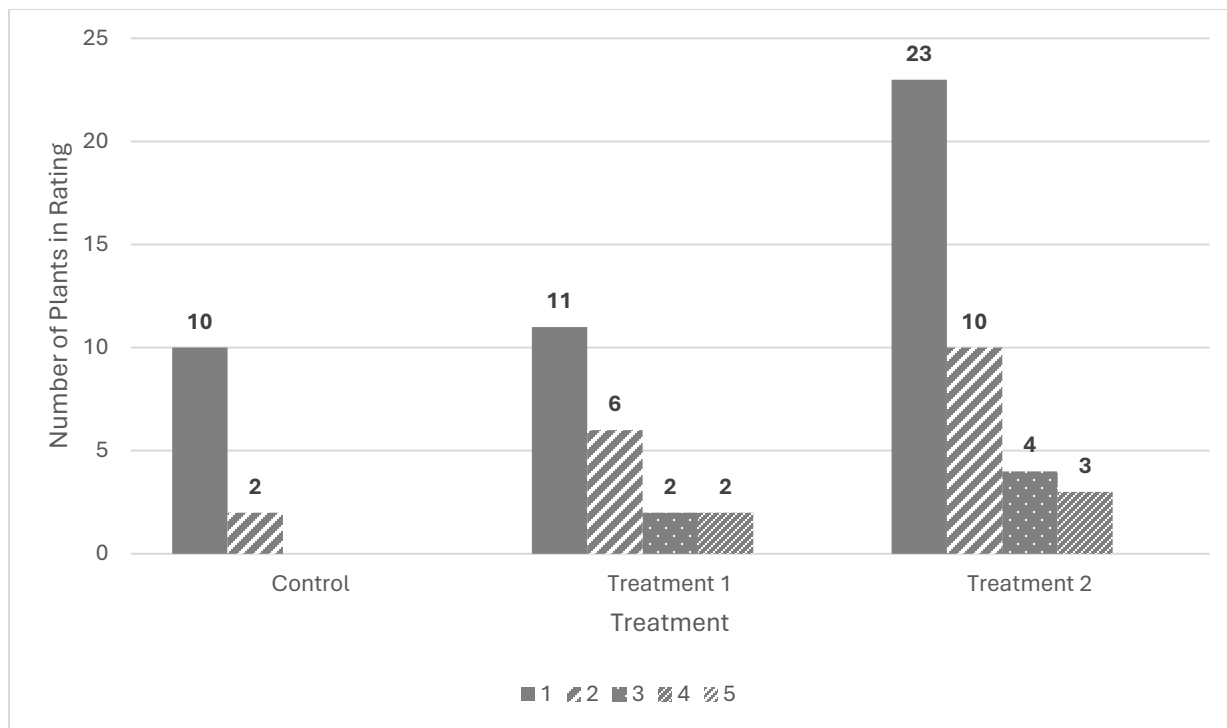


Figure 17. Composition of Total Tip Burn Ratings on a 1-5 Scale for Plants in Each Treatment Showing Tip Burn Symptoms.

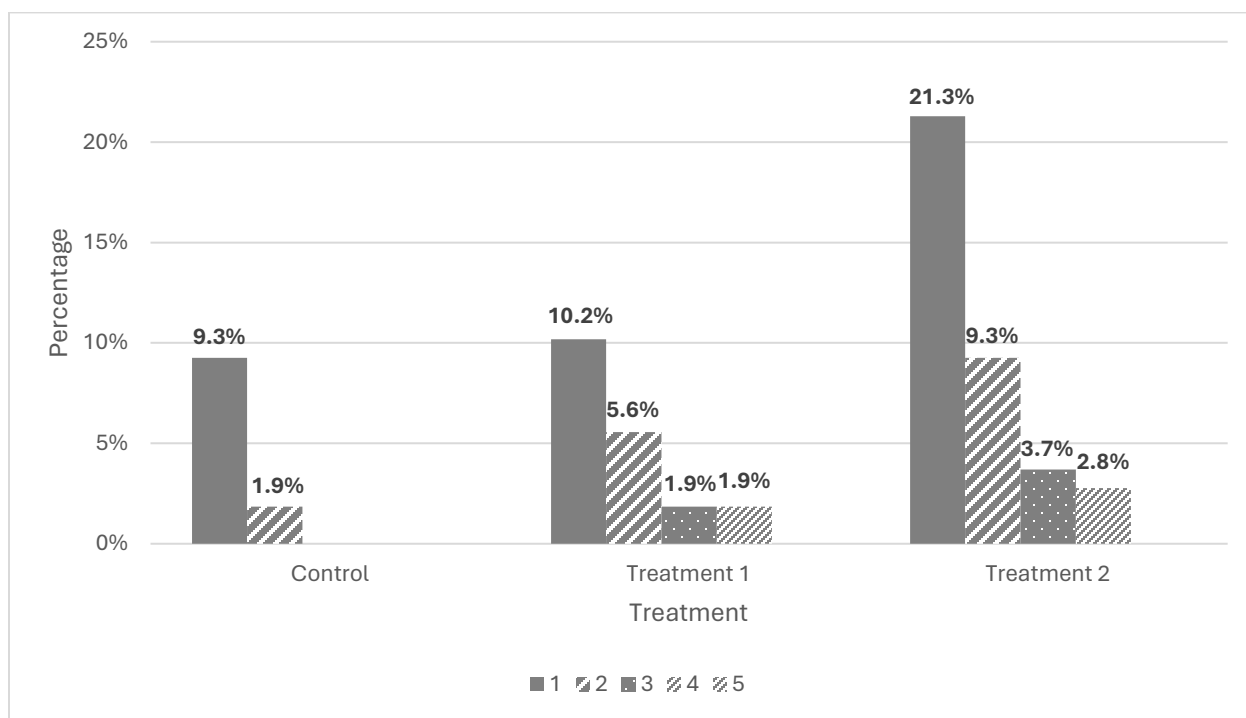


Figure 18. Composition of Total Tip Burn Ratings on a 1-5 Scale for Plants in Each Treatment Showing Tip Burn Symptoms as a Percentage of the Total Harvested Plants.

4. Profitability and Waste

Using the rating system for tip burn severity, the profitability and waste of the lettuce grown in different aerial environments can be analyzed. Defined in the rating system to determine the severity of the tip burn necrosis, a rating of 2 and below is considered eligible for sale, while a rating of 3 and above is considered waste. Tip burn ratings of 3 and above indicate a lettuce head with clearly apparent tip burn symptoms, a trait that is unattractive to consumers, especially in a crop that is predominantly consumed raw. Using this rating system, it was found that the Control levels had 0% waste, meaning all tip burn occurrences were below the waste threshold. Plants exposed to Treatment 1 experienced 3.7% waste, indicating losses for growers at market. The Treatment 2 levels had the highest level of waste, with 6.5% of the lettuce heads deemed unmarketable by the rating (Figure 19). The amount of waste associated with each treatment level has a direct correlation to the profits made by growers, as higher waste translates to lower profits overall. The ANOVA analysis performed on the profitability versus waste comparisons between treatments, coupled with the Tukey HSD test showed that between airflow treatments, there was a statistically significant difference between the waste of the Control and Treatment 2 plants at harvest (Table 7, **Error! Reference source not found.**). The tests also showed that when comparing the harvest waste of the Control to Treatment 1 plants, there was not a statistically significant difference between the two treatments, as the p-value was greater than the established $\alpha = 0.05$ value.

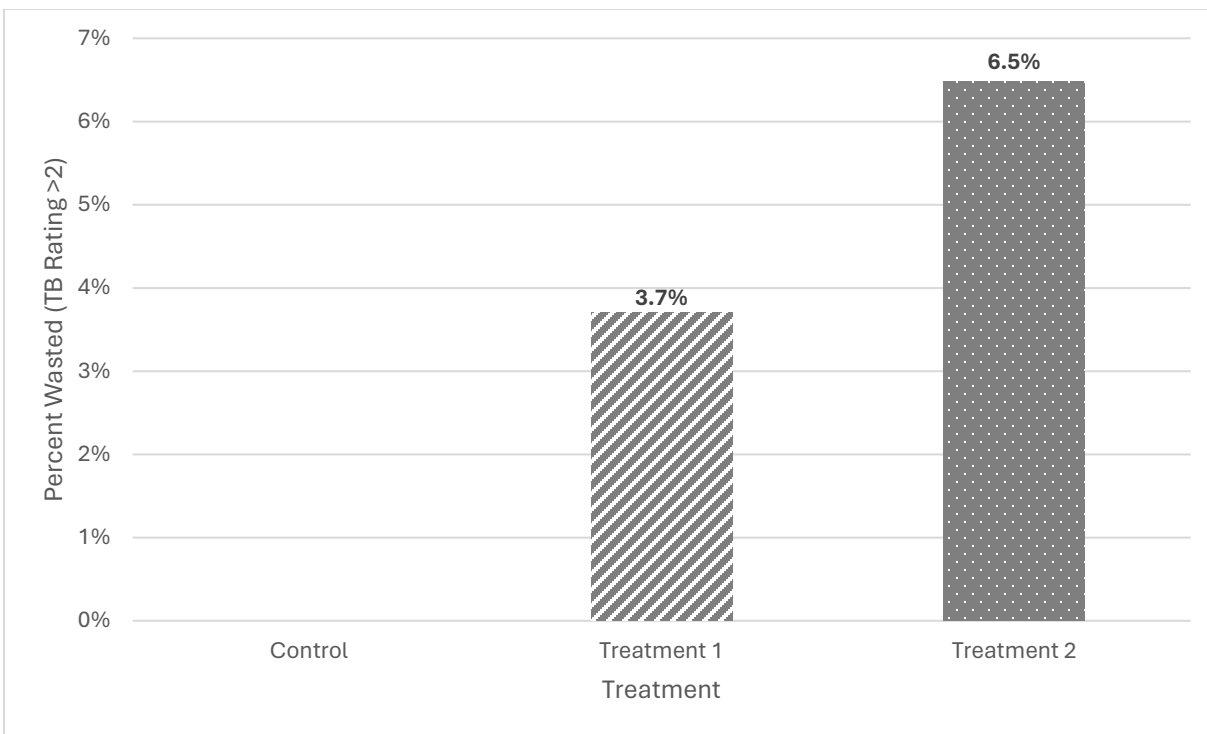


Figure 19. Percent of Harvest Deemed Unmarketable per Treatment Due to Tip Burn Ratings above Level 2.

Table 5: Analysis of Variance (ANOVA) Test Comparing the Effect of the Treatment, Rack, and Level on the Profitability of the Lettuce Harvested.

Profitability ANOVA Analysis						
Factor	df	Sum sq	Mean sq	F-Value	p-value	Significance?
Treatment	2	0.228	0.114	3.521	0.031	Significant
Rack	1	0.028	0.028	0.856	0.356	Insignificant
Level	2	0.056	0.028	0.856	0.426	Insignificant
Residuals	318	10.315	0.032			

Table 6: Tukey's Honest Significant Difference (HSD) Test Comparing the Individual Factor Levels to Each Other to Determine Statistical Significance. Level 1 = Top, Level 2 = Middle, Level 3 = Bottom.

Profitability Tukey HSD Analysis					
Treatment Comparison					
	diff	lwr	upr	p-adj	Significance?
Treatment 1-Control	0.037	-0.021	0.095	0.287	Insignificant
Treatment 2-Control	0.065	0.007	0.123	0.023	Significant
Treatment 2-Treatment 1	0.028	-0.030	0.085	0.494	Insignificant
Rack Comparison					
Rack 2-Rack 1	-0.019	-0.058	0.021	0.355	Insignificant
Level Comparison					
Level 2-Level 1	0.014	-0.044	0.072	0.838	Insignificant
Level 3-Level 1	-0.014	-0.072	0.044	0.838	Insignificant
Level 3-Level 2	-0.028	-0.085	0.030	0.494	Insignificant

5. Effect of Airflow Treatments on Fresh Shoot Biomass

The summary statistics of the different airflow treatments (Control, Treatment 1, Treatment 2) can be seen in Table 7 as well as Figure 20 and Figure 21, comparing the average fresh weights of the lettuce (*cv.* Rouxai) that were exposed to the different aerial environments. Plants exposed to constant airflow for the 28-day growth period had an average weight of 150.1 ± 2.3 grams per plant. Rouxai lettuce grown with constant airflow in the final 14 days of growth was found to have an average weight of 149.9 ± 1.7 grams per plant. Treatment 2 plants, exposed to vertical airflow during the photoperiod of the final 14 days of growth showed the greatest average fresh weight, averaging 155.2 ± 1.9 grams per plant. The Analysis of Variance (ANOVA) test ($\alpha=0.05$) performed in Table 7 shows that no airflow treatment was found to have a statistically significant effect on the fresh biomass of the lettuce grown within. All of the airflow treatments were shown to be statistically insignificant to the lettuce fresh weights. The Rack and Level differences were known and accounted for through the randomization of treatment placements within the vertical farm during the experiment.

Although statistically insignificant, the weight variation of Treatment 2 compared to the Control and Treatment 1 levels can be explained by the slightly warmer microclimate established in those levels due to decreased airflow. With the vertical airflow, fans turned off for 8 hours per day, the environment within the Treatment 2 levels was slightly more stagnant than the Control or Treatment 1 levels, both of which utilized constant airflow. Warmer canopy level temperatures have been shown to increase the fresh biomass production of plants (Thompson, et al., 1998), which explains the slightly higher average weight seen in Treatment 2 plants. The difference in weight is statistically insignificant, however it was also expected, due to this knowledge.

Table 7. Analysis of Variance (ANOVA) Comparing Intermittent Airflow Treatments on Lettuce (cv. Rouxai) as a Function of Fresh Shoot Biomass (g plant⁻¹) at Daily Light Integral of 13.

Biomass ANOVA Analysis						
Factor	df	Sum sq	Mean sq	F-Value	p-value	Significance?
Treatment	2	1945	973	2.419	0.091	Insignificant
Rack	1	3082	3082	7.667	0.006	Significant
Level	2	9675	4838	12.033	0.000	Significant
Residuals	318	127851	402			

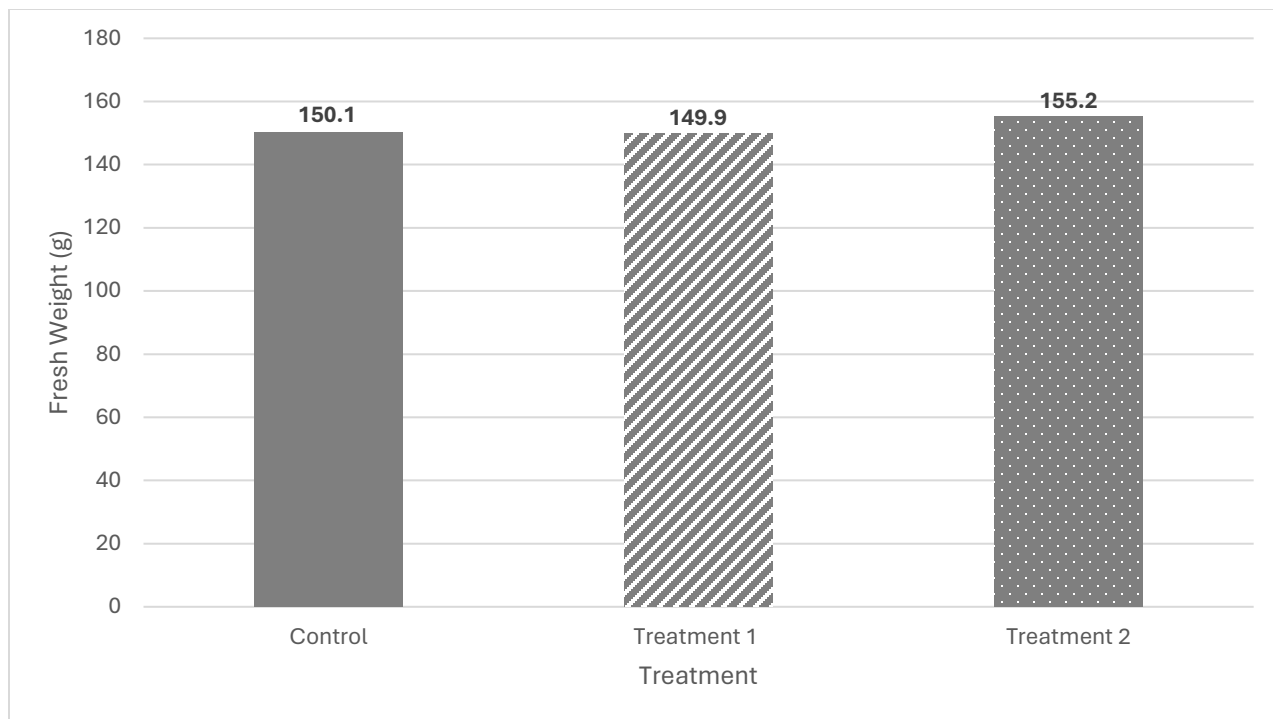


Figure 20. Average Fresh Shoot Biomass (g) for Lettuce (cv. Rouxai) as a Function of Intermittent Airflow Treatment Grown for 28 Days at Daily Light Integral of 13. Weight Differences Were Determined to be Insignificant Through ANOVA Analysis.

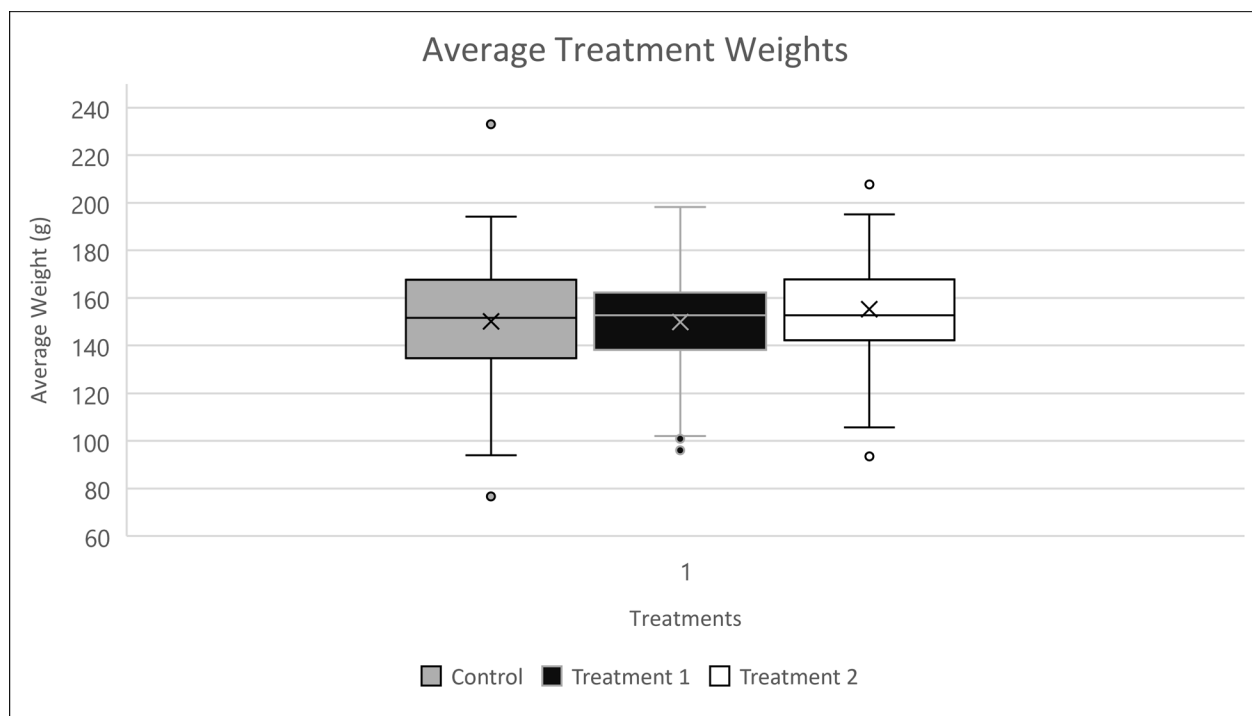


Figure 21: Fresh Shoot Biomass (g) for Lettuce (cv. Rouxai) as a Function of Intermittent Airflow Treatments Grown for 28 Days at Daily Light Integral of 13. Weight Differences Were Determined to be Insignificant Through ANOVA Analysis.



Figure 22. Sample of Control (Left), Treatment 1 (Middle), and Treatment 2 (Right) Lettuce (cv. Rouxai) Heads' Fresh Biomass Immediately After Harvest

6. Blower Fan Energy Savings

Electrical use efficiency (EUE) is a significant consideration in indoor agriculture, especially in vertical farming where operational costs are dominated by electrical consumption. As shown in

Table 8, fan operation times varied by treatment, and as such changed the EUE of the overall system. The Control fans ran for 24 hours per day for the entire 28-day growth cycle, representing 672 hours of total operational time. Treatment 1 fans were operational for 14 days of the growing cycle, running for 336 hours total, contributing to a 50% fan electrical consumption savings overall. Treatment 2 fans operated for 16 hours per day for 14 days, running for a total of 224 hours in the 28-day growing cycle, leading to a 66.7% power consumption saving overall. Depending on the location, the pricing of electricity per kilowatt hour (kWh) may vary, but the total percent of savings will remain constant. The greatest savings in electricity were achieved through the Treatment 2 operational strategy, with the Treatment 1 strategy also contributing to significant electricity savings.

Table 8. Energy Savings as a Function of Fan Operation Time per Treatment. Kilowatt Hour Consumption Calculations Based on the Assumption That AC Infinity Cloudline S8 Quiet Inline Duct Fans Are Being Run For Identical Time Intervals at Full Power.

	Control	Treatment 1	Treatment 2
Total Hours of Operation	672	336	224
Kilowatt Hours (per fan)	52.416	26.208	17.472
Hours Saved	0	336	448
Percent Savings	0%	50%	66.7%

Conclusions

1. *Effect of Intermittent Airflow on Tip Burn*

One primary objective during the course of this experiment was to create an aerial environment conducive to the mitigation of tip burn in lettuce (*cv. Rouxai*), while also exploring the possibility of minimizing blower fan run time. The desired vertical airflow velocity known to disrupt the leaf boundary layer and reduce tip burn occurrences is between $0.3 - 1.0 \text{ m s}^{-1}$, which allows increased gas exchange between the leaf and its surrounding environment, promoting the uptake of nutrients from the roots as transpiration takes effect. This study successfully implemented airflow systems and achieved desired levels of air velocities in each treatment level (Control, Treatment 1, and Treatment 2), with the primary difference being the timing of airflow application to the plants. When comparing the three treatments on the sole basis of tip burn occurrence, constant application of airflow from transplant to harvest (Control) is seen to have the best effect. Treatment 1 and Treatment 2 follow the Control in that order, showing the trend that more access to airflow results in lower tip burn occurrences. When considered from the grand scale, however, the rates of tip burn in Treatment 1 and Treatment 2 may well be within

satisfactory loss conditions for growers, as they resulted in 3.7% and 6.5% waste respectively, especially because there was no statistical significance found in the waste creation between the Control and Treatment 1 groups. Depending on the operational margins set by the growing team, losses up to and beyond these values may be acceptable, considering the electricity savings accompanying the intermittent airflow strategies.

2. Intermittent Airflow for Cost Savings

The treatment levels in this experiment were designed to provide adequate airflow to the growing plants, while also reducing the overall time spent operating. The Control levels experienced vertical airflow for 24 hours each day, for the entire 28-day growing cycle from transplant to harvest. Plants in the Treatment 1 group were exposed to vertical airflow for 24 hours each day in the final 14 days of growth, resulting in 50% energy savings overall. Treatment 2 plants received vertical airflow for the final 14 days of growth, for 16 hours each day, concurrent with the photoperiod. Treatment 2 resulted in a 66.7% fan electrical consumption saving overall, the largest of the treatments. In decreasing the operating time of the blower fans, slight increases in tip burn occurrence and waste were observed, representing a decision for growers. Balancing the benefits of a reduction in electricity payments with an increased waste percentage of Treatment 2 fan operation is a decision that will vary depending on company priorities and procedures. The actual dollar amount for cost savings will also vary between location and regional electricity suppliers, as there is no standardized rate per kilowatt hour.

3. Further Considerations for Intermittent Airflow Strategies

The two-fold goal of this research was to reduce the occurrence of tip burn in lettuce (*cv.* Rouxai) while simultaneously increasing the electrical use efficiency of the vertical farm through manipulating airflow. Considering the timing of Treatments 1 and 2, the decision to initiate

vertical airflow after the second week of growth was based on the knowledge that tip burn symptoms primarily manifest near that time (Kaufmann, 2023). Because calcium is an element that experiences very slow uptake into a leafy green, pre-empting the establishment of tip burn symptoms is crucial in providing consistent and high-quality harvests. Beyond the strategies employed by Treatment 1 and Treatment 2, further savings could also be found in fan operation only during off-peak hours, or time periods associated with discounted electricity rates. The different airflow treatments also resulted in slightly different average fresh biomass (g) weights for the sampled lettuce, with the average Control being 150.1 g, the average of Treatment 1 being 149.9 g, and the average of Treatment 2 being 155.2 g. Although statistically insignificant, growers looking to maximize yield and biomass production may look into this option to slightly increase yield while still keeping tip burn wastes to a low percentage of overall yield.

4. Recommendations and Future Research

This experiment illustrated the possibility of mitigating tip burn in leafy greens while also minimizing the electrical consumption of a vertical farm fans through intermittent airflow. The strategies and results presented in this study will serve as a baseline for future research into not only intermittent airflow in a plant factory setting but also the co-optimization of other environmental factors to further increase the efficacy of intermittent airflow. With manipulations of variables such as atmospheric carbon dioxide concentration, relative humidity, temperature, light intensity, light quality, or nutrient solution, the findings in this study can be built upon to further increase the resource use efficiency of indoor agriculture. This study quantified tip burn quantitatively and qualitatively, but further insight into the delineation separating profitable vs waste qualities in lettuce could be further explored through focus groups. Allowing consumers to dictate their comfort level with tip burn severity in their produce would provide growers with

greater knowledge on the subject and allow them to make more accurate decisions on quality control. Although this study utilized the Rouxai cultivar of lettuce, establishing a cultivar of lettuce capable of robustly countering the establishment of tip burn symptoms would be another avenue of exploration in further iterations of this project. With lettuce bred for indoor agriculture conditions, the effects of intermittent airflow may be more pronounced, resulting in significantly lower levels of waste to growers. Nutrient density is another aspect that carries the potential for further experimentation, as the quantity of key nutrients or flavor compounds was not explored in this research. Manipulation of the nutrient solution, selection of appropriate lettuce cultivars, and dynamic environmental conditions would allow for the greatest optimization of the growing environment with the least input required, and this experiment accounts for a piece of that greater puzzle.

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