

# Optimizing Downward Airflow to Prevent Lettuce Tipburn in Vertical Farms

Parker Egan Persons

Department of Horticulture, University of Georgia, Athens, GA 30605, USA

Paul M. Severns

Department of Plant Pathology, University of Georgia, Athens, GA 30605, USA

Anish Malladi and Ruanito Soranz Ferrarezi

Department of Horticulture, University of Georgia, Athens, GA 30605, USA

**Keywords.** calcium deficiency, crop physiology, environmental control, production, transpiration

**Abstract.** Vertical farming offers a promising solution to urban food demand through precise environmental control. However, rapid plant growth induced by high light intensity often leads to tipburn in lettuce (*Lactuca sativa*), a physiological disorder associated with calcium deficiency in expanding tissues, resulting in food waste and economic loss. While enhancing transpiration by applying airflow above the canopy has been proposed to alleviate tipburn, few studies have examined the combined effects of airflow and light intensity across multiple levels to maximize growth and quality. This study investigated the combined effects of downward airflow (0.4, 0.7, 1.0, and 1.3 m·s<sup>-1</sup>) and light intensity (200, 350, and 500 μmol·m<sup>-2</sup>·s<sup>-1</sup>) on tipburn incidence in two lettuce cultivars, Casey and Dragoon. The effects of airflow and light were independent, with no significant interaction between them. Higher airflow rates consistently reduced tipburn incidence and severity and increased the percentage of marketable plants, without affecting shoot biomass, quality, or nutrient concentrations. In contrast, high light intensity increased photosynthetic rate, biomass, and quality (soluble solids, chlorophyll content) but also exacerbated tipburn symptoms despite high transpiration rate, likely due to rapid tissue expansion. ‘Dragoon’ exhibited more severe tipburn than ‘Casey’ across treatments, highlighting the importance of cultivar selection for indoor lettuce production. These findings demonstrated that increasing airflow can effectively mitigate tipburn under high light conditions without compromising growth or quality.

Food production evolved quite drastically in recent decades, with indoor “smart” farming becoming the most advanced farming technique in recent years because of the possibility to fully control the environment for crop production (Mitchell 2022). Vertical farming has been at the forefront of agricultural interests over the past several years due to the ability to transform indoor spaces with no sunlight and artificial lighting into high-yield plant factories. Moving forward, indoor farming could be widely adopted to keep up with our ever-growing world population. Food deserts are one of the primary motivations for incorporating vertical farming into the future of agriculture. As of the 2000 census, there are ~6500 food deserts in the United States, meaning people have limited access to plentiful and nutritious food (Dutko et al. 2012). Vertical farms aim to solve this problem by growing fresh produce near these food deserts, minimizing the distance needed to transport healthy foods to places that lack them. Vertical farms also increase shelf life and create a larger abundance of consumer-marketable produce, resulting in less food waste.

Vertical farms are well-suited for leafy greens and small fruit crop production, and controlling the environment allows vertical farmers

to yield large quantities of produce year-round while minimizing inputs. The appeal of vertical farming lies in its ability to precisely control the environment, including factors such as lighting, CO<sub>2</sub> concentration, air temperature, fertilizer solution, relative humidity, and vapor pressure deficit (VPD). Production cycles are incredibly fast, and resources are used more efficiently since crop yields are maximized, especially because disease and pest management become a lesser burden on the farmer.

Growers reap the benefits of such environmental precision, but there are unexpected consequences, especially stemming from these indoor plant production environments catered to fast plant growth (Ertle and Kubota 2023). Tipburn in leafy greens is among the most detrimental physiological disorders in vertical farming, leading to unmarketable products and increasing food waste, resulting in a negative economic impact. Tipburn is caused by a lack of Ca transport to newly formed leaves, as the fast-paced growth-induced environments cause new growth to be faster than the rate at which Ca can be translocated into these leaves (Barta and Tibbitts 2000). Visually, tipburn is a marginal necrosis on the tips of plant leaves. Ca is an important nutrient for maintaining the cell walls of plant leaves, and

a lack of Ca in the tips of leaves exacerbates tipburn (Collier and Tibbitts 1982). As an immobile plant macronutrient, Ca does not readily transport through the phloem pathway of the plant tissue. Instead, Ca is transported through the xylem pathway through mass flow in solution with water.

Tipburn is typically induced toward the end of the lettuce (*Lactuca sativa*) production cycle. Growth rates of lettuce increase exponentially near harvest, as confirmed in a study on light intensity and tipburn (Sago 2016). Another reason is that the growing meristem becomes crowded in the established plant canopy, resulting in reduced airflow within the center of the lettuce canopy, which leads to a thicker boundary layer and prevents transpiration (Caplan 2018; Kaufmann 2023). With little transpiration occurring in newly developing leaves, a hot and humid microclimate forms around those leaves, and consequently, nutrients and water are unable to be efficiently transported (Caplan 2018; Collier and Tibbitts 1984; Kaufmann 2023).

There are many recommended environmental conditions for the optimal growth of lettuce that increase the incidence of tipburn in indoor lettuce production. Generally, due to the environmental conditions favoring quicker lettuce growth, these same conditions increase tipburn occurrence and severity. Higher air temperatures are highly correlated with increased plant growth up to a threshold, and increasing temperatures enhance physiological growth processes in plants (Ahmed et al. 2020). Reduced temperatures have been shown to delay and suppress the onset of tipburn in lettuce (Choi et al. 2000; Cox et al. 1976). Choi et al. (2000) concluded that the optimum temperatures for butterhead and leaf lettuce cultivars were between 22 and 26 °C during the day and 20 to 24 °C at night. In the same study, higher temperatures increased the incidence of tipburn in both butterhead and leaf lettuce cultivars. There is a tradeoff between air temperature and tipburn. Higher air temperatures allow growers to achieve a faster crop turnover rate and increase annual yields, but this comes at the expense of increased tipburn incidence.

CO<sub>2</sub> concentrations of 1000 to 1500 μmol·mol<sup>-1</sup> have been deemed the optimum concentrations to maximize lettuce growth (Ahmed et al. 2020). However, CO<sub>2</sub> concentrations of 850 μmol·mol<sup>-1</sup> were reported to create the best environment for minimizing lettuce tipburn while still achieving higher crop yields (Caplan 2018). A lack of CO<sub>2</sub> supplementation in a vertical farm comes at the cost of lower crop yields, since CO<sub>2</sub> supplementation increases the growth rate of lettuce, therefore leading to greater tipburn incidence (Read and Tibbitts 1970).

Light intensity is one of the principal driving factors of plant productivity and physiological processes (Kozai 2013). The net photosynthetic rate ( $P_n$ ) of lettuce was reported to be greatest, with a light intensity of 500 μmol·m<sup>-2</sup>·s<sup>-1</sup>, with a significant decrease in  $P_n$  at a light intensity of 600 μmol·m<sup>-2</sup>·s<sup>-1</sup> (Zhou et al. 2019), most likely due to photoinhibition caused by light saturation with direct effect on carbon

assimilation (Li 2002). This result suggests the law of diminishing returns when increasing light intensity beyond the point of maximum yield. It has also been reported that lettuce production has been detrimentally affected by either too-high or too-low light intensities: 800 and 100  $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ , respectively (Fu et al. 2012). In a review of optimal environmental conditions for lettuce growth Ahmed et al. (2020) concluded that a photoperiod of between 16 and 18 h/day is optimal. A positive correlation exists between increasing light intensity and tipburn incidence. Reportedly, in a study comparing different light intensity effects on tipburn in butterhead lettuce, a 300  $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$  treatment had 22.5 and 10.0 times greater number of tipburned leaves than the 150  $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$  treatment at 30 and 35 d after sowing, respectively (Sago 2016).

The time from sowing to lettuce harvest is another tradeoff considered by the producers. As reported by Sago (2016), Japanese markets consider butterhead lettuce yields greater than 80 g marketable. Lettuce harvested 30 d after sowing failed to reach a weight of 80 g under any experimental light intensity. The study also found that the incidence of tipburn increased between 30 and 35 d (Sago 2016). Consequently, many indoor growers harvest lettuce early in its production cycle to ensure the crop is marketable and to avoid tipburn.

Lettuce cultivar selection has a great impact on tipburn incidence (Beacham et al. 2023; Ertle and Kubota 2023). When grown under the same environmental conditions, Ertle and Kubota (2023) reported that lettuce morphology (butterhead, leafy, or romaine) did not significantly affect tipburn incidence

or severity. ‘Klee’ ranked first in tipburn severity, although the canopy never crowded the meristem. In the same study, ‘Klee’ ranked eighth in yield but first in tipburn severity, suggesting that yield only influences tipburn within the same cultivar, and comparisons cannot be made between lettuce cultivars. Genetics of lettuce cultivars suggest an important role in the ability of the crop to transpire and transport Ca at a rate that supports its growth (Beacham et al. 2023; Ertle and Kubota 2023).

Optimal relative humidity (RH) levels are another important environmental condition that can improve lettuce growth. RH is a challenging environmental parameter to control to mitigate tipburn, as RH that is too high will deter transpiration, and too-low RH will cause the stomata to close (Kroggel and Kubota 2017). Greater RH increases the water vapor concentration in the air, decreasing the VPD. Low VPD causes lettuce transpiration rates to decline because the stomata cannot release as much water vapor into the air due to the unfavorable concentration gradient. In a study comparing 85% to 50% in RH differences on lettuce biomass, the growth rate was significantly higher for the 85% RH treatment (Tibbitts and Bottenberg 1976).

Airflow velocity is another important factor in indoor lettuce production, as it regulates other environmental conditions like air temperature and RH. Optimal airflow rates are essential for improving plant growth by increasing transpiration and photosynthetic rates (Korthals et al. 1994). The optimal air velocity directed on lettuce canopies for plant growth was reported to be between 0.3 and 1.0  $\text{m}\cdot\text{s}^{-1}$ , although recommendations vary with plant species and airflow direction (Ahmed et al. 2020; Goto and Takakura 1992b; Kaufmann 2023; Kitaya et al. 2003). Supplemental airflow is important in a vertical farm to break the boundary layer of stagnant air above the plant canopy, as indoor plant production facilities lack the natural air movement of traditional outdoor agriculture and greenhouses (Ferrarezi et al. 2024). If the boundary layer remains stagnant, transpiration rates decrease, which induces more tipburn. Nutrients and water are not taken up by the plant as effectively if transpiration rates are low, as the xylem aids the phloem in nutrient uptake by mass flow (Kitaya et al. 2000). VPD in the microclimate above the inner plant canopy is reported to increase with vertical airflow, meaning transpiration rates increase, and Ca transport by mass flow is more likely to reach the meristem (Goto and Takakura 1992b).

Airflow on the lettuce canopy can be achieved by horizontal and vertical airflow or a combination of both. Many vertical farm growers have adopted the practice of using horizontal airflow, but the innermost parts of the crop canopy do not receive the same airflow as the outermost parts. Naturally, lettuce morphology forms a wall of leaves around the meristem, limiting the ability of air to reach the growing meristem (Chang and Miller 2004; Kaufmann 2023). Downward vertical airflow is more effective at reaching

the inner canopy, and this has proven to be a great way to minimize tipburn in indoor farms (Goto and Takakura 1992a). A vertical airflow rate of 1.3  $\text{m}\cdot\text{s}^{-1}$  was supplied 24 h and was reported to eliminate tipburn in vertical farm lettuce under a steep  $\text{CO}_2$  concentration of 1500  $\mu\text{mol}\cdot\text{mol}^{-1}$ , 14 h photoperiod, and a low light intensity of  $\sim 264 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ . In the same study, the authors compared the effect of supplying vertical airflow during only light or dark periods, as well as the leaf position that the air was directed on, at  $\text{CO}_2$  concentrations of 500  $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ , light intensity of 198  $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ , and a 14 h photoperiod. Goto and Takakura (1992a) concluded that airflow supplied only during either the light or dark periods was as effective for lowering tipburn incidence and that airflow directed toward the inner leaves was more effective in reducing tipburn than directing airflow to the outer leaves. These results were based on lettuce plants harvested between 75 and 105 g of fresh weight, which is a small plant in production settings. Although vertical airflow is a proven strategy for managing tipburn in leafy greens, introducing this practice in commercial vertical farms requires additional equipment and higher electricity costs (Kaufmann 2023). As mentioned by Kaufmann (2023), there is a lack of research comparing horizontal to vertical airflow systems in the reduction of tipburn in vertical farms and a lack of literature that combines horizontal and vertical airflow to mitigate tipburn in leafy greens.

Literature that explores varying vertical airflow rates on lettuce canopy under sole-source lighting is also scarce. Only one study used a vertical airflow rate as high as 1.3  $\text{m}\cdot\text{s}^{-1}$  in a plant factory (Goto and Takakura 1992a). Multiple studies prove that increasing light intensity positively correlates with higher tipburn incidence and severity in lettuce. No study has been found to date that explores varying light intensities and vertical airflow rates together to understand this relationship. Few studies grow lettuce through a full production cycle that uses vertical airflow for tipburn mitigation in vertical farm production.

Our study has four main objectives. The first is to understand the relationship between varying downward vertical airflow rates and light intensities on the incidence and severity of tipburn in indoor vertical farm lettuce production. While creating an indoor environment conducive to tipburn and optimal lettuce growth, our study explores how the individual and combined effects of vertical airflow rates and light intensities affect tipburn in lettuce. The second objective is to investigate which airflow rate would mitigate tipburn at a high light intensity. The industry would benefit from this result because growers desire the highest yield possible, achieved with greater light intensities, without the risk of tipburn. The third objective is to examine tipburn incidence and severity after a full lettuce production cycle to determine whether growers can achieve their full crop yield potential without fear of economic loss due to

Received for publication 18 Aug 2025. Accepted for publication 11 Oct 2025.

Published online 13 Nov 2025.

This research was funded by the University of Georgia Department of Horticulture, the University of Georgia College of Agricultural and Environmental Sciences, and the University of Georgia Office of the Senior Vice President for Academic Affairs and Provost. We thank the Horticultural Physiology and Controlled Environment Agriculture Crop Physiology and Production lab members for technical support, especially Matthew Housley, Chris Nieters, and Dr. Kuan Qin. We thank Dr. Marc W. van Iersel (*in memoriam*) for all the wisdom shared with his colleagues throughout his time at the University of Georgia. His colleagues miss him very much. May he rest in peace. We also thank Agrify (Micah Gilbert) for providing the LED lights for these experiments, and J. R. Peters (Dr. Cari Peters) for the donation of fertilizer.

P.E.P. and R.S.F.: Conceptualization and data curation; P.E.P. and P.M.S.: formal analysis; R.S.F.: funding acquisition; P.E.P., P.M.S., A.M., and R.S.F.: investigation and methodology; R.S.F.: project administration and resources; P.E.P.: software; R.S.F.: supervision; P.E.P., P.M.S., A.M., and R.S.F.: validation, visualization, writing – original draft and writing – review and editing.

R.S.F. is the corresponding author. E-mail: ferrarezi@uga.edu.

This is an open access article distributed under the CC BY-NC license (<https://creativecommons.org/licenses/by-nc/4.0/>).

tipburn. Finally, our study aims to analyze the results in two cultivars separately: a butterhead lettuce, 'Casey', and a romaine lettuce, 'Dragoon'.

## Materials and Methods

**Location, environmental conditions, and vertical farm setup.** Our study was performed in two sequential seasons at the University of Georgia (College of Agricultural and Environmental Sciences, Department of Horticulture, Controlled Environment Agriculture Crop Physiology and Production Laboratory) in Athens, GA, USA (lat. 33°55'55.10"N, long. 83°21'50.51"W, elevation 198 m). The two seasons were from Dec 2023 to Jan 2024 and Jan to Feb 2024, respectively. The indoor vertical farm had three equally spaced racks with dimensions 3.6 × 0.6 × 2.4 m (length × width × height) each (ULINE, Pleasant Prairie, WI, USA). The racks had four shelves, with each shelf containing nine light-emitting diode (LED) lights (Model R; Agrify, Billerica, MA, USA) with a red:blue (R:B) ratio of 5.0 (12% blue, 26% green, 60% red, and 1.6% far red). The spectrum was calculated using a spectrometer (LI-180; LI-COR, Lincoln, NE, USA). Each shelf was divided into three experimental sections with three LED lights per section. The daily light integral was 11.52 mol·m<sup>-2</sup>·d<sup>-1</sup> for the low light intensity treatment (200 μmol·m<sup>-2</sup>·s<sup>-1</sup>), 20.16 mol·m<sup>-2</sup>·d<sup>-1</sup> for the medium light intensity treatment (350 μmol·m<sup>-2</sup>·s<sup>-1</sup>), and 28.8 mol·m<sup>-2</sup>·d<sup>-1</sup> for the high light intensity treatment (500 μmol·m<sup>-2</sup>·s<sup>-1</sup>), with all plants receiving a 16-h daily photoperiod.

The air temperature of the vertical farm was controlled by two air conditioning units (X30A132A; Mitsubishi Electric, Tokyo, Japan). The environmental conditions were controlled by a temperature/CO<sub>2</sub>/RH sensor (HT0-45D; Rotronic, Hauppauge, NY, USA), and 24 thermocouples (type T; Reotemp, San Diego, CA, USA). The environmental conditions were recorded by a datalogger (CR1000X; Campbell Scientific, Logan, UT, USA). CO<sub>2</sub> was supplemented into the vertical farm with gaseous CO<sub>2</sub> tanks (Airgas, Radnor, PA, USA) coupled with a CO<sub>2</sub> regulator (CO<sub>2</sub> regulator emitter system; Vivosun, Ontario, CA, USA). A homemade humidification and dehumidification (model PD160A; Keson, Gaffney, SC, USA) system was designed and installed in the vertical farm to keep the RH and VPD stable throughout the two seasons. The homemade humidifier was created by plumbing water into a container (ULINE) with a 2.54 cm-thick insulation board (GreenGuard GG25-LG XPS; Kingspan, Atlanta, GA, USA), and a float valve automatically filled the container with water when needed. A fog maker (six-head ultrasonic mist maker fogger; Mxmoonant, Lewistown, MT, USA) floated in the water, and a small computer fan was situated into the insulation board, and these were connected to a solid-state relay switch (Power-Tail II; Digital Loggers, Santa Clara, CA, USA) that was triggered to turn on or off by a datalogger (CR1000x; Campbell Scientific) when the

VPD in the room went above 1.1 kPa. The average temperature, RH, CO<sub>2</sub>, and VPD inside the vertical farm for season 1 during the day was 21.59 ± 0.87 °C, 65.46% ± 9.57%, 774 ± 198 μmol·mol<sup>-1</sup>, and 0.90 ± 0.28 kPa [mean ± standard deviation (SD)], respectively, and during the night (when lights were off) was 21.59 ± 0.87 °C, 65.40% ± 9.72%, 772 ± 200 μmol·mol<sup>-1</sup>, and 0.90 ± 0.28 kPa, respectively. The average temperature, RH, CO<sub>2</sub>, and VPD inside the vertical farm for season 2 during the day was 21.71 ± 0.63 °C, 66.64% ± 7.09%, 801 ± 173 μmol·mol<sup>-1</sup>, and 0.87 ± 0.20 kPa, respectively, and during the night was 21.72 ± 0.58 °C, 66.83% ± 7.03%, 797 ± 176 μmol·mol<sup>-1</sup>, and 0.87 ± 0.20 kPa, respectively. Although CO<sub>2</sub> was only supplemented during the day (16-h photoperiod), similar concentrations were present both day and night because the photoperiod ran from 7:00 PM to 11:00 AM, and most measurements were taken between 11:00 AM and 7:00 PM. Humans release CO<sub>2</sub> when breathing, and measurements were taken mostly during the night cycle; hence, the nighttime CO<sub>2</sub> concentrations were similar to the daytime levels. Due to this, it was unnecessary to supplement CO<sub>2</sub> during the nighttime. These environmental conditions were deployed to create an environment conducive to tipburn. When inducing enough tipburn, we can better understand the effects of airflow rates and light intensities on minimizing tipburn.

A deep water culture (DWC) hydroponics system in polypropylene trays (Garland, West Midlands, England) with dimensions of 60.96 × 60.96 × 12.70 cm (length × width × height) was used for plant growth. The trays were filled with 25 L of fertilizer solution and covered with polystyrene insulation sheathing (GreenGuard XPS; Kingspan), each with four evenly spaced holes, allowing for four plants per tray. Aeration in the fertilizer solution was provided by a 13.5 m<sup>3</sup>·h<sup>-1</sup> 48 kPa aeration pump with a 1.27 cm outlet (EcoAir 7; EcoPlus, Vancouver, WA, USA) with 0.79 × 0.48 cm (outside × inner diameter) clear extruded acrylic tubes (Dernord; Tangxia, Dongguan, China) connected to the pump with 2.03 × 1.78 cm (diameter × height) air stones (Pawfly 0.8-inch air stone; Amazon, Seattle, WA, USA).

**Plant material, treatments, and growth conditions.** The same growth conditions, treatments, and plant material were used for both seasons. Two lettuce cultivars, Dragoon and Casey, were grown (Johnny's Selected Seeds, Winslow, ME, USA). 'Casey' was selected because it is a new cultivar on the market known to be resistant to Ca tipburn and is a butterhead variety, and 'Dragoon' was chosen because it is very sensitive to Ca tipburn and is a romaine variety (Ertle and Kubota 2023). The seeds were sown into rockwool plugs (AO 36/40; Grodan, Milton, ON, Canada). A clear dome was placed over each plug to trap moisture, and the trays were then placed into a walk-in growth chamber equipped with an automated ebb-and-flow subirrigation system. The plugs were misted daily with tap water until the seeds

germinated (~3 d). Once the seeds germinated, the clear domes were removed, and the seedlings were subirrigated every other day until transplant for 5 min with 100 mg·L<sup>-1</sup> N made with a 15N-2.2P-12.45K water-soluble fertilizer (15-5-15 Ca-Mg Professional LX; J.R. Peters, Allentown, PA, USA). The average temperature, CO<sub>2</sub> concentration, and VPD inside the seedling growth chamber for season 1 were 23.7 ± 0.04 °C, 812 ± 4 μmol·mol<sup>-1</sup>, and 0.93 ± 0.03 kPa, respectively, and those for season 2 were 24.04 ± 1.12 °C, 822 ± 22 μmol·mol<sup>-1</sup>, and 1.03 ± 0.15 kPa, respectively. Only one shelf in the growth chamber was used to start the plugs for each season, with minimal variation in environmental conditions for both. The same growth chamber setup was used to grow the set of plugs for each season. Plants received a light intensity of 250 μmol·m<sup>-2</sup>·s<sup>-1</sup> from the above LEDs and a 16-h photoperiod from seed to transplant. Plugs grew for 14 d in the growth chamber before being transplanted into the vertical farm to ensure that there were four true leaves on each lettuce plug. At transplant, the plugs were randomly selected, separated, and placed inside a 4.45-cm top diameter × 3.33-cm bottom diameter × 5.08-cm deep net cup (Teku; Amazon). The net pots were then placed into the holes of the polystyrene sheathing in the vertical farm.

The study was arranged in a factorial complete randomized block design, and the treatment factors were downward airflow rates and light intensities (Fig. 1). The first experimental factor was downward airflow rates of 0.4, 0.7, 1.0, and 1.3 m·s<sup>-1</sup>. The downward airflow rates were achieved with in-line air blowers (7.5 cm 12 V in-line; Sea-Flo, South Bend, IN, USA) with a flow rate of 3.68 m<sup>3</sup>·min<sup>-1</sup> connected with 3-mil and 7.6-cm diameter poly sleeves (ULINE). Holes were punched on both sides of the sleeves at an angle of 30° off center, different airflow rates were created by adjusting the spacing between the holes and varying the hole diameter, and these airflow rates were confirmed by a hot-wire anemometer (Climomaster; Kanomax, Andover, NJ, USA) (Table 1) (Ferrarezi et al. 2024).

The second experimental factor was light intensity: 200, 350, and 500 μmol·m<sup>-2</sup>·s<sup>-1</sup>. Different light intensities were achieved by using a control system (Agrify, Billerica, MA, USA) that could adjust the voltage sent to the LEDs. Seven LED drivers were used to power the 108 LED lights. The wiring from the drivers to the LEDs was distributed in a way that had more LEDs connected to the drivers that provided the lower light levels and fewer LEDs connected to the drivers that supplied the higher light levels, respectively. This allowed us to achieve the desired light intensities, with all lighting treatments having a standard deviation of less than 10%.

A total of 36 experimental units were present across the three racks. Each section was randomized using a random number generator to create a treatment combination of a downward airflow rate paired with light intensity, resulting in 12 different treatment

Dual airflow sleeves per shelf fit in the two gaps between the LED fixtures

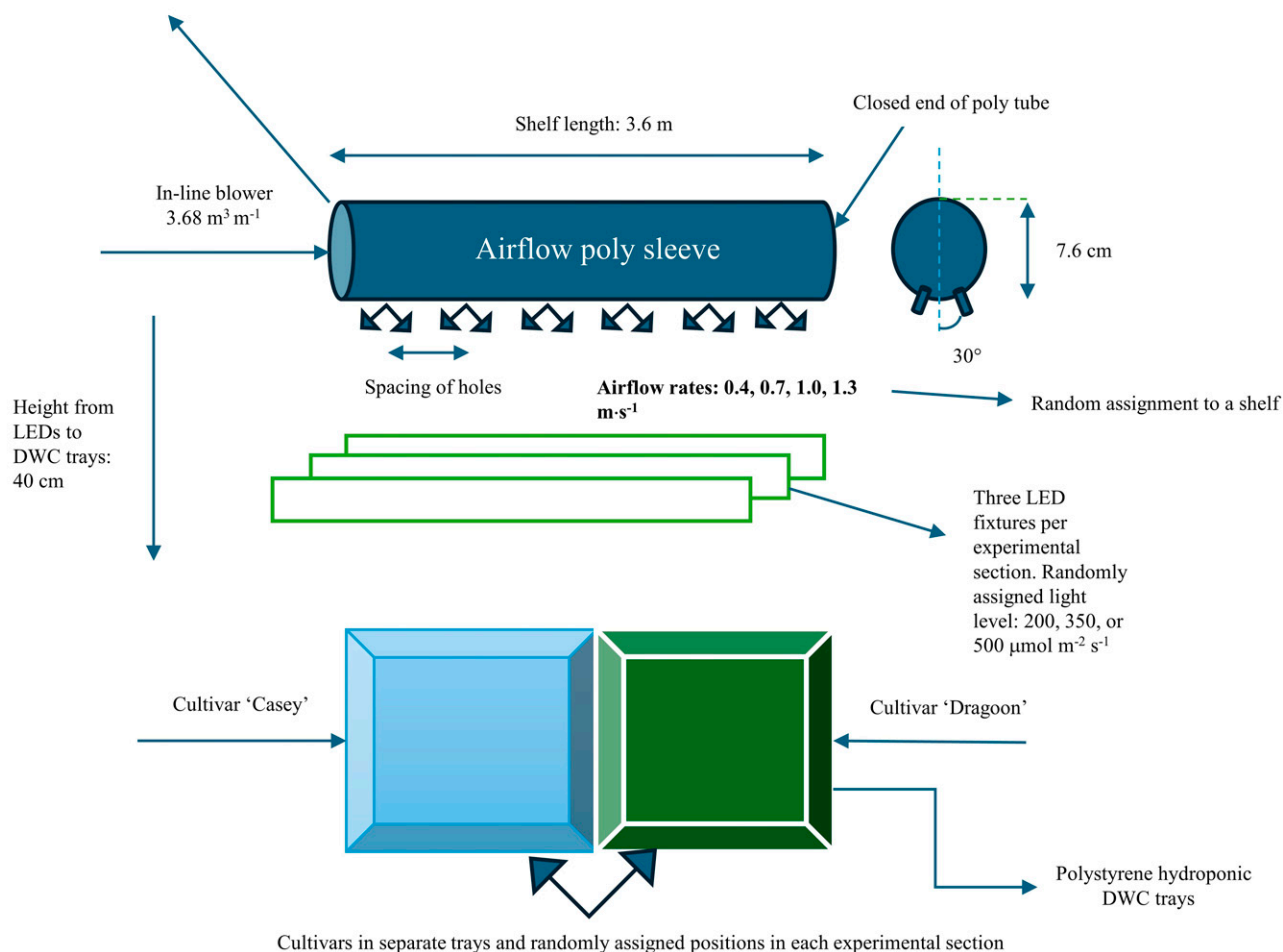


Fig. 1. Diagram of the two experimental treatments (downward airflow rates and light intensity). Each experimental unit was configured as illustrated. There were 36 total experimental units for each cultivation. DWC = deep water culture; LED = light-emitting diode.

combinations. Three replications of each treatment combination were used, with each rack containing one replicate. Each season had 72 experimental DWC trays: 36 with 'Casey' and the other 36 with 'Dagoon'. Each section contained two DWC trays, one with 'Casey' and another with 'Dagoon', but the cultivars were separated.

**Fertilizer solution nutrient concentrations and streamline measurements.** Each DWC tray received the same fertilizer solution. Three separate 18.9-L stock solution buckets were mixed and labeled A (nitrates), B (phosphates and sulfates), and C (carbonates). Stock bucket A was created by adding 800 g

of calcium nitrate (YaraTera Calcinit; Yara, Tampa, FL, USA), 650 g of potassium nitrate (Haifa Multi-K GG; Agriros, Hague, Netherlands), and 55 g of Fe-EDDHA (LidoQuest Fe 6% EDDHA 80% Ortho; LidoChem, Hazlet, NJ, USA). Stock bucket B was created by adding 70 g of monopotassium phosphate (MKP) (Haifa 0-52-34; Agriros, CA, USA), 0.8 g of zinc sulfate (Epsotop Magnesium Sulfate K+S; HortAmericas, Bedford, TX, USA), 2.52 g of boric acid (Boric Acid Technical Grade Granular; National Borax Corporation, Cleveland, OH, USA), 0.7 g of manganese sulfate (manganese sulfate monohydrate granular; Valudor Products, Encinitas, CA, USA), 0.8 g of zinc sulfate, 0.07 g of ammonium molybdate, and 100 g of monoammonium phosphate (technical monoammonium phosphate 12-61-0; WeGrow AG, Thalwil, Switzerland). Stock bucket C was created by adding 373 mL of liquid potassium carbonate (liquid potassium solution 0-0-25; Growth Products, Miami, FL, USA). Each stock bucket was then diluted with tap water to a total volume of 18.9 L. The fertilizer solution was mixed into a large 1,356-L reservoir using three connected proportional injectors (D14MZ2; Dosatron, Clearwater, FL, USA) at an injector ratio of 1:100 (fertilizer solution:water). Once

the solution was mixed, phosphoric acid (pH-adjusting agent) was added to the solution to achieve the desired pH range of 5.5 to 6.0 (Table 2).

Using a flow meter, the DWC trays were filled with 25 L of the mixed fertilizer solution on the transplant day by extending a hose attached to a submersible pump from the reservoir to the vertical farm. A piece of tape was placed exactly where the solution line was, which served as the reference for refilling each tray back to the 25-L line. Fourteen days after transplant, the first nutrient top-off occurred, which was done with a half-strength solution using a proportional injector set to a 1:200 injector ratio. Because the DWC trays evaporated water, which concentrated the nutrients in the solution and raised the electrical conductivity (EC), a half-strength solution was selected as a top-off method to maintain the EC within a range of 1.3 to 1.8 mS·cm⁻¹. Then, 21 d after the transplant, the DWC trays were all topped off with full-strength solution (the same solution that initially filled the trays) to maintain a favorable EC. The same fertilizer solution and refill methods were used for both seasons. Maintaining the EC in a range of 1.3 to 1.8 mS·cm⁻¹ was critical to ensure a sufficient supply of nutrients

Table 1. Hole diameter and space between holes adjusted in the poly tubing to manipulate airflow rates.

| Airflow rates at 20 cm (m·s⁻¹) | Hole diam (mm) | Space between the center of adjacent holes (cm) |
|--------------------------------|----------------|-------------------------------------------------|
| 0.4                            | 3.5            | 5                                               |
| 0.7                            | 4.5            | 5                                               |
| 1.0                            | 4.5            | 3                                               |
| 1.3                            | 7.9            | 6                                               |

Source: Ferrarezi et al. (2024).

Table 2. Detailed fertilizer concentrations of the full-strength and half-strength blends.

| Nutrients                       | Full-strength blend (mg·L <sup>-1</sup> ) | Half-strength blend (mg·L <sup>-1</sup> ) |
|---------------------------------|-------------------------------------------|-------------------------------------------|
| Season 1                        |                                           |                                           |
| NO <sub>3</sub> -N              | 149                                       | 87.5                                      |
| NH <sub>4</sub> <sup>+</sup> -N | 13.7                                      | 13.6                                      |
| P                               | 82.9                                      | 48.2                                      |
| K                               | 229                                       | 131                                       |
| Ca                              | 104                                       | 60                                        |
| Mg                              | 41                                        | 22.6                                      |
| S                               | 173                                       | 96.8                                      |
| B                               | 0.41                                      | 0.22                                      |
| Cu                              | 0.02                                      | 0.02                                      |
| Fe                              | 2.20                                      | 1.23                                      |
| Mn                              | 0.16                                      | 0.10                                      |
| Zn                              | 0.18                                      | 0.10                                      |
| Season 2                        |                                           |                                           |
| NO <sub>3</sub> -N              | 161                                       | 81.8                                      |
| NH <sub>4</sub> <sup>+</sup> -N | 11.2                                      | 11.2                                      |
| P                               | 67.1                                      | 52.1                                      |
| K                               | 233                                       | 140                                       |
| Ca                              | 104                                       | 53.4                                      |
| Mg                              | 30.4                                      | 32.9                                      |
| S                               | 130                                       | 137                                       |
| B                               | 0.20                                      | 0.27                                      |
| Cu                              | 0.01                                      | 0.02                                      |
| Fe                              | 2.06                                      | 1.18                                      |
| Mn                              | 0.14                                      | 0.14                                      |
| Zn                              | 0.11                                      | 0.15                                      |

to the lettuce plants. Too-low or too-high EC levels induce stress in lettuce crops. Both full-strength and half-strength fertilizer solutions were collected and sent to a commercial laboratory (Waters Agricultural Laboratories, Camilla, GA, USA) for analysis of individual nutrient concentrations (Table 2).

To collect accurate plant water use data, we measured the height of the fertilizer solution level at the start of each fill cycle and right before the next refill with a ruler. This method of calculating plant water use was implemented because our flow meter had a slight error rate (~5%) in measuring the amount of solution added. To be able to use the height of the fertilizer solution as a plant water use proxy, we filled five different DWC trays liter by liter until they were full, and then we took the height of each water level and created a linear regression curve to calculate what height of the solution would correlate to the amount of volume present. The equation developed from the linear regression curve:  $[-11.62 + (2836.44 \times \text{height})]/1000$ . The volume of solution at the end of a fill cycle was then subtracted from the volume of solution at the start to calculate the volume of solution lost. The total volume of fertilizer solution lost per treatment/replicate was then added to calculate the total plant water use over the growth period for the respective replicate. Plant water use was calculated per treatment combination to understand how the transpiration rates of the lettuce plants differed. Observing higher plant water use suggests that transpiration rates were greater for the respective treatment, therefore likely supplying more calcium to the shoots. pH, temperature, and EC of the solution in each DWC tray were checked 3 days a week using a portable tester

(HI98131; Hanna Instruments, Smithfield, RI, USA). The target pH range was between 5.5 and 6.0, and the fertilizer solutions were adjusted with either phosphoric acid (pure concentrate pH Down; Advanced Nutrients, Woodland, WA, USA) or potassium hydroxide (KOH) to lower or raise the pH into the desired range, respectively. Maintaining a pH of 5.5 to 6.0 ensured that the lettuce plants had sufficient access to the nutrients in the solution, eliminating any confounding variables when explaining the causes of tipburn in lettuce across treatments. Dissolved oxygen (DO) was measured weekly using a dissolved oxygen meter (HI98198; Hanna Instruments, Smithfield, RI, USA) to maintain the DO above 5 mg·L<sup>-1</sup>. A dissolved oxygen level above 5 mg·L<sup>-1</sup> ensured the plants had an abundance of oxygen for optimal growth, eliminating another confounding variable.

Leaf chlorophyll content for three quarters of the plants was recorded using a chlorophyll meter (CCM-200plus; Opti-Science, Hudson, NH, USA). Anthocyanin content was recorded for three quarters of the plants using an anthocyanin meter (ACM-200plus; Opti-Science, Hudson, NH, USA). Both measurements were taken from three leaves on each plant, and these values were averaged. Leaf chlorophyll and anthocyanin content provide information on plant health, growth, and photosynthetic potential and therefore deemed important to record.

**Gas exchange measurements.** Gas exchange was measured in season 2 with a gas exchange analyzer (CIRAS-4; PP Systems, Amesbury, MA, USA). Three plants were measured from each treatment combination. ‘Draughton’ was measured on 5 Feb and ‘Casey’ on 6 Feb. The LED cuvette attachment was adjusted for each light treatment to match the spectrum and light intensity of the above LEDs. To determine the spectrum of the LEDs, a spectrometer was used (LI-180; LI-COR). Three spectral measurements of each light intensity were recorded and then averaged to match the spectrum of the LEDs at the respective light treatment. The low light intensity (200  $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ ) treatment’s spectrum was 11% blue, 24% green, 65% red, and 1% far-red. The medium light intensity (350  $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ ) treatment’s spectrum was 11% blue, 23% green, 66% red, and 1% far-red. The high light intensity (500  $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ ) treatment’s spectrum was 13% blue, 28% green, 59% red, and 1% far-red. The cuvette temperature was set to the ambient temperature of the air in the vertical farm (22.5 °C), and the reference CO<sub>2</sub> concentration was set to 800  $\mu\text{mol}\cdot\text{mol}^{-1}$  to match the growing environment. This was done to collect gas exchange data under the real environmental conditions of the respective growing environment. Gas exchange was collected to better understand the differing transpiration and photosynthetic rates between treatment combinations.

**Harvest measurements.** ‘Draughton’ was grown in the vertical farm for 27 d after transplant, and ‘Casey’ was grown for 28 d after transplant, for total production cycles of 41 and 42 d, respectively. A total of 144 plants of each cultivar were grown and harvested for

analysis over two seasons. The length, width, and height of three plants per DWC tray were recorded using a ruler on the morning of harvest (for three quarters of the plants) to calculate the plant canopy volume. Plant canopy volume was calculated to indicate the openness of the canopy. Greater plant canopy volume would indicate a more open canopy and lower tipburn incidence, and severity would be expected. An open canopy allows greater volumes of air to reach the growing meristem, allowing plentiful transpiration in newly forming leaves.

Regardless of cultivar, every plant had fresh root and shoot weight recorded. Measuring the fresh weights of the lettuce plants was important to determine yield based on treatment combinations. Growers desire high lettuce yields, and comparing the yield to tipburn incidence and severity shows growers how large of a crop can be produced based on the light and airflow treatments while mitigating tipburn.

One plant from each replication was sent to a commercial laboratory (Waters Agricultural Laboratories, Camilla, GA, USA) for plant tissue analysis. Leaf nitrogen (N) was determined using a high-temperature combustion (Nelson and Sommers 1973). Leaf phosphorus (P), potassium (K), magnesium (Mg), Ca, and sulfur (S) were found by using nitric acid and hydrogen peroxide in a technique of inductively coupled plasma atomic emission spectrophotometer (ICP-AES) after acid digestion. Leaf boron (B), zinc (Zn), manganese (Mn), iron (Fe), and copper (Cu) were found by using nitric acid and hydrogen peroxide in ICP-AES after acid digestion (Twyman 2005).

After fresh weight measurements, lettuce shoots and roots were placed in an oven dryer set at 80 °C for 4 d. Dry weight was recorded for three quarters of the plants, as one plant per replicate was sent for tissue analysis, but all roots were recorded for dry weight. Dry weight was measured to determine the amount of plant biomass accumulated per treatment, which directly suggests higher yields. Leaf area was measured for half of the plants using a leaf area meter (LI-3100; LI-COR). Leaf area correlates positively with yield, and greater leaf area could result in higher yield.

The plants sent off for analysis had a representative sample of the leaves squeezed to retain roughly 3 mL of the leaf juice for titratable acidity (Ti-Touch; Metrohm, Herisau, Switzerland) and soluble solids content measurements (HI 96801; Hanna instruments, Smithfield, RI, USA). Titratable acidity and soluble solids content are characteristics of lettuce quality; hence, the reason for measuring.

Every plant was measured for tipburn intensity on a scale of 0 to 5, with a score of 0 indicating no visible tipburn (Fig. 2) (Beacham et al. 2023). Three quarters of the plants, including those sent off for tissue analysis, had the total number of healthy leaves counted and the total number of tipburned leaves counted to create a ratio of tipburned leaves to healthy leaves based on treatment combination. Tipburn intensity was measured as a visual proxy for marketable lettuce as growers strive to





Fig. 2. Ordinal tipburn intensity scoring system used for grading lettuce (*Lactuca sativa*) plants from 0 to 5 (top left to bottom right, respectively). A score of 0 corresponds to no visible tipburn, and a score of 5 corresponds to the highest tipburn intensity visibly observed. Lettuce ‘Casey’ is shown in the figure, and lettuce ‘Dragoon’ was scored according to the same scoring system.

produce marketable crops and maximize profits. An ordinal value of 0 or 1 was considered marketable, and values of 2 to 5 were considered unmarketable. The ratio of tipburned leaves to healthy leaves was measured to quantify the amount of tipburn based on the treatment combination. A lower ratio proves the respective rate of airflow and light level combination is better suited to minimize tipburn in vertical farm lettuce production.

#### Experimental design and statistical analysis.

The study was arranged on a factorial completely randomized block design for both seasons. The four airflow rates (0.4, 0.7, 1.0, and 1.3 m·s<sup>-1</sup>) and the three light intensities (200, 350, and 500 μmol·m<sup>-2</sup>·s<sup>-1</sup>) throughout combinations were randomly assigned to the four shelves on each of the three growing racks, with four plants per replicate. Two different lettuce cultivars, Dragoon and Casey, were grown simultaneously. The trials were conducted by two different growing seasons, using the same experimental design for both seasons.

Two-way analysis of variance (ANOVA) statistical analyses were performed with Tukey’s post hoc test at 5% probability to compare significant differences for every measurement except the ordinal tipburn intensity and pH, EC, and temperature measurements. For the ordinal tipburn ranking system, a nonparametric two-way ANOVA was performed using statistical software (R version 4.4.1; R Foundation for Statistical Computing, Vienna, Austria). The ordinal tipburn scale was transformed into a rank, and then a two-way ANOVA

analyzed differences between treatments. The pH, EC, and temperature measurements were analyzed via a multivariate ANOVA because the number of days after transplant was an additional factor in these measurements. All data, except tipburn intensity, were analyzed using statistical software (JMP Pro version 15; SAS Institute; Cary, NC, USA). All graphs were made using a graphing software (Sigma Plot version 15.0; Systat Software, San Jose, CA, USA).

## Results and Discussion

**Calcium tipburn and plant water use analysis of ‘Dragoon’ over two seasons.** In both seasons, light intensity and airflow rates independently played a significant role in the tipburn of ‘Dragoon’ (Tables 3-5). In both seasons of ‘Dragoon’ cultivation, light intensity influenced tipburn intensity ( $P < 0.0001$ ), tipburn ratio ( $P < 0.0001$ ), and plant water use ( $P < 0.0001$ ). In the first season, the 500 and the 350 μmol·m<sup>-2</sup>·s<sup>-1</sup> light levels had greater ordinal ranks for tipburn intensity (86 and 90, respectively) compared with the 200 μmol·m<sup>-2</sup>·s<sup>-1</sup> light level (41) (Table 3). In the second season, the 500 and the 350 μmol·m<sup>-2</sup>·s<sup>-1</sup> light levels had greater ordinal ranks for tipburn intensity (93 and 80, respectively) compared with the 200 μmol·m<sup>-2</sup>·s<sup>-1</sup> light level (45) (Table 3). The tipburn ratio was at least 24.56% and 40% greater for the 350 and the 500 μmol·m<sup>-2</sup>·s<sup>-1</sup> light levels than the 200 μmol·m<sup>-2</sup>·s<sup>-1</sup> light level for seasons 1 and 2, respectively. Additionally, the 500 μmol·m<sup>-2</sup>·s<sup>-1</sup> light level had 36.22%

Table 3. Ordinal tipburn intensity ranks of ‘Dragoon’ lettuce (*Lactuca sativa*) subjected to different airflow rates and light levels in two growing seasons.

| Conditions                                | TBI rank     |               |
|-------------------------------------------|--------------|---------------|
|                                           | First season | Second season |
| Airflow rate (Af)                         |              |               |
| 0.4 m·s <sup>-1</sup>                     | 92 a         | 83 a          |
| 0.7 m·s <sup>-1</sup>                     | 70 b         | 80 a          |
| 1.0 m·s <sup>-1</sup>                     | 71 b         | 71 ab         |
| 1.3 m·s <sup>-1</sup>                     | 57 b         | 55 b          |
| Light intensity (Li)                      |              |               |
| 200 μmol·m <sup>-2</sup> ·s <sup>-1</sup> | 41 b         | 45 b          |
| 350 μmol·m <sup>-2</sup> ·s <sup>-1</sup> | 90 a         | 80 a          |
| 500 μmol·m <sup>-2</sup> ·s <sup>-1</sup> | 86 a         | 93 a          |
| P value                                   |              |               |
| Af                                        | <0.0001      | 0.0024        |
| Li                                        | <0.0001      | <0.0001       |
| Af × Li                                   | NS           | NS            |

Each value represents the rank that was created during the nonparametric two-way ANOVA. A greater value for rank corresponds to greater tipburn intensity. Statistical analyses were performed with two-way nonparametric ANOVA and Tukey’s honestly significant difference using a significance level of 5% ( $P < 0.05$ ). Means within a column followed by the same letter are not significantly different. ANOVA = analysis of variance; NS = not significant.

and 24.22% greater plant water use than the 200 μmol·m<sup>-2</sup>·s<sup>-1</sup> light level for seasons 1 and 2, respectively (Table 4).

Airflow rates played a significant role in tipburn intensity in both seasons. In season 1, the 0.4 m·s<sup>-1</sup> airflow rate had a greater tipburn intensity rank (92) than the 0.7, 1.0, and 1.3 m·s<sup>-1</sup> airflow rates (70, 71, and 57, respectively) ( $P < 0.0001$ ) (Table 3). In season 2, the 0.4 and 0.7 m·s<sup>-1</sup> airflow rates had greater tipburn intensity ranks (83 and 80, respectively) than the 1.3 m·s<sup>-1</sup> airflow rate (55) ( $P = 0.0024$ ) (Table 3). Airflow rates also influenced plant water use in season 2 ( $P < 0.0001$ ). The 1.0 and 1.3 m·s<sup>-1</sup> airflow rates had 10.93% and 14.80% higher plant water use than the 0.4 m·s<sup>-1</sup> airflow rate, respectively (Table 4).

For the first season, the 0.7 and 1.3 m·s<sup>-1</sup> airflow rates had 163.40% and 49.89% greater number of marketable plants than the 0.4 and 1.0 m·s<sup>-1</sup> airflow rates, respectively. In the second season, the 1.3 m·s<sup>-1</sup> airflow rate had 48.14%, 32.29%, and 18.10% greater number of marketable plants than the 0.4, 0.7, and 1.0 m·s<sup>-1</sup> airflow rates, respectively. Half of the ‘Dragoon’ lettuce plants were marketable in the second season (Table 5).

In season 1, the 200 μmol·m<sup>-2</sup>·s<sup>-1</sup> light level had 169% and 183.88% greater number of marketable plants than the 350 and 500 μmol·m<sup>-2</sup>·s<sup>-1</sup> light levels, respectively. Half of the lettuce plants were marketable at the 200 μmol·m<sup>-2</sup>·s<sup>-1</sup> light level in season 1. In season 2, the 200 μmol·m<sup>-2</sup>·s<sup>-1</sup> light level had 91.6% and 117.99% greater number of marketable plants than the 350 and 500 μmol·m<sup>-2</sup>·s<sup>-1</sup> light levels, respectively. Almost three quarters of the ‘Dragoon’ lettuce plants were

Table 4. Tipburn ratio and plant water use of 'Dragoon' lettuce (*Lactuca sativa*) subjected to different airflow rates and light levels in two growing seasons.

| Source                                    | TBR           | WU (L/plant)   |
|-------------------------------------------|---------------|----------------|
| First season                              |               |                |
| Airflow rates (Af)                        |               |                |
| 0.4 m·s <sup>-1</sup>                     | 0.32 ± 0.02   | 2.91 ± 0.20    |
| 0.7 m·s <sup>-1</sup>                     | 0.31 ± 0.02   | 3.07 ± 0.16    |
| 1.0 m·s <sup>-1</sup>                     | 0.30 ± 0.02   | 2.97 ± 0.19    |
| 1.3 m·s <sup>-1</sup>                     | 0.32 ± 0.02   | 3.18 ± 0.23    |
| Light intensity (Li)                      |               |                |
| 200 µmol·m <sup>-2</sup> ·s <sup>-1</sup> | 0.25 ± 0.02 b | 2.51 ± 0.07 c  |
| 350 µmol·m <sup>-2</sup> ·s <sup>-1</sup> | 0.32 ± 0.02 a | 2.97 ± 0.09 b  |
| 500 µmol·m <sup>-2</sup> ·s <sup>-1</sup> | 0.37 ± 0.02 a | 3.62 ± 0.14 a  |
| P values                                  |               |                |
| Af                                        | NS            | NS             |
| Li                                        | <0.0001       | <0.0001        |
| Af × Li                                   | NS            | NS             |
| Second season                             |               |                |
| Airflow rates (Af)                        |               |                |
| 0.4 m·s <sup>-1</sup>                     | 0.30 ± 0.03   | 2.94 ± 0.12 c  |
| 0.7 m·s <sup>-1</sup>                     | 0.31 ± 0.17   | 3.19 ± 0.13 b  |
| 1.0 m·s <sup>-1</sup>                     | 0.27 ± 0.03   | 3.28 ± 0.11 ab |
| 1.3 m·s <sup>-1</sup>                     | 0.28 ± 0.03   | 3.41 ± 0.13 a  |
| Light intensity (Li)                      |               |                |
| 200 µmol·m <sup>-2</sup> ·s <sup>-1</sup> | 0.20 ± 0.03 b | 2.83 ± 0.06 c  |
| 350 µmol·m <sup>-2</sup> ·s <sup>-1</sup> | 0.30 ± 0.02 a | 3.17 ± 0.06 b  |
| 500 µmol·m <sup>-2</sup> ·s <sup>-1</sup> | 0.36 ± 0.02 a | 3.61 ± 0.07 a  |
| P values                                  |               |                |
| Af                                        | NS            | <0.0001        |
| Li                                        | <0.0001       | <0.0001        |
| Af × Li                                   | NS            | NS             |

Statistical analyses were performed with two-way analysis of variance and Tukey's honestly significant difference using a significance level of 5% ( $P < 0.05$ ). Means within a column followed by the same letter are not significantly different. Each value represents the average ± standard error. NS = not significant; TBR = Tipburn ratio; WU = plant water use.

marketable under the 200 µmol·m<sup>-2</sup>·s<sup>-1</sup> light level in season 2 (Table 5).

Generally, as the airflow rates increased above 0.4 m·s<sup>-1</sup>, we observed an increase in the number of marketable plants, regardless of light intensity. There was only one instance in which a decrease in marketable yield was observed from the 0.4 to the 0.7 m·s<sup>-1</sup> airflow rate, which occurred at the 500 µmol·m<sup>-2</sup>·s<sup>-1</sup> light level (25% to 8.3%, respectively) (Table 5).

**Calcium tipburn and plant water use analysis of 'Casey' over two seasons.** Tipburn analysis and plant water use for 'Casey' (Tables 6-8) were very similar to 'Dragoon' (Tables 3-5). In season 1, the 0.4 m·s<sup>-1</sup> airflow rate had a greater tipburn intensity rank (85) than the 1.0 and 1.3 m·s<sup>-1</sup> airflow rates

(69 and 65, respectively) ( $P = 0.0042$ ). There were no significant differences in airflow rates on tipburn intensity for 'Casey' in season 2 (Table 6).

In both seasons of 'Casey' cultivation, light intensity influenced tipburn intensity ( $P < 0.0001$ ), as observed in 'Dragoon'. In the first season, the 500 µmol·m<sup>-2</sup>·s<sup>-1</sup> light level had a greater ordinal rank for tipburn intensity (111) than the 200 and 350 µmol·m<sup>-2</sup>·s<sup>-1</sup> light levels (42 and 65, respectively). In the second season, the 500 µmol·m<sup>-2</sup>·s<sup>-1</sup> light level had a greater ordinal rank for tipburn intensity (106) compared with the 200 and 350 µmol·m<sup>-2</sup>·s<sup>-1</sup> light levels ranking (47 and 64, respectively) (Table 6).

Light intensity played a highly significant role in both seasons of 'Casey' cultivation on the

Table 5. Percent of marketable 'Dragoon' lettuce (*Lactuca sativa*) plants subjected to different airflow rates and light levels in two growing seasons.

| Treatment                                    | Marketable 'Dragoon' lettuce (%) |                          |                          |                          |                          |
|----------------------------------------------|----------------------------------|--------------------------|--------------------------|--------------------------|--------------------------|
|                                              | Average                          | 0.4 m·s <sup>-1</sup> Af | 0.7 m·s <sup>-1</sup> Af | 1.0 m·s <sup>-1</sup> Af | 1.3 m·s <sup>-1</sup> Af |
| First season                                 |                                  | 2.8                      | 27.8                     | 16.7                     | 27.8                     |
| 200 µmol·m <sup>-2</sup> ·s <sup>-1</sup> Li | 50                               | 8.3                      | 75                       | 41.7                     | 75                       |
| 350 µmol·m <sup>-2</sup> ·s <sup>-1</sup> Li | 4.2                              | 0                        | 0                        | 8.3                      | 8.3                      |
| 500 µmol·m <sup>-2</sup> ·s <sup>-1</sup> Li | 2.1                              | 0                        | 8.3                      | 0                        | 0                        |
| Second season                                |                                  | 30.6                     | 36.1                     | 41.7                     | 50                       |
| 200 µmol·m <sup>-2</sup> ·s <sup>-1</sup> Li | 72.9                             | 58.3                     | 83.3                     | 50                       | 100                      |
| 350 µmol·m <sup>-2</sup> ·s <sup>-1</sup> Li | 27.1                             | 8.3                      | 16.7                     | 50                       | 33.3                     |
| 500 µmol·m <sup>-2</sup> ·s <sup>-1</sup> Li | 18.8                             | 25                       | 8.3                      | 25                       | 16.7                     |

A marketable plant is ranked 0 or 1 based on the ordinal tipburn intensity measurement system shown in Table 3.

Af = airflow rate; Li = light intensity.

Table 6. Ordinal tipburn intensity ranking values of 'Casey' lettuce (*Lactuca sativa*) subjected to different airflow rates and light levels in two growing seasons.

| Conditions                                | TBI rank     |               |
|-------------------------------------------|--------------|---------------|
|                                           | First season | Second season |
| Airflow rates (Af)                        |              |               |
| 0.4 m·s <sup>-1</sup>                     | 85 a         | 77            |
| 0.7 m·s <sup>-1</sup>                     | 71 ab        | 78            |
| 1.0 m·s <sup>-1</sup>                     | 69 b         | 69            |
| 1.3 m·s <sup>-1</sup>                     | 65 b         | 65            |
| Light intensity (Li)                      |              |               |
| 200 µmol·m <sup>-2</sup> ·s <sup>-1</sup> | 42 c         | 47 c          |
| 350 µmol·m <sup>-2</sup> ·s <sup>-1</sup> | 65 b         | 64 b          |
| 500 µmol·m <sup>-2</sup> ·s <sup>-1</sup> | 111 a        | 106 a         |
| P values                                  |              |               |
| Af                                        | 0.0042       | NS            |
| Li                                        | <0.0001      | <0.0001       |
| Af × Li                                   | NS           | NS            |

Each value represents the rank that was created during the nonparametric two-way ANOVA. A greater value for rank corresponds to greater tipburn intensity. Statistical analyses were performed with two-way nonparametric ANOVA and Tukey's honestly significant difference using a significance level of 5% ( $P < 0.05$ ). Values sharing the same letter are not significantly different.

ANOVA = analysis of variance; NS = not significant; TBI = tipburn intensity.

plant tipburn ratio. The 500 µmol·m<sup>-2</sup>·s<sup>-1</sup> light level had at least 190.48% greater tipburn ratio for both seasons than the 200 µmol·m<sup>-2</sup>·s<sup>-1</sup> light level ( $P < 0.0001$  for both seasons) (Table 7).

Airflow rates and light intensity influenced the tipburn ratio during the first season. In season 1, the tipburn ratio was lowest for the 1.3 m·s<sup>-1</sup> airflow rate, reducing the tipburn ratio by 52.63% vs. the 0.4 m·s<sup>-1</sup> airflow rate ( $P = 0.0008$ ). The 500 µmol·m<sup>-2</sup>·s<sup>-1</sup> light level had at least 190.48% greater tipburn ratio in both seasons than the 200 µmol·m<sup>-2</sup>·s<sup>-1</sup> light level ( $P < 0.0001$  for both seasons) (Table 7).

In both seasons, airflow rates encouraged plant water use ( $P = 0.0033$  and  $P < 0.0001$ , respectively). In season 1, the 1.3 m·s<sup>-1</sup> airflow rate had 19.81% higher plant water use than the 0.4 m·s<sup>-1</sup> airflow rate. In season 2, the 1.3 m·s<sup>-1</sup> airflow rate had 19.54% greater plant water use than the 0.4 m·s<sup>-1</sup> airflow rate. Plant water use was also affected by light level in the second season, with the 500 µmol·m<sup>-2</sup>·s<sup>-1</sup> light level having 27.08% greater plant water use than the 200 µmol·m<sup>-2</sup>·s<sup>-1</sup> light level ( $P < 0.0001$ ) (Table 7).

In the first season, the 1.0 m·s<sup>-1</sup> airflow rate had 33.28%, 7.47%, and 7.47% greater number of marketable plants than the 0.4, 0.7, and 1.3 m·s<sup>-1</sup> airflow rates, respectively. In the second season, the 1.3 m·s<sup>-1</sup> airflow rate had 25.39%, 10.13%, and 3.31% greater number of marketable plants than the 0.4, 0.7, and 1.0 m·s<sup>-1</sup> airflow rates, respectively. Nearly three quarters or more of the plants were marketable at the 0.7, 1.0, and 1.3 m·s<sup>-1</sup> airflow rates compared with the 0.4 m·s<sup>-1</sup> airflow rate in both seasons. About 50% of the

Table 7. Tipburn ratio and water use of 'Casey' lettuce (*Lactuca sativa*) subjected to different airflow rates and light levels in two growing seasons.

| Conditions                                | TBR            | WU (L/plant)   |
|-------------------------------------------|----------------|----------------|
| First season                              |                |                |
| Airflow rates (Af)                        |                |                |
| 0.4 m·s <sup>-1</sup>                     | 0.24 ± 0.04 a  | 2.91 ± 0.09 b  |
| 0.7 m·s <sup>-1</sup>                     | 0.17 ± 0.03 ab | 3.27 ± 0.12 ab |
| 1.0 m·s <sup>-1</sup>                     | 0.23 ± 0.04 a  | 3.10 ± 0.09 b  |
| 1.3 m·s <sup>-1</sup>                     | 0.14 ± 0.03 b  | 3.55 ± 0.14 a  |
| Light intensity (Li)                      |                |                |
| 200 µmol·m <sup>-2</sup> ·s <sup>-1</sup> | 0.01 ± 0.01 c  | 3.05 ± 0.11    |
| 350 µmol·m <sup>-2</sup> ·s <sup>-1</sup> | 0.17 ± 0.02 b  | 3.29 ± 0.12    |
| 500 µmol·m <sup>-2</sup> ·s <sup>-1</sup> | 0.41 ± 0.02 a  | 3.27 ± 0.11    |
| P values                                  |                |                |
| Af                                        | 0.0008         | 0.0033         |
| Li                                        | <0.0001        | NS             |
| Af × Li                                   | NS             | NS             |
| Second season                             |                |                |
| Af                                        |                |                |
| 0.4 m·s <sup>-1</sup>                     | 0.12 ± 0.04    | 2.91 ± 0.17 b  |
| 0.7 m·s <sup>-1</sup>                     | 0.11 ± 0.03    | 3.13 ± 0.14 b  |
| 1.0 m·s <sup>-1</sup>                     | 0.08 ± 0.03    | 3.41 ± 0.12 a  |
| 1.3 m·s <sup>-1</sup>                     | 0.09 ± 0.03    | 3.54 ± 0.14 a  |
| Li                                        |                |                |
| 200 µmol·m <sup>-2</sup> ·s <sup>-1</sup> | -4.2e-17 ± 0 b | 2.81 ± 0.11 c  |
| 350 µmol·m <sup>-2</sup> ·s <sup>-1</sup> | 0.05 ± 0.01 b  | 3.24 ± 0.08 b  |
| 500 µmol·m <sup>-2</sup> ·s <sup>-1</sup> | 0.26 ± 0.03 a  | 3.69 ± 0.08 a  |
| P values                                  |                |                |
| Af                                        | NS             | <0.0001        |
| Li                                        | <0.0001        | <0.0001        |
| Af × Li                                   | NS             | NS             |

Statistical analyses were performed with two-way analysis of variance and Tukey's honestly significant difference using a significance level of 5% ( $P < 0.05$ ). Means within a column followed by the same letter are not significantly different. Each value represents the average ± standard error.

NS = not significant; TBR = Tipburn ratio; WU = plant water use.

plants were marketable at the 0.4 m·s<sup>-1</sup> airflow rate (Table 8).

In both seasons, all the lettuce plants were marketable under the 200 µmol·m<sup>-2</sup>·s<sup>-1</sup> light level treatment. In season 1, the 200 µmol·m<sup>-2</sup>·s<sup>-1</sup> light level had a 15.75% and 125.47% greater number of marketable plants than the 350 and 500 µmol·m<sup>-2</sup>·s<sup>-1</sup> light levels, respectively. In season 2, the 200 µmol·m<sup>-2</sup>·s<sup>-1</sup> light level had 8.66% and 78.16% greater number of marketable plants than the 350 and 500 µmol·m<sup>-2</sup>·s<sup>-1</sup> light levels, respectively. In both seasons, more than three quarters of the 'Casey' lettuce plants were marketable under the 200 and 350 µmol·m<sup>-2</sup>·s<sup>-1</sup> light levels (Table 8).

Regardless of the airflow rate, all 'Casey' plants were marketable at the 200 µmol·m<sup>-2</sup>·s<sup>-1</sup> light level, suggesting that the airflow rate

does not affect tipburn at this light intensity. At a light level of 350 µmol·m<sup>-2</sup>·s<sup>-1</sup> and an airflow rate of 1.0 m·s<sup>-1</sup>, 100% of the lettuce plants were marketable in both seasons. In season 2, 100% of the plants were marketable at a light level of 350 µmol·m<sup>-2</sup>·s<sup>-1</sup> with an airflow rate of 1.3 m·s<sup>-1</sup>. These results confirm that increasing airflow rates can almost eliminate tipburn at a medium light intensity (350 µmol·m<sup>-2</sup>·s<sup>-1</sup>), and these findings are consistent with those of Goto and Takakura (1992a). In both seasons, we observed that airflow rates above 0.4 m·s<sup>-1</sup> can substantially decrease tipburn severity, regardless of light intensity up to 500 µmol·m<sup>-2</sup>·s<sup>-1</sup> (Table 8).

Regardless of cultivar, tipburn was reduced at the three airflow rates greater than 0.4 m·s<sup>-1</sup>, and this was consistent over both

seasons (Tables 3-8). Although tipburn was not eliminated in many cases, this result suggests transpiration rates of the lettuce plants under 0.7, 1.0, and 1.3 m·s<sup>-1</sup> are likely sufficient to aid the transport of Ca to the meristem and decrease tipburn incidence and severity. Increases in percent marketable yield with increasing airflow rates are a great indicator (Tables 5 and 8). For example, with the 'Casey', the percent marketable yield at the 1.0 m·s<sup>-1</sup> airflow rate was 100%, even at the 350 µmol·m<sup>-2</sup>·s<sup>-1</sup> light level, in both seasons. Lower downward airflow rates on a lettuce canopy create a less favorable transpiration environment than higher airflow rates. This is consistent with a study demonstrating increased tipburn incidence of lettuce under an airflow rate of 0.1 m·s<sup>-1</sup> (Ertle and Kubota 2023). The lack of statistically significant differences in tipburn intensity and tipburn ratio in our study at airflow rates of 0.7, 1.0, and 1.3 m·s<sup>-1</sup> is likely due to the minimal decrease in boundary layer resistance observed by Kitaya et al. (2003) at airflow rates above 0.2 m·s<sup>-1</sup>. Any increase in downward airflow rate above 0.2 m·s<sup>-1</sup> was reported to minimally decrease the boundary layer above lettuce canopies up to 1.0 m·s<sup>-1</sup>. When evaporation rates are lower, this is correlated with a lower transpiration rate of lettuce leaves, providing further evidence as to why the lowest airflow rate in our study experienced the greatest tipburn incidence (Papio 2021).

Consistent with our results, increasing light intensities increases the tipburn intensity of lettuce in a plant factory, as demonstrated by Lee et al. (2013). Although transpiration rates increase with higher light intensity, the rate of lettuce growth cannot keep pace with the ability of Ca to be transported into the new leaves. Although tipburn increases with higher light intensities, growers can still use higher light intensities in production systems, as tipburn can be minimized by using higher airflow rates in tandem. The degree of tipburn intensity, marketable yield, and tipburn ratio varied between both 'Casey' and 'Dragoon', suggesting a cultivar-specific response to tipburn at varying airflow rates and light intensities (Tables 3-8). Our result is consistent with a study conducted by Ertle and Kubota (2023), in which the authors measured cultivar sensitivity to tipburn incidence. Ertle and Kubota (2023) concluded that tipburn incidence and severity are highly dependent on the genetics of the cultivar, regardless of morphology.

Plant water use generally increased with increasing airflow rates in both cultivars (Tables 4 and 7), suggesting increased transpiration rates in lettuce under higher airflow rates, which diminishes the stagnant boundary layer above the canopy. The increase in plant water use observed with increasing light intensities can be attributed to the corresponding rise in growth and transpiration rates in lettuce. Note that during both seasons, the air stones in the fertilizer solution would occasionally reposition themselves overnight to the corners of the DWC trays, and small amounts of water dripped onto the floor, possibly skewing the results of plant

Table 8. Percent of marketable 'Casey' lettuce (*Lactuca sativa*) plants subjected to different airflow rates and light levels in two growing seasons.

| Treatment                                    | Marketable 'Casey' lettuce (%) |                          |                          |                          |                          |
|----------------------------------------------|--------------------------------|--------------------------|--------------------------|--------------------------|--------------------------|
|                                              | Avg                            | 0.4 m·s <sup>-1</sup> Af | 0.7 m·s <sup>-1</sup> Af | 1.0 m·s <sup>-1</sup> Af | 1.3 m·s <sup>-1</sup> Af |
| First season                                 |                                |                          |                          |                          |                          |
| 200 µmol·m <sup>-2</sup> ·s <sup>-1</sup> Li | 100                            | 100                      | 100                      | 100                      | 100                      |
| 350 µmol·m <sup>-2</sup> ·s <sup>-1</sup> Li | 85.4                           | 58.3                     | 91.7                     | 100                      | 91.7                     |
| 500 µmol·m <sup>-2</sup> ·s <sup>-1</sup> Li | 22.9                           | 8.3                      | 25                       | 33.3                     | 25                       |
| Second season                                |                                |                          |                          |                          |                          |
| 200 µmol·m <sup>-2</sup> ·s <sup>-1</sup> Li | 100                            | 100                      | 100                      | 100                      | 100                      |
| 350 µmol·m <sup>-2</sup> ·s <sup>-1</sup> Li | 91.7                           | 75                       | 91.7                     | 100                      | 100                      |
| 500 µmol·m <sup>-2</sup> ·s <sup>-1</sup> Li | 43.8                           | 25                       | 41.7                     | 50                       | 58.3                     |

A marketable plant is ranked 0 or 1 in the ordinal tipburn intensity measurement system shown in Table 6.

Af = airflow rate; Li = light intensity.



Table 9. Shoot fresh weight, shoot dry weight, root fresh weight, root dry weight, leaf area, and canopy volume of 'Dragoon' lettuce (*Lactuca sativa*) subjected to different airflow rates and light levels in two growing seasons.

| Conditions                                | SFW (g)        | SDW (g)        | RFW (g)        | RDW (g)       | LA (cm <sup>2</sup> ) | CV (cm <sup>3</sup> ) |
|-------------------------------------------|----------------|----------------|----------------|---------------|-----------------------|-----------------------|
| <b>First season</b>                       |                |                |                |               |                       |                       |
| <b>Airflow rates (Af)</b>                 |                |                |                |               |                       |                       |
| 0.4 m·s <sup>-1</sup>                     | 321.8 ± 14.01  | 11.04 ± 0.57   | 17.39 ± 1.66   | 0.60 ± 0.06   | 1925 ± 64             | 5801 ± 167            |
| 0.7 m·s <sup>-1</sup>                     | 329.5 ± 13.00  | 10.87 ± 0.57   | 16.64 ± 1.45   | 0.51 ± 0.04   | 2048 ± 58             | 6285 ± 196            |
| 1.0 m·s <sup>-1</sup>                     | 325.4 ± 13.18  | 11.17 ± 0.60   | 16.98 ± 1.45   | 0.58 ± 0.05   | 1897 ± 39             | 6005 ± 210            |
| 1.3 m·s <sup>-1</sup>                     | 326.2 ± 12.70  | 11.26 ± 0.58   | 16.12 ± 1.31   | 0.53 ± 0.05   | 1972 ± 44             | 6001 ± 176            |
| <b>Light intensity (Li)</b>               |                |                |                |               |                       |                       |
| 200 μmol·m <sup>-2</sup> ·s <sup>-1</sup> | 241.9 ± 4.29 c | 7.82 ± 0.16 c  | 8.02 ± 0.26 c  | 0.27 ± 0.01 c | 1945 ± 49             | 6652 ± 198 a          |
| 350 μmol·m <sup>-2</sup> ·s <sup>-1</sup> | 326.8 ± 5.83 b | 11.12 ± 0.20 b | 15.83 ± 0.49 b | 0.52 ± 0.02 b | 1937 ± 36             | 5796 ± 122 b          |
| 500 μmol·m <sup>-2</sup> ·s <sup>-1</sup> | 408.4 ± 6.67 a | 14.32 ± 0.28 a | 26.49 ± 0.95 a | 0.87 ± 0.04 a | 1998 ± 52             | 5621 ± 100 b          |
| <b>P values</b>                           |                |                |                |               |                       |                       |
| Af                                        | NS             | NS             | NS             | NS            | NS                    | NS                    |
| Li                                        | <0.0001        | <0.0001        | <0.0001        | <0.0001       | NS                    | <0.0001               |
| Af × Li                                   | NS             | NS             | NS             | NS            | NS                    | NS                    |
| <b>Second season</b>                      |                |                |                |               |                       |                       |
| <b>Af</b>                                 |                |                |                |               |                       |                       |
| 0.4 m·s <sup>-1</sup>                     | 292.6 ± 10.99  | 10.78 ± 0.55   | 15.01 ± 1.22   | 0.55 ± 0.05   | 1763 ± 39             | 5123 ± 172 a          |
| 0.7 m·s <sup>-1</sup>                     | 296.9 ± 11.73  | 10.75 ± 0.58   | 14.78 ± 1.26   | 0.53 ± 0.05   | 1810 ± 39             | 5787 ± 269 a          |
| 1.0 m·s <sup>-1</sup>                     | 292.4 ± 12.75  | 11.28 ± 0.62   | 14.76 ± 1.18   | 0.54 ± 0.05   | 1784 ± 44             | 5258 ± 166 a          |
| 1.3 m·s <sup>-1</sup>                     | 299.6 ± 14.25  | 10.70 ± 0.64   | 14.96 ± 1.32   | 0.56 ± 0.05   | 1759 ± 56             | 5607 ± 252 a          |
| <b>Li</b>                                 |                |                |                |               |                       |                       |
| 200 μmol·m <sup>-2</sup> ·s <sup>-1</sup> | 216.2 ± 4.19 c | 7.52 ± 0.18 c  | 7.44 ± 0.29 c  | 0.26 ± 0.01 c | 1747 ± 40             | 6199 ± 215 a          |
| 350 μmol·m <sup>-2</sup> ·s <sup>-1</sup> | 302.0 ± 5.89 b | 10.95 ± 0.20 b | 14.30 ± 0.54 b | 0.53 ± 0.02 b | 1772 ± 38             | 5251 ± 116 b          |
| 500 μmol·m <sup>-2</sup> ·s <sup>-1</sup> | 367.0 ± 7.10 a | 14.17 ± 0.31 a | 22.91 ± 0.74 a | 0.84 ± 0.03 a | 1817 ± 37             | 4880 ± 127 b          |
| <b>P values</b>                           |                |                |                |               |                       |                       |
| Af                                        | NS             | NS             | NS             | NS            | NS                    | 0.0440                |
| Li                                        | <0.0001        | <0.0001        | <0.0001        | <0.0001       | NS                    | <0.0001               |
| Af × Li                                   | NS             | NS             | NS             | NS            | NS                    | NS                    |

Statistical analyses were performed with two-way analysis of variance and Tukey's honestly significant difference using a significance level of 5% ( $P < 0.05$ ). Means within a column followed by the same letter are not significantly different. Each value represents the average ± standard error.

NS = not significant; SFW = Shoot fresh weight; SDW = shoot dry weight; RFW = root fresh weight; RDW = root dry weight; LA = leaf area; CV = canopy volume.

water use. The air stones were always repositioned to the center of the hydroponic tray.

**Yield of 'Dragoon' and 'Casey' over two seasons.** In both seasons of 'Dragoon' cultivation, increasing light intensities encouraged differences in root and shoot fresh and dry weights, with the highest yield being of the 500 μmol·m<sup>-2</sup>·s<sup>-1</sup> light level and the lowest yield of the 200 μmol·m<sup>-2</sup>·s<sup>-1</sup> light level ( $P < 0.0001$ ). The canopy volume of 'Dragoon' followed the opposite trend, with the 200 μmol·m<sup>-2</sup>·s<sup>-1</sup> light level having the greatest canopy volume, and the 500 μmol·m<sup>-2</sup>·s<sup>-1</sup> light level having the lowest canopy volume. Only the canopy volume of lettuce for the 200 μmol·m<sup>-2</sup>·s<sup>-1</sup> light level was significantly higher than the other two light levels in both seasons (Table 9).

As with 'Dragoon', 'Casey' had similar yield results. In both seasons, light intensity had a significant effect on shoot and root fresh and dry weights ( $P < 0.0001$  for both), with the 500 μmol·m<sup>-2</sup>·s<sup>-1</sup> light level being at least 36.06% (shoot fresh weight), 51.08% (shoot dry weight), 56.85% (root fresh weight), and 82.71% (shoot dry weight) greater than the 200 μmol·m<sup>-2</sup>·s<sup>-1</sup> light level (Table 10).

In both seasons, light intensity influenced canopy volume in 'Casey' ( $P < 0.0001$ ), as observed in 'Dragoon'. The 200 μmol·m<sup>-2</sup>·s<sup>-1</sup> light level had an average canopy volume at least 8.05% higher than the other two light treatments (Table 10). In season 1, there was a two-way interaction between light intensities and airflow rates for the leaf area (Fig. 3). Leaf area

was ~25% higher for the 350 μmol·m<sup>-2</sup>·s<sup>-1</sup> light level and 1.0 m·s<sup>-1</sup> airflow rate combination (3,993 cm<sup>2</sup>), compared with the 500 μmol·m<sup>-2</sup>·s<sup>-1</sup> light level and 1.0 m·s<sup>-1</sup> airflow rate (Fig. 3).

In both seasons and cultivars, yield was greatest for the highest light intensity, 500 μmol·m<sup>-2</sup>·s<sup>-1</sup> and lowest for the 200 μmol·m<sup>-2</sup>·s<sup>-1</sup> light intensity (Tables 9 and 10). This finding is consistent with a study that reported a relationship between light intensity and air temperature, in which lettuce grown at an air temperature of 23°C and a light intensity of 500 μmol·m<sup>-2</sup>·s<sup>-1</sup> had the greatest average fresh weight compared with treatments at 200 and 350 μmol·m<sup>-2</sup>·s<sup>-1</sup> (Zhou et al. 2022). In the same study by Zhou et al. (2022), when the light intensity was increased to 600 μmol·m<sup>-2</sup>·s<sup>-1</sup>, the authors reported diminished returns in yield. This is why 500 μmol·m<sup>-2</sup>·s<sup>-1</sup> was the highest light intensity in our study. The same consistency in higher yields under higher light intensity is reported in another study (Miao et al. 2023). Light intensity is an important environmental parameter manipulated by growers to increase the yield of lettuce, and our results suggest that higher airflow rates coupled with high light intensities can lower tipburn incidence in vertical farm lettuce production, granted the results tend to be cultivar specific (Tables 3-8).

Airflow rates did not affect the shoot or root fresh or dry weights of either cultivar in both seasons (Tables 9 and 10). This is the same effect observed in a study that explored the impact of Ca concentrations, fertilizer

solution recipes, and airflow rates on lettuce growth in vertical farm production, as airflow rates did not affect shoot or root fresh and dry weights of either the spinach or lettuce (Ferrarezi et al. 2024).

Separately, light intensity and airflow rate had no influence over the leaf area of either cultivar in either season. The airflow rate's negligible effect on leaf area is consistent with the study by Ferrarezi et al. (2024). Light intensity having no significant effect on leaf area was also seen in a study by Miao et al. (2023). In this study, compared with the low light intensity of 120 μmol·m<sup>-2</sup>·s<sup>-1</sup>, the width of lettuce leaves increased with increasing light intensity, but the length of the leaves decreased, therefore balancing out the leaf areas in comparison with lettuce grown under higher light levels. Lettuce tends to compact under higher light intensities, but a plant adapts and grows outward under lower light intensities to capture as much light as possible. Because of this adaptation to low light levels, lettuce canopies become more open, allowing directed vertical airflow to reach the new growth. As a result, increased transpiration and Ca uptake occur, which likely reduces the occurrence and severity in lettuce. This is an important result, as tipburn incidence and intensity were lower under the 200 μmol·m<sup>-2</sup>·s<sup>-1</sup> light level in our study (Tables 3-8).

**Tissue analysis of 'Dragoon' over two seasons.** In both seasons, the N concentration in 'Dragoon' was 5.02% and 4.53% higher for

Table 10. Shoot fresh weight, shoot dry weight, root fresh weight, root dry weight, leaf area, and canopy volume of lettuce (*Lactuca sativa*) 'Casey' subjected to different airflow rates and light levels in two growing seasons.

| Conditions                                | SFW (g)         | SDW (g)        | RFW (g)        | RDW (g)       | LA (cm <sup>2</sup> ) | CV (cm <sup>3</sup> ) |
|-------------------------------------------|-----------------|----------------|----------------|---------------|-----------------------|-----------------------|
| First season                              |                 |                |                |               |                       |                       |
| Airflow rates (Af)                        |                 |                |                |               |                       |                       |
| 0.4 m·s <sup>-1</sup>                     | 388.8 ± 13.85   | 13.88 ± 0.69   | 17.65 ± 1.21   | 0.59 ± 0.04   | 3188 ± 136            | 8806 ± 207            |
| 0.7 m·s <sup>-1</sup>                     | 361.2 ± 15.25   | 13.07 ± 0.68   | 16.51 ± 1.26   | 0.57 ± 0.04   | 3363 ± 470            | 8778 ± 266            |
| 1.0 m·s <sup>-1</sup>                     | 367.3 ± 14.85   | 13.56 ± 0.66   | 17.51 ± 1.39   | 0.60 ± 0.05   | 3443 ± 157            | 8543 ± 211            |
| 1.3 m·s <sup>-1</sup>                     | 373.8 ± 13.79   | 13.16 ± 0.68   | 16.09 ± 1.17   | 0.58 ± 0.04   | 3331 ± 71             | 8483 ± 206            |
| Light intensity (Li)                      |                 |                |                |               |                       |                       |
| 200 µmol·m <sup>-2</sup> ·s <sup>-1</sup> | 297.9 ± 7.74 c  | 9.87 ± 0.28 c  | 9.63 ± 0.35 c  | 0.34 ± 0.01 c | 3324 ± 101            | 9250 ± 193 a          |
| 350 µmol·m <sup>-2</sup> ·s <sup>-1</sup> | 382.6 ± 9.51 b  | 13.75 ± 0.36 b | 16.05 ± 0.48 b | 0.56 ± 0.02 b | 3467 ± 121            | 8534 ± 153 b          |
| 500 µmol·m <sup>-2</sup> ·s <sup>-1</sup> | 437.8 ± 10.55 a | 16.64 ± 0.41 a | 25.14 ± 0.79 a | 0.86 ± 0.03 a | 3203 ± 91             | 8174 ± 189 b          |
| P values                                  |                 |                |                |               |                       |                       |
| Af                                        | NS              | NS             | NS             | NS            | NS                    | NS                    |
| Li                                        | <0.0001         | <0.0001        | <0.0001        | <0.0001       | NS                    | 0.0002                |
| Af × Li                                   | NS              | NS             | NS             | NS            | 0.0454                | NS                    |
| Second season                             |                 |                |                |               |                       |                       |
| Af                                        |                 |                |                |               |                       |                       |
| 0.4 m·s <sup>-1</sup>                     | 332.8 ± 10.61   | 12.68 ± 0.62   | 15.86 ± 0.92   | 0.69 ± 0.04   | 2970 ± 109            | 7897 ± 269 a          |
| 0.7 m·s <sup>-1</sup>                     | 328.4 ± 13.64   | 12.43 ± 0.67   | 15.42 ± 1.35   | 0.66 ± 0.06   | 3181 ± 92             | 8520 ± 273 a          |
| 1.0 m·s <sup>-1</sup>                     | 324.5 ± 13.45   | 12.63 ± 0.83   | 14.58 ± 1.14   | 0.61 ± 0.05   | 2964 ± 140            | 7704 ± 274 a          |
| 1.3 m·s <sup>-1</sup>                     | 339.9 ± 13.32   | 12.79 ± 0.71   | 14.40 ± 1.08   | 0.61 ± 0.05   | 3252 ± 82             | 8533 ± 332 a          |
| Li                                        |                 |                |                |               |                       |                       |
| 200 µmol·m <sup>-2</sup> ·s <sup>-1</sup> | 269.4 ± 6.54 c  | 9.09 ± 1.48 c  | 9.27 ± 0.36 c  | 0.39 ± 0.02 c | 3038 ± 80             | 9133 ± 221 a          |
| 350 µmol·m <sup>-2</sup> ·s <sup>-1</sup> | 336.9 ± 8.54 b  | 12.50 ± 0.32 b | 14.11 ± 0.57 b | 0.61 ± 0.03 b | 3196 ± 88             | 7914 ± 208 b          |
| 500 µmol·m <sup>-2</sup> ·s <sup>-1</sup> | 387.9 ± 10.15 a | 16.31 ± 0.46 a | 21.81 ± 0.86 a | 0.94 ± 0.03 a | 3041 ± 115            | 7444 ± 209 b          |
| P values                                  |                 |                |                |               |                       |                       |
| Af                                        | NS              | NS             | NS             | NS            | NS                    | 0.0306                |
| Li                                        | <0.0001         | <0.0001        | <0.0001        | <0.0001       | NS                    | <0.0001               |
| Af × Li                                   | NS              | NS             | NS             | NS            | NS                    | NS                    |

Statistical analyses were performed with two-way analysis of variance and Tukey's honestly significant difference using a significance level of 5% ( $P < 0.05$ ). Means within a column followed by the same letter are not significantly different. Each value represents the average ± standard error.

NS = not significant; SFW = Shoot fresh weight; SDW = shoot dry weight; RFW = root fresh weight; RDW = root dry weight; LA = leaf area; CV = canopy volume.

the 200 µmol·m<sup>-2</sup>·s<sup>-1</sup> light level than the 500 µmol·m<sup>-2</sup>·s<sup>-1</sup> light level ( $P = 0.0284$  and  $P = 0.001$ ), respectively. In the second season, the average Ca concentration for the 500 µmol·m<sup>-2</sup>·s<sup>-1</sup> light level was 23.08% greater than the 200 µmol·m<sup>-2</sup>·s<sup>-1</sup> light level ( $P = 0.0185$ ) (Table 11). The relationship between lettuce nutrient concentrations and light intensity, combined with airflow rate, is important to understand nutrient uptake patterns in lettuce. Observing greater concentrations of immobile plant nutrients, especially Ca, in a lettuce plant can be an explanatory response, suggesting optimal transpiration rates in lettuce under the treatments in our study.

Three two-way interactions were observed between the treatments for macronutrients P, Mg, and S (Fig. 4A, 4B, and 4C) ( $P = 0.0079$ ,  $P = 0.0417$ , and  $P = 0.0089$ , respectively). However, few defining trends were observed across the concentrations of these nutrients between airflow rates and light levels. The lowest light level typically had the highest P, Mg, and S concentrations, regardless of the airflow rate. Note that for all the macronutrient two-way interactions for 'Dragoon', the lowest light level for the 0.7 m·s<sup>-1</sup> airflow rate had significantly lower concentrations than all the other treatment combinations. Additionally, all these interactions occurred in the second season. The treatment combination of 1.3 m·s<sup>-1</sup> airflow rate and 500 µmol·m<sup>-2</sup>·s<sup>-1</sup> had significantly higher Mg and S concentrations, possibly indicating the higher airflow rate's role in

supporting nutrient transport via transpiration to the shoots (Fig. 4B and 4C).

In season 1, airflow rates had a significant effect on leaf Cu concentration in 'Dragoon' ( $P = 0.0375$ ), with the 1.3 m·s<sup>-1</sup> airflow rate having a 36.76% greater leaf Cu concentration than the 1.0 m·s<sup>-1</sup> airflow rate (Table 12). Although Ca concentration was unaffected by higher airflow rates, Cu is also an immobile plant nutrient, and increases in transpiration by the highest airflow rate could aid in the mass flow of Cu in the xylem to the growing shoots of the plant (Table 15). Although Cu is transported in some capacity in the phloem, Cu is often compartmentalized into the cell wall of the plant tissue, therefore providing an easier path for uptake in the xylem pathway (Ducic and Polle 2005). No Cu concentrations reported are a concern of plant toxicity, but this result in our study is further evidence to suggest greater transpiration rates of lettuce, as caused by higher airflow rates (Mir et al. 2021). As explained in a study examining the effects of varying airflow rates on gas exchange in hydroponic lettuce in a plant factory, airflow rates of 0.01 to 0.2 m·s<sup>-1</sup> significantly decreased the leaf boundary layer, but airflow rates of 0.3 to 1.0 m·s<sup>-1</sup>, while still positively enhancing transpiration, only gradually decreased the boundary layer above lettuce canopies (Kitaya et al. 2003). These conclusions by Kitaya et al. (2003) could explain the insignificance of Ca concentration in our lettuce samples, as all airflow rates were above 0.2 m·s<sup>-1</sup>.

A two-way interaction between airflow rates and light intensity was observed for Zn concentration ( $P = 0.0377$ ) (Fig. 4D). The highest airflow rate combined with the highest light level had at least 19.43% higher leaf Zn concentrations than the other treatment combinations. The 0.7 m·s<sup>-1</sup> airflow rate, combined with the lowest light level, resulted in the lowest concentration of all combinations, with at least 19.26% lower concentrations (Fig. 4D). A similar trend is observed in the Zn concentration treatment combinations, as the macronutrient interactions for 'Dragoon'. The 1.3 m·s<sup>-1</sup> airflow rate and 500 µmol·m<sup>-2</sup>·s<sup>-1</sup> treatment combination had the highest Zn concentration, suggesting that the process of transpiration is adequate to supplement Zn in lettuce at high light levels. Another notable observation is that in all nutrient concentration treatment interactions (Fig. 4A, 4B, 4C, and 4D) for 'Dragoon', the 0.7 m·s<sup>-1</sup> airflow rate and 200 µmol·m<sup>-2</sup>·s<sup>-1</sup> treatment combination had greatly lower nutrient concentrations than the other treatment combinations. This could be indicative of a poor sample for that respective treatment combination by chance.

*Tissue analysis of 'Casey' over two seasons.* Similar trends are reported for the tissue analysis of 'Casey' and 'Dragoon'. In season 1, light intensity had a significant effect on N ( $P = 0.0484$ ), P ( $P = 0.0198$ ), and S ( $P = 0.0054$ ) leaf concentrations. N and P concentrations were 18.76% and 10.62% higher for the 200 µmol·m<sup>-2</sup>·s<sup>-1</sup> light level

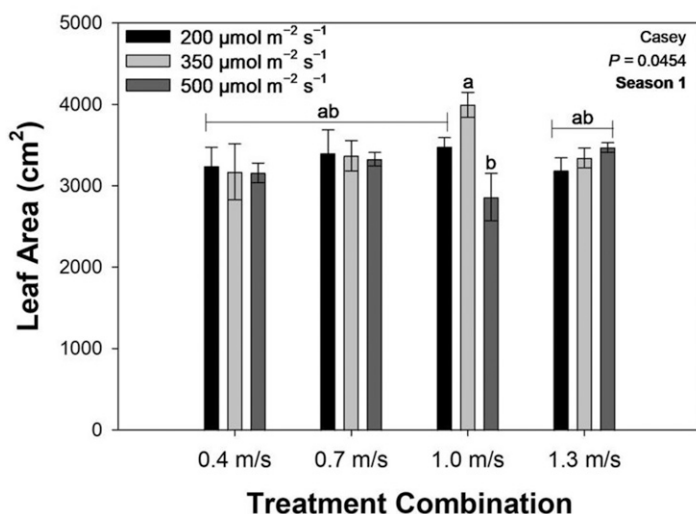


Fig. 3. Two-way interaction for leaf area in season 1 between airflow rates and light intensity of lettuce (*Lactuca sativa*) 'Casey'. Statistical analyses were done with two-way analysis of variance and Tukey's honestly significant difference using a significance level of 5% ( $P < 0.05$ ). Each bar represents the average with the standard error bars in both directions.

than the 500  $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$  light level. The 500  $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$  light level was 10.53% higher for S concentrations than the other two light levels (Table 13).

In season 2, light intensity influenced N ( $P < 0.0001$ ), P ( $P = 0.0008$ ), K ( $P = 0.0028$ ), Mg ( $P = 0.0082$ ), Ca ( $P = 0.0003$ ), and S ( $P = 0.0016$ ) leaf concentrations. The 200  $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$  light level was 10.85%, 14.63%, and 16.54% higher for P, Mg, and Ca

concentrations than the 350  $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$  light level, respectively. The 200  $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$  light level had 15.48% and 14.82% greater K and S concentrations than the 500  $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$  light level. The 200  $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$  light level was at least 5% higher for N concentration than the other two light levels, and the 500  $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$  light level had 10.44% lower N concentrations than the 200  $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$  light level (Table 13).

In season 1, the light intensity influenced only Cu leaf concentration ( $P = 0.001$ ), with the 200  $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$  light level having at least 20.42% greater concentrations than the other two light levels (Table 14). In season 2, light intensity influenced B ( $P = 0.0467$ ), Zn ( $P = 0.0257$ ), Mn ( $P = 0.0125$ ), and Cu ( $P < 0.0001$ ) leaf concentrations. The 200  $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$  light level was 22.35% and 32.19% higher in Zn and Mn concentrations than the 500  $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$  light level. The 200  $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$  light level had an 11.75% greater concentration of B than the 350  $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$  light level. In season 2, the 200  $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$  light level had Cu concentrations at least 20.73% higher than those at the two higher light levels. There were no significant two-way interactions between the treatments or for airflow rates alone for the micronutrient concentrations in either season of 'Casey' cultivation (Table 14).

A representative sample of all leaves in the tissue analysis was likely the reason for observing minimal differences in plant macro- and micronutrient concentrations for the airflow treatment (Tables 11-14), as a sample of only the tips of the younger inner leaves would have been more adequate to better understand the differences in nutrient accumulation based on airflow rate and light intensity, specifically Ca. Although significant increases in Ca uptake or concentration with increasing airflow rates were not observed, the literature states that Ca uptake does increase in lettuce plants outer and inner leaves with vertically directed

Table 11. Leaf nitrogen, phosphorus, potassium, magnesium, calcium, and sulfur concentrations of 'Dragoon' lettuce (*Lactuca sativa*) subjected to different airflow rates and light levels in two growing seasons.

| Conditions                                              | N (%)              | P (%)           | K (%)           | Mg (%)          | Ca (%)             | S (%)            |
|---------------------------------------------------------|--------------------|-----------------|-----------------|-----------------|--------------------|------------------|
| <b>First season</b>                                     |                    |                 |                 |                 |                    |                  |
| <b>Airflow rates (Af)</b>                               |                    |                 |                 |                 |                    |                  |
| 0.4 $\text{m}\cdot\text{s}^{-1}$                        | 5.78 $\pm$ 0.09    | 1.07 $\pm$ 0.02 | 7.57 $\pm$ 0.18 | 0.46 $\pm$ 0.02 | 1.37 $\pm$ 0.09    | 0.35 $\pm$ 0.01  |
| 0.7 $\text{m}\cdot\text{s}^{-1}$                        | 5.72 $\pm$ 0.08    | 1.04 $\pm$ 0.02 | 7.65 $\pm$ 0.16 | 0.46 $\pm$ 0.02 | 1.43 $\pm$ 0.06    | 0.35 $\pm$ 0.01  |
| 1.0 $\text{m}\cdot\text{s}^{-1}$                        | 5.70 $\pm$ 0.12    | 1.05 $\pm$ 0.03 | 7.71 $\pm$ 0.16 | 0.44 $\pm$ 0.02 | 1.25 $\pm$ 0.08    | 0.35 $\pm$ 0.01  |
| 1.3 $\text{m}\cdot\text{s}^{-1}$                        | 5.75 $\pm$ 0.09    | 1.09 $\pm$ 0.01 | 7.57 $\pm$ 0.13 | 0.46 $\pm$ 0.01 | 1.37 $\pm$ 0.07    | 0.36 $\pm$ 0.01  |
| <b>Light intensity (Li)</b>                             |                    |                 |                 |                 |                    |                  |
| 200 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ | 5.92 $\pm$ 0.06 a  | 1.06 $\pm$ 0.02 | 7.82 $\pm$ 0.11 | 0.47 $\pm$ 0.02 | 1.33 $\pm$ 0.05    | 0.36 $\pm$ 0.01  |
| 350 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ | 5.67 $\pm$ 0.07 ab | 1.06 $\pm$ 0.01 | 7.62 $\pm$ 0.14 | 0.44 $\pm$ 0.02 | 1.30 $\pm$ 0.07    | 0.34 $\pm$ 0.01  |
| 500 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ | 5.63 $\pm$ 0.09 b  | 1.06 $\pm$ 0.02 | 7.44 $\pm$ 0.14 | 0.46 $\pm$ 0.02 | 1.43 $\pm$ 0.07    | 0.35 $\pm$ 0.004 |
| <b>P values</b>                                         |                    |                 |                 |                 |                    |                  |
| Af                                                      | NS                 | NS              | NS              | NS              | NS                 | NS               |
| Li                                                      | 0.0284             | NS              | NS              | NS              | NS                 | NS               |
| Af $\times$ Li                                          | NS                 | NS              | NS              | NS              | NS                 | NS               |
| <b>Second season</b>                                    |                    |                 |                 |                 |                    |                  |
| <b>Af</b>                                               |                    |                 |                 |                 |                    |                  |
| 0.4 $\text{m}\cdot\text{s}^{-1}$                        | 5.75 $\pm$ 0.07    | 1.14 $\pm$ 0.03 | 8.90 $\pm$ 0.29 | 0.42 $\pm$ 0.02 | 1.42 $\pm$ 0.08    | 0.34 $\pm$ 0.01  |
| 0.7 $\text{m}\cdot\text{s}^{-1}$                        | 5.72 $\pm$ 0.05    | 0.99 $\pm$ 0.08 | 7.92 $\pm$ 0.59 | 0.35 $\pm$ 0.03 | 1.16 $\pm$ 0.12    | 0.29 $\pm$ 0.03  |
| 1.0 $\text{m}\cdot\text{s}^{-1}$                        | 5.78 $\pm$ 0.05    | 1.13 $\pm$ 0.03 | 9.04 $\pm$ 0.36 | 0.39 $\pm$ 0.02 | 1.27 $\pm$ 0.06    | 0.33 $\pm$ 0.01  |
| 1.3 $\text{m}\cdot\text{s}^{-1}$                        | 5.68 $\pm$ 0.09    | 1.06 $\pm$ 0.06 | 8.66 $\pm$ 0.54 | 0.40 $\pm$ 0.03 | 1.35 $\pm$ 0.10    | 0.32 $\pm$ 0.02  |
| <b>Li</b>                                               |                    |                 |                 |                 |                    |                  |
| 200 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ | 5.87 $\pm$ 0.05 a  | 1.04 $\pm$ 0.07 | 8.53 $\pm$ 0.56 | 0.37 $\pm$ 0.03 | 1.15 $\pm$ 0.10 b  | 0.31 $\pm$ 0.02  |
| 350 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ | 5.73 $\pm$ 0.05 ab | 1.11 $\pm$ 0.05 | 8.80 $\pm$ 0.41 | 0.39 $\pm$ 0.02 | 1.30 $\pm$ 0.07 ab | 0.33 $\pm$ 0.02  |
| 500 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ | 5.61 $\pm$ 0.04 b  | 1.09 $\pm$ 0.02 | 8.56 $\pm$ 0.18 | 0.40 $\pm$ 0.01 | 1.45 $\pm$ 0.05 a  | 0.33 $\pm$ 0.01  |
| <b>P values</b>                                         |                    |                 |                 |                 |                    |                  |
| Af                                                      | NS                 | NS              | NS              | NS              | NS                 | NS               |
| Li                                                      | 0.001              | NS              | NS              | NS              | 0.0185             | NS               |
| Af $\times$ Li                                          | NS                 | 0.0079          | NS              | 0.0417          | NS                 | 0.0089           |

Statistical analyses were performed with two-way analysis of variance and Tukey's honestly significant difference using a significance level of 5% ( $P < 0.05$ ). Means within a column followed by the same letter are not significantly different. Each value represents the average  $\pm$  standard error.

NS = not significant; N = nitrogen; P = phosphorus; K = potassium; Mg = magnesium; Ca = calcium; S = sulfur.

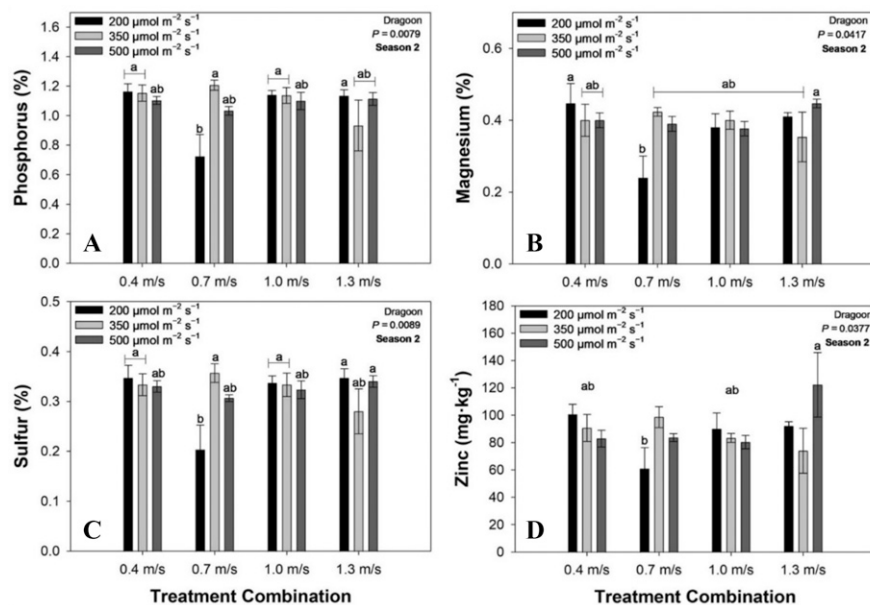


Fig. 4. Two-way interaction for leaf phosphorus (A), magnesium (B), sulfur (C), and zinc (D) concentrations between airflow rates and light intensity in season 2 of lettuce (*Lactuca sativa*) 'Drogon'. Statistical analyses were done with two-way analysis of variance and Tukey's honestly significant difference using a significance level of 5% ( $P < 0.05$ ). Each bar represents the average with the standard error bars in both directions.

airflow in a plant factory (Goto and Takakura 1992b; Kitaya et al. 2003).

A dilution effect can explain the increase in nutrient concentrations in lower light intensities (Tables 11-14). Low light intensities produce less biomass, while under higher

light intensities, greater biomass dilutes the percentage of nutrients per total biomass. However, lettuce harvested at increasing light intensities has a greater overall nutrient content and uptake. We confirmed this effect in other studies (Kazuo and Nobutoshi 1998;

Song et al. 2020; Zhou et al. 2019). As described in a study on the effect of temperature and light intensity on lettuce growth, N, P, and K concentrations experienced a dilution effect; however, when examining uptake, the trend was reversed (Zhou et al. 2019). Only one nutrient concentration increased with increasing light levels, and that was Ca in season 2 of 'Drogon' production (Table 11). This could be explained by increased transpiration rates in lettuce at higher light intensities. Therefore, more Ca is translocated through the xylem and throughout the canopy of the crop (Ahmed et al. 2022; Miao et al. 2023; Park and Lee 1999).

#### Gas exchange of 'Drogon' and 'Casey'.

Gas exchange measurements were taken only in season 2 of this study. Light intensity influenced the differences observed in net assimilation rate ( $P < 0.0001$ ), transpiration rate ( $P = 0.0004$ ), and water use efficiency ( $P = 0.0009$ ) for 'Drogon'. Net assimilation rate was 76.29% higher for the  $500 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$  than the  $200 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$  light level, and 23.86% higher than the  $350 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$  light level. The transpiration rate was 39.05% higher for the  $500 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$  than the  $200 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$  light level and 17.20% higher than the  $350 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$  light level. Water use efficiency was 35.42% and 28.96% higher for the 500 and the  $350 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$  light levels than the  $200 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$  light levels, respectively. No difference was observed from the two-way ANOVA analyses

Table 12. Leaf boron, zinc, manganese, iron, and copper concentrations of 'Drogon' lettuce (*Lactuca sativa*) subjected to different airflow rates and light levels in two growing seasons.

| Conditions                                              | B ( $\text{mg}\cdot\text{kg}^{-1}$ ) | Zn ( $\text{mg}\cdot\text{kg}^{-1}$ ) | Mn ( $\text{mg}\cdot\text{kg}^{-1}$ ) | Fe ( $\text{mg}\cdot\text{kg}^{-1}$ ) | Cu ( $\text{mg}\cdot\text{kg}^{-1}$ ) |
|---------------------------------------------------------|--------------------------------------|---------------------------------------|---------------------------------------|---------------------------------------|---------------------------------------|
| <b>First season</b>                                     |                                      |                                       |                                       |                                       |                                       |
| Airflow rates (Af)                                      |                                      |                                       |                                       |                                       |                                       |
| 0.4 $\text{m}\cdot\text{s}^{-1}$                        | 41.56 $\pm$ 2.10                     | 104.33 $\pm$ 5.64                     | 94.78 $\pm$ 8.13                      | 212.89 $\pm$ 21.79                    | 5.78 $\pm$ 0.32 ab                    |
| 0.7 $\text{m}\cdot\text{s}^{-1}$                        | 40.78 $\pm$ 1.63                     | 111.33 $\pm$ 8.98                     | 97.44 $\pm$ 7.38                      | 216.89 $\pm$ 16.13                    | 6.33 $\pm$ 0.41 ab                    |
| 1.0 $\text{m}\cdot\text{s}^{-1}$                        | 37.44 $\pm$ 1.98                     | 102.11 $\pm$ 8.59                     | 83.89 $\pm$ 6.65                      | 200.67 $\pm$ 8.47                     | 5.44 $\pm$ 0.38 b                     |
| 1.3 $\text{m}\cdot\text{s}^{-1}$                        | 42.67 $\pm$ 1.99                     | 125.56 $\pm$ 9.14                     | 104.78 $\pm$ 5.87                     | 214.11 $\pm$ 12.80                    | 7.89 $\pm$ 1.06 a                     |
| Light intensity (Li)                                    |                                      |                                       |                                       |                                       |                                       |
| 200 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ | 41.42 $\pm$ 1.72                     | 104.92 $\pm$ 5.93                     | 96.33 $\pm$ 5.55                      | 225 $\pm$ 14.99                       | 7.08 $\pm$ 0.90                       |
| 350 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ | 40.58 $\pm$ 2.21                     | 114.17 $\pm$ 8.81                     | 94.92 $\pm$ 7.32                      | 210.92 $\pm$ 14.52                    | 5.83 $\pm$ 0.32                       |
| 500 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ | 39.83 $\pm$ 1.11                     | 113.42 $\pm$ 7.24                     | 94.42 $\pm$ 6.29                      | 197.5 $\pm$ 8.36                      | 6.17 $\pm$ 0.30                       |
| <b>P values</b>                                         |                                      |                                       |                                       |                                       |                                       |
| Af                                                      | NS                                   | NS                                    | NS                                    | NS                                    | 0.0375                                |
| Li                                                      | NS                                   | NS                                    | NS                                    | NS                                    | NS                                    |
| Af $\times$ Li                                          | NS                                   | NS                                    | NS                                    | NS                                    | NS                                    |
| <b>Second season</b>                                    |                                      |                                       |                                       |                                       |                                       |
| Af                                                      |                                      |                                       |                                       |                                       |                                       |
| 0.4 $\text{m}\cdot\text{s}^{-1}$                        | 36.67 $\pm$ 2.06                     | 91.44 $\pm$ 4.71                      | 86.89 $\pm$ 2.70                      | 185.33 $\pm$ 13.90                    | 5.78 $\pm$ 0.22                       |
| 0.7 $\text{m}\cdot\text{s}^{-1}$                        | 31.33 $\pm$ 2.84                     | 81.11 $\pm$ 7.42                      | 74.78 $\pm$ 8.87                      | 149.67 $\pm$ 14.51                    | 5.11 $\pm$ 0.42                       |
| 1.0 $\text{m}\cdot\text{s}^{-1}$                        | 33.78 $\pm$ 1.46                     | 84.56 $\pm$ 4.01                      | 77.89 $\pm$ 3.98                      | 166.56 $\pm$ 8.74                     | 5.44 $\pm$ 0.24                       |
| 1.3 $\text{m}\cdot\text{s}^{-1}$                        | 36 $\pm$ 2.14                        | 96.11 $\pm$ 10.93                     | 82.33 $\pm$ 6.92                      | 186.11 $\pm$ 17.15                    | 6.11 $\pm$ 0.51                       |
| Li                                                      |                                      |                                       |                                       |                                       |                                       |
| 200 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ | 33.17 $\pm$ 2.53                     | 85.92 $\pm$ 6.31                      | 72 $\pm$ 6.17                         | 162.5 $\pm$ 12.75                     | 5.58 $\pm$ 0.38                       |
| 350 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ | 33.58 $\pm$ 1.55                     | 86.67 $\pm$ 5.25                      | 82.33 $\pm$ 4.98                      | 169.75 $\pm$ 5.91                     | 5.58 $\pm$ 0.34                       |
| 500 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ | 36.58 $\pm$ 1.46                     | 92.33 $\pm$ 7.47                      | 87.08 $\pm$ 3.70                      | 183.5 $\pm$ 16.31                     | 5.67 $\pm$ 0.28                       |
| <b>P values</b>                                         |                                      |                                       |                                       |                                       |                                       |
| Af                                                      | NS                                   | NS                                    | NS                                    | NS                                    | NS                                    |
| Li                                                      | NS                                   | NS                                    | NS                                    | NS                                    | NS                                    |
| Af $\times$ Li                                          | NS                                   | 0.0377                                | NS                                    | NS                                    | NS                                    |

Statistical analyses were performed with two-way analysis of variance and Tukey's honestly significant difference using a significance level of 5% ( $P < 0.05$ ). Means within a column followed by the same letter are not significantly different. Each value represents the average  $\pm$  standard error.

NS = not significant; B = boron; Zn = zinc; Mn = manganese; Fe = iron; Cu = copper.

Table 13. Leaf nitrogen, phosphorus, potassium, magnesium, calcium, and sulfur concentrations of lettuce (*Lactuca sativa*) ‘Casey’ subjected to different airflow rates and light levels in two growing seasons.

|                                           | N (%)          | P (%)          | K (%)          | Mg (%)        | Ca (%)        | S (%)          |
|-------------------------------------------|----------------|----------------|----------------|---------------|---------------|----------------|
| <b>First season</b>                       |                |                |                |               |               |                |
| <b>Airflow rates (Af)</b>                 |                |                |                |               |               |                |
| 0.4 m·s <sup>-1</sup>                     | 5.59 ± 0.11    | 1.10 ± 0.03    | 7.94 ± 0.17    | 0.48 ± 0.01   | 1.52 ± 0.06   | 0.28 ± 0.01    |
| 0.7 m·s <sup>-1</sup>                     | 5.58 ± 0.16    | 1.14 ± 0.03    | 8.29 ± 0.18    | 0.51 ± 0.03   | 1.59 ± 0.09   | 0.28 ± 0.01    |
| 1.0 m·s <sup>-1</sup>                     | 5.64 ± 0.15    | 1.10 ± 0.04    | 7.80 ± 0.20    | 0.48 ± 0.04   | 1.47 ± 0.14   | 0.27 ± 0.01    |
| 1.3 m·s <sup>-1</sup>                     | 5.08 ± 0.64    | 1.18 ± 0.04    | 7.98 ± 0.18    | 0.49 ± 0.02   | 1.57 ± 0.08   | 0.29 ± 0.01    |
| <b>Light intensity (Li)</b>               |                |                |                |               |               |                |
| 200 µmol·m <sup>-2</sup> ·s <sup>-1</sup> | 5.89 ± 0.09 a  | 1.19 ± 0.03 a  | 8.08 ± 0.11    | 0.47 ± 0.01   | 1.44 ± 0.05   | 0.30 ± 0.01 a  |
| 350 µmol·m <sup>-2</sup> ·s <sup>-1</sup> | 5.65 ± 0.12 ab | 1.14 ± 0.03 ab | 7.96 ± 0.21    | 0.46 ± 0.02   | 1.49 ± 0.09   | 0.27 ± 0.01 b  |
| 500 µmol·m <sup>-2</sup> ·s <sup>-1</sup> | 4.88 ± 0.45 b  | 1.07 ± 0.02 b  | 7.97 ± 0.16    | 0.54 ± 0.03   | 1.68 ± 0.09   | 0.27 ± 0.01 b  |
| <b>P values</b>                           |                |                |                |               |               |                |
| Af                                        | NS             | NS             | NS             | NS            | NS            | NS             |
| Li                                        | 0.0484         | 0.0198         | NS             | NS            | NS            | 0.0054         |
| Af × Li                                   | NS             | NS             | NS             | NS            | NS            | NS             |
| <b>Second season</b>                      |                |                |                |               |               |                |
| <b>Af</b>                                 |                |                |                |               |               |                |
| 0.4 m·s <sup>-1</sup>                     | 5.84 ± 0.09    | 1.25 ± 0.06    | 9.73 ± 0.38    | 0.39 ± 0.02   | 1.27 ± 0.08   | 0.27 ± 0.01    |
| 0.7 m·s <sup>-1</sup>                     | 5.90 ± 0.11    | 1.24 ± 0.05    | 9.45 ± 0.33    | 0.39 ± 0.01   | 1.22 ± 0.05   | 0.27 ± 0.01    |
| 1.0 m·s <sup>-1</sup>                     | 5.80 ± 0.16    | 1.25 ± 0.06    | 9.87 ± 0.31    | 0.42 ± 0.02   | 1.37 ± 0.08   | 0.28 ± 0.01    |
| 1.3 m·s <sup>-1</sup>                     | 5.84 ± 0.09    | 1.22 ± 0.03    | 9.50 ± 0.43    | 0.38 ± 0.02   | 1.19 ± 0.06   | 0.26 ± 0.01    |
| <b>Li</b>                                 |                |                |                |               |               |                |
| 200 µmol·m <sup>-2</sup> ·s <sup>-1</sup> | 6.15 ± 0.06 a  | 1.36 ± 0.03 a  | 10.44 ± 0.27 a | 0.44 ± 0.02 a | 1.44 ± 0.06 a | 0.29 ± 0.01 a  |
| 350 µmol·m <sup>-2</sup> ·s <sup>-1</sup> | 5.85 ± 0.07 b  | 1.22 ± 0.04 b  | 9.53 ± 0.26 ab | 0.38 ± 0.02 b | 1.22 ± 0.04 b | 0.27 ± 0.01 ab |
| 500 µmol·m <sup>-2</sup> ·s <sup>-1</sup> | 5.54 ± 0.06 c  | 1.14 ± 0.03 b  | 8.94 ± 0.23 b  | 0.37 ± 0.02 b | 1.13 ± 0.04 b | 0.25 ± 0.01 b  |
| <b>P values</b>                           |                |                |                |               |               |                |
| Af                                        | NS             | NS             | NS             | NS            | NS            | NS             |
| Li                                        | <0.0001        | 0.0008         | 0.0028         | 0.0082        | 0.0003        | 0.0016         |
| Af × Li                                   | NS             | NS             | NS             | NS            | NS            | NS             |

Statistical analyses were performed with two-way analysis of variance and Tukey’s honestly significant difference using a significance level of 5% ( $P < 0.05$ ). Means within a column followed by the same letter are not significantly different. Each value represents the average ± standard error. Values sharing the same letter are not significantly different.

NS = not significant; N = nitrogen; P = phosphorus; K = potassium; Mg = magnesium; Ca = calcium; S = sulfur.

Table 14. Leaf boron, zinc, manganese, iron, and copper concentrations of lettuce (*Lactuca sativa*) ‘Casey’ subjected to different airflow rates and light levels in two growing seasons.

| Conditions                                | B (mg·kg <sup>-1</sup> ) | Zn (mg·kg <sup>-1</sup> ) | Mn (mg·kg <sup>-1</sup> ) | Fe (mg·kg <sup>-1</sup> ) | Cu (mg·kg <sup>-1</sup> ) |
|-------------------------------------------|--------------------------|---------------------------|---------------------------|---------------------------|---------------------------|
| <b>First season</b>                       |                          |                           |                           |                           |                           |
| <b>Airflow rates (Af)</b>                 |                          |                           |                           |                           |                           |
| 0.4 m·s <sup>-1</sup>                     | 31.78 ± 0.85             | 88.67 ± 3.57              | 79.11 ± 2.77              | 155.11 ± 10.80            | 4.56 ± 0.53               |
| 0.7 m·s <sup>-1</sup>                     | 34.44 ± 1.73             | 87.33 ± 5.53              | 79.44 ± 5.83              | 167.67 ± 15.16            | 4.89 ± 0.39               |
| 1.0 m·s <sup>-1</sup>                     | 34.56 ± 2.70             | 81.56 ± 5.80              | 68.11 ± 6.45              | 159.33 ± 7.58             | 5.00 ± 0.41               |
| 1.3 m·s <sup>-1</sup>                     | 36.22 ± 1.13             | 90.44 ± 4.24              | 83.44 ± 4.61              | 180.22 ± 14.57            | 5.22 ± 0.49               |
| <b>Light intensity (Li)</b>               |                          |                           |                           |                           |                           |
| 200 µmol·m <sup>-2</sup> ·s <sup>-1</sup> | 34.33 ± 1.69             | 89 ± 3.93                 | 78.33 ± 5.07              | 167 ± 10.54               | 5.83 ± 0.30 a             |
| 350 µmol·m <sup>-2</sup> ·s <sup>-1</sup> | 32.33 ± 1.25             | 86.58 ± 4.27              | 75.5 ± 4.54               | 163.25 ± 13.11            | 4.75 ± 0.28 b             |
| 500 µmol·m <sup>-2</sup> ·s <sup>-1</sup> | 36.08 ± 1.53             | 85.42 ± 4.53              | 78.75 ± 4.35              | 166.5 ± 8.80              | 4.17 ± 0.21 b             |
| <b>P values</b>                           |                          |                           |                           |                           |                           |
| Af                                        | NS                       | NS                        | NS                        | NS                        | NS                        |
| Li                                        | NS                       | NS                        | NS                        | NS                        | 0.001                     |
| Af × Li                                   | NS                       | NS                        | NS                        | NS                        | NS                        |
| <b>Second season</b>                      |                          |                           |                           |                           |                           |
| <b>Af</b>                                 |                          |                           |                           |                           |                           |
| 0.4 m·s <sup>-1</sup>                     | 27.89 ± 1.16             | 76.33 ± 5.09              | 65.33 ± 4.93              | 123.89 ± 7.44             | 4.78 ± 0.32               |
| 0.7 m·s <sup>-1</sup>                     | 27.33 ± 1.00             | 73.44 ± 4.76              | 56.67 ± 3.91              | 121 ± 7.56                | 4.56 ± 0.34               |
| 1.0 m·s <sup>-1</sup>                     | 30.44 ± 1.19             | 78.22 ± 5.85              | 64 ± 7.95                 | 140.78 ± 6.88             | 5.22 ± 0.40               |
| 1.3 m·s <sup>-1</sup>                     | 26.78 ± 0.88             | 71.33 ± 4.35              | 54.78 ± 3.43              | 120.67 ± 5.29             | 4.89 ± 0.26               |
| <b>Li</b>                                 |                          |                           |                           |                           |                           |
| 200 µmol·m <sup>-2</sup> ·s <sup>-1</sup> | 30 ± 0.87 a              | 82.92 ± 3.64 a            | 69.42 ± 3.97 a            | 136.08 ± 5.96             | 5.75 ± 0.25 a             |
| 350 µmol·m <sup>-2</sup> ·s <sup>-1</sup> | 26.67 ± 0.76 b           | 75.33 ± 4.21 ab           | 61 ± 5.14 ab              | 123.25 ± 6.44             | 4.67 ± 0.14 b             |
| 500 µmol·m <sup>-2</sup> ·s <sup>-1</sup> | 27.67 ± 1.07 ab          | 66.25 ± 3.71 b            | 50.17 ± 3.00 b            | 120.42 ± 5.61             | 4.17 ± 0.24 b             |
| <b>P values</b>                           |                          |                           |                           |                           |                           |
| Af                                        | NS                       | NS                        | NS                        | NS                        | NS                        |
| Li                                        | 0.0467                   | 0.0257                    | 0.0125                    | NS                        | <0.0001                   |
| Af × Li                                   | NS                       | NS                        | NS                        | NS                        | NS                        |

Statistical analyses were performed with two-way analysis of variance and Tukey’s honestly significant difference using a significance level of 5% ( $P < 0.05$ ). Means within a column followed by the same letter are not significantly different. Each value represents the average ± standard error.

NS = not significant; B = boron; Zn = zinc; Mn = manganese; Fe = iron; Cu = copper.



Table 15. Lettuce gas exchange (net photosynthetic rate, transpiration rate, water use efficiency) of lettuce (*Lactuca sativa*) 'Dragoon' and 'Casey' subjected to different airflow rates and light levels in the second growing season.

| Conditions                                              | $P_n$ ( $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ ) | $E$ ( $\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ ) | WUE ( $\mu\text{mol}\cdot\text{mol}^{-1}$ ) |
|---------------------------------------------------------|---------------------------------------------------------------|----------------------------------------------------------|---------------------------------------------|
| <b>'Dragoon'</b>                                        |                                                               |                                                          |                                             |
| Airflow rates (Af)                                      |                                                               |                                                          |                                             |
| 0.4 $\text{m}\cdot\text{s}^{-1}$                        | 16.39 $\pm$ 1.72                                              | 3.21 $\pm$ 0.22                                          | 5.12 $\pm$ 0.44                             |
| 0.7 $\text{m}\cdot\text{s}^{-1}$                        | 15.71 $\pm$ 1.71                                              | 3.26 $\pm$ 0.39                                          | 4.99 $\pm$ 0.35                             |
| 1.0 $\text{m}\cdot\text{s}^{-1}$                        | 15.98 $\pm$ 1.85                                              | 3.58 $\pm$ 0.25                                          | 4.49 $\pm$ 0.45                             |
| 1.3 $\text{m}\cdot\text{s}^{-1}$                        | 16.06 $\pm$ 1.86                                              | 3.50 $\pm$ 0.27                                          | 4.56 $\pm$ 0.33                             |
| Light intensity (Li)                                    |                                                               |                                                          |                                             |
| 200 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ | 9.64 $\pm$ 0.29 c                                             | 2.72 $\pm$ 0.23 b                                        | 3.81 $\pm$ 0.29 b                           |
| 350 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ | 16.94 $\pm$ 0.27 b                                            | 3.40 $\pm$ 0.15 ab                                       | 5.10 $\pm$ 0.24 a                           |
| 500 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ | 21.53 $\pm$ 0.55 a                                            | 4.04 $\pm$ 0.18 a                                        | 5.45 $\pm$ 0.29 a                           |
| <b>P values</b>                                         |                                                               |                                                          |                                             |
| Af                                                      | NS                                                            | NS                                                       | NS                                          |
| Li                                                      | <0.0001                                                       | 0.0004                                                   | 0.0009                                      |
| Af $\times$ Li                                          | NS                                                            | NS                                                       | NS                                          |
| <b>'Casey'</b>                                          |                                                               |                                                          |                                             |
| Af                                                      |                                                               |                                                          |                                             |
| 0.4 $\text{m}\cdot\text{s}^{-1}$                        | 17.21 $\pm$ 1.73                                              | 2.28 $\pm$ 0.10 b                                        | 7.55 $\pm$ 0.68 a                           |
| 0.7 $\text{m}\cdot\text{s}^{-1}$                        | 17.20 $\pm$ 1.63                                              | 2.33 $\pm$ 0.15 b                                        | 7.50 $\pm$ 0.72 a                           |
| 1.0 $\text{m}\cdot\text{s}^{-1}$                        | 17.02 $\pm$ 1.69                                              | 2.56 $\pm$ 0.15 ab                                       | 6.71 $\pm$ 0.63 ab                          |
| 1.3 $\text{m}\cdot\text{s}^{-1}$                        | 17.47 $\pm$ 1.86                                              | 2.96 $\pm$ 0.14 a                                        | 5.87 $\pm$ 0.55 b                           |
| Li                                                      |                                                               |                                                          |                                             |
| 200 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ | 11.00 $\pm$ 0.12 c                                            | 2.33 $\pm$ 0.12                                          | 4.85 $\pm$ 0.24 b                           |
| 350 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ | 18.24 $\pm$ 0.39 b                                            | 2.54 $\pm$ 0.12                                          | 7.39 $\pm$ 0.44 a                           |
| 500 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ | 22.43 $\pm$ 0.53 a                                            | 2.73 $\pm$ 0.16                                          | 8.48 $\pm$ 0.41 a                           |
| <b>P values</b>                                         |                                                               |                                                          |                                             |
| Af                                                      | NS                                                            | 0.0089                                                   | 0.0228                                      |
| Li                                                      | <0.0001                                                       | NS                                                       | <0.0001                                     |
| Af $\times$ Li                                          | NS                                                            | NS                                                       | NS                                          |

Statistical analyses were performed with two-way analysis of variance and Tukey's honestly significant difference using a significance level of 5% ( $P < 0.05$ ). Means within a column followed by the same letter are not significantly different. Each value represents the average  $\pm$  standard error. Values sharing the same letter are not significantly different.

NS = not significant;  $P_n$  = net photosynthetic rate;  $E$  = transpiration rate; WUE = water use efficiency.

Table 16. Lettuce quality metrics [soluble solids content (SSC), titratable acidity (TA)] and pigments [leaf chlorophyll content (LCC), leaf anthocyanin content (LAC)] of lettuce (*Lactuca sativa*) 'Dragoon' subjected to different airflow rates and light levels in two growing seasons.

| Conditions                                              | SSC (%)            | TA (%)          | LCC (CCI)          | LAC (ACI)          |
|---------------------------------------------------------|--------------------|-----------------|--------------------|--------------------|
| <b>First season</b>                                     |                    |                 |                    |                    |
| Airflow rates (Af)                                      |                    |                 |                    |                    |
| 0.4 $\text{m}\cdot\text{s}^{-1}$                        | 2.29 $\pm$ 0.18    | 2.70 $\pm$ 0.16 | 44.84 $\pm$ 2.43   | 8.10 $\pm$ 0.41    |
| 0.7 $\text{m}\cdot\text{s}^{-1}$                        | 2.16 $\pm$ 0.09    | 2.45 $\pm$ 0.11 | 39.48 $\pm$ 2.46   | 7.77 $\pm$ 0.42    |
| 1.0 $\text{m}\cdot\text{s}^{-1}$                        | 2.31 $\pm$ 0.10    | 2.56 $\pm$ 0.10 | 39.67 $\pm$ 1.99   | 8.73 $\pm$ 0.51    |
| 1.3 $\text{m}\cdot\text{s}^{-1}$                        | 2.18 $\pm$ 0.13    | 2.52 $\pm$ 0.15 | 41.32 $\pm$ 2.67   | 8.09 $\pm$ 0.35    |
| Light intensity (Li)                                    |                    |                 |                    |                    |
| 200 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ | 2.04 $\pm$ 0.08 b  | 2.40 $\pm$ 0.11 | 30.35 $\pm$ 0.96 c | 6.41 $\pm$ 0.22 c  |
| 350 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ | 2.18 $\pm$ 0.13 ab | 2.53 $\pm$ 0.13 | 43.32 $\pm$ 1.48 b | 8.03 $\pm$ 0.20 b  |
| 500 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ | 2.48 $\pm$ 0.07 a  | 2.75 $\pm$ 0.09 | 50.31 $\pm$ 2.06 a | 10.00 $\pm$ 0.35 a |
| <b>P values</b>                                         |                    |                 |                    |                    |
| Af                                                      | NS                 | NS              | NS                 | NS                 |
| Li                                                      | 0.0144             | NS              | <0.0001            | <0.0001            |
| Af $\times$ Li                                          | NS                 | NS              | NS                 | NS                 |
| <b>Second season</b>                                    |                    |                 |                    |                    |
| Af                                                      |                    |                 |                    |                    |
| 0.4 $\text{m}\cdot\text{s}^{-1}$                        | 2.64 $\pm$ 0.16    | 2.60 $\pm$ 0.12 | 44.27 $\pm$ 2.94   | 5.45 $\pm$ 0.34    |
| 0.7 $\text{m}\cdot\text{s}^{-1}$                        | 2.33 $\pm$ 0.10    | 2.41 $\pm$ 0.06 | 40.31 $\pm$ 2.81   | 5.42 $\pm$ 0.38    |
| 1.0 $\text{m}\cdot\text{s}^{-1}$                        | 2.56 $\pm$ 0.08    | 2.50 $\pm$ 0.08 | 47.12 $\pm$ 2.71   | 4.74 $\pm$ 0.32    |
| 1.3 $\text{m}\cdot\text{s}^{-1}$                        | 2.43 $\pm$ 0.16    | 2.42 $\pm$ 0.14 | 42.94 $\pm$ 2.99   | 6.02 $\pm$ 0.55    |
| Li                                                      |                    |                 |                    |                    |
| 200 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ | 2.30 $\pm$ 0.10    | 2.43 $\pm$ 0.09 | 32.23 $\pm$ 1.51 c | 5.04 $\pm$ 0.19    |
| 350 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ | 2.48 $\pm$ 0.09    | 2.48 $\pm$ 0.07 | 44.02 $\pm$ 2.15 b | 5.35 $\pm$ 2.10    |
| 500 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ | 2.69 $\pm$ 0.12    | 2.54 $\pm$ 0.10 | 54.74 $\pm$ 2.16 a | 5.83 $\pm$ 0.47    |
| <b>P values</b>                                         |                    |                 |                    |                    |
| Af                                                      | NS                 | NS              | NS                 | NS                 |
| Li                                                      | NS                 | NS              | <0.0001            | NS                 |
| Af $\times$ Li                                          | NS                 | NS              | NS                 | 0.0015             |

Statistical analyses were performed with two-way analysis of variance and Tukey's honestly significant difference using a significance level of 5% ( $P < 0.05$ ). Means within a column followed by the same letter are not significantly different. Each value represents the average  $\pm$  standard error.

ACI = anthocyanin content index; CCI = chlorophyll content index; NS = not significant; SSC = soluble solids content; TA = titratable acidity; LCC = leaf chlorophyll content; LAC = leaf anthocyanin content.

for airflow rates on gas exchange for 'Dragoon' (Table 15).

Light intensity influenced the net assimilation rate ( $P < 0.0001$ ) and water use efficiency ( $P < 0.0001$ ) for 'Casey'. The 500  $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$  light level had a 20.61% and 68.38% higher net  $\text{CO}_2$  assimilation rate than the 350 and 200  $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$  light levels, respectively. As with 'Dragoon', water use efficiency was 54.46% and 41.50% higher for the 500 and the 350  $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$  light levels than the 200  $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$  light levels, respectively. Airflow rates significantly affected transpiration rate ( $P = 0.0089$ ) and water use efficiency ( $P = 0.0228$ ) in 'Casey'. The transpiration rate was 25.95% higher for the 1.3  $\text{m}\cdot\text{s}^{-1}$  airflow rate than the 0.4  $\text{m}\cdot\text{s}^{-1}$  airflow rate. Water use efficiency was 25.04% lower for the 1.3  $\text{m}\cdot\text{s}^{-1}$  airflow rate than the 0.4  $\text{m}\cdot\text{s}^{-1}$  airflow rate for 'Casey' (Table 15). The increase in transpiration with increasing airflow rates in 'Casey' suggests the impact that vertical airflow has in breaking the boundary layer and lowering the VPD to encourage a favorable microclimate for transpiration (Table 15) (Goto and Takakura 1992a; Kitaya et al. 2000, 2003).

Increasing light intensities, at least up to 500  $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ , are associated with enhanced photosynthetic rates, transpiration rates, and water use efficiency. Increasing airflow rates decrease water use efficiency, and that is indicative of a greater transpiration rate present in the lettuce.

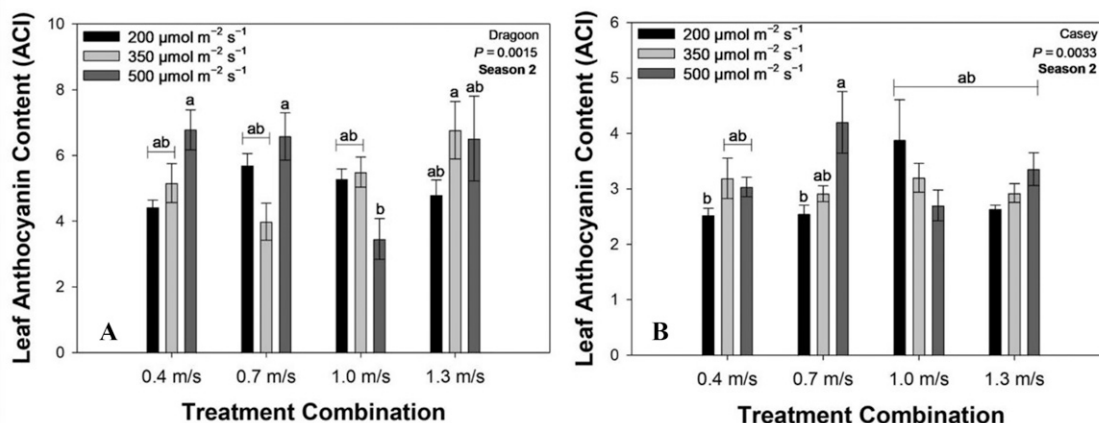


Fig. 5. Two-way interaction for leaf anthocyanin content between airflow rates and light intensity in season 2 of lettuce (*Lactuca sativa*) 'Dragoon' (A) and 'Casey' (B). Statistical analyses were done with two-way analysis of variance and Tukey's honestly significant difference using a significance level of 5% ( $P < 0.05$ ). Each bar represents the average with the standard error bars in both directions.

**Pigment accumulation and quality metrics of 'Dragoon' and 'Casey' over two seasons.** In season 1 of 'Dragoon' cultivation, light intensity influenced soluble solids content ( $P = 0.0144$ ), leaf chlorophyll ( $P < 0.0001$ ), and anthocyanin content ( $P < 0.0001$ ). As light intensity increased, the content of leaf chlorophyll and anthocyanin increased. The leaf chlorophyll content was 49.49% greater for the 500  $\mu\text{mol m}^{-2} \text{s}^{-1}$  light level than 200  $\mu\text{mol m}^{-2} \text{s}^{-1}$  light level, and the leaf anthocyanin content was 43.75% greater for the 500  $\mu\text{mol m}^{-2} \text{s}^{-1}$  light level than

200  $\mu\text{mol m}^{-2} \text{s}^{-1}$  light level. The 500 and the 350  $\mu\text{mol m}^{-2} \text{s}^{-1}$  light levels had 19.47% and 6.64% higher soluble solids content than the 200  $\mu\text{mol m}^{-2} \text{s}^{-1}$  light levels, respectively (Table 16).

In the second season, light intensity only influenced leaf chlorophyll content ( $P < 0.0001$ ), which was 51.77% greater for the 500  $\mu\text{mol m}^{-2} \text{s}^{-1}$  light level than the 200  $\mu\text{mol m}^{-2} \text{s}^{-1}$  light level, and the 200  $\mu\text{mol m}^{-2} \text{s}^{-1}$  light level had the lowest leaf chlorophyll content (chlorophyll content index, 32.23) (Table 16). There

was a significant two-way interaction between light intensity and airflow rates for leaf anthocyanin content in season 2 only ( $P = 0.0015$ ) (Fig. 5A).

Excluding the 1.0 and 1.3  $\text{m s}^{-1}$  airflow rate, the highest light level had at least 17.34% greater leaf anthocyanin content than the lowest light level. Interestingly, the 1.0  $\text{m s}^{-1}$  airflow rate and high light level combination had the least leaf anthocyanin content of any treatment combination (anthocyanin content index, 3.46), which was likely an outlier (Fig. 5A).

Table 17. Lettuce quality metrics (soluble solids content, titratable acidity) and pigments (leaf chlorophyll content, leaf anthocyanin content) of lettuce (*Lactuca sativa*) 'Casey' subjected to different airflow rates and light levels in two growing seasons.

| Conditions                               | SSC (%)            | TA (% citric acid) | LCC (CCI)          | LAC (ACI)         |
|------------------------------------------|--------------------|--------------------|--------------------|-------------------|
| <b>First season</b>                      |                    |                    |                    |                   |
| <b>Airflow rates (Af)</b>                |                    |                    |                    |                   |
| 0.4 $\text{m s}^{-1}$                    | 2.03 $\pm$ 0.12    | 2.30 $\pm$ 0.06 b  | 12.84 $\pm$ 0.63   | 3.28 $\pm$ 0.09   |
| 0.7 $\text{m s}^{-1}$                    | 1.99 $\pm$ 0.12    | 2.58 $\pm$ 0.07 ab | 13.15 $\pm$ 0.65   | 3.30 $\pm$ 0.09   |
| 1.0 $\text{m s}^{-1}$                    | 2.28 $\pm$ 0.19    | 2.65 $\pm$ 0.10 a  | 13.63 $\pm$ 0.64   | 3.36 $\pm$ 0.11   |
| 1.3 $\text{m s}^{-1}$                    | 2.12 $\pm$ 0.21    | 2.36 $\pm$ 0.07 ab | 13.47 $\pm$ 0.69   | 3.23 $\pm$ 0.08   |
| <b>Light intensity (Li)</b>              |                    |                    |                    |                   |
| 200 $\mu\text{mol m}^{-2} \text{s}^{-1}$ | 1.73 $\pm$ 0.08 b  | 2.36 $\pm$ 0.06    | 9.63 $\pm$ 0.27 c  | 2.79 $\pm$ 0.03 c |
| 350 $\mu\text{mol m}^{-2} \text{s}^{-1}$ | 2.23 $\pm$ 0.16 a  | 2.50 $\pm$ 0.07    | 13.85 $\pm$ 0.30 b | 3.39 $\pm$ 0.04 b |
| 500 $\mu\text{mol m}^{-2} \text{s}^{-1}$ | 2.36 $\pm$ 0.10 a  | 2.56 $\pm$ 0.10    | 16.34 $\pm$ 0.37 a | 3.69 $\pm$ 0.06 a |
| <b>P values</b>                          |                    |                    |                    |                   |
| Af                                       | NS                 | 0.0129             | NS                 | NS                |
| Li                                       | 0.0008             | NS                 | <0.0001            | <0.0001           |
| Af $\times$ Li                           | NS                 | NS                 | NS                 | NS                |
| <b>Second season</b>                     |                    |                    |                    |                   |
| <b>Af</b>                                |                    |                    |                    |                   |
| 0.4 $\text{m s}^{-1}$                    | 2.59 $\pm$ 0.14    | 2.64 $\pm$ 0.11    | 13.87 $\pm$ 0.80   | 2.92 $\pm$ 0.15   |
| 0.7 $\text{m s}^{-1}$                    | 2.66 $\pm$ 0.08    | 2.66 $\pm$ 0.10    | 14.22 $\pm$ 0.90   | 3.22 $\pm$ 0.24   |
| 1.0 $\text{m s}^{-1}$                    | 2.87 $\pm$ 0.11    | 2.75 $\pm$ 0.06    | 13.84 $\pm$ 0.85   | 3.26 $\pm$ 0.28   |
| 1.3 $\text{m s}^{-1}$                    | 2.71 $\pm$ 0.09    | 2.61 $\pm$ 0.07    | 13.21 $\pm$ 0.66   | 2.97 $\pm$ 0.13   |
| <b>Li</b>                                |                    |                    |                    |                   |
| 200 $\mu\text{mol m}^{-2} \text{s}^{-1}$ | 2.58 $\pm$ 0.08 b  | 2.72 $\pm$ 0.07    | 10.20 $\pm$ 0.39 c | 2.89 $\pm$ 0.21   |
| 350 $\mu\text{mol m}^{-2} \text{s}^{-1}$ | 2.64 $\pm$ 0.09 ab | 2.56 $\pm$ 0.08    | 13.66 $\pm$ 0.39 b | 3.06 $\pm$ 0.12   |
| 500 $\mu\text{mol m}^{-2} \text{s}^{-1}$ | 2.90 $\pm$ 0.08 a  | 2.73 $\pm$ 0.07    | 17.49 $\pm$ 0.63 a | 3.32 $\pm$ 0.19   |
| <b>P values</b>                          |                    |                    |                    |                   |
| Af                                       | NS                 | NS                 | NS                 | NS                |
| Li                                       | 0.0346             | NS                 | <0.0001            | NS                |
| Af $\times$ Li                           | NS                 | NS                 | NS                 | 0.0033            |

Statistical analyses were performed with two-way analysis of variance and Tukey's honestly significant difference using a significance level of 5% ( $P < 0.05$ ). Means within a column followed by the same letter are not significantly different. Each value represents the average  $\pm$  standard error.

ACI = anthocyanin content index; CCI = chlorophyll content index; NS = not significant; SSC = soluble solids content; TA = titratable acidity; LCC = leaf chlorophyll content; LAC = leaf anthocyanin content.

Table 18. Fertilizer solution properties in the deep water culture hydroponic trays over time (pH, electrical conductivity, temperature) of lettuce (*Lactuca sativa*) 'Dragoon' subjected to different airflow rates and light levels in two growing seasons.

| Conditions                              | pH ( $-\log H^+$ )  | EC ( $mS \cdot cm^{-1}$ ) | Temp ( $^{\circ}C$ ) |
|-----------------------------------------|---------------------|---------------------------|----------------------|
| <b>First season</b>                     |                     |                           |                      |
| Airflow rates (Af)                      |                     |                           |                      |
| 0.4 $m \cdot s^{-1}$                    | 5.68 $\pm$ 0.04     | 1.59 $\pm$ 0.02           | 20.59 $\pm$ 0.14 ab  |
| 0.7 $m \cdot s^{-1}$                    | 5.68 $\pm$ 0.04     | 1.59 $\pm$ 0.01           | 20.76 $\pm$ 0.14 a   |
| 1.0 $m \cdot s^{-1}$                    | 5.70 $\pm$ 0.04     | 1.59 $\pm$ 0.01           | 20.66 $\pm$ 0.15 ab  |
| 1.3 $m \cdot s^{-1}$                    | 5.68 $\pm$ 0.04     | 1.60 $\pm$ 0.01           | 20.53 $\pm$ 0.14 b   |
| Light intensity (Li)                    |                     |                           |                      |
| 200 $\mu mol \cdot m^{-2} \cdot s^{-1}$ | 5.60 $\pm$ 0.03 c   | 1.62 $\pm$ 0.01 a         | 20.60 $\pm$ 0.12 c   |
| 350 $\mu mol \cdot m^{-2} \cdot s^{-1}$ | 5.68 $\pm$ 0.03 b   | 1.60 $\pm$ 0.01 b         | 20.62 $\pm$ 0.12 b   |
| 500 $\mu mol \cdot m^{-2} \cdot s^{-1}$ | 5.77 $\pm$ 0.04 a   | 1.55 $\pm$ 0.02 c         | 20.68 $\pm$ 0.13 a   |
| Days after transplant (DAT)             |                     |                           |                      |
| 0                                       | 5.58 $\pm$ 0.003 de | 1.56 $\pm$ 0.002 d        | 17.2 $\pm$ 0 f       |
| 4                                       | 6.07 $\pm$ 0.01 a   | 1.74 $\pm$ 0.004 a        | 21.26 $\pm$ 0.09 b   |
| 5                                       | 5.72 $\pm$ 0.02 cd  | 1.65 $\pm$ 0.01 b         | 20.85 $\pm$ 0.05 c   |
| 7                                       | 5.61 $\pm$ 0.02 de  | 1.63 $\pm$ 0.01 bc        | 21.02 $\pm$ 0.07 bc  |
| 12                                      | 5.28 $\pm$ 0.05 f   | 1.75 $\pm$ 0.01 a         | 21.79 $\pm$ 0.08 a   |
| 14                                      | 5.66 $\pm$ 0.02 d   | 1.60 $\pm$ 0.01 c         | 19.07 $\pm$ 0.06 e   |
| 18                                      | 5.48 $\pm$ 0.08 e   | 1.44 $\pm$ 0.01 e         | 21.34 $\pm$ 0.09 b   |
| 19                                      | 5.84 $\pm$ 0.04 bc  | 1.47 $\pm$ 0.02 e         | 21.41 $\pm$ 0.08 b   |
| 21                                      | 5.97 $\pm$ 0.04 ab  | 1.52 $\pm$ 0.01 d         | 20.08 $\pm$ 0.06 d   |
| 25                                      | 6.01 $\pm$ 0.05 ab  | 1.38 $\pm$ 0.02 f         | 21.13 $\pm$ 0.09 bc  |
| <b>P values</b>                         |                     |                           |                      |
| Af                                      | NS                  | NS                        | 0.0194               |
| Li                                      | <0.0001             | <0.0001                   | NS                   |
| DAT                                     | <0.0001             | <0.0001                   | <0.0001              |
| Af $\times$ Li                          | NS                  | 0.0008                    | NS                   |
| Af $\times$ DAT                         | NS                  | NS                        | NS                   |
| Li $\times$ DAT                         | <0.0001             | <0.0001                   | NS                   |
| Af $\times$ Li $\times$ DAT             | NS                  | NS                        | NS                   |
| <b>Second season</b>                    |                     |                           |                      |
| Af                                      |                     |                           |                      |
| 0.4 $m \cdot s^{-1}$                    | 5.83 $\pm$ 0.03     | 1.51 $\pm$ 0.01 b         | 20.46 $\pm$ 0.29 ab  |
| 0.7 $m \cdot s^{-1}$                    | 5.80 $\pm$ 0.03     | 1.52 $\pm$ 0.01 ab        | 20.65 $\pm$ 0.29 a   |
| 1.0 $m \cdot s^{-1}$                    | 5.80 $\pm$ 0.03     | 1.51 $\pm$ 0.01 ab        | 20.42 $\pm$ 0.30 ab  |
| 1.3 $m \cdot s^{-1}$                    | 5.79 $\pm$ 0.03     | 1.53 $\pm$ 0.01 a         | 20.33 $\pm$ 0.29 b   |
| Li                                      |                     |                           |                      |
| 200 $\mu mol \cdot m^{-2} \cdot s^{-1}$ | 5.70 $\pm$ 0.02 c   | 1.57 $\pm$ 0.01 a         | 20.34 $\pm$ 0.25 b   |
| 350 $\mu mol \cdot m^{-2} \cdot s^{-1}$ | 5.82 $\pm$ 0.03 b   | 1.51 $\pm$ 0.01 b         | 20.44 $\pm$ 0.25 ab  |
| 500 $\mu mol \cdot m^{-2} \cdot s^{-1}$ | 5.89 $\pm$ 0.03 a   | 1.48 $\pm$ 0.01 c         | 20.62 $\pm$ 0.26 a   |
| DAT                                     |                     |                           |                      |
| 0                                       | 5.59 $\pm$ 0.001 f  | 1.59 $\pm$ 0.001 ab       | 11.67 $\pm$ 0.05 d   |
| 4                                       | 5.99 $\pm$ 0.01 bc  | 1.56 $\pm$ 0.002 c        | 21.33 $\pm$ 0.14 abc |
| 6                                       | 5.86 $\pm$ 0.01 d   | 1.59 $\pm$ 0.003 ab       | 21.73 $\pm$ 0.16 a   |
| 8                                       | 5.77 $\pm$ 0.01 e   | 1.57 $\pm$ 0.004 bc       | 21.37 $\pm$ 0.13 ab  |
| 11                                      | 5.50 $\pm$ 0.03 g   | 1.62 $\pm$ 0.01 a         | 21.13 $\pm$ 0.12 bc  |
| 13                                      | 5.33 $\pm$ 0.02 h   | 1.60 $\pm$ 0.01 ab        | 21.70 $\pm$ 0.13 ab  |
| 15                                      | 5.86 $\pm$ 0.01 d   | 1.43 $\pm$ 0.01 d         | 20.74 $\pm$ 0.08 c   |
| 19                                      | 5.94 $\pm$ 0.06 c   | 1.41 $\pm$ 0.01 d         | 21.14 $\pm$ 0.09 abc |
| 21                                      | 6.02 $\pm$ 0.08 b   | 1.55 $\pm$ 0.02 c         | 21.54 $\pm$ 0.10 ab  |
| 22                                      | 5.85 $\pm$ 0.03 d   | 1.40 $\pm$ 0.02 d         | 21.26 $\pm$ 0.10 abc |
| 26                                      | 6.13 $\pm$ 0.04 a   | 1.34 $\pm$ 0.02 e         | 21.52 $\pm$ 0.10 ab  |
| <b>P values</b>                         |                     |                           |                      |
| Af                                      | NS                  | 0.002                     | 0.0411               |
| Li                                      | <0.0001             | <0.0001                   | 0.0133               |
| DAT                                     | <0.0001             | <0.0001                   | <0.0001              |
| Af $\times$ Li                          | NS                  | 0.0006                    | NS                   |
| Af $\times$ DAT                         | NS                  | NS                        | NS                   |
| Li $\times$ DAT                         | <0.0001             | <0.0001                   | NS                   |
| Af $\times$ Li $\times$ DAT             | NS                  | NS                        | NS                   |

Statistical analyses were performed with three-way multivariate analysis of variance and Tukey's honestly significant difference using a significance level of 5% ( $P < 0.05$ ). Means within a column followed by the same letter are not significantly different. Each value represents the average  $\pm$  standard error.

NS = not significant; EC = electrical conductivity.

In season 1 of 'Casey' cultivation, light intensity greatly influenced soluble solids content ( $P = 0.0008$ ), leaf chlorophyll ( $P < 0.0001$ ), and anthocyanin content ( $P < 0.0001$ ). The 500 and 350  $\mu mol \cdot m^{-2} \cdot s^{-1}$  light levels had at least 25.25% higher soluble solids content than the 200  $\mu mol \cdot m^{-2} \cdot s^{-1}$  light level. Leaf chlorophyll and anthocyanin content were 51.68%

and 27.78% greater for the 500  $\mu mol \cdot m^{-2} \cdot s^{-1}$  light level than the 200  $\mu mol \cdot m^{-2} \cdot s^{-1}$  light level in both seasons, respectively (Table 17).

In the second season, light intensity only influenced leaf chlorophyll content ( $P < 0.0001$ ). The leaf chlorophyll content was 52.65% higher for the 500  $\mu mol \cdot m^{-2} \cdot s^{-1}$

light level than the 200  $\mu mol \cdot m^{-2} \cdot s^{-1}$  light level. The soluble solids content was also affected by light level ( $P = 0.0346$ ), with the 500  $\mu mol \cdot m^{-2} \cdot s^{-1}$  light level having an 11.68% greater average than the 200  $\mu mol \cdot m^{-2} \cdot s^{-1}$  light level. There was a significant two-way interaction between light intensity and airflow rates for the leaf anthocyanin content in season 2.

Table 19. Fertilizer solution properties in the deep water culture hydroponic trays over time (pH, electrical conductivity, temperature) of ‘Casey’ lettuce (*Lactuca sativa*) subjected to different airflow rates and light levels in two growing seasons.

| Conditions                              | pH ( $-\log H^+$ )  | EC ( $mS \cdot cm^{-1}$ ) | Temp ( $^{\circ}C$ )  |
|-----------------------------------------|---------------------|---------------------------|-----------------------|
| <b>First season</b>                     |                     |                           |                       |
| Airflow rates (Af)                      |                     |                           |                       |
| 0.4 $m \cdot s^{-1}$                    | 5.73 $\pm$ 0.05     | 1.56 $\pm$ 0.02 c         | 20.64 $\pm$ 0.14 ab   |
| 0.7 $m \cdot s^{-1}$                    | 5.69 $\pm$ 0.04     | 1.60 $\pm$ 0.02 a         | 20.72 $\pm$ 0.14 a    |
| 1.0 $m \cdot s^{-1}$                    | 5.70 $\pm$ 0.05     | 1.58 $\pm$ 0.02 b         | 20.61 $\pm$ 0.14 ab   |
| 1.3 $m \cdot s^{-1}$                    | 5.70 $\pm$ 0.05     | 1.61 $\pm$ 0.02 a         | 20.50 $\pm$ 0.13 b    |
| Light intensity (Li)                    |                     |                           |                       |
| 200 $\mu mol \cdot m^{-2} \cdot s^{-1}$ | 5.63 $\pm$ 0.03 b   | 1.63 $\pm$ 0.01 a         | 20.55 $\pm$ 0.12 b    |
| 350 $\mu mol \cdot m^{-2} \cdot s^{-1}$ | 5.71 $\pm$ 0.04 a   | 1.58 $\pm$ 0.01 b         | 20.54 $\pm$ 0.12 b    |
| 500 $\mu mol \cdot m^{-2} \cdot s^{-1}$ | 5.77 $\pm$ 0.04 a   | 1.55 $\pm$ 0.02 c         | 20.77 $\pm$ 0.12 a    |
| Days after transplant (DAT)             |                     |                           |                       |
| 0                                       | 5.58 $\pm$ 0.003 cd | 1.56 $\pm$ 0.002 d        | 17.20 $\pm$ 0 g       |
| 4                                       | 6.07 $\pm$ 0.01 b   | 1.75 $\pm$ 0.003 a        | 21.24 $\pm$ 0.08 bc   |
| 5                                       | 5.72 $\pm$ 0.02 c   | 1.66 $\pm$ 0.003 b        | 20.84 $\pm$ 0.05 d    |
| 7                                       | 5.62 $\pm$ 0.02 cd  | 1.65 $\pm$ 0.01 b         | 20.96 $\pm$ 0.07 cd   |
| 12                                      | 5.19 $\pm$ 0.06 e   | 1.76 $\pm$ 0.01 a         | 21.77 $\pm$ 0.07 a    |
| 14                                      | 5.55 $\pm$ 0.02 cd  | 1.61 $\pm$ 0.01 c         | 19.10 $\pm$ 0.06 f    |
| 18                                      | 5.50 $\pm$ 0.09 d   | 1.44 $\pm$ 0.01 f         | 21.32 $\pm$ 0.08 b    |
| 19                                      | 5.93 $\pm$ 0.03 b   | 1.46 $\pm$ 0.02 f         | 21.39 $\pm$ 0.08 b    |
| 21                                      | 6.11 $\pm$ 0.02 ab  | 1.50 $\pm$ 0.02 e         | 20.11 $\pm$ 0.06 e    |
| 25                                      | 6.27 $\pm$ 0.03 a   | 1.30 $\pm$ 0.02 g         | 21.10 $\pm$ 0.09 bcd  |
| <b>P values</b>                         |                     |                           |                       |
| Af                                      | NS                  | <0.0001                   | 0.0096                |
| Li                                      | <0.0001             | <0.0001                   | 0.0003                |
| DAT                                     | <0.0001             | <0.0001                   | <0.0001               |
| Af $\times$ Li                          | NS                  | <0.0001                   | NS                    |
| Af $\times$ DAT                         | NS                  | NS                        | NS                    |
| Li $\times$ DAT                         | <0.0001             | <0.0001                   | NS                    |
| Af $\times$ Li $\times$ DAT             | NS                  | NS                        | NS                    |
| <b>Second season</b>                    |                     |                           |                       |
| Af                                      |                     |                           |                       |
| 0.4 $m \cdot s^{-1}$                    | 5.86 $\pm$ 0.04     | 1.48 $\pm$ 0.01 c         | 20.43 $\pm$ 0.29 b    |
| 0.7 $m \cdot s^{-1}$                    | 5.83 $\pm$ 0.04     | 1.50 $\pm$ 0.01 b         | 20.74 $\pm$ 0.29 a    |
| 1.0 $m \cdot s^{-1}$                    | 5.84 $\pm$ 0.04     | 1.51 $\pm$ 0.01 ab        | 20.41 $\pm$ 0.30 b    |
| 1.3 $m \cdot s^{-1}$                    | 5.85 $\pm$ 0.04     | 1.51 $\pm$ 0.01 a         | 20.42 $\pm$ 0.29 b    |
| Li                                      |                     |                           |                       |
| 200 $\mu mol \cdot m^{-2} \cdot s^{-1}$ | 5.78 $\pm$ 0.03 c   | 1.53 $\pm$ 0.01 a         | 20.44 $\pm$ 0.25 ab   |
| 350 $\mu mol \cdot m^{-2} \cdot s^{-1}$ | 5.84 $\pm$ 0.03 b   | 1.49 $\pm$ 0.01 b         | 20.41 $\pm$ 0.25 b    |
| 500 $\mu mol \cdot m^{-2} \cdot s^{-1}$ | 5.90 $\pm$ 0.04 a   | 1.47 $\pm$ 0.01 c         | 20.65 $\pm$ 0.26 a    |
| DAT                                     |                     |                           |                       |
| 0                                       | 5.59 $\pm$ 0.001 f  | 1.59 $\pm$ 0.001 ab       | 11.67 $\pm$ 0.05 e    |
| 4                                       | 6.00 $\pm$ 0.01 c   | 1.56 $\pm$ 0.001 c        | 21.35 $\pm$ 0.13 abcd |
| 6                                       | 5.87 $\pm$ 0.01 de  | 1.59 $\pm$ 0.002 ab       | 21.85 $\pm$ 0.14 a    |
| 8                                       | 5.79 $\pm$ 0.01 e   | 1.58 $\pm$ 0.003 bc       | 21.40 $\pm$ 0.12 abc  |
| 11                                      | 5.50 $\pm$ 0.03 f   | 1.62 $\pm$ 0.004 a        | 21.18 $\pm$ 0.11 cd   |
| 13                                      | 5.20 $\pm$ 0.03 g   | 1.60 $\pm$ 0.01 ab        | 21.77 $\pm$ 0.13 ab   |
| 15                                      | 5.79 $\pm$ 0.01 e   | 1.44 $\pm$ 0.01 e         | 20.81 $\pm$ 0.09 d    |
| 19                                      | 5.95 $\pm$ 0.07 cd  | 1.39 $\pm$ 0.01 f         | 21.17 $\pm$ 0.09 cd   |
| 21                                      | 6.23 $\pm$ 0.05 b   | 1.52 $\pm$ 0.02 d         | 21.55 $\pm$ 0.10 abc  |
| 22                                      | 5.97 $\pm$ 0.03 cd  | 1.37 $\pm$ 0.01 f         | 21.24 $\pm$ 0.11 bcd  |
| 26                                      | 6.36 $\pm$ 0.02 a   | 1.24 $\pm$ 0.02 g         | 21.52 $\pm$ 0.10 abc  |
| <b>P values</b>                         |                     |                           |                       |
| Af                                      | NS                  | <0.0001                   | 0.0038                |
| Li                                      | <0.0001             | <0.0001                   | 00179                 |
| DAT                                     | <0.0001             | <0.0001                   | <0.0001               |
| Af $\times$ Li                          | NS                  | <0.0001                   | NS                    |
| Af $\times$ DAT                         | NS                  | NS                        | NS                    |
| Li $\times$ DAT                         | <0.0001             | <0.0001                   | NS                    |
| Af $\times$ Li $\times$ DAT             | NS                  | NS                        | NS                    |

Statistical analyses were performed with three-way multivariate analysis of variance and Tukey’s honestly significant difference using a significance level of 5% ( $P < 0.05$ ). Means within a column followed by the same letter are not significantly different. Each value represents the average  $\pm$  standard error. NS = not significant; EC = electrical conductivity.

‘Casey’ results were similar to ‘Dragoon’ (Table 17).

The 500  $\mu mol \cdot m^{-2} \cdot s^{-1}$  light level and 0.7  $m \cdot s^{-1}$  airflow rate had the greatest leaf anthocyanin content (LAC) of all treatment combinations (4.2 ACI). The 200  $\mu mol \cdot m^{-2} \cdot s^{-1}$  light level with 0.4 and 0.7  $m \cdot s^{-1}$  combinations had at least 4.27% lower LAC

than the other treatment combinations (Fig. 5B).

Airflow rates did not affect the accumulation of chlorophyll or anthocyanin in lettuce (Tables 16 and 17). Airflow also did not affect soluble solids content or titratable acidity for either cultivar in either season. Again, this result can be attributed to the fact that after

an airflow rate of 0.3  $m \cdot s^{-1}$ , net photosynthetic rate increases are nonsignificant, which was found in a study by Kitaya et al. (2003), and less carbon assimilation leads to less photoassimilate accumulation. Although we notice a significant difference in titratable acidity for ‘Casey’ in season 1, it is tough to determine any trends from the data. Although

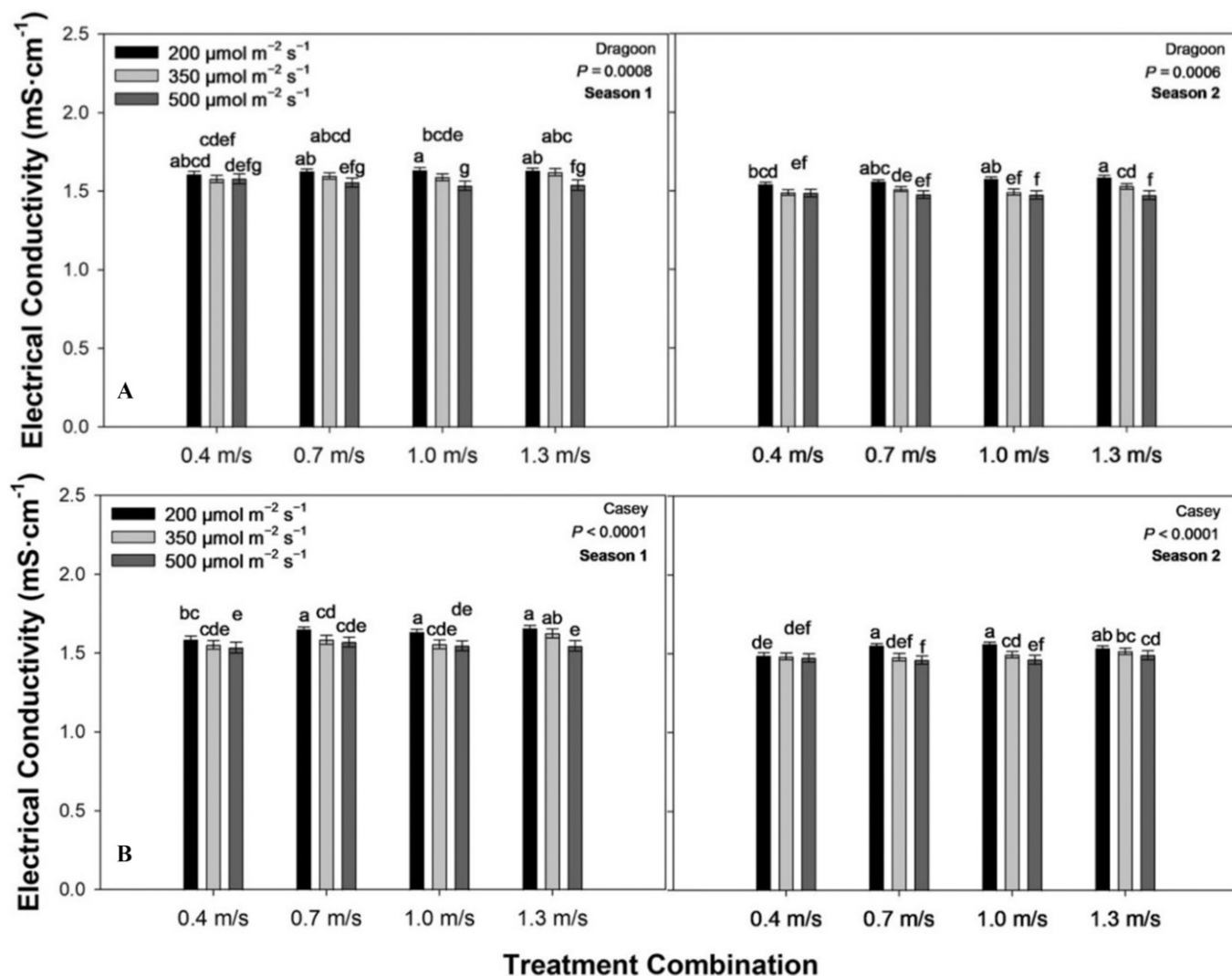


Fig. 6. Two-way interaction for electrical conductivity of fertilizer solution between airflow rates and light intensity in both seasons (A and B) of lettuce (*Lactuca sativa*) 'Dragoon' (A) and 'Casey' (B). Statistical analyses were done with multivariate analysis of variance and Tukey's honestly significant difference using a significance level of 5% ( $P < 0.05$ ). Each bar represents the average with the standard error bars in both directions.

not significant, we can note that soluble solids content was highest in the 1.0 m·s<sup>-1</sup> airflow rate in both cultivars and seasons, possibly suggesting that this airflow rate is sufficient for sugar accumulation in indoor lettuce production, and any increase in airflow rate is negligible.

**Fertilizer solution analysis of 'Dragoon' and 'Casey' over two seasons.** As the study was precisely replicated over two seasons, no significant biological differences were observed in pH, EC, and temperature of the fertilizer solution in either season or cultivar. pH, EC, and temperature of the fertilizer solution followed similar trends throughout both seasons of the experiment across both cultivars (Tables 18 and 19). No biologically relevant pH, EC, and temperature differences should have affected the results. The average pH was maintained between 5.55 and 5.80 for both cultivars and seasons. EC was maintained between 1.47 and 1.63 mS·cm<sup>-1</sup>. The average temperature of the solution never fell below 20.34 °C and never exceeded

20.77 °C. pH varied over time, as lettuce growth follows an exponential growth pattern, and when roots start to form in the solution and take up nutrients at a greater rate, pH changes (Holsteijn 1980). pH was the one fertilizer solution parameter that was closely maintained, as significant differences in pH can alter nutrient availability for lettuce, and any large deviations would negatively affect the results (Anderson et al. 2017). Therefore, the pH was adjusted at least three times weekly with acid or base.

Based on the EC and pH data, we can confidently state that there were no nutrient deficiencies in the solution in either season or cultivar that would have affected the other results in this experiment. EC was closely maintained between 1.3 and 1.8 mS·cm<sup>-1</sup>, as recommended by Sandoya et al. (2021). EC changed over time due to the exponential growth pattern of lettuce, and as the plant grows more rapidly in later development stages, they take more nutrients out of solution, lowering the EC. The first refill

occurred 2 weeks after transplant with a half-strength nutrient blend to reduce the EC creeping toward 1.8 mS·cm<sup>-1</sup>. Having too high of an EC was a concern for further increasing the growth rate of our lettuce; consequently, this would have led to more unnecessary tipburn in our study. The second refill occurred 3 weeks after the transplant, using a full-strength nutrient blend (identical to the transplant blend) to balance the EC of the fertilizer solution. Finding equilibrium in EC is important for keeping hydroponic lettuce growth within the recommended range. Miller et al. (2020) demonstrated that EC between 1.3 and 2.0 mS·cm<sup>-1</sup> is optimal for hydroponic lettuce growth. Treatment interaction effects on EC show that there were minimal differences in the EC over both seasons and cultivars (Fig. 6A and 6B).

The temperature of the fertilizer solution increased over time until the two refill days temporarily lowered it. This is a common occurrence in any growing environment as the air temperature rises over time, which in turn

heats the fertilizer solution. The temperature of the fertilizer solution for hydroponic lettuce around 21 °C is optimal for growth, but higher temperatures do increase the growth rates of lettuce (Miller and Nemali 2019). Our goal was to create an environment for the plants that was consistent over both seasons, and we are confident that this was properly done.

Both 'Casey' and 'Dragoon' yielded similar results in many measurements taken over both seasons. After all, both are lettuce cultivars, and they were grown in the same environmental conditions, closely replicated over two seasons. Notice that throughout the discussion, transpiration rates are discussed. When interpreting the results, it was essential to examine data that suggested an increase in the transpiration rates of lettuce. Ca is transported to the growing shoots by mass flow in the xylem through the process of transpiration, and any indication of an increase in transpiration rates confidently tells us that Ca is more readily available to new lettuce growth, therefore minimizing tipburn.

## Conclusions

The results of this study have demonstrated the effectiveness of vertical downward airflow on minimizing tipburn in commercial vertical farm lettuce production. Paired with high light intensities, increasing airflow rates are beneficial in minimizing the incidence and severity of tipburn in indoor lettuce production under sole-source LED lighting. Any airflow rates above 0.4 m·s<sup>-1</sup> in this study proved effective at minimizing tipburn at any intensity of light tested. The suggested vertically directed airflow rates to minimize tipburn for 'Casey' and 'Dragoon' are 0.7, 1.0, and 1.3 m·s<sup>-1</sup>, as all three of these airflow rates minimized tipburn in a similar capacity.

Our study reinforced the negative effects that increasing light intensity has on tipburn development in lettuce but demonstrated that using a higher intensity of light can be used while minimizing tipburn by using vertical airflow rates above 0.4 m·s<sup>-1</sup>. If we were to suggest a light intensity based solely on the ability to reduce tipburn, 200 μmol·m<sup>-2</sup>·s<sup>-1</sup> would be the one, but we believe boosting yield with slight increases in tipburn is worth the tradeoff with 350 μmol·m<sup>-2</sup>·s<sup>-1</sup>. A light intensity of 500 μmol·m<sup>-2</sup>·s<sup>-1</sup> produced excessive tipburn under any airflow treatment, making it unsuitable for vertical farm lettuce producers.

Cultivar is another important factor in minimizing tipburn in vertical farm lettuce production. We observed 'Dragoon' having much greater tipburn intensity and tipburn incidence than 'Casey', further suggesting the importance of cultivar selection in vertical farm lettuce production. Future studies should explore higher rates of vertical airflow on lettuce tipburn incidence in vertical farms, as there is a lack of literature reporting tipburn effects on any vertical airflow rate above 1.3 m·s<sup>-1</sup>.

## Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

## References Cited

- Ahmed HA, Tong Y, Li L, Sahari SQ, Almogahed AM, Cheng R. 2022. Integrative effects of CO<sub>2</sub> concentration, illumination intensity and air speed on the growth, gas exchange and light use efficiency of lettuce plants grown under artificial lighting. *Horticulturae*. 8(3):270. <https://doi.org/10.3390/horticulturae8030270>.
- Ahmed HA, Yu-Xin T, Qi-Chang Y. 2020. Optimal control of environmental conditions affecting lettuce plant growth in a controlled environment with artificial lighting: A review. *S Afr J Bot*. 130:75–89. <https://doi.org/10.1016/j.sajb.2019.12.018>.
- Anderson TS, Martini MR, De Villiers D, Timmons MB. 2017. Growth and tissue elemental composition response of butterhead lettuce (*Lactuca sativa*, cv. flandria) to hydroponic conditions at different pH and alkalinity. *Horticulturae*. 3:41. <https://doi.org/10.3390/horticulturae3030041>.
- Barta DJ, Tibbitts TW. 2000. Calcium localization and tipburn development in lettuce leaves during early enlargement. *J Am Soc Hortic Sci*. 125(3):294–298. <https://doi.org/10.21273/JASHS.125.3.294>.
- Beacham AM, Hand P, Teakle GR, Barker GC, Pink DAC, Monaghan JM. 2023. Tipburn resilience in lettuce (*Lactuca* spp.)—The importance of germplasm resources and production system-specific assays. *J Sci Food Agric*. 103(9):4481–4488. <https://doi.org/10.1002/jsfa.12523>.
- Caplan B. 2018. Optimizing carbon dioxide concentration and daily light integral combination in a multi-level electrically lighted lettuce production system (MS Thesis). University of Arizona, Tucson, AZ, USA. <https://www.proquest.com/docview/2108648139/abstract/ADD898B8063446D8PQ/1>.
- Chang Y-C, Miller WB. 2004. The relationship between leaf enclosure, transpiration, and upper leaf necrosis on liliun 'Star Gazer'. *J Am Soc Hortic Sci*. 129(1):128–133. <https://doi.org/10.21273/JASHS.129.1.0128>.
- Choi KY, Paek KY, Lee YB. 2000. Effect of air temperature on tipburn incidence of butterhead and leaf lettuce in a plant factory, p 166–171. In: Kubota C, Chun C (eds). *Transplant production in the 21st century*. Springer, Amsterdam, Netherlands. [http://link.springer.com/10.1007/978-94-015-9371-7\\_27](http://link.springer.com/10.1007/978-94-015-9371-7_27).
- Collier GF, Tibbitts TW. 1982. Tipburn of lettuce, p 49–65. In: Janick J (ed). *Hortic Rev* (1st ed). Wiley, Hoboken, NJ, USA. <https://onlinelibrary.wiley.com/doi/10.1002/9781118060773.ch2>.
- Collier GF, Tibbitts TW. 1984. Effects of relative humidity and root temperature on calcium concentration and tipburn development in lettuce. *J Am Soc Hortic Sci*. 109(2):128–131. <https://doi.org/10.21273/JASHS.109.2.128>.
- Cox EF, McKee JMT, Dearman AS. 1976. The effect of growth rate on tipburn occurrence in lettuce. *J Hortic Sci*. 51(3):297–309. <https://doi.org/10.1080/00221589.1976.11514693>.
- Ducic T, Polle A. 2005. Transport and detoxification of manganese and copper in plants. *Braz J Plant Physiol*. 17(1):103–112. <https://doi.org/10.1590/S1677-04202005000100009>.
- Dutko P, Ver Ploeg M, Farrigan TL. 2012. Characteristics and influential factors of food deserts. US Department of Agriculture, Economic Research Service. <https://faunalytics.org/wp-content/uploads/2015/05/Citation2108.pdf>. [accessed 23 Apr 2024].

- Ertle J, Kubota C. 2023. Testing cultivar-specific tipburn sensitivity of lettuce for indoor vertical farms. *HortScience*. 58(10):1257–1266. <https://doi.org/10.21273/HORTSCI171313-23>.
- Ferrarezi RS, Qin K, Hazard C, Gatzard E, Gastaldo TB, Housley MJ, Nieters CE, Mesquita M. 2024. Airflow, fertilizer solution recipes, and calcium concentrations influence lettuce and spinach growth in an indoor vertical farm. *Sci Hortic*. 328:112948. <https://doi.org/10.1016/j.scienta.2024.112948>.
- Fu W, Li P, Wu Y. 2012. Effects of different light intensities on chlorophyll fluorescence characteristics and yield in lettuce. *Sci Hortic*. 135:45–51. <https://doi.org/10.1016/j.scienta.2011.12.004>.
- Goto E, Takakura T. 1992a. Prevention of lettuce tipburn by supplying air to inner leaves. *Trans ASAE*. 35(2):641–645. <https://doi.org/10.13031/2013.28644>.
- Goto E, Takakura T. 1992b. Promotion of Ca accumulation in inner leaves by air supply for prevention of lettuce tipburn. *Trans ASAE*. 35(2):647–650. <https://doi.org/10.13031/2013.28645>.
- Holsteijn HMCV. 1980. Growth of lettuce: Quantitative analysis of growth. <https://research.wur.nl/en/publications/growth-of-lettuce-quantitative-analysis-of-growth>. [accessed 14 Mar 2024].
- Kaufmann C. 2023. Reducing tipburn in lettuce grown in an indoor vertical farm: Comparing the impact of vertically distributed airflow vs. horizontally distributed airflow in the growth of *Lactuca sativa* (MS Thesis). University of Arizona, Tucson, AZ, USA. <https://www.proquest.com/docview/2825771585/abstract/F0BDC2D9737E4FB6PQ/1>.
- Kazuo Nobutoshi S. 1998. Effect of temperature and light intensity on the growth and flowering of odontoglossum intergeneric hybrids. *J Jpn Soc Hortic Sci*. 67(4):619–625. <https://doi.org/10.2503/jjshs.67.619>.
- Kitaya Y, Tsuruyama J, Kawai M, Shibuya T, Kiyota M. 2000. Effects of air current on transpiration and net photosynthetic rates of plants in a closed plant production system, p 83–90. In: Kubota C, Chun C (eds). *Transplant production in the 21st century*. Springer, Amsterdam, Netherlands.
- Kitaya Y, Tsuruyama J, Shibuya T, Yoshida M, Kiyota M. 2003. Effects of air current speed on gas exchange in plant leaves and plant canopies. *Adv Space Res*. 31(1):177–182. [https://doi.org/10.1016/s0273-1177\(02\)00747-0](https://doi.org/10.1016/s0273-1177(02)00747-0).
- Korthals RL, Knight SL, Christianson LL, Spomer LA. 1994. Chambers for studying the effects of airflow velocity on plant growth 23:113–119.
- Kozai T. 2013. Resource use efficiency of closed plant production system with artificial light: Concept, estimation, and application to plant factory. *Proc Jpn Acad Ser B*. 89(10):447–461. <https://doi.org/10.2183/pjab.89.447>.
- Kroggel M, Kubota C. 2017. Controlled environment strategies for tipburn management in greenhouse strawberry production. *Acta Hortic*. 1156:529–536. <https://doi.org/10.17660/ActaHortic.2017.1156.78>.
- Lee JG, Choi CS, Jang YA, Jang SW, Lee SG, Um YC. 2013. Effects of air temperature and air flow rate control on the tipburn occurrence of leaf lettuce in a closed type plant factory system. *Hortic Environ Biotechnol*. <https://doi.org/10.1007/s13580-013-0031-0>.
- Li Z. 2002. Vertical column and system of columnar soilless culture and its application to the cultivation of lettuce. *Chin J Appl Environ Biol*. 8(2):142–147.



- Miao C, Yang S, Xu J, Wang H, Zhang Y, Cui J, Zhang H, Jin H, Lu P, He L, Yu J, Zhou Q, Ding X. 2023. Effects of light intensity on growth and quality of lettuce and spinach cultivars in a plant factory. *Plants*. 12(18):3337. <https://doi.org/10.3390/plants12183337>.
- Miller A, Langenhoven P, Nemali K. 2020. Optimal fertilizer solution concentration for hydroponic lettuce production. Purdue University Extension. <https://www.extension.purdue.edu/extmedia/HO/HO-309-W.pdf>. [accessed 18 Mar 2024].
- Miller A, Nemali K. 2019. Growing hydroponic lettuce using a heated nutrient solution under cooler air temperature. Purdue University Extension. <https://www.purdue.edu/hla/sites/cea/article/growing-hydroponic-lettuce-using-heated-nutrient-solution-under-cooler-air-temperature/>. [accessed 18 Mar 2024].
- Mir AR, Pichtel J, Hayat S. 2021. Copper: Uptake, toxicity and tolerance in plants and management of Cu-contaminated soil. *Biometals*. 34(4): 737–759. <https://doi.org/10.1007/s10534-021-00306-z>.
- Mitchell CA. 2022. History of controlled environment horticulture: Indoor farming and its key technologies. *HortScience*. 57(2):247–256. <https://doi.org/10.21273/HORTSCI16159-21>.
- Nelson DW, Sommers LE. 1973. Determination of total nitrogen in plant material. *Agron J*. 65:109–112. <https://doi.org/10.2134/agronj1973.00021962006500010033x>.
- Papio GA. 2021. Development of a new hydroponic nutrient management strategy and a tool to assess microclimate conditions in indoor leafy green production (MS Thesis). Ohio State University, Columbus, OH, USA. [https://etd.ohiolink.edu/acprod/odb\\_etd/etd/r/1501/10?clear=10&p10\\_accession\\_num=osu1628780410728194](https://etd.ohiolink.edu/acprod/odb_etd/etd/r/1501/10?clear=10&p10_accession_num=osu1628780410728194).
- Park M-H, Lee Y-B. 1999. Effects of light intensity and nutrient level on growth and quality of leaf lettuce in a plant factory. *J Bio-Environ Control*. 8(2):108–114. <https://koreascience.kr/article/JAKO199911922406624.page>.
- Read M, Tibbitts TW. 1970. Lettuce growth and tipburn incidence as influenced by CO<sub>2</sub> concentration and light intensity. *HortScience*. 5:4.
- Sago Y. 2016. Effects of light intensity and growth rate on tipburn development and leaf calcium concentration in butterhead lettuce. *HortScience*. 51(9):1087–1091. <https://doi.org/10.21273/HORTSCI10668-16>.
- Sandoya GV, Bosques J, Rivera F, Campoverde EV. 2021. Growing lettuce in small hydroponic systems: HS1422, 9/2021. *EDIS*. 2021(5). <https://doi.org/10.32473/edis-hs1422-2021>.
- Song J, Huang H, Hao Y, Song S, Zhang Y, Su W, Liu H. 2020. Nutritional quality, mineral and antioxidant content in lettuce affected by interaction of light intensity and nutrient solution concentration. *Sci Rep*. 10(1): 2796. <https://doi.org/10.1038/s41598-020-59574-3>.
- Tibbitts TW, Bottenberg G. 1976. Growth of lettuce under controlled humidity levels. *J Am Soc Hortic Sci*. 101(1):70–73. <https://doi.org/10.21273/JASHS.101.1.70>.
- Twyman RM. 2005. Sample Dissolution for Elemental Analysis: Wet Digestion p 146–153. In: Worsfold P, Townshend A, Poole C (eds). *Encyclopedia of Analytical Science*. Vol 8. Elsevier Science, London, UK. <https://doi.org/10.1016/B0-12-369397-7/00539-2>.
- Zhou J, Li P, Wang J. 2022. Effects of light intensity and temperature on the photosynthesis characteristics and yield of lettuce. *Horticulturae*. 8(2):178. <https://doi.org/10.3390/horticulturae8020178>.
- Zhou J, Li P, Wang J, Fu W. 2019. Growth, photosynthesis, and nutrient uptake at different light intensities and temperatures in lettuce. *HortScience*. 54(11):1925–1933. <https://doi.org/10.21273/HORTSCI14161-19>.