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Article

# Thermoelectric cooling in greenhouses: Implications for small-holder production

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## SUMMARY

**Greenhouses protect plants year-round by creating controlled microclimates that rely on environmental control systems to regulate temperature, carbon dioxide, humidity, and other environmental factors. However, even with such systems in place, farmers and greenhouse operators face difficulties in managing humidity and temperature. The cost to buy, install, run, and maintain such systems is also a limiting factor for small-holder farmers who need to control their indoor growing spaces. Controlling humidity and temperature in a greenhouse is vital for plant growth as it limits pests and prevents the spread of fungal diseases and root rot. In this paper, we present the development and testing of the Dehumidification Device, a thermoelectric cooling and drying system developed from low-cost, market-available technology, designed to improve temperature and humidity management practices in greenhouse systems while increasing economic accessibility to such systems. To test the efficiency of the thermoelectric cooling system, the Dehumidification Device was placed in one of two identical greenhouses. The internal temperature and relative humidity in each greenhouse were recorded every 30 minutes during a 150-minute experimental period for seven days. The data revealed that the presence of the Dehumidification Device was statistically significant, improving temperature by 2.71°C and humidity by 14% during the 150-minute period. Thus, we were able to show the potential for thermoelectric cooling to support the greenhouse industry in managing humidity and help ease greenhouse management. The low-cost and accessible materials used to create the device illustrate the positive implications for assisting local, small-holder practices.**

## INTRODUCTION

Greenhouses have been used by communities and farmers around the world for centuries to ensure the year-round growth of crops, independent of climatic and seasonal variations (1–3). Greenhouses can support a variety of plants by creating stable microclimates that fit specific growth requirements, leading to higher crop yields (4). Modern greenhouses achieve suitable microclimates for the continued production of plants by utilizing the greenhouse effect and temperature control systems (3). When sunlight enters the greenhouse, a portion of the energy is trapped, leading to a warming effect (4). The warm air rises and is immediately replaced by cool air, producing a convection current of warm air surrounding the plants at ground level (5). This heating cycle is effective within small enclosures like greenhouses, creating a higher temperature inside the greenhouse compared to the outdoor temperature (6). The challenge many greenhouse operations currently face is designing and managing the heating of their greenhouses to reduce heating costs and increase energy efficiency while maintaining the relative humidity required for a healthy plant growth environment (7-9).

Humidity is commonly measured using relative humidity, a percentage of the water vapor in the air compared to the amount of water vapor that the air could hold, and dew point, the temperature at which water vapor starts to condense out of the air at a constant pressure (5). In the context of a greenhouse, humidity control can be a challenge due to high interior temperatures, the continuous presence of moisture in the environment from plant transpiration, and the residual water left on plant canopies and soil from irrigation (4). If not controlled, the humidity will quickly become detrimental to the health and growth of plants through disease and pest outbreaks as well as growth disorders and deficiencies (10–14). Romero *et al.* demonstrated through global fungal disease outbreak data that humidity and temperature are primary drivers of fungal disease outbreaks in crops in agricultural systems (15). Since fungal spores spread in humid air without movement, the stale, humid air and high population density of plants inside the greenhouse serve as a breeding ground for pathogens and spores to spread and promote the onset of fungal diseases such as those caused by *Botrytis cinerea,* affecting plants in the vicinity (8,11,12,13). Uncontrolled disease pressure will lead to the loss of crop yields and quality, resulting in unrecoverable losses for farmers (10).

As previously stated, humidity is directly proportional to temperature, making it difficult for agricultural scientists and greenhouse managers to alter humidity without creating drastic changes in temperature (7). Current practices to manage humidity include incorporating ventilation, shading and window tinting, and evaporative cooling systems (16–18). A combination of active and passive cooling systems or techniques is usually used to control humidity (12). Fans and shading techniques are the most used passive ventilation systems in greenhouses today (10). However, ventilation fans are unable to create uniform ventilation throughout the greenhouse, so stale, humid air can remain in the greenhouse and continue to affect plants (9,10). In addition, ventilation fans are costly to use in greenhouses: a single ventilation fan costs an average of $500 (20). Shading using fabric or window tinting techniques may be used in combination with ventilation fans to reduce the solar radiation coming into the greenhouse while the fans circulate the air (17). However, it deprives plants of the necessary sunlight they need (17). Thus, the addition of an evaporative cooling system may be incorporated as well, however, the challenge that arises is the additional water present in the greenhouse atmosphere as part of the cooling technique (20). Evaporative coolers are also expensive, costing $3,000 for a single unit, with industrial greenhouses requiring five such units (20). It can become a costly situation for greenhouse managers as they must decide to incorporate a variety of cooling and heating technologies and techniques to ensure a stable plant growth environment, while maintaining low costs (21, 22).

To better manage and utilize such cooling and heating systems when adjustments and new installations are costly, digital agricultural technology such as climate sensors and monitoring systems that integrate with environmental control systems is an area of innovation that is becoming increasingly present in greenhouse design and development (19, 24). In this study, we seek to further address the benefits of incorporating digital technology in temperature and humidity management and test an affordable and accessible cooling system that is currently not common in the greenhouse industry: thermoelectric cooling.

Thermoelectric cooling offers multiple benefits when compared to other cooling systems. For example, thermoelectric cooling does not use toxic fluorocarbons or refrigerants to cool, requires only low maintenance with a long life cycle, is not as costly as traditional temperature and humidity control systems, and can operate effectively in regions with more extreme temperature differences (25). Thermoelectric cooling offers the advantage of a similar cooling capability as other forms of cooling devices, but also provides the advantages of being compact, reliable, eco-friendly, and low cost (19).

To address the challenge of temperature and humidity control in greenhouses and innovate new solutions that bring in emerging technology, the objectives of our research were to: 1) analyze the current price ranges of temperature and humidity devices in the United States market as of 2022; 2) develop a Dehumidification Device for greenhouse use that incorporates digital technology while remaining accessible and affordable to small-holder farmers; and 3) evaluate if the device could effectively reduce the relative humidity and temperature in a greenhouse. We hypothesized that a thermoelectric cooling system within the cost range of $500 would reduce the temperature within a greenhouse by at least 2°C and would reduce the relative humidity by at least 6%, parameters chosen based on extensive research on average changes required by greenhouses located in equatorial regions today.

Our custom Dehumidification Device incorporated thermoelectric cooling systems to reduce the humidity and temperature in greenhouses by operating at ground level and facilitating condensation during the day. The experiment used two greenhouses with different treatments - *Device Absent*, in which the Dehumidification Device is absent, and *Device Present*, in which the Dehumidification Device is present. Temperature and relative humidity sensors were present in both greenhouses to measure the long-term and short-term changes in temperature and relative humidity during the experimental periods. The results showed statistically significant differences in mean temperature change and mean relative humidity change between the two greenhouses over the long-term, 150-minute experimental periods and the short-term, 30-minute operational periods, with *Device Present* decreasing in temperature and relative humidity beyond our hypothesized changes in temperature and relative humidity. Thus, the results supported our hypothesis that the device would effectively reduce temperature and relative humidity in a greenhouse environment, providing critical insight into the potential use of thermoelectric cooling systems in the greenhouse industry.

## RESULTS

As part of the testing, we created two greenhouses to replicate the real-life usage of a dehumidifying device in a crop production greenhouse with different treatments: *Device Absent* and *Device Present*. Temperature and relative humidity in both greenhouses were measured at the start of each daily experimental period and then measured every 30-minutes to set a constant frame of reference for change in temperature and change in relative humidity over 150-minutes. The 150-minute experimental period was divided into three 30-minute operational periods and two 30-minute, interspersed rest periods.

### Dehumidification Device Economics and Construction

The device required 24 parts and minimal labor to put together, for a total price of $126.67 (**Table 1**). Accounting for industrial costs such as profit margins and industrial production, the Dehumidification Device could reasonably be available to consumers at $250.00. The device had dimensions of 15 inches (length) by 10 inches (width) by 10 inches (height). The device had a tendency to overheat since it was constructed in non-industrial methods. In order to take device construction into account, we chose to have the presence of two 30-minute rest periods between the 30-minute operational periods in order to maximize safety by preventing the device from overheating.

| Part in Dehumidification Device | Number of Parts in Dehumidification Device | Cost of Part |
|---|---|---|
| **Power Supply** | 4 | $12.99 |
| **Peltier Modules** | 3 | $4.5 |
| **CPU Cooler Fan** | 1 | $5.76 |
| **Regular Mini Fans** | 6 | $0.99 |
| **Copper Coils** | 1 | $5.99 |
| **Water Pump** | 1 | $4.59 |
| **Water Cooler Radiator** | 1 | $15.99 |
| **Cooling Block** | 1 | $3.99 |
| **Frame of Device** | 1 | $6.99 |
| **Heatsink** | 5 | $0.99 |

**Table 1. Dehumidification Device cost table.** The number of components required for the Dehumidification Device, their respective costs as of July 15th, 2022, and the component source information.

### Long-Term Change in Temperature: 150-Minute Experimental Periods

To analyze the long-term change in temperature within *Device Absent* and *Device Present*, we subtracted the final temperature reading at time 17:30 from the initial temperature reading at time 15:00 for each daily 150-minute experimental period (**Figure 1**). *Device Absent* showed a mean change in temperature of -2.0 ± 2.4°C over the seven-day test period (**Figure 1A**). *Device Present* showed a mean change in temperature of -7.2 ± 1.8°C over the seven-day test period (**Figure 1B**). A one-way repeated measures ANOVA (Analysis of Variance) revealed a significant interaction effect between the treatment groups on change in temperature ($F(1,6) = [23.8]$, $p = 3e\text{-}3$). Pairwise comparison of the treatment groups confirmed the result that the change in temperature means between *Device Absent* and *Device Present* were significantly different. Thus, there was a significantly larger decrease in temperature over the 150-minute experimental period with *Device Present* than *Device Absent* ($p < 0.0$, **Figure 2A**).

### Short-Term Change in Temperature: 30-Minute Operational Periods

To analyze the short-term change in temperature within *Device Absent* and *Device Present*, we subtracted the final temperature reading for each 30-minute operational period from the initial temperature reading for the corresponding 30-minute operational period, for a total of three changes in temperature per daily experimental period (**Figure 1**). *Device Absent* showed a mean change in temperature of -0.4°C±2.0°C for the 30-minute operational periods over the seven-day test period (**Figure 1A**). *Device Present* showed a mean change in temperature of -2.7±1.0°C for the 30-minute operational periods over the seven-day test period (**Figure 1B**). An ANOVA analysis revealed a significant interaction effect between the treatment groups on change in temperature ($F(1,20) = [24.1]$, $p = 8.3e\text{-}5$). Pairwise comparison of the treatment groups with the Bonferroni multiple testing correction method confirmed the result that the change in temperature means of *Device Absent* and *Device Present* were significantly different. Thus, there was a significantly larger difference in temperature over the 30-minute operational periods in *Device Present* than *Device Absent* ($p < 1e\text{-}4$) (**Figure 2B**). It is important to note the two outliers in the boxplot (**Figure 2B**). To determine where the outliers occurred in the experimental period, we analyzed each of the three operational periods separately.

There is a change between temperature results for Operational Period 1, Operational Period 2, and Operational Period 3 (**Figure 2C**). One-way repeated measures ANOVA followed by pairwise comparisons with the Bonferroni multiple testing correction method were used to analyze each operational period. For OP 1 and OP 2, the ANOVA revealed a significant interaction effect between the treatment groups on change in temperature ($F(1,6) = [311]$, $p = 2.1e\text{-}6$ and $F(1,6) = [12.0]$, $p = 1.3e\text{-}3$, respectively), with a pairwise comparison of the treatment groups confirming that the change in temperature means between *Device Absent* and *Device Present* were significantly different ($p < 1e\text{-}4$ and $p < .05$, respectively). Furthermore, OP 1 showed a mean change in temperature of 1.0 ± 0.5°C in *Device Absent* and a mean change in temperature of -2.9 ± 0.5°C in *Device Present*. OP 2 showed a mean change in temperature of -0.2 ± 0.9°C in *Device Absent* and a mean change in temperature of -1.5°C ± 0.4°C in *Device Present*. The ANOVA analysis for OP 3 revealed that the interaction effect between the treatment groups did not have a significant effect on change in temperature ($F(1,6) = [1.97]$, $p = 0.2$), with a pairwise comparison of the treatment groups confirming that the change in temperature means between *Device Absent* and *Device Present* were not significantly different ($p > .05$). OP 3 showed a mean change in temperature of -2.2°C ± 2.7°C in *Device Absent* and a mean change in temperature of -3.8°C ± 0.6°C in *Device Present*. The boxplot for OP 3 contained the two outliers (**Figure 2B**). The two outliers occurred on testing days one and three. We observed that at the time the temperature readings were taken for OP 3 on testing days one and three, the temperature outside of the greenhouse dropped due to increased cloud cover. If the outlier data was removed from the data set for days one and three, the statistical results would change to the following: 150-minute experimental period ($F(1,4) = 64.4$, $p = 1e\text{-}3$), 30-minute operational periods ($F(1,18) = [73.6]$, $p = 8.87e\text{-}08$), and Operational Period 3 ($F(1,4) = 64.4$, $p = 1e\text{-}3$).

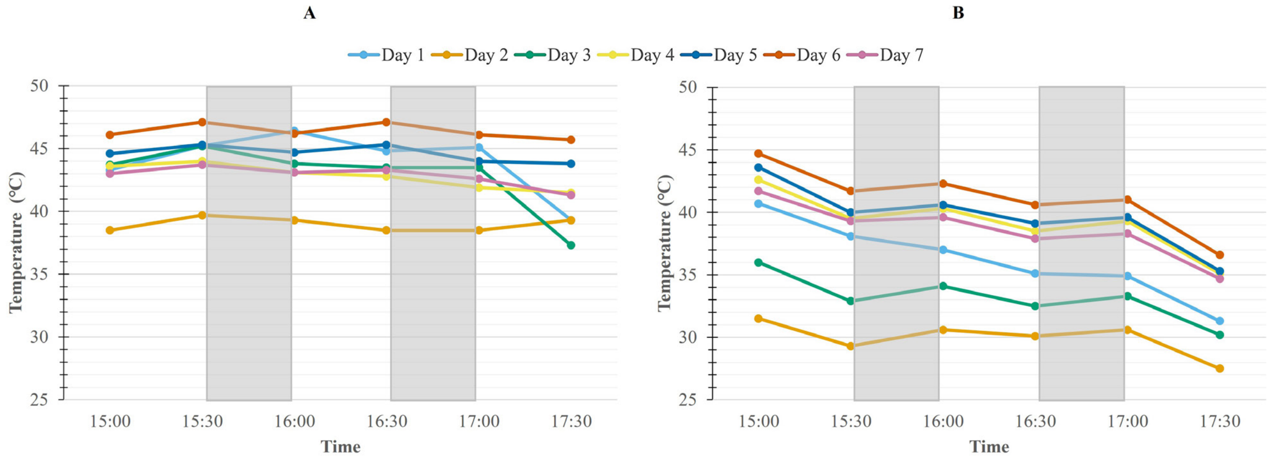

**Figure 1. Change in temperature over seven days of testing** Dehumidification Device absence in *Device Absent* and presence in *Device Present*. Starting and ending temperature points (°C) recorded every 30-minutes with a trend line between each point for a total of 150-minutes for **(A)** *Device Absent* and **(B)** *Device Present*. White columns represent operational periods, while gray columns indicate rest periods.

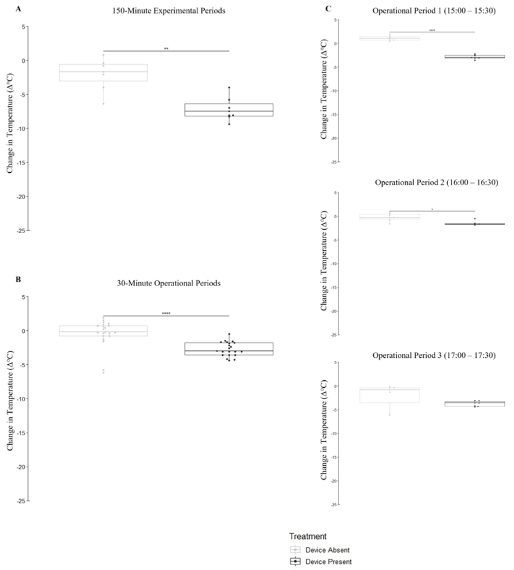

**Figure 2. The effect of the Dehumidification Device on greenhouse internal temperature.** Temperature recordings were taken at the start of the experimental period and at every 30-minute point until the final reading at 150-minutes to determine the change in temperature. Change in temperature results over seven days for **(A)** 150-minute experimental periods (n = 7), **(B)** all 30-minute operational periods (n = 21), and **(C)** each individual operational period (n = 7 for Operational Periods 1, 2, and 3, respectively). Middle quartile lines present the mean. Boxplot whiskers present the standard deviation. *p < 0.05, **p < 0.01, ****p < 0.0001.

## Long-Term Change in Relative Humidity: 150-Minute Experimental Periods

We analyzed the long-term change in relative humidity within *Device Absent* and *Device Present* and subtracted the final relative humidity reading at time 17:30 from the initial relative humidity reading at time 15:00 for each daily 150-minute experimental period (**Figure 3**). A negative change in relative humidity indicated a decrease in relative humidity, and a positive change in relative humidity indicated an increase in relative humidity. *Device Absent* showed a mean change in relative humidity of -1.3% ± 1.9% over the seven-day test period (**Figure 3A**). *Device Present* showed a mean change in relative humidity of -14% ± 3.9% over the seven-day test period (**Figure 3B**). A one-way repeated measures ANOVA revealed a significant interaction effect between the treatment groups on change in relative humidity ($F(1,6) = [58.8]$, $p = 2.6e\text{-}4$). Pairwise comparison of the treatment groups with the Bonferroni multiple testing correction method confirmed the result that the change in relative humidity means between *Device Absent* and *Device Present* were significantly different. There was a significant difference in change in relative humidity means between treatment groups, with *Device Present* revealing a larger decrease in relative humidity over the 150-minute experimental period than *Device Absent* ($p < 1e\text{-}3$) (**Figure 4A**).

## Short-Term Change in Relative Humidity: 30-Minute Operational Periods

We analyzed the short-term change in relative humidity within *Device Absent* and *Device Present* by subtracting the final relative humidity reading for each 30-minute operational period from the initial relative humidity reading for the corresponding 30-minute operational period, for a total of three changes in relative humidity per daily experimental period (**Figure 3**). *Device Absent* showed a mean change in relative humidity of 0.14% ± 1.1% for the 30-minute operational periods over the seven-day test period (**Figure 3A**). *Device Present* showed a mean change in relative humidity of -6.2% ± 3.0% for the 30-minute operational periods over the seven-day test period (**Figure 3B**). A one-way repeated measures ANOVA revealed a significant interaction effect between the treatment groups on change in relative humidity ($F(1,20) = [66.5]$, $p = 8.61e\text{-}08$). Pairwise comparison of the treatment groups with the Bonferroni multiple testing correction method confirmed the result that the change in relative humidity means between *Device Absent* and *Device Present* were significantly different. There was a significant difference in change in relative humidity means between treatment groups, with *Device Present* revealing a larger decrease in relative humidity over the 30-minute operational periods than *Device Absent* ($p < 1e\text{-}4$) (**Figure 4B**).

The 30-minute operational periods were further analyzed by using one-way repeated measures ANOVA followed by pairwise comparisons with the Bonferroni multiple

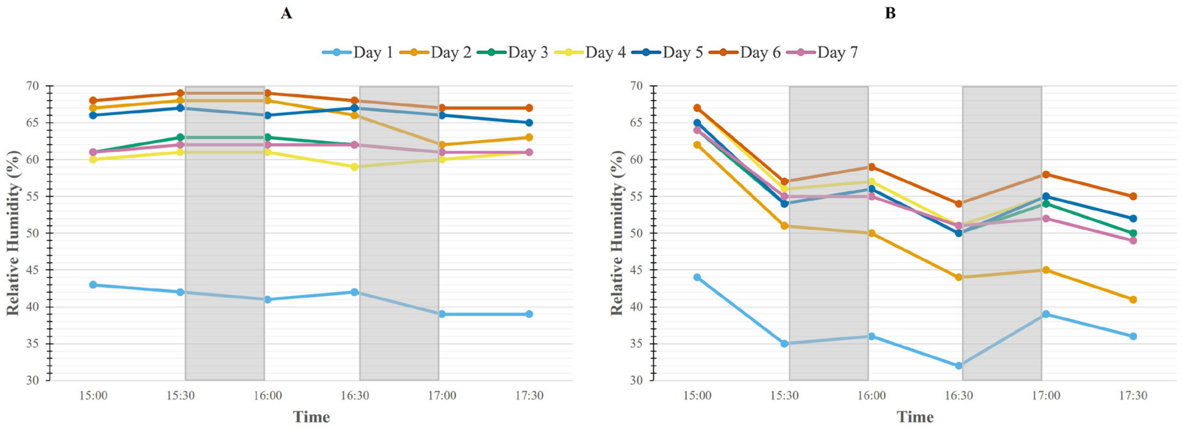

**Figure 3. Change in relative humidity over seven days of testing Dehumidification Device absence in *Device Absent* and presence in *Device Present*.** Starting and ending relative humidity points in percent (%) recorded every 30-minutes with a trend line between each point for a total of 150-minutes for (A) *Device Absent* (treatment) and (B) *Device Present*. White columns represent operational periods while gray columns indicate rest periods.

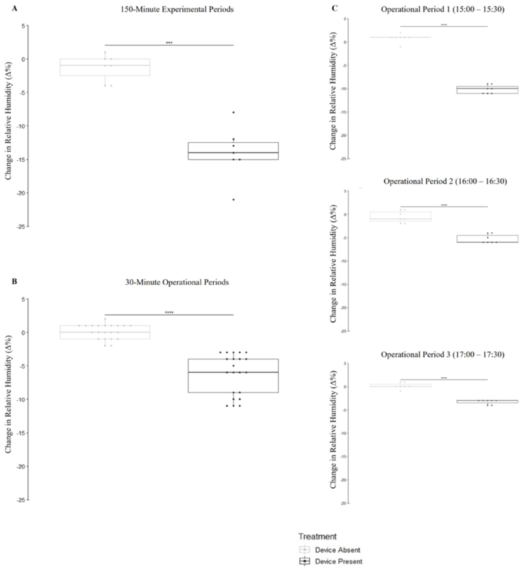

**Figure 4. The effect of the Dehumidification Device on greenhouse internal relative humidity.** Change in relative humidity results over seven days for **(A)** 150-minute experimental periods (n = 7), **(B)** all 30-minute operational periods (n = 21), and **(C)** each individual operational period (n = 7 for Operational Periods 1, 2, and 3, respectively). Middle quartile lines present the mean. Boxplot whiskers present the standard deviation. ***p < 0.001, ****p < 0.0001.

testing correction method to analyze Operational Period 1, Operational Period 2, and Operational Period 3 separately. For Operational Period 1, Operational Period 2, and Operational Period 3, the ANOVA revealed a significant interaction effect between the treatment groups on change in relative humidity ($F(1,6) = [363]$, $p = 1.4e{-}6$; $F(1,6) = [125]$, $p = 3.0e{-}5$; and $F(1,6) = [86.4]$, $p = 8.8e{-}5$, respectively), with a pairwise comparison of the treatment groups confirming that the change in temperature means between *Device Absent* and *Device Present* were significantly different ($p < 1e{-}4$ for all operational periods) (**Figure 4C**). Furthermore, Operational Period 1 showed a mean change in relative humidity of 0.9% ± 0.93% in *Device Absent* and a mean change in relative humidity of -10.1% ± 0.94% in *Device Present*. Operational Period 2 showed a mean change in relative humidity of -0.57% ± 1.3% in *Device Absent* and a mean change in relative humidity of -5.3% ± 0.9% in *Device Present*. Operational Period 3 showed a mean change in relative humidity of 0.14% ± 0.69% in *Device Absent* and a mean change in relative humidity of -3.3% ± 0.49% in *Device Present*.

## DISCUSSION

The parts of the device came out to a total of $126.67. Currently, however, the market cost of industrial greenhouse systems will vary on the scale of hundreds to thousands of dollars depending on the airflow capacity of the system ($m^3$ per hour), its energy efficiency (liters per kWh), air circulation capabilities, as well as the operational requirements of the system influenced by the technology used to run the system (21). One objective of our experiment was to develop an accessible and affordable device that incorporates digital technology and thermoelectric cooling. We created the device using the technology available on the market at a low cost per part. No cost was necessary for labor as the device was put together using standard tools. The device in its current stage is also small enough to be portable, which allows for easy movement of the system around a greenhouse or for transport to different greenhouses. For small-holder farming operations, personal-use greenhouses, or community-use greenhouses, integrating effective and efficient environmental control technology with market-available technology at low cost and with little to no need of a specialist for installation or repair creates an opportunity for cost savings and minimal interruption to operations. The system also does not release toxic products such as fluorocarbons into the environment, making it safe for the environment and the local community.

Having analyzed the economics and implications of a thermoelectric cooling system, we now analyze the temperature and humidity control using thermoelectric cooling. *Device Present* experienced a mean temperature change of -7.16°C over seven days of 150-minute experimental periods and a mean temperature change of -2.71°C over seven days of 30-minute operational periods (**Figure 1B**). We hypothesized that the presence of the Dehumidification Device inside a greenhouse environment would reduce the internal temperature by at least 2°C using thermoelectric cooling, evaporative cooling, and air circulation technology. Our hypothesis was supported by the change in temperature results from *Device Present*'s long-term, 150-minute experimental periods and the short-term, 30-minute operational periods. *Device Absent* did experience a mean temperature change of -2.09°C for the seven days of 150-minute experimental periods (**Figure 1A**), which was likely influenced by the two outlier data points in Operational Period 3 (**Figure 2C**). The external weather conditions at the time of each temperature reading were recorded as increased cloud cover with cooler ambient temperatures compared to earlier in the experimental period, which likely resulted in the decrease in internal temperature in *Device Absent* as the two outliers. In tandem, outliers were not observed during the same operational period for *Device Present*. We believe this was likely due to the presence of the Dehumidification Device and its priming and buffering effect on greenhouse internal temperature from the last two operational periods. Even with the presence of the two outliers for *Device Absent*, the differences in the change in temperature means between *Device Absent* and *Device Present* were statistically significant, as *Device Present* experienced larger changes or decreases in internal temperature over the tested time periods (**Figure 2**).

Next, *Device Present* experienced a mean relative humidity change of -14% over seven days of the 150-minute experimental periods and a mean change in relative humidity of -6.2% over seven days of the 30-minute operational periods (**Figure 3B**). We hypothesized that the presence of the Dehumidification Device inside a greenhouse environment would reduce the internal relative humidity by at least 6%. Our hypothesis was supported by the change in relative humidity results from *Device Present*'s long-term and short-term test periods. In contrast, *Device Absent* maintained changes in relative humidity closer to 0% (**Figure 3A**), which resulted in the change in relative humidity means between *Device Absent* and *Device Present* being statistically significant (**Figure 4**). Importantly, we did not observe any outliers for change in relative humidity that would correspond to the change in temperature outliers found in *Device Absent* during

Operational Period 3 on day one and day three. Even though humidity is directly proportional to temperature, as the above results showed with smaller changes in relative humidity corresponding to smaller changes in temperature in *Device Absent* compared to the larger changes shown in *Device Present*, the lack of outliers in the change in relative humidity data points, in this case, was likely due to a natural lag in relative humidity response to rapid change or a rapid drop in external temperature (and thus internal temperature) during the 30-minute operational period.

With the only difference between *Device Absent* and *Device Present* being the presence of the Dehumidification Device, we can conclude that the significant results for change in temperature and change in relative humidity were due to the presence of the Dehumidification Device in *Device Present* and the absence of the device in *Device Absent*. Additionally, the temperature and relative humidity sensors were placed at the level of the plant canopy, as moisture buildup has been shown to be the most problematic in closely-packed plant canopies. The results in *Device Present* revealed that the device's fans were effective in circulating the cooled and dehumidified air throughout the greenhouse structure at the plant canopy level.

The next steps for device development will be to understand where resistance is occurring in the electronics and improve efficiency to prevent heat buildup. The experimental design of 30-minute interrupted operational periods over the 150-minute experimental period was a result of the Dehumidification Device heating up after 30 minutes of operation. Running the device for consecutive and longer time intervals would allow for a more real-world, application-oriented understanding of the energy efficiency of the device and if the device has the capability to further decrease the temperature and relative humidity in a greenhouse. As the individual operational period data showed, the efficiency of the device changed between Operational Period 1, Operational Period 2, and Operational Period 3 for changes in temperature mean and standard deviation and changes in relative humidity mean and standard deviation. Each operational period had a different starting temperature and relative humidity percentage. There was also the potential of a priming effect impacting the long-term and short-term data from the device operating over three 30-minute operational periods with two 30-minute rest periods between. External climatic shifts also may have had an influence on the results, as shown by the *Device Absent* outliers. As the change in temperature outliers revealed in *Device Absent*, without the buffering capacity of the Dehumidification Device, the internal temperature of a greenhouse could fluctuate dramatically over short periods of time. Thus, additional tests on the device will need to include testing the efficiency of the device based on different starting temperatures and relative humidity percentages and under different external climatic conditions as well as over various time intervals of operation.

Currently, dehumidification practices in greenhouses reduce relative humidity, on average, by 15% at high energy costs and the cost of environmental factors such as plant access to sunlight, the creation of windy conditions that affect plant growth, and uneven temperature distributions (28). The Dehumidification Device was able to significantly reduce the temperature and relative humidity in a greenhouse using low-cost technology and a low-energy and low-waste thermoelectric cooling system. The results of the experiment show the potential for small-holder farmers, communities, and individuals to access effective temperature and humidity control systems at a fraction of the costs of current environmental control systems. With more cost-effective technology, farmers who do not have the economic backing or access to current market-priced environmental control technology can diversify their production system by incorporating greenhouses where they can better control the plant growth environment. The reduction in disturbances by local climate and weather by moving crop production into a greenhouse has the potential to help farmers protect their crops and increase crop yields. Additionally, scaling up the Dehumidification Device to support larger greenhouses seems to have potential as the significant results in the experiment were obtained within a noncommercial, low-cost greenhouse structure and with a handmade device. It is anticipated that under an industrial greenhouse setting and with more precise manufacturing capabilities, the device will increase its efficiency and capability to reduce temperature and relative humidity. With the economic and technological possibilities presented by the results of the experiment, future research will need to incorporate a detailed cost analysis of the energy efficiency, airflow capacity, water extraction rates, and air circulation capabilities of the device compared to systems currently on the market at similar costs of sale. The cooling and air circulation systems of the device should also be expanded for larger indoor spaces to determine the scalability of the system. Finally, future iterations of the device should also incorporate more digital integration technology such as temperature and humidity detectors and thermostat control as part of the system unit.

## Materials and Methods

### Dehumidification Device System

The Dehumidification Device was composed of three cooling systems to dehumidify and cool the air. The three dehumidification systems were connected to power supplies to have a constant supply of voltage. The combined systems cooled the air brought into the chamber by fans (**Figure 5**, #1).

The first dehumidification system was composed of a Central Processing Unit cooler fan (**Figure 5**, #2), Peltier Module (**Figure 5**, #3), and a double heatsink (**Figure 5**, #4). The Peltier Module created a temperature difference of up to 60 °C across its conducting plates, resulting in a cool side and a hot side. The cooling effect of the cool side of the conducting plate was amplified using a double heatsink. The heatsink, due to its metallic properties, cooled the air further and facilitated the condensation of water vapor from humid air. To further increase the efficiency of the Peltier Module, the CPU cooler fan reduced the temperature on the hot side of the conducting plate.

The second dehumidification system was composed of a water cooling and flow system. A water pump (**Figure 5**, #6) pushed cold water through copper coils (**Figure 5**, #8), which facilitated the condensation of water vapor from humid air. The water continued to remain cool as it flowed through an iron cooling block (**Figure 5**, #5) and was insulated with thick plastic tubing (**Figure 5**, #7).

The third dehumidification system was a modification of the first system, composed of a regular fan (**Figure 5**, #9), heatsink separator (**Figure 5**, #10), Peltier Module (**Figure 5**, #11), and a large heatsink (**Figure 5**, #12). The system facilitated the condensation of water vapor from humid air in the same way as the first system, but the heatsink had a larger surface area. Once the air went through the third dehumidification system, the cooled and dehumidified air was pushed out of the device using two cooling fans (**Figure 5**, #13). All three systems were powered by 12-volt power supplies (**Figure 5**, #14). The three units were combined in a custom housing to form the final Dehumidification Device (**Figure 5**, #6).

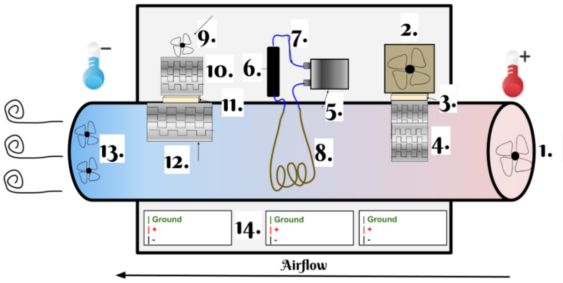

**Figure 5. Schematic diagram of the proposed dehumidification device with its individual components numbered. (1)** front-side fan, **(2)** CPU cooling fan, **(3)** Peltier module, **(4)** double heat sink combination, **(5)** iron cooling block, **(6)** water pump, **(7)** tubing with cold water flow, **(8)** copper coils with cold water flow, **(9)** mini fan for hot air distribution, **(10)** heat sink, **(11)** Peltier Module, **(12)** large heat sink, **(13)** double fans, **(14)** 12 Volt Power supply.

### Experiment Location

The experiment was performed in San Jose, California, from August 18th to August 25th, 2021. The local temperature was over 26°C for the majority of the week with clear skies and sun. August 18th (Day One) and August 20th (Day Three) were the only exceptions to the temperature condition with cloud cover causing a decrease in outside temperature after 17:00.

### Greenhouse Setup

Two identical greenhouses of dimensions 55”×28”×76” were built using thick, high-density polyethylene as the window material and metallic pipes to support the greenhouse. Each greenhouse had three bean plants and one cauliflower plant, each grown in four planter cups, spaced evenly in the greenhouse. The plants were planted and germinated at the same time for consistency. *Device Absent* was set up as the control and did not contain the Dehumidification Device. *Device Present* contained the Dehumidification Device which was placed at one end of the greenhouse on a short stand in order to maximize the dehumidification effect throughout the greenhouse. Both greenhouses were placed next to each other in the same location to ensure each received equal amounts of sunlight. The temperature and relative humidity of each greenhouse were measured using temperature and relative humidity sensors placed in the middle of the greenhouse at the same level as the planter cups or the plant canopy level.

### Initial Humidity Setup

To create similar humidity conditions between *Device Absent* and *Device Present*, each greenhouse was sprayed with the same amount of water. The greenhouses were then sealed and allowed to sit for a day before initial relative humidity readings were taken. The starting relative humidity in *Device Absent* was 43%. The starting relative humidity in *Device Present* was 44%. Additionally, the plants in *Device Absent* and *Device Present* were each given 57 mL of water per day.

### Data Collection: Economics

The cost of each component part of the Dehumidification Device was recorded from prices listed on the Amazon.com marketplace. The list was compiled in June 2022.

### Data Collection: Change in Temperature and Change in Relative Humidity

The device was operated for three 30-minute operational periods with two 30-minute rest periods interspersed between the operational periods for a total experimental period of 150-minutes. The experimental periods were run from 15:00 to 17:30 for seven days of testing. At the start and end of each operational period, the temperature and relative humidity readings were recorded in *Device Absent* and *Device Present*. *Device Absent* contained the treatment group *Device Absent*. *Device Present* contained the treatment group *Device Present*. Once the seven-day experiment finished, the change in temperature and the change in relative humidity data from each treatment group were compared.

### Data Analysis: Change in Temperature and Change in Relative Humidity

The change in temperature data and the change in relative humidity data were analyzed for the long-term, 150-minute experimental periods and the short-term, 30-minute operational periods. The change in temperature and the change in relative humidity for the 30-minute rest periods were not considered. The long-term and short-term data were analyzed using one-way repeated measures ANOVA statistical analysis followed by a pairwise comparison of the treatment groups with the Bonferroni multiple testing correction method using RStudio version 022.02.3+492. The significance cutoff was at 2 significant figures.

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